A palaeo-glaciological reconstruction of the last lrish lce Sheet.

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SECTION D:

Discussion and Conclusions



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Chapter 10. Discussion: the Irish Ice Sheet reconstruction in the context of the Irish literature

10.1 Introduction

Countrywide glacial landform mapping, synthesis and interpretation has driven the development of a new model of the geometry and behaviour of the last Irish Ice Sheet. The reconstruction presented in Chapter 9 is argued to best fit the landform legacy of glaciation. This reconstruction has been based, qualitatively, on assumptions of glacial geomorphological processes and guided by analogues sought from modern ice sheets and other palaeoglaciological work. It stimulates three points for discussion:

- Is the reconstruction compatible with previous interpretations of the glacial record and proposed models of Irish glaciation?
- Is the reconstruction glaciologically plausible?
- What does it tell us about the nature of the ice sheet?

These questions are explored in this final section of the thesis, Section D.

Chapter 10 addresses the first of these questions: how securely does the reconstruction capture the evidence of glaciation, and how does it relate to the interpretations of the record which have previously been proposed? There is an extensive literature concerned with the glacial history of Ireland and the interpretation of glacial evidence. Many elements of this literature – landforms, erratic dispersal properties, stratigraphic relationships - have been fed into the reconstruction process to ensure that all the relevant, available information contributes to the final interpretation. Care has been taken to use reported information as best as possible detached from the interpretation laden upon it by other authors, such that the interpretation reached in this thesis is based consistently upon an objective dataset. It is now interesting to return to examine the compatibility of this reconstruction with earlier conceptualisations of the ice sheet's history. The following discussion is bilateral and asks whether and how the literature supports the new reconstruction, and whether the reconstruction can, in turn, enlighten debates which are, as yet, unresolved in the literature. Chapter 2 discussed the models of the Irish Ice Sheet hitherto invoked in the published literature, in the context of the key elements of an ice sheet which a palaeo-glaciological reconstruction seeks to decipher. In doing so, some fundamental 'unknowns' and key debates within the Irish glacial literature were highlighted. These themes form the basis for the following discussion. Throughout this chapter, the reader is referred to Map 4 for the favoured reconstructed stages of the ice sheet history.

10.2 Traditional ice sheet models

Ice sheet-wide conceptual models of the last Irish Ice Sheet (Figure 10.1) underpin the long history of Irish glacial research. The original ice sheet geometries described by Close (1867) and Hull (1878) manifest themselves in more recent literature through Warren (1992) and

McCabe (1985), and have survived over a century of changing 'fashions' of research and scientific paradigms. However, there are numerous conflicts between the two main models (i.e. Figure 10.1c vs 10.1d) and it has been strongly argued in recent literature and a number of times throughout this thesis that these models are inadequate explanations of the geometry and behaviour of the last Irish Ice Sheet.

The limitations of these ice sheet models are threefold. Firstly, whilst elements of both can be supported by the geological and geomorphological evidence, some of the basic properties of the ice sheet are still poorly understood (Chapter 2, Section 2.2.8). Secondly, not only do the models provide inadequate or insecure descriptions of ice sheet properties, but the two principal models conflict on the representation of almost all ice sheet elements but the major flow paths. There is little consensus on the ice sheet-wide structure, the location of the main ice centres or divides, the ice sheet extent, the behaviour of ice flow paths, and the manner and pattern of deglaciation. Furthermore, it has been argued that overriding conceptual ice sheet models have acted as straightjackets on research (Meehan, 2004), so firmly entrenched in the scientific consciousness that all lines of evidence are automatically explained in light of the model, rather than acting as loose frameworks to be tested critically by newly observed evidence. Debate appears to have hindered, rather than assisted the development of a consensus, and little insight has been offered to reconcile the competing ideas. It is only in the last 10 years or so that detailed observations of the glacial record have been used to re-examine the traditional models of the ice sheet's history, and information has begun to be reorganised into new frameworks (e.g. Knight and McCabe, 1997; McCabe et al., 1998, 1999, 2005, 2007a,b; Knight, 1999, 2003a,b; Clark and Meehan, 2001; Meehan, 1999, 2004; Delaney, 2002).

These arguments were fully outlined in Chapter 2, drawn from a critical review of the Irish literature. The rejection of traditional models is supported by the new landform data and observations presented in this thesis (Chapter 7, Section 7.3). The traditional McCabe model (Figure 10.1d) was rejected both on grounds of its representation of ice sheet extent (Figure 10.2) and the main ice axis position (Figure 10.3). The coastal region shown in Figure 10.2 is overwhelmed by ice from Stages IIIb to IV (the maximum period of glaciation), whilst the 'false divide' position rejected in Chapter 7 is instead interpreted as the product of an ice divide migration, moving first towards the east (Stage II - IIIb) and subsequently back towards the west (Stage IV - Va). Finally, both of the traditional models (Figures 10.1c and 10.1d) were falsified in Chapter 7 on the basis of their representation of ice flow patterns. Common to both of these models is the regionally generalised representation of ice flow evidence. This approach was argued to be flawed since it assumes contemporaneity of all landform evidence. Whilst flow *patterns* documented by the mapping conducted in this thesis were shown to successfully match previously identified ice flow paths (Sections 5.4 and 7.3), the assumption of synchronicity has been undermined by implausible flow geometries and landform superimposition (Figure 10.4). It is argued that regionally generalised ice flowlines are a poor method of data generalisation. Instead, a flowset approach which maintains the spatial and



Figure 10.1 Traditional models of the last Irish Ice Sheet. The original conflict between a) Close (1867) and b) Hull (1878) has persisted and propagated through 140 years of literature, to manifest itself between c) Warren and Ashley (1994) and d) McCabe (1985). A multi-domed structure with considerable offshore extent competes against a more spatially limited and single-axis ice sheet. These conceptual models underpin the Irish glacial literature.

temporal information yielded by the landform record has assigned different flow patterns to temporally separated ice sheet geometries and, in so doing, has revealed a pattern of ice sheet evolution.



Figure 10.2 The distribution of glacial landforms in the south-east of Ireland requires modification to the model of limited ice extent (Synge and Stephens, 1960; Synge, 1969, 1970, 1979; McCabe, 1985). A model of a more extensive ice sheet is favoured by a number of other workers (e.g. Warren, 1992; Warren and Ashley, 1994; Gallagher and Thorp, 1997; McCabe, 1998; Bowen *et al.*, 2002; Hegarty, 2002; Kilfeather, 2004; Ó Cofaigh and Evans, 2007).



Figure 10.3 The position of a single ice divide (e.g. McCabe, 1985) is rejected on the grounds that it is a 'false divide'. Its interpretation is based upon landform divergence, but landform genesis cannot occur so close to a divide position. Scale: gridmarks at 20 km.



Figure 10.4 Lineation superimposition and cross-cutting (a), and implausible flow geometries (b – from ribbed moraine patterns) falsify a 'generalised flowlines' approach to ice sheet reconstruction and argue for a multi-temporal explanation of ice flow patterns. Scale: 5 x 5 km grid.

The fundamental problem with the traditional ice sheet models is their representation of time. In Chapter 7 it was shown that whilst flow *patterns* were consistent between the literature and the newly collected data, it is their arrangement in *time* which has not hitherto been captured. New descriptions of an *evolving* ice sheet geometry have emerged in the literature over the last 10 years. These are typically based upon regional-scale analysis of the glacial record (e.g. McCabe *et al.*, 1998, 1999, and the subsequent body of work; and Clark and Meehan, 2001) but are yet to be scaled up to consider the whole ice sheet. Furthermore, neither of these new models addresses all basic ice sheet properties. McCabe *et al.* (1999) describe a sequence of flow patterns, and attempt to set these in both a relative and absolute chronology (e.g. McCabe, 2005, 2008). Clark and Meehan (2001) reconstruct changing ice flow patterns, their requisite ice divide locations, and a relative chronology of events. Neither model considers ice sheet extent nor the manner and pattern of ice margin retreat; both cover the same, regionally limited area of the last ice sheet. Since these are partial reconstructions, specific elements are discussed in the relevant sections of this chapter. The new ice sheet reconstruction presented in this thesis aims to address (at least partially, even if comprehensive conclusions cannot be drawn) all fundamental ice sheet properties, and the discussion considers each element accordingly in relation to the existing literature: ice divide, or source locations, ice extent, ice flow patterns, retreat patterns and a chronology for the evolution of the ice sheet.

10.3 Ice divides

A lack of consensus concerning the disposition of centres of ice dispersal is closely tied to the competing, overriding ice sheet models. It is difficult, therefore, to assess the new reconstruction in terms of literature support for its representation of ice divides and ice sheet structure, since the literature itself is conflicting. Instead, the new reconstruction can be used to explore the key problems which have previously been encountered. Two fundamental debates regarding the understanding of ice centre locations arose from the discussion of the Irish glacial literature in Chapter 2:

- A single axis of dispersal versus a multi-domed ice sheet?
- Mountain versus lowland ice sources?

These two questions are considered in light of the new ice sheet reconstruction.

10.3.1 Single axis vs multi-domed: ice sheet reorganisation & ice divide migration

Elements of both conceptualisations of the ice sheet structure receive some support from the physical record, which partly explains why the two competing models have persisted. Landform divergence across the central lowlands and from Lough Neagh has been used in support of a single axis model, with a northern branch axis passing south of the Sperrin Mountains (Hull, 1878; Synge and Stephens, 1960; Synge, 1970; Colhoun, 1970, 1971; McCabe, 1985; Knight *et al.*, 2004). The two major esker systems of Ireland, across the central lowlands and across Cos. Mayo and Roscommon, are argued to require a more substantial western source than the single axis model can accommodate, and instead support a multi-domed ice sheet model (Warren, 1992; Warren and Ashley, 1994). The two competing models of ice sheet structure therefore stem largely from different lines of evidence, and it is not altogether surprising (or, at least, it is understandable) that workers have arrived at different conclusions.

The reconstruction which emerges from this research reveals elements of both styles of ice sheet structure. However, they operate separated in time, and the ice sheet is revealed to change its structure throughout its evolution. The build-up and maximum phases see the establishment and evolution of a main axis system, with northern and southern branched, subsidiary divides. This configuration, in a broad sense, persists from Stage II to Stage IV. During deglaciation, the ice sheet structure is revealed to change. Stage V of the new reconstruction reveals the fragmentation, or uncoupling of the ice sheet into separate domes. The main axis must break for this to occur, and the ice sheet reorganises from a main axis structure to a multi-domed system. Different landform assemblages with different glaciodynamic contexts reveal different ice sheet structures. This is best explained by the separation of the landform evidence into different temporal stages, and interpreting reorganisation of the ice sheet.

Not only are the broad phases in the ice sheet's history characterised by a different ice sheet structure, but ice divides are revealed to migrate within these overriding periods. During the period of a main axis structure, particularly from Stages II to IIIb, the main axis must migrate from west to east in order to capture the divergence of landform and sediment dispersal patterns from an apparent axis across the central lowlands. Under the assumptions of landform genesis employed in this reconstruction these flow patterns cannot be assimilated into a single configuration as preferred by the traditional McCabe model. Therefore, all of the different positions which have been invoked for the single axis (Hull, 1878; Kilroe, 1888; McCabe, 1985; see Figure 10.5), whose variety was argued by Charlesworth (1924) to undermine the whole model, can be accounted for simply by allowing the ice divide to migrate.



Figure 10.5 Charlesworth (1924) argued that the variety of axis positions purported to have been inferred from the same evidence undermined the single axis ice sheet model. Each of these ice divides can be accommodated in a model of ice divide migration.

Specific ice centres identified in previous literature are captured during some, but rarely all of the reconstructed stages in the ice sheet's history. A divide may, at certain times, lie over a predicted centre of ice dispersal but, at other times, migrates away from it. Central Tyrone, south of the Sperrin Mountains, has been widely cited as a centre of ice dispersal, the northern branch of the single axis model (e.g. Colhoun, 1970, 1971; Colhoun *et al.*, 1972; McCabe *et al.*, 1978; Knight, 2003b). A sub-divide is reconstructed in such a position during Stages II, IV and VI; it is clear that this region has experienced a fluctuating divide which likely swung northwards and southwards at various times. Co. Donegal has been suggested by many to

support a centre of dispersal (e.g. Charlesworth, 1924; McCabe, 1985; Ballantyne *et al.*, 2007); the region holds an ice divide to some extent throughout the glaciation. Finally, Lough Neagh has long been thought to be the site of an ice centre (Synge and Stephens, 1960; Synge, 1970; Hill and Prior, 1968; McCabe *et al.*, 1999; Knight *et al.*, 2004). The interpretation of divergent landform patterns which leads to this conclusion has been rejected on the grounds of a 'false divide interpretation' but, nonetheless, the importance of this area as a hinge point for ice divide migration is indirectly revealed by the reconstruction.

A new conceptualisation which interprets the record in the context of migrating ice divides and changing structures helps to reconcile the dichotomies in the previous literature, allowing well-supported elements of both models to be captured in a single, but evolving ice sheet reconstruction. Migrating ice divides are not a new phenomenon, but widely recognised from other palaeo-ice sheet reconstructions (Boulton and Clark, 1990a,b; Clark, 1993; Clark *et al.*, 2000; Kleman *et al.*, 1997; Boulton *et al.*, 2001). Furthermore, as a concept, ice divide migrations have been previously suggested to explain elements of the Irish glacial record.

Synge (1970) predicted a west-east-west shift in the main axis to explain the shape and configuration of moraines (his Drumlin Readvance Moraine, or Fedamore moraine, and the SIEM, or Ballylanders moraine). Whilst these moraines, and perhaps Synge's related logic for ice divide migrations can be questioned, this sequence of ice axis movement is exactly what has been reconstructed here using bedforms as the primary unit of reconstruction. Knight (2003a,b, 2006a) has reconstructed a change in ice divide position through 180° around Omagh Basin, implying the reorganisation of the ice sheet between two episodes of landform genesis. The sequence Knight invokes is also captured here: a source NE of Omagh Basin in Stage III, followed (albeit separated by other ice sheet geometries) by an ice divide positioned to its SW in the final stages of decay, Stage VII.

Clark and Meehan (2001) are the first to explicitly describe the scale and pattern of ice sheetwide divide migrations in Ireland. They invoke a 120 km east to north-west migration of a single ice divide, to account first for west coast flowsets and subsequently for the main bedform belt of the north-east midlands (Figure 10.6). The divide is initially positioned over the eastcentral lowlands, and moves to a location approximately linking the Sperrin Mountains and Donegal Bay. A similar interpretation of the same flow patterns is made here (Stage IIIb – V), and this migration is set in context with a full ice sheet-wide reconstruction. This migration is revealed to be the last major geometric change before a wholesale reorganisation of the ice sheet's structure from a single entity into its component domes (Stage Vb – c).

10.3.2 Mountain vs lowland ice centres

The question of mountain versus lowland centres of ice dispersal relates closely to the question of a single axis or a multi-domed ice sheet. A single axis model positions the ice divide across the central lowlands, whilst those who invoke a multi-domed ice sheet typically envisage domes



Figure 10.6 A major migration of the main ice divide identified by Clark and Meehan (2001) is supported by, and supports the reconstruction derived here from the countrywide glacial landform record. The Clark and Meehan divide movement is set in the wider context of the evolution of the last Irish Ice Sheet. Here it is interpreted that the divide position over the east of Ireland occurs early in the maximum period of glaciation; the divide shifts to the north-west at the start of deglaciation.

developing over the major mountain groups of Ireland. Charlesworth (e.g. 1924, 1939) saw the single axis model of the Irish Ice Sheet as a paradox; he could not reconcile ice nucleation in mountain masses, where precipitation is enhanced and temperatures lower with elevation, with a model of ice sheet outflow from lowland regions (e.g. Synge, 1969, 1970; see Chapter 2). The reconstruction presented here contributes to, and may help to reconcile this debate.

The section above, 10.3.1, has described the reorganisation of the ice sheet structure from a single axis to a multi-domed model. Landform evidence is undoubtedly consistent with a main axis positioned over the central lowlands of Ireland, and such a configuration is reconstructed from Stages II – IV. However, it is also most likely that the ice sheet decays to (and locally builds up from?) mountain groups, particularly those of the west coast of Ireland: in Donegal, Leitrim, Connemara, and Kerry (Stages VI - VII). Throughout the glaciation, even when the ice sheet is structured around a main axis, the major mountains groups tend to 'hold' or 'pin' the branched sub-divides reasonably steadily. The Donegal mountains hold the northern branch axis

in some way through all reconstructed stages of the ice sheet's history, apart from the period of maximum glaciation (Stage IV); Connemara supports either the end of an ice divide or an independent dome both early and late in the glaciation.

Charlesworth's 'paradox' is in a fact a common feature of palaeo-ice sheets: in Fennoscandia the LGM ice divide is positioned far to the east of the Norwegian mountains, over the Gulf of Bothnia (Kleman et al., 1997); in Britain, the Rannoch Moor basin is a major dispersal centre of the ice sheet (Sutherland, 1984); and the Laurentide Ice Sheet deglaciates to a Keewatin dome situated over the lowlands bordering the west of Hudson Bay (Boulton et al., 1985). Payne and Sugden (1990) examined the relationship between topography and ice divide location, and expressed through modelling a qualitative concept that reconciles the apparent problem. They demonstrate that whilst mountains, or areas of high relative relief, may serve as ice nucleation points, if ice advances out of the mountains into an enclosed basin, then this basin must become a site of accumulation. Ice can only build upwards since it cannot be easily discharged, and the basin can rapidly turn from a sink to a source of ice dispersal. Ireland's broad morphology resembles a basin, and therefore an axis of ice dispersal positioned over the central lowlands is a likely product of inward ice growth from peripheral regions. Using a modelling medium, which is structured around a sequence of time-steps, the role of time is inherently much better acknowledged and expressed than using a geological approach. Changing behaviour, ice sheet geometry and ice sheet structure throughout its evolution is easily incorporated and understood. Such changes are more difficult to recognise from a geological approach, which must interpret a composite record of the entire glaciation. Different interpretative schemes have likely promoted different models of glaciation; disentangling the composite record in light of its multi-temporal nature helps to reconcile such conflicts.

10.4 Ice extent

There has been a full circle evolution of ideas regarding the extent of the last Irish Ice Sheet. When a model for the ice sheet was first proposed in the late 19^{th} century, passage of ice onto the continental shelf was envisaged (Close, 1867; Hull, 1878). Morphological and sedimentological observations onshore led a number of workers to refine these early models and propose only a limited extent of ice, leaving some coastal peninsulas and much of southern Ireland ice free during the maximum periods of the most recent glaciation (Carvill Lewis, 1894; Charlesworth, 1928; Synge and Stephens, 1960; Stephens and Synge, 1965; Synge, 1969, 1970). In recent years ideas have returned full circle, to extensive continental shelf glaciation (e.g. Warren and Ashley, 1994; Scourse *et al.*, 2000; Knutz *et al.*, 2001; Bowen *et al.*, 2002; Sejrup *et al.*, 2005; Stoker *et al.*, 2006; Bradwell, *et al.*, 2008 in press; Ballantyne *et al.*, 2007, 2008). The reconstruction presented here is in accordance with the most recent ideas of extensive glaciation. It can contribute to the two key discussion points raised in Chapter 2:

- the significance of the 'Southern Ireland End Moraine', once thought to represent the maximum limit of Midlandian glaciation
- the offshore extent of the last ice sheet.

10.4.1 The SIEM

There are two lasting 'unknowns' or controversies regarding the Southern Ireland End Moraine, the long-regarded limit of the last Irish Ice Sheet. Firstly, its continuity, or lack thereof, across the country from west to east coast. Secondly, the significance of any such ice limit: a maximum limit or recessional standstill line?

The landform mapping presented in Chapter 6 did not identify any continuous moraine along the proposed path of the Southern Ireland End Moraine. The only strong evidence for any part of such a moraine is found in Co. Limerick, where arcuate moraines record the splaying of the terminal zone of an ice sheet over the plains, bounded by surrounding high terrain. However, whilst little direct evidence has been found to support a continuous *moraine* across the country, a ~synchronous ice sheet limit has been reconstructed which follows the approximate line of the so-called SIEM. East of the Limerick moraines ice-marginal landsystems are inferred based on the disposition of subglacial lineations and meltwater landforms, particularly eskers. In the reconstruction presented in Chapter 9 these landform assemblages are attributed to the same stage of the ice sheet's history (Stage Va – Vb) and individual ice margin positions are linked to interpret an approximately synchronous ice sheet limit (Figure 10.7).



Figure 10.7 Moraines have only been observed at the western end of the proposed SIEM ice limit (a). However, across the country ice-marginal landsystems are interpreted along the approximate line of the SIEM, and the retreat pattern presented in Chapter 9 (Figure 9.21) links these assemblages with those bounded by the Limerick moraines (b) (solid lines are evidence-constrained margin positions, dashed lines speculate how these margins link spatially). This ice margin geometry is assigned to Stage Va, in which the ice sheet terminates at a SIEM-type limit during the first major landforming period in deglaciation (c).

There is clearly more to the SIEM debate than simply the presence or absence of a moraine. Moraines have been found to be largely absent, both here and in other studies (e.g. Hegarty, 2002a, 2004; Kilfeather, 2004), but the proposed limit undoubtedly bounds ice-marginal landsystems, and represents a plausible shape for a terrestrial ice sheet limit, with lobes splaying in between higher ground. Moraines are restricted to its western end. This difference in the composition of the marginal landsystem may relate to differential sediment delivery to the margin, or the length of time for which the margin was pinned at a particular standstill point. Potentially, moraines only developed in the west because the margin rested here for a longer period. This interpretation is consistent with the reconstructed dynamics of deglaciation, in which the eastern end of the margin must withdraw at a faster rate, the western end acting as a

hinge on the pattern and direction of ice margin retreat.

The significance of this potential ice sheet limit is a separate question. Based on a critical literature review (Chapter 2) and new observations of the glacial record (Chapters 5 & 6), the SIEM has been rejected as a maximum limit of the last glaciation (Chapter 7). Subglacial bedforms and meltwater landforms continue south of the limit, with little apparent perturbation to their morphology (here, and Hegarty, 2002a, 2004; Kilfeather, 2004), there is no sedimentological basis for distinguishing glacigenic deposits of separate glaciations, and there is good evidence for the passage of ice over the south coast onto the Celtic Shelf during the last glacial period (see Chapter 2, Section 2.2.3 for references and discussion of this literature). Instead, this new reconstruction attributes a SIEM-type limit to Stage Va, the first major halt in the deglaciation of the ice sheet and the first position in which the ice sheet has deposited a recessional moraine during its retreat onshore from the continental shelf. This interpretation is consistent with a growing consensus that the SIEM more likely marks a recessional standstill position than a maximum ice sheet extent (Warren, 1991; McCabe and Ó Cofaigh, 1996; McCabe, 1998; Ó Cofaigh and Evans, 2007). The absolute timing of such a standstill remains open to debate. The more widely accepted view interprets the SIEM as a marker of retreat from the continental shelf sometime after a maximum position at the 'LGM'. Bowen et al. (2002) instead argue that the maximum extent of the ice sheet occurred much earlier, at approximately 40 cal ka, and the SIEM represents the limit of ice at the conventional 'LGM'. This debate remains active and is considered further in Section 10.7, below.

10.4.2 Continental shelf glaciation

Glaciation of the continental shelf of the British Isles is now a generally accepted model of the last glacial period. A limitation of the reconstruction interpreted in this thesis is the absence of offshore data with which to constrain the extent and dynamics of ice on the continental shelf. To achieve a first-order reconstruction of the ice sheet history this limitation is not deemed to be too severe. It is argued that the majority of first-order ice dynamics will leave an imprint in the onshore record, and a reconstruction may require some future refinement in light of lower-order dynamics which are evident closer to the margin. A by-product of this data limitation is we can only make strong inferences about the geometry and style of continental shelf glaciation; specific ice sheet limits, or flow patterns, cannot yet be critically evaluated.

The evidence documented in this thesis, and interpreted in terms of an ice sheet reconstruction, is consistent in virtually all ice sheet sectors with the offshore passage of ice. Furthermore, the majority of flowsets which feed offshore exhibit a glaciodynamic context unrelated to margin retreat or proximity to the ice margin. We can therefore hypothesise that where such flowsets pass offshore – the western coastal embayments, Co. Clare, Co. Waterford, north Co. Donegal – the ice margin was *not* close by. These flowsets have been reconstructed within Stages II, III and IV of the ice sheet history presented in Chapter 9, and margins for these respective ice sheet stages have been inferred to be located some distance away from the present-day coast.

Not only do a number of flowsets feed offshore, but other elements of the reconstructed ice sheet geometries specifically *demand* offshore ice cover. During build-up Stage II and during the first reconstructed stage of deglaciation, Stage V, an ice divide is located towards the western coast of Ireland. The implication of these positions is that either the ice sheet profile falls very sharply to a land, or nearshore terminating western margin, which is difficult to reconcile with the extent of the eastern margin in both stages as far as the ISB coast; or, more plausibly, we must invoke extensive shelf glaciation to maintain approximate profile symmetry. Continental shelf ice cover is required yet the ice sheet during the relevant stages is not at its maximum extent. One would expect ice to remain in and expand across the shelf region throughout the maximum period of glaciation.

Actual offshore margin positions remain unclear, and this reconstruction cannot shed further light on this question. Insights yielded by the available offshore information previously reported in the literature (e.g. western moraines - Sejrup *et al.*, 2005; offshore sediment fluxes - Knutz *et al.*, 2001, 2002; Peck *et al.*, 2007; Celtic Sea limit - Scourse *et al.*, 1991; Scourse and Furze, 2001; Hiemstra *et al.*, 2006; Ó Cofaigh and Evans, 2007) were incorporated into the inversion model for ice sheet reconstruction in the manner outlined in Sections B and C of this thesis. The reconstruction is therefore compatible with these predictions of extensive continental shelf glaciation. Independent of this information, onshore landform assemblages demand continental shelf glaciation and suggest it was more extensive than merely a limited ice cover with nearshore margins. These two sources of information are mutually compatible.

10.5 Flow patterns

The general patterns of ice flow have long been known in Ireland (from Close, 1867; Hull, 1878; see Chapter 2), and are largely in accordance with the mapping conducted in this thesis (Chapters 5 and 6, see Sections 5.4, 6.3.2 & 6.4.2). Two key issues which the Irish literature has yet to resolve were discussed in Chapter 2:

- a greater complexity of flow patterns is revealed at the local and regional scale than is commonly discussed in the context of ice sheet-wide models
- the behaviour, or the dynamics of flow patterns has only recently received attention, as the glaciologically important role of ice streams has come to light.

These issues are discussed below in the context of the new ice sheet reconstruction.

10.5.1 Flow patterns

At the final, rather abstracted level of interpretation, the flow geometries of the reconstructed ice sheet stages broadly reflect literature models of ice flow paths (see Section 9.4 & Map 4). At the intermediate level of abstraction, the complexity and the contradictions inherent to previous literature discussion of ice flow patterns has been documented here in the form of landform overprinting and geometrically incompatible flowsets. It has been argued in above sections that the reconciliation of conflicting ideas regarding ice divide positions or ice sheet structure is an outcome of a multi-temporal interpretation of the glacial record. Flow pattern incompatibilities are the explicit evidence of such a multi-temporal record.

The treatment of a temporal element in the geological record of glaciation has varied through the body of literature, from commenting on but subsequently omitting from an ice sheet model (e.g. Close, 1867; Kinahan and Close, 1872; Farrington, 1936; Warren, 1992), to specifically assigning to a different glaciation (e.g. Farrington, 1954; Synge and Stephens, 1960; Synge, 1970; Stephens *et al.*, 1975; McCabe, 1985), to assigning to a different phase in the same glaciation (e.g. Hill and Prior, 1968; Hill, 1970; Knight and McCabe, 1997; McCabe *et al.*, 1999; Clark and Meehan, 2001; Knight, 2003a,b). It is perhaps the case that contradiction of interpretations between different workers is a key indicator of a landform assemblage which cannot, and perhaps should not be interpreted as the product of a single, simple flow pattern. The recognition of a multi-temporal record is an important step in untangling the complexity of ice flow patterns into more coherent stories of the ice sheet history.

Eleven stages or sub-stages of the history of the last Irish Ice Sheet have been reconstructed in this thesis. Such division of the glacial record is necessary in order to avoid the assimilation of incompatible ice sheet sectors, or incompatible individual flowsets, into apparently contemporaneous ice sheet configurations. An ice sheet model whose geometry evolves through the glacial period allows some of the conflicting flow evidence described in Chapter 2 to be reconciled: the cross-cutting of eskers (Stage Vc) upon lineations (Stage III) in Cos. Mayo and Roscommon (e.g. Warren, 1992; Warren and Ashley, 1994); the south-easterly dispersal of erratics (Stage II, also Stage Va-b) and the south-westerly landform indicators (Stage IV) in Co. Clare (Farrington, 1965; Simms, 2005; Farrell et al., 2005); the distribution of Scottish erratics across north-east Ireland (Stage I) and landforms emanating from Irish sources (Stages IV - V) (Charlesworth, 1939; Hill and Prior, 1968; Hill, 1970, 1973; McCabe et al., 1999). As a consequence of this separation of evidence into ice sheet stages, it will be noted that several stages presented in Chapter 9 and on Map 4 are based solely on one or two ice sheet sectors. Not all sectors of all stages have left a legacy of their ice flow patterns. This raises important questions of processes of landform generation and preservation, which are returned to in Chapter 11. Nonetheless, ice flow patterns can clearly be much better understood when their temporal component is pulled apart from their spatial component.

10.5.2 Flow behaviour: sheet or stream flow?

As a first level of trying to understand the dynamics of individual ice flow patterns, flow behaviour is most easily characterised as either sheet or stream flow of ice. Ice streams have a considerable control upon the dynamics and stability of the wider ice sheet, and to understand the behaviour of the ice sheet as a whole, it is necessary to identify and evaluate the evidence for ice streams in the palaeo-record (e.g. Stokes and Clark, 1999; Clark and Stokes, 2003; Winsborrow *et al.*, 2004). Flow behaviour, as sheet or stream flow, has been relatively little considered hitherto in the Irish glacial literature (see Chapter 2, Section 2.2.4.3). McCabe *et al.* (1998) and Knight *et al.* (1999) discuss palaeo-ice streams on the east coast of Ireland, as part of

the 'drumlin belt' landsystem, and there is a relatively well-founded assumption that ice funnelled through the Irish Sea Basin flowed at ice streaming velocities. In the reconstruction presented in Chapter 9, ice streams characterise the maximum phases of glaciation. An onset/tributary system is firmly reconstructed feeding the western coastal embayments (the Western Bays ice stream), and an ISB ice stream and North Channel ice stream are consistent with the maximum period ice flow geometries. Clearly there is a variable level of agreement and consistency between the literature models of ice streaming and that proposed here.

10.5.2.1 East coast ice streams?

McCabe, Knight and colleagues (McCabe *et al.*, 1998; Knight *et al.*, 1999) propose the operation of ice streams on the east coast of Ireland (Figure 10.8a). Lateral spatial transitions in bedform morphology have, indeed, been noted in this area. A sector of more elongate lineations and more heavily modified ribbed moraine can be identified where Knight *et al.* (1999) interpret their Cavan ice stream, and some sub-flowset level convergence of ice flowlines occurs along their Armagh ice stream. There is, however, no evidence to support their Bannbridge ice stream (Figure 10.8b). Drumlins are short, do not possess a high parallel conformity, no lateral boundary to this apparent ice stream track can be found in the morphological record, and drumlins appear to respond strongly to the topographic barrier presented by the Mourne Mountains. Multiple flowsets are interpreted in this region; the one most relevant to the Bannbridge flow path is in fact interpreted as a signature of ice thinning during deglaciation, and its increased response to the surrounding topography.



Figure 10.8 a) ice streams cited by McCabe *et al.* (1998) and Knight *et al.* (1999) (figure modified from McCabe *et al.*). Some lateral variability in landform morphology has been observed, but these proposed routes are not convincing candidates for palaeo-ice streams on the basis of their geomorphology. The path of the Bannbridge route (b), in particular, is dominated by ribbed moraine and drumlins of very low elongation. This flow pattern does not equate to an ice stream imprint. Scale for b: gridmarks at 10 km.

A number of problems with an ice stream interpretation for east coast landform assemblages were raised in Chapter 2, most notably the association of drumlin genesis with ice stream dynamics. Where ribbed moraine have been drumlinised to a greater degree, faster ice velocities have been invoked (Knight *et al.*, 1999). Taken to its logical conclusion, this genetic association

would imply that wherever drumlins occur, ice streaming must be invoked for their genesis. Given the considerable flux of ice discharged through such arteries, and the considerable distribution of drumlins in Ireland and elsewhere, this interpretation is implausible: an ice sheet could not sustain such fluxes. The independent landform mapping conducted herein, and the associated ice sheet reconstruction, does not find support for the ice streams proposed by McCabe, Knight and colleagues on the east coast. When judged against the landform imprints of other palaeo-ice streams (e.g. Clark, 1993; Stokes and Clark, 1999, 2001, 2003; Shipp *et al.*, 1999; Winsborrow *et al.*, 2004; De Angelis and Kleman, 2005, 2007; Sejrup *et al.*, 2003; Ottesen *et al.*, 2005; Everest *et al.*, 2005) these proposed routes in eastern Ireland are not convincing candidates. The term *ice stream* possesses a specific meaning and implication for ice sheet dynamics, and the evidence is not considered sufficiently strong to invoke such an interpretation in this reconstruction. Rather than ice streaming, an interpretation of lateral variability in flow behaviour within the overriding flowset is preferred.

10.5.2.2 Western Bays ice stream?

Export of ice through the bays of the west coast has been known since the early models of Close (1867) and Hull (1878). However, ice streaming has not previously been invoked for the inscription of these landform assemblages. The landforms here have received little attention in recent years with respect to their glaciodynamic interpretation, the focus being instead directed at the eastern bedform belt. Good evidence has been documented in this thesis for the presence of a palaeo-ice stream network feeding the region offshore from the west coast bays.

Across Cos. Mayo and Roscommon, lineations elongate within a short distance along a flowline, to a scale comparable to mega-scale glacial lineations (see Chapter 5). Flowlines converge towards the gap in the Ox –Nephin mountains at Foxford, and it is hypothesised that this system continued to export ice through Killala Bay on the north Mayo/Sligo coast. Through Sligo Bay and Donegal Bay, ice has clearly been funnelled, the landform imprint is strong, drumlins are by no means short, and they display high parallel conformity. When the whole west coast system is viewed as one (which the temporal rules of Chapter 8 allow), a larger ice stream tributary system or network emerges.

The alternative interpretation of this funnelled tributary system would assign all flowsets to a deglacial period. The landforms funnelled through the coastal bays would instead be interpreted as the imprint of lobes which retreated onshore through the bays during deglaciation. This scenario cannot be conclusively ruled out on the basis of the geomorphological record. Indeed, it is likely lobes did retreat through these bays (see reconstructed retreat map, Figure 9.21). However, low ground surrounded by high terrain will always be favoured as a route of ice discharge, be it during the build-up, maximum or deglacial phases of the ice sheet history. If the landform record is considered as a multi-temporal composite of the whole glacial period, then a scenario is allowed in which one suite of bedforms can relate to a particular phase of the glaciation, and is not necessarily coeval with the deglacial pattern which is inferred to proceed

in the same way. The bedforms which are interpreted as ice stream tributaries have few associations with deglacial landform assemblages. There are no eskers aligned with the flowsets and lineations display high parallel conformity. The few moraines and the meltwater channels which border these flowsets likely relate to deglaciation through the same outlets as the earlier streaming ice flow. Furthermore, some flowsets are cross-cut by other ice flow geometries, which is inconsistent with their interpretation as a record of the late-stage deglaciation of topographically constrained lobes. A system of ice stream tributaries is therefore favoured, which has not previously been recognised in western Ireland.

10.5.2.3 Offshore ice streams: the Irish Sea Basin & the North Channel – Malin Shelf? It was argued in Chapter 9 (Section 9.4.2.2) that both the Irish Sea Basin and the North Channel – Malin Shelf system are prime candidates for British-Irish Ice Sheet ice streams. Both are deep troughs, located at a point of confluence of ice flow paths and likely to receive ice from both the British and Irish sectors of the ice sheet. Ice would flow over soft, deformable marine sediments, likely to calving margins which would promote the rapid drawdown of ice from the ice sheet interior. The large Barra-Donegal Fan which has accumulated at the break of the Malin Shelf is a key indicator of the concentrated discharge of ice and sediment, with higher fluxes than elsewhere along the shelf edge where no such accumulation exists, and/or for a longer period of time. Indeed, punctuated discharge events have been identified in a long piston core from the Barra Fan throughout the maximum and deglacial periods of the last glaciation (Kroon *et al.*, 2000; Knutz *et al.*, 2001). In every other continental shelf trough and for every other glacial fan along the NW European margin, an ice stream has been inferred (Ottesen *et al.*, 2002, 2005; Nielsen *et al.*, 2005; Sejrup *et al.*, 2005; Stoker *et al.*, 2006a,b; Figure 10.9). It is unlikely that the North Channel – Malin Shelf – Barra Fan system would be any different.

There is little direct flow evidence of ice streaming via these routes. However, ice streams in the North Channel and Irish Sea Basin emerge as likely products of the reconstructed ice sheet geometry given the convergence of flowlines between Britain and Ireland and the necessary acceleration of ice in order to export the volume brought into the trough systems. The ISB has long been cited as an ice stream or dynamic flow route of the ice sheet (e.g. Eyles and McCabe, 1989; Ó Cofaigh and Evans, 2001a; Boulton and Hagdorn, 2006). The North Channel system has received less attention in this respect, although would be consistent with trough aligned (north-west directed) flowsets on the western Scottish coast (A. Hughes, pers. comm. 2008) and with lineations, possibly MSGLs, identified from multibeam swath bathymetry imagery on the Malin Shelf by Shannon (2006). The evidence presented in this thesis cannot directly contribute to an evaluation of the evidence previously proposed for ice streaming in either of these trough systems, but streaming emerges as a necessary outcome of the independently reconstructed ice flow geometry.

10.5.2.4 Ice streams: summary

Ice streams of the last Irish Ice Sheet are still quite poorly constrained. Their onshore imprint is





Figure 10.9 Ice streams have been proposed for all troughs along the NW European continental margin: a) Nielsen *et al.* (2005); b) Ottesen *et al.* (2005). The North Channel – Malin Shelf – Barra Fan system is likely no different.

limited and it is likely that most evidence of ice streaming will be found on the continental shelves. Rather, tributary systems which feed an offshore ice stream have been identified in this thesis. The western coastal bays contain such a system, not previously interpreted as such, perhaps due to an over-focus by researchers on eastern sectors of the ice sheet. Despite the attention they have received, the glaciodynamic and temporal interpretation of the east coast landform assemblages favoured here contrasts with Knight and colleagues' (1999) interpretation of ice streams feeding the ISB. It is suggested that the bedform record can be better explained by more subtly variable flow behaviour across this sector of the ice sheet. The remaining two of the three main systems – the Irish Sea Basin and the North Channel – emerge as a product of the reconstructed onshore ice sheet geometries. These routes are broadly consistent with those ideas which exist in the literature.

10.6 Ice sheet retreat

In a review of previous literature concerned with the last Irish Ice Sheet, Chapter 2, it was suggested that relatively little research has been directed at reconstructing the pattern, i.e. the spatial or geometric properties of ice sheet retreat at the ice sheet-scale. Rather, specific lines of evidence have been interpreted in terms of a particular manner of ice sheet retreat, and quickly

these scenarios have transcended their original evidential basis and been developed into overriding frameworks for deglaciation. The following section discusses the new reconstruction of ice sheet retreat with regards to these debated frameworks of deglaciation. It then asks whether anything more has been learnt regarding the pattern of ice margin retreat, which has been little considered hitherto at ice sheet-scale.

10.6.1 A model for deglaciation

Two frameworks have emerged in the literature which describe a context for deglaciation of the last Irish Ice Sheet. Firstly, a model of retreat punctuated by a major margin readvance, originally based on the configuration of countywide moraines which bound major drumlin fields (the 'Drumlin Readvance'; Synge, 1969, 1970) and more recently developed, based on chronologically constrained coastal stratigraphies, into a model of Heinrich Event participation (McCabe and Clark, 1998, 2003; McCabe *et al.*, 1998, 2005, 2007b). The alternative framework proposes steady margin retreat, and 'unzipping' of the ice sheet into two component domes, i.e. a model of fragmentation. In Chapter 9, a model of fragmentation was proposed. It was argued that fragmentation, or uncoupling of the ice sheet into component domes is necessary regardless of whether a major margin readvance is incorporated or not into the reconstruction. It was also argued that such a margin readvance can be included, and could be supported by the landform evidence, but is not necessary for their full explanation. The support for either of these two overriding models from this reconstruction and literature arguments is now examined.

10.6.1.1 Retreat and readvance?

The readvance model appears in the literature as a largely accepted model for deglaciation. The Killard Point advance (Figure 10.10) is widely cited (e.g. Knutz *et al.*, 2001; Nygård *et al.*, 2004; Everest *et al.*, 2006; Shennan *et al.*, 2006; Roberts *et al.*, 2007) as a key feature of the history of the last Irish Ice Sheet (and, indeed, the last British-Irish Ice Sheet). Its scale is purported to have ice sheet-wide significance, although the degree of deglaciation which occurred prior to the readvance is not clear; McCabe has variably argued for the decay of $\frac{2}{3}$ of the ice sheet (e.g. McCabe and PU Clark, 2003) or a margin withdrawal of only ~25 km prior to margin readvance (e.g. McCabe and PU Clark, 1998). In Chapter 2, brief arguments were put forward which question the basis for retreat and readvance. These arguments derive from other opposition in the literature (Warren, 1992; Warren and Ashley, 1994; CD Clark and Meehan, 2001; Meehan, 1999, 2004, 2006a), and some theoretical concerns with the way evidence has been used to underpin a readvance model.

The reconstruction presented here suggests that a readvance is not *necessary* to explain the geomorphological record of the ice sheet, but it can be accommodated should it be explicitly required by other lines of evidence. It is important that the basis for a large-scale margin readvance is sound if ice sheet-wide (and continental-scale) interpretations of climate – ice sheet relationships are drawn from it, and clearly the matter of a readvance is a crux issue for understanding the history of the last Irish Ice Sheet. The arguments considered in previous



Figure 10.10 Sites along the Co. Down coast which reveal ice margin readvances have been inferred to represent a readvance limit associated with onshore drumlin patterns. This ice limit is correlated with the Bride moraine on the Isle of Man and the St. Bees moraine in Cumbria. It has been suggested that all the drumlin patterns this limit purportedly bounds are the product of ice margin readvance and an episode of ice flow reconfiguration during overall deglaciation of the ice sheet. (From McCabe *et al.*, 1998 and McCabe and Clark, 1998.)

chapters are reiterated and elaborated here in order to examine the security of a readvance interpretation and, consequently, the security of any 'favoured' ice sheet reconstruction presented in this thesis. This section asks the following three questions:

- what evidence do we need to prove a readvance?
- what evidence might we expect from a readvance?
- what evidence have we observed?

What do we need? Conclusive proof of a margin readvance will be stratigraphical (Figure 10.11). However, a single, point data item cannot answer whether the readvance observed is a minor margin oscillation on the order of metres, or a major, ice sheet-wide readvance event. To address the question of scale, several well-constrained stratigraphies are required, distributed both radially *and* longitudinally with respect to the palaeo-margin (e.g. Knies *et al.*, 2007; Laberg *et al.*, 2007).



Figure 10.11 Stratigraphical evidence for a readvance. a) in situ organic deposits (must indicate ice-free conditions) overlie and interject two tills. b) the spatial properties of a readvance can only be determined with a well-distributed array of sites which stratigraphically exhibit a margin readvance; this spatial information must have both a radial and longitudinal element.

What might we expect? The issue of spatial scale relies on well-distributed point data, between which the manner of margin movement can be interpolated. The geomorphological record has a more explicit spatial component, and we may expect to see an imprint of a major

margin readvance in the landform record. The clearest evidence would be the overprinting of a deglacial landform assemblage by a subglacial bedform pattern which does not suggest proximity to a margin (Figure 10.12). This landform arrangement could take the form of drumlins overriding a moraine, bedforms overprinting eskers or, more subtly, an isochronous bedform flowset overprinting one attributed to lobate margin retreat.



Figure 10.12 Potential expectations of landform arrangements following readvance of an ice margin. a) an isochronous flowset overprints a deglacial flowset. b) lineations overprint a moraine.

What do we observe? The stratigraphies observed at coastal sections around northern Ireland form a fundamental basis of the readvance model. Although less explicit than illustrated in Figure 10.11, sections generally reveal margin withdrawal and subsequent re-encroachment on the sites in question (Figure 10.13a). Marine sediments (which indicate margin withdrawal to allow a marine incursion) are typically either interbedded with or underlie more proximal glacigenic sediments, or are consistently deformed or sheared which suggests they have been overridden. The fundamental problem which undermines the strength of support the stratigraphy offers for a readvance model is the distribution of information. Several sites around the Irish coast possess readvance stratigraphies but their distribution is entirely radial; there is no element of longitudinal scale (Figure 10.13b). As a result, there are no clear-cut grounds on which to differentiate between a model of minor margin oscillations all around the present-day coastline, and a model of major margin retreat and subsequent readvance.



Figure 10.13 a) sections in coastal moraines typically reveal the stratigraphical evidence for margin readvance: e.g. Killard Point – interbedded outwash with tidewater marine muds (McCabe *et al.*, 1984, 1998); e.g. Linns – marine mud underlies sheared sands, gravels and muds, which underlie till (McCabe *et al.*, 2007b). b) sites with chronologically constrained stratigraphic evidence of margin movements. Note that their distribution has only a radial, not a longitudinal component. Approximate ice divide positions inferred from ice flow arrows presented by McCabe and PU Clark (2003) for the Killard Point stage ice sheet.

Presumably to compensate for the lack of a longitudinal component in the stratigraphical body of evidence for a readvance, point data at coastal sites have been linked with the onshore landform record (McCabe, 1996, 2005; McCabe and PU Clark, 1998, 2003; McCabe *et al.*, 1998, 2005, 2007b), to provide the desired spatial information. The 'drumlin belt' landform suite, traditionally described under a readvance model (Synge, 1969, 1970), has been genetically linked with the section stratigraphies along the Co. Down and Dundalk Bay coasts which reveal a margin readvance: the drumlin belt is thus taken as the spatial signature and the landform imprint of this readvance. Linking point data with the landform record in this way implicitly invokes a number of assumptions:

- drumlins form under advancing ice
- drumlins terminate at the coastal moraines, in which the observed stratigraphies lie
- outwash gravels and other morainic material are the sedimentary product of drumlinisation (i.e. a genetic link between the drumlins and the apparently bounding moraines would place them in the same timeframe).

On theoretical and evidential grounds, a number of problems with these assumptions can be identified. The first assumption, that drumlin fields can be related to a margin advance, is nonsensical. Ice flows forward, and is capable of streamlining its bed, irrespective of the movement of the margin. Subglacial conditions, not margin movement, control drumlin genesis. The second and third assumptions relate to the genetic link between drumlins and a moraine. Undoubtedly, where a moraine closely bounds a drumlin field, and all landforms are geometrically arranged such that they form a coherent assemblage, it is a valid interpretation that the moraine relates genetically to the phase of drumlin formation (Figure 10.14a). However, in Ireland this clear-cut association is not observed (Figure 10.14b,c).

It is unclear whether the drumlins of the eastern midlands do terminate at the coastal moraines. Near the Killard Point moraine drumlins are found within ~3 km, but further south, drumlins stop well short of Dundalk Bay, and ~22 km short of the approximate ice limit with which their association is inferred (Figure 10.14c). Drumlins from the Solway Firth and Southern Uplands which are purportedly linked to the Killard Point event are closer to 50 km from their relevant moraines (see Figure 10.10). Furthermore, since these are coastal moraines, it is also yet to be shown that drumlins are not found *past* the inferred ice margin. Drumlins have not been sought offshore and the seabed data with which to do so has only very recently been gathered and released. The onshore extension of coastal moraines, the 'Drumlin Readvance Moraine', has not been identified during the mapping (Meehan, 1999, 2004, 2006a). Its apparent line does not bound drumlin patterns; rather, drumlins assigned to the same flowset appear both up and downstream of its supposed position. The spatial associations of landforms observed in north and east Ireland remain to convince of a genetic association.



Figure 10.14 Where the geometry and spatial arrangement of landforms presents a coherent landform assemblage it is legitimate to interpret a temporal association between drumlins and their bounding moraine (a). However, it is argued here that such a coherent landform assemblage is not observed on the Down or Louth coasts. Drumlins (e.g. *lins fs9*) are not explicitly associated with coastal moraines (b,c). It has not yet been shown that drumlins either reach as far as the moraines or, indeed, whether drumlins surpass them. In Dundalk Bay, a gap of ~22 km exists between the end of the observed bedforms and the limit proposed by McCabe *et al*; this distance is almost as far as the scale of the readvance for which they supposedly provide evidence. It is suggested this landform assemblage more likely indicates an earlier phase of drumlinisation before ice margin stabilisation during overall retreat deposited a moraine on the topographic step of the present-day coast. (Note that only lineations and moraines are shown in (c) to preserve the clarity of the figure.) Scale for (c): gridmarks at 50 km.

Finally, the readvance model assumes the coastal moraines are advance moraines, the sedimentary product of drumlinisation during margin advance. An interpretation of recessional moraines is equally plausible: a recessional moraine would naturally form along the present-day coastline, where there is a topographic step. Temporary stabilisation and standstill of the margin at this step would promote moraine genesis during an overall period of ice margin withdrawal. This moraine forming episode need not be temporally associated with drumlin formation, which could equally likely have occurred whilst the margin was located some further distance offshore. The moraines in which the observed readvance stratigraphies are situated are therefore not necessarily features of ice margin advance, nor can they be conclusively linked with the

landform assemblages which have been used to give spatial scale to point data.

These arguments are based on simple logic, supported by landform observations within the mapping programme in this thesis and some earlier reported analyses (e.g. Meehan, 1999, 2004, 2006a). The wider scale of this reconstruction further weakens the basis for an ice sheet-wide readvance. Flowsets with a spatial connection to the relevant stratigraphies have been assigned to different reconstruction stages (Stages Va-c, VI) based on a geometric incompatibility of their respective ice sheet sectors: they cannot occur contemporaneously as an ice sheet-wide event would demand. Finally, the recent discovery of multiple margin readvances across the Down and Louth coasts (McCabe et al., 2007b) has in fact undermined the very basis for a major readvance. Chronologically constrained coastal stratigraphies reveal two episodes of margin retreat and marine transgression, each followed by renewed ice proximal sedimentation. Two separate readvances are invoked, the Clogher Head episode and the Killard Point episode (McCabe et al., 2007b). However, in appealing to such a scenario, the longitudinal element of the readvance model has been lost. To which episode of margin advance does the 'drumlin belt' belong? Even if all the assumptions outlined above were accepted, only one of these readvances has a longitudinal spatial component. What was the extent of the other? Repeated minor margin oscillations could explain the sedimentary record equally well as major readvances.

The future of the readvance model? Coastal stratigraphies undoubtedly reveal retreat and subsequent readvance(s) of the margins of the last Irish Ice Sheet. The key issue for assessing the validity of reconstructed models, is one of scale. At what scale of readvance does a 'local oscillation' become an 'ice sheet significant' event? Longitudinal scale is missing from the literature model of ice sheet-wide readvance. The association of coastal stratigraphies with the onshore landform record is not deemed to be secure, and the stratigraphic record is not as simple as once thought, given the recent findings of multiple readvances (McCabe *et al.*, 2007b).

Delaney (2002) has also invoked a margin retreat-readvance sequence to account for the disposition of the central esker systems. Delaney invokes a retreat first to the west, followed by a local readvance from the north-west (Figure 10.15). This model, she argues, better explains both the geometry and the sedimentology of the esker systems around Lough Ree. This model more explicitly describes the longitudinal scale of a readvance: if the whole W-E system must be laid down prior to the NW-SE system, a readvance on the order of ~ 40-50 km is invoked. Here, however, the lateral scale of the readvance is unknown. Delaney (2002) has been cautious to link this local readvance to the ice sheet-wide readvance of McCabe and colleagues (Mitchell and Delaney, 1997; Delaney, 2002). The basis for doing so would be the consistency of orientation of eskers in Cos. Roscommon and Westmeath and the bedforms across Cos. Westmeath, Meath and Louth (as in deglacial Scenario B, Section 9.4.3). However, it has been argued in this thesis that spatial coincidence should not necessarily be assumed to equate to temporal coincidence, despite this being the simplest explanation, especially among different landform types. The potential scale and spatial extent of this, or any such readvance determines

whether it is more appropriate to 'accommodate' a more local event in an overriding model of steady deglaciation or whether we should appeal to a model of ice sheet-wide retreat and readvance to better represent ice sheet decay.



Figure 10.15 Delaney (2002) invokes a margin readvance to account for the geometry of eskers around Lough Ree (a). She does not associate this local event with the ice sheet-wide event advocated by McCabe and colleagues (1998). Local margin dynamics can be accommodated by a deglacial model lying somewhere between an end member scenario of steady retreat (\mathbf{b} – deglacial Scenario A, Chapter 9) and the large-scale readvance scenario (Scenario B, in Chapter 9).

Chapter 9 argued that the two scenarios of deglaciation which can be reconstructed from the landform record should represent end members of a spectrum which encapsulates the true manner of ice sheet retreat. The most likely scenario would accommodate margin oscillations in sectors across the ice sheet, but without going so far as invoking total ice sheet reorganisation and margin movements on the order of ~80 km (such as McCabe and Clark, 1998, 2003; McCabe *et al.*, 1998; McCabe, 2005). Such a model throughout deglaciation would capture multiple readvances around the Co. Down and Dundalk Bay coasts (McCabe *et al.*, 2007b), local readvances onshore (Delaney, 2001, 2002; Glanville, 1997), margin oscillations recorded throughout the Irish Sea Basin (Thomas and Summers, 1983; Evans and Ó Cofaigh, 2003; Thomas *et al.*, 2004; Thomas and Chiverrell, 2007), and records of margin oscillation and ice sheet 'pulsing' on the western seaboard (Knutz *et al.*, 2001, 2007; Peck *et al.*, 2006, 2007).

A large-scale readvance such as that reconstructed by McCabe and others is not firmly rejected here; deglaciation may have proceeded in this way. However, there is neither the landform evidence nor a strong logical basis for demonstrating such an ice sheet-wide event. It is deemed more secure to interpret the stratigraphic evidence as the product of repeated minor oscillations of outlet lobes during ice sheet retreat.

10.6.1.2 Fragmentation

Uncoupling of separate component domes of the last Irish Ice Sheet was proposed as a framework for deglaciation by Warren (1992; Warren and Ashley, 1994) in order to explain the disposition of eskers more satisfactorily than the existing retreat and readvance model. Whilst

she invokes a different model for the genesis of the central esker system, Delaney (2002) also describes a deglacial model which requires more than one component ice sheet dome. The reconstruction presented here finds support for this model, driven in the same way by the need to explain the major central esker systems. Warren's and, indeed, this reconstruction envisages the whole ice sheet unzipping along a suture line from the Athlone esker to Sligo Bay (although this reconstruction finds little support, either evidential or theoretical for the extension of Warren's model: the development of a large proglacial lake dammed between the uncoupling domes (van der Meer and Warren, 1997), see Figure 2.14).

Fragmentation is a necessary product of this reconstructed framework of ice sheet history, whether or not a large-scale margin readvance is invoked. The Connemara and bedform belt flowsets (*lins fs17* and associated eskers and moraines; *lins fs9, fs11, fs12 & fs14* and associated eskers and moraines) must all be assigned to a post-maximum period ice sheet stage, and therefore require both a western and a northern source of ice dispersal, as Warren inferred. The Irish literature and, perhaps, the literature review conducted in Chapter 2 of this thesis set up the models of retreat/readvance and ice sheet unzipping as a dichotomy of views, two mutually exclusive models of deglaciation. The reconstruction derived in this thesis from the countrywide landform record suggests that this discord is not so straightforward. A large-scale readvance could occur within an ice sheet framework characterised by ice sheet fragmentation. Fragmentation could certainly be associated with local lobe or sector reorganisations and margin oscillations.

10.6.2 Ice sheet retreat pattern

An overall framework for the deglaciation of the last Irish Ice Sheet has been discussed in the sections above. The specific pattern, or geometry of ice margin withdrawal has been less wellconsidered in the previous literature, particularly at the scale of the whole ice sheet. Two BIISwide (and NW European ice sheet-wide) compilations suggest a pattern of ice margin retreat across Ireland (Andersen, 1981; Boulton et al., 1985; Figure 10.16). Andersen's map depicts isochrones describing ice sheet decay but, despite this apparent level of detail drawn from the meagre dating information available at the time of publication, is largely schematic and offers little insight into the detailed pattern of ice margin withdrawal. Boulton and colleagues' retreat map offers a considerably greater level of detail. However, it is built from an assumption that ice margins can be reconstructed orthogonal to all ice flow indicators; drumlins, for example, are assumed to form shortly behind the ice margin, and all landform imprints relate to the deglacial ice sheet geometry (Boulton et al., 1985). Ice margins are drawn across all the major flow patterns of Ireland (although are notably absent from the midlands of Ireland where flow indicators do not reveal a straightforward pattern) and suggest the final vestiges of the ice sheet were located over Cos. Donegal and Tyrone, in much the same position as the Andersen reconstruction suggested. Since the paradigm for interpretation of subglacial geomorphology has shifted to recognise multi-temporal imprints, not exclusively related to the last stages of the ice sheet's history, the basis for the Boulton retreat map has been somewhat undermined.



Figure 10.16 Retreat patterns for the last (British-)Irish Ice Sheet. a) Andersen (1981), in Denton and Hughes; b) Boulton et al. (1985); c) margin retreat pattern derived from this study.

Using purely deglacial landform assemblages rather than the whole geomorphological record, a retreat map was reconstructed in Chapter 9. For some ice sheet sectors, this retreat pattern offers new information compared to the earlier maps (Figure 10.16c). A considerable westerly retreat of ice has been reconstructed, which is not identified by Boulton *et al.*, and the westerly component of which is underestimated by Andersen. Westwards retreat from the midlands has previously been invoked (Warren, 1992; Warren and Ashley, 1994; Delaney, 2002) but the implications of such a pattern for the manner of ice sheet retreat further south has been little considered. This reconstruction reveals that to withdraw in this manner, the margin must be hinged across Cos. Clare and Limerick. As margin retreat progresses from the approximate line of the so-called SIEM to the position of the central eskers, the direction of ice retreat must shift from NNW to almost due west. A steady recession of eskers at the eastern end of the SIEM margin records this shift in direction, but beyond the Limerick moraines, no landform legacy of deglaciation has been left across Co. Clare. The solution favoured here is that the ice margin lingered at the Limerick moraines, acting as a hinge whilst rapid margin recession ensued further east.

The final, northern retreat centre depicted by both previous authors is not observed here. Rather, ice is reconstructed to have retreated southwards over this region. This pattern is consistent with other workers who have reconstructed deglaciation at more localised scales. Colhoun (1970, 1971) proposes ice dispersal from, and retreat to, an ice source located south of the Sperrin Mountains. He uses meltwater channels and moraines mapped throughout this mountain range to infer breaching of mountain cols and retreat back through the lower passes to a more southerly ice centre. Knight (2003a,b, 2006a) also reconstructs retreat of ice towards the southwest of northern Ireland during the final stages of deglaciation. Over Omagh Basin and the Tempo and Clogher Valleys in Cos. Tyrone and Fermanagh, Knight has used the disposition of eskers, moraines, glaciofluvial and glaciolacustrine deltas, fans and outwash spreads, and reworked subglacial landforms to infer retreat from north-east to the south-west, towards Co. Leitrim, in direct opposition to the earlier flow direction sourced from the NE (Figure 10.17). Knight offers a further layer of information, which suggests that ice withdrawing towards the SW splits into two lobes, which cover the low ground of Omagh Basin and the Clogher/Tempo Valley, whilst the Fintona Hills which separate these two emerge from the thinning ice sheet. This level of detail is not explicitly reconstructed here, but is easily accommodated and a distinctly plausible scenario. Finally, Clark and Meehan (2001), who use a flowset approach to ice sheet reconstruction and do not explicitly incorporate deglacial landform indicators into their approach also invoke final retreat from northern Ireland towards the south-west of this region. Their flowsets *lin-4* and *rm-i* could not be assigned to any other ice sheet geometry in their reconstruction, and the authors suggest they likely relate to some late stage flow dynamic as ice retreats south-westwards between the Cuilcagh Mountains and Slieve Rushen. The same landforms have been recognised in this thesis, assigned to *lins fs24* and *rm fsD*. It is difficult to determine the flow direction responsible for rm fsD, and this flowset could potentially be

assigned to Stage I of the reconstructed ice sheet history. *Lins fs24*, however, is clearly a product of north-eastward ice flow, and adds to the body of data which points to a late-stage ice sheet geometry with an ice source potentially as far south as Cos. Sligo and Leitrim (Stage VI).



Whilst some insights revealed by the retreat map reconstructed in this thesis add information to, or confirm other proposals for the manner of ice margin retreat, in many regions deglacial landform indicators are absent at the scale mapped and analysed in this thesis, and the retreat map is far from complete. It has been drawn up at an ice sheet-scale, the focus of this thesis, but there are likely numerous local-scale dynamics of deglaciation which are not captured (Lafferty *et al.*, 2006; see below, Section 10.9). However, this retreat pattern improves upon those which were previously available at ice sheet-scale, and identifies three final sites of ice sheet decay, which have been little discussed hitherto: the mountains of Connemara, Co. Leitrim, and Co. Donegal.

10.7 Chronology

10.7.1 Relative chronology

It has been argued several times (in particular Chapter 7, Chapter 9, and throughout this chapter) that a multi-temporal reconstruction is a more appropriate way of interpreting the landform record of glaciation, and it reconciles many of the contradictions and controversies encountered in the earlier conceptual ice sheet models. The following discussion section considers how consistently the new reconstruction captures the multi-temporal ice dynamics which have been reconstructed by other workers at more local and regional scales.

10.7.1.1 Relative chronology of flow patterns

The Irish Ice Sheet literature identifies a wealth of sites which possess relative chronological information. Point information, such as local stratigraphies where multiple tills are exposed (e.g. Stephens and Synge, 1965; Hill and Prior, 1968; Hill, 1971; Colhoun, 1970, 1971), cross-cutting landforms (e.g. Knight and McCabe, 1997) or striations (e.g. Hill, 1971; McCabe, 1972), or successive patterns of sediment dispersal (e.g. Farrington, 1965), have been incorporated into the reconstruction as best as possible as additional temporal 'rules' to constrain the reconstructed sequence of events. Whilst it is impossible to document each and every passing comment about cross-cutting striations, for example, from the dense body of literature, the reconstruction should be consistent with those sites where relative chronological information has been clearly presented and an ice flow context (i.e. flow direction or ice flow source) has been provided.

It is often the case that point information has been assimilated by the original researchers into a local or regional model of ice history, and it is relevant to examine how these models, which may be based upon an array of relative chronological information, compare to that derived in this thesis. Three recent, regional models recognise a multi-temporal glacial record from within a single glacial period, and describe a sequence of events from the last glaciation (McCabe *et al.*, 1999; Clark and Meehan, 2001; Knight, 2003a,b, 2006a). These are now considered.

McCabe et al. (1999) describe an ice sheet history from the NE midlands, the main bedform belt of Ireland (Figure 10.18). Their events B and C are reinterpreted here as the product of a single phase of ice flow, albeit one which is suggested to have evolved and fluctuated during its inscription of a landform record. Nonetheless, their first three events are captured, in order, by the reconstruction presented here (Stage 1 and Stage V). The last stage of McCabe and colleagues, event D, is less clearly captured as a distinct, independent stage. McCabe et al. record a south-westwards pattern of drumlins directed from Lough Neagh through Clogher Valley and on the southern side of Slieve Beagh. These overprint the flow indicators associated with the main NW-SE ice flow path of the 'drumlin belt'. As a discrete stage, this flow pattern is not recognised in the new reconstruction. The only major movement from Lough Neagh towards the south-west occurs in the initial stages of ice sheet growth, not at the end as cited by McCabe et al. However, during the final part of Stage V, part Vc, the main ice flowline direction has pivoted to such an extent that at its most northerly end, flow is directed towards the SW and SSW (lins fs11). This remains part of the sequence of events which inscribed the main bedform belt, rather than a discrete, subsequent snapshot of ice flow geometry. It is not interpreted to have inscribed a landform record through Clogher Valley or the head of Omagh Basin, but does direct ice south-westwards in the region around Rosslea, Clones and Monaghan, south of the Slieve Beagh uplands (Figure 10.18).

A short distance further west, in the area of the Clogher Valley and Omagh Basin, Knight (2003a,b, 2006a) also presents a four-stage reconstruction of the major events of ice history to

influence the development of this local glacial record (Figure 10.19). The compatibility of his model with the reconstruction presented in this thesis is variable. Knight's stage C (Knight, 2003b) is the only stage which receives firm support from the new reconstruction, yet the others are theoretically plausible. His stage A describes ice sheet initiation in the area and is largely based on concepts of where ice was initially nourished: all the mountain groups around Omagh Basin discharge ice into the basin. His model could easily fit with the pattern of ice sheet growth depicted in this reconstruction's Stages I and II, but firm evidence is lacking. Knight's stage B could fit with Stage II reconstructed here, but would require the Stage II divide to be repositioned further NW and the ice flow pattern Knight depicts would likely have been less substantial than he envisaged. He acknowledges there is little landform evidence of this stage, merely striations and bedrock scouring, and he suggests that cold-based ice was dominant. These forms of ice flow indicators are difficult to position in relative time given the greater preservation potential of bedrock to drift forms, but could suggest that Knight's stage B exists in a manner less pronounced than he envisaged, compatible with this reconstruction's Stage II. Stage C is the most evident flow stage in Omagh Basin, attributed in this thesis to Stage III. Finally, Knight's stage D, which he attributes to the early stages of deglaciation of the basin, is broadly consistent with the reconstruction Stage VI. The central parts of Omagh Basin undoubtedly experienced SW-NE ice flow, but Knight's depiction of contemporaneous NE-SW flow directions south of the Fintona Hills is questionable: this would set up a shear within the ice mass which is most unlikely. Rather than attempting to step straight from Knight's stage C to D, which has probably caused this problem to arise, several other stages between the two are depicted by this reconstruction. These are likely not all recorded in the landform assemblages of Omagh Basin and the Clogher Valley; variable processes of preservation and landform generation, potentially related to the proximity of an ice divide during the intervening stages, will have determined the nature of the final composite landform record. Knight's reconstructed mode of deglaciation, from his stage D and onwards (see Knight, 2003b), is entirely compatible with this reconstruction's Stage VI and VII (see Figure 10.17, above).

A final model which has emerged in recent years which attempts to unravel a relative chronology of ice flow events is described by Clark and Meehan (2001). Like the approach taken in this thesis, these authors employ a flowset-based inversion model for ice sheet reconstruction. The sequence of events described is broadly consistent with the reconstruction presented here (Figure 10.20). Clark and Meehan's (2001) phases A, B, C & D correspond to this reconstruction's Stages I, III, V & VI. The four stages which Clark and Meehan capture could be argued to record the major events of the last glaciation: the eastern position of a single ice divide, a north-westwards ice divide shift, and a final retreat pattern towards the south of the main northern mountain groups. Landform imprints from peripheral areas add further information (Stages II, IV, Va and VII): a first, major shift of the ice divide to attain its eastern position, a rapid southwards advance of ice during the maximum period, and uncoupling of the ice sheet during deglaciation into two main, component domes.



these stages to be positioned within the context of the rest of the ice sheet's history.

260



Figure 10.19 The consistency between the local-scale reconstruction of Knight (2003b) and the ice sheet-wide reconstruction presented here is variable. Knight's stage C is represented in this reconstruction's Stage IIIb, but to account for all others would require some minor modifications of either this reconstruction or that of Knight. The general pattern and relative chronology of events depicted by both models are, however, broadly complementary. Omagh Basin is starred for the reader's reference on the new reconstruction figures.



Figure 10.20 The new reconstruction is consistent with that derived by Clark and Meehan (2001). These authors' stages a-d are captured, in relative chronological order, and set in context by the rest of the reconstruction.

262

Regional relative chronological models of ice flow events can clearly provide good constraints on the overall ice sheet history. A limitation of these models and of the point information which feeds the ice sheet-wide reconstruction is their spatial restriction; when considered in isolation, the context of the rest of the ice sheet is lost. Consequently, local successions of events are revealed here to be punctuated by events which occur elsewhere in the ice sheet. A comparison of the reconstruction presented in this thesis shows a good level of consistency with models recently emerging from the literature. Where inconsistency occurs, it could likely be reconciled by minor modifications either to this reconstruction or that proposed by other authors, in order to accommodate any extra information or insights which either model may provide the other.

10.7.1.2 The last glaciation?

An undoubted limitation of relative chronological reconstructions is their inability to situate the model in absolute time. In particular, the question of whether all evidence can be (or should be) accommodated within the last glacial cycle is always pertinent. The question of a 'Scottish invasion' of ice over Ireland is a good example of conflicting models of interpretation. This ice flow event has variably been attributed to the penultimate glaciation (Synge and Stephens, 1960; Synge, 1970; Stephens *et al.*, 1975; McCabe, 1985) or an early phase of the last glaciation (Charlesworth, 1939; Hill and Prior, 1968; McCabe *et al.*, 1999; Clark and Meehan, 2001). The 'Scottish invasion' is reconstructed in Stage I of the ice sheet history presented in Chapter 9, and extends previous suggestions of the spatial influence of this ice flow geometry up to 200 km across central Ireland. This ice flow geometry and, indeed, the whole landform record documented from Ireland within this thesis is attributed to the last Irish Ice Sheet, rather than the penultimate or any other. This assertion underpins a number of potential conclusions drawn from the reconstruction, and cannot be validated until every flowset can be either directly (i.e. landform genesis) or indirectly (e.g. via exposure) dated. However, it has a logical basis:

- Earlier divisions of the Irish record into a Midlandian and Munsterian period were based, in part, upon a division of surface sediments into an 'older drift' and 'newer drift' which has subsequently been argued to be unfounded (Warren, 1991; Hegarty, 2002; Jordan, 2002). All therefore belong to the same glaciation.
- There is little well-dated stratigraphic evidence for multiple glaciations in Ireland.
- Landform mapping reveals few of the signatures of extensive cold-based ice (lateral meltwater channels, zones with a dearth of glacial features). The abundance of bedforms and subglacial meltwater traces throughout Ireland is testament to a warm-based subglacial environment, thus eliminating a key mechanism for flow pattern preservation from previous glacial episodes (Kleman, 1994; Kleman and Hättestrand, 1999; Hättestrand and Stroeven, 2002). However, if a thermal fracturing model of ribbed moraine genesis is favoured (Hättestrand, 1997; Kleman et al., 1997; Kleman and Hättestrand, 1999) over a bed deformation model (Boulton, 1987; Hindmarsh, 1998; Dunlop, 2004) it could be argued there is plentiful evidence of cold conditions (see Chapter 11).
- There are numerous independent indications, particularly from offshore and ice-marginal records, that the last Irish Ice Sheet displayed dynamic behaviour (e.g. McCabe *et al.*,
1998, 2005, 2007a,b; Knutz *et al.*, 2001, 2007; Peck *et al.*, 2006, 2007). It would be expected that this dynamic ice sheet would leave a landform imprint. It is therefore the most logical conclusion to attribute all the evidence we see of dynamic behaviour to the last ice sheet, rather than partition the evidence amongst multiple glaciations.

The simplest and least controversial assumption is adopted. Landform preservation simply from the LGM through deglaciation requires a suite of mechanisms to protect an underlying flow pattern. To expect landform preservation from an earlier glacial cycle throughout the whole history of the last Irish Ice Sheet would not be the most straightforward conclusion to draw from the landform record.

These arguments, however, remain theoretical, and the allocation of all ice flow evidence to the last glacial period remains a logically guided assumption.

10.7.2 An absolute chronology for the last Irish Ice Sheet?

Thus far in this thesis the chronology of the last Irish Ice Sheet's evolution has been considered in relative terms. However, the importance of absolute (radiometric) constraints on the chronology has been highlighted above. The partitioning of evidence within and between glacial cycles cannot be entirely secure without radiometric information, the rates of dynamic behaviour cannot be assessed (is the duration of Stage II the same as the duration of Stage III, IV or V?), and the wider context of the evolution of the ice sheet, its leads and lags with other Earth system changes cannot be well determined in the absence of an absolute chronology. The available absolute dates which constrain the history of the Irish Ice Sheet were collated as described in thesis Section C. Chapter 8 commented on two alternative ways in which this information can be integrated:

- assign an age to individual flowsets or moraines (assists the building of the reconstruction), or
- attach a date, or range of dates to the reconstructed relative chronological stages in the ice sheet evolution.

It was argued that there is insufficient information available from Ireland for the first to be a successful route. Here, the way in which the reconstructed relative chronology can be situated in absolute time is considered. The dates collated in Section C are reviewed with regards to their ice sheet context and age information. This effort to assign ages to relative chronological stages makes no judgement of the reliability of the dates recorded or the comparability of ages derived using different methods, but calibrates radiocarbon ages and takes all information at face value.

10.7.2.1 Ice sheet onset

Only three onshore and five offshore sites have been identified which possess information to constrain the onset of glaciation in Ireland (Figure 10.21). (Note that the database of dating information may not be complete.) The three onshore sites are all located within the interior of the eventual ice sheet and their ice-free context is interpreted to signify there is no ice sheet in Ireland at this time. The youngest date is the most centrally located and likely to be the first glaciated of the three sites; it constrains the onset of glaciation to some time after 35.9 cal ka.





Offshore cores provide a continuous record of sedimentation. Whilst the significance of sedimentation is not always clear, certain fundamental properties of the glacial system can be inferred from the sedimentological record on the continental shelf and slopes: marine margins must be present; debris flows and turbidites are taken to indicate shelf edge glaciation (e.g. Knutz *et al.*, 2001, 2002); rates of sediment discharge from the ice margin are revealed; and the timings of these events can be determined. Substantial fluxes of ice-rafted material begin at ~30 cal ka on the Barra Fan (Knutz *et al.*, 2001, 2002) and at ~26.5 cal ka on the Porcupine Seabight (Peck *et al.*, 2006, 2007). Extensive and persistent marine margins are inferred from these times onwards, and they reveal that the onset of glaciation must have occurred prior to 30 cal ka. Given the onshore dates, onset could be constrained to the period between 35.9 and 30 cal ka and implies rapid expansion of ice to its maximum position.

There is a growing body of evidence of fluxes from the BIIS prior to this period. Periodic input to the PSB core occurs from 46 ka, and from ~45 cal ka on the Barra Fan. This may reveal a conflict between the offshore record and a small, but significant collection of dates from onshore in both Britain and Ireland which reveal an absence of ice cover in areas central to the ice sheet during MIS3 (Brown *et al.*, 2007). A resolution to this conflict may be yielded by more rigorous on- and offshore dating programmes. If both sets of information are secure, this perhaps indicates a small but dynamic ice sheet reaching marine margins episodically between periods of substantial withdrawal during MIS3. It is suggested that any such potential phases are not clear in the landform record, and this reconstruction's Stage I begins shortly after 35 cal ka.

10.7.2.2 Maximum period of glaciation

The reconstruction promoted in this thesis yields different relative timings of maximum ice extent at different margins: the western maximum margin is reached (Stage IIIb) prior to the advance to the maximum in the southern sector of the ice sheet (Stage IV). Three suites of chronological information constrain this period of ice sheet history (Figure 10.22): the North Mayo dates, the Celtic Sea dates, and the offshore information.



Figure 10.22 Information constraining the timing of the arrival of the ice sheet (a) at its maximum stage configurations (b). Coastal dates constrain the timing of ice advance towards its maximum position. Note that different interpretations are offered for essentially the same stratigraphic context for sites in North Mayo (McCabe et al., 2007a, shells are derived from isostatic depression and marine transgression) and the south coast (Ó Cofaigh and Evans, 2007, shells are derived from deformation of a marine sediment substrate by a grounded ice mass). Solid arrows indicate the direction of ice flow favoured by the original authors for the till with which the dates are associated; if an alternative stratigraphic context were interpreted, the opposing direction could be invoked (dashed arrows). All dates are given in calendar years.



Shelf edge glaciation has been inferred at the Barra Fan margin from \sim 30-22 cal ka (Knutz *et al.*, 2001, 2002). At the Porcupine Seabight and Goban Spur core sites a significant and abrupt increase in sediment flux occurs at \sim 27 cal ka, and continues from then on through the Late Midlandian/Devensian. These timings are compatible with the limited information which records the passage of ice over or along the present-day coastline towards its maximum extent. McCabe *et al.* (2007a) interpret an offshore movement of ice from Co. Mayo \sim 28 cal ka; in the south, the advance of ice into the Celtic Sea is constrained to \sim 24 cal ka, or shortly thereafter (Ó Cofaigh and Evans, 2007). These are limiting ages based upon the incorporation of shell fragments into tills; Scourse (2006) offers two dates from the northern Scilly Isles which he suggests are coeval with a maximum margin position (25.1 and 22.7 ka). Both the coastal and offshore data reveal a lag of \sim 3ka between the attainment of substantial shelf edge glaciation in the north and west sectors of the Irish Ice Sheet, and the advance of Celtic Sea ice to its maximum in the south. With the information available, a timing of \sim 30-28 cal ka is tentatively assigned to reconstruction Stage II, \sim 24 cal ka to the southern advance of Stage IV, and the expansion of ice to a western maximum (from Stage III) consequently occurring from 28-24 ka.

10.7.2.3 Deglaciation

A greater array of dates constrain the deglacial period of the ice sheet. These dates comprise a mixture of sources of information:

- exposure ages (cosmogenic dates): constrain timings of margin withdrawal; may be affected by inherited cosmic ray signals (gives a falsely old age).
- radiocarbon ages: point data revealing ice free conditions; ages given are typically the deepest date from peat or lake sediment cores, providing a minimum age for ice withdrawal (if core does not bottom in glacigenic material then the degree of age underestimation is not known).
- radiocarbon ages: sequential chronology through a sediment column, revealing a series of events. Lowermost dates reveal the onset of ice free conditions; readvance signatures have been interpreted through the column, and the uppermost date reveals the timing of final margin retreat from the area. The significance of these types of dates is less explicit and more subject to the interpretative model of the original author.

The limitations of each of these data types are an important consideration when analysing the full dataset of chronological information relevant to the decay of the ice sheet (Figure 10.23). Dates have been grouped into bands to ease the visualisation of the information. This compilation stimulates two potential routes of exploration: i) attempt to assign timings to the reconstructed stages of ice flow configuration; or ii) explore a chronology for the retreat pattern. Since the retreat pattern and flow geometry reconstruction are largely consistent (Section 9.4.5) the retreat pattern is explored first in the context of the available dates, and it is subsequently examined whether this assists the fitting of a chronology to the reconstruction.

If the ice sheet decayed in a simple concentric manner, one would expect to see a concentric arrangement of progressively younger dates towards the centre of the ice sheet. Figure 10.23

reveals this is not a simple case. An immediately obvious problem is the occurrence of deglacial ages prior to 24 cal ka (the age assigned to Stage IVa, the maximum extent of glaciation) and their distribution throughout the landmass. All but one suite of pre-24ka dates are exposure ages presented by Bowen et al. (2002). Other workers (Ó Cofaigh and Evans, 2007; Ballantyne et al., 2007, 2008) have found conflicts with several of these dates and suggest they contain an inherited signal from previous cosmic ray exposure; the 'clock' has not been reset by sufficient erosion prior to the most recent exposure. Bowen's full dataset is included in Figure 10.23 but his dates are interpreted with some caution. The other set of early dates are presented by McCabe et al. (2007a) on the north coast of Co. Mayo. In fact, the oldest of these dates overlaps with the age proposed by the same authors for margin advance across this coast. The maximum period was therefore either very shortlived at this margin, which seems unlikely given continuous offshore sedimentation for a much longer period and the deglacial dates of ~19-20 cal ka a short distance to the west (McCabe et al., 2005), or the interpretation of the dates which are attributed to ice advance and deglaciation must be revised. It is suggested here that evidence for an early deglaciation prior to 24 cal ka is not sufficiently well-supported to use these dates in this analysis, although it is recognised that this scenario is a possibility.

Omitting the pre-24 ka dates it is possible, with some further caveats and uncertainties, to sketch some minimum bounding polygons (isochrons) from the dataset (Figure 10.23). Ice free dates in the south of Ireland are ignored as the material in which the core bottoms is unknown (the degree to which they are a minimum age is unknown), and this helps the pattern somewhat. It remains unclear which early dates relate to one another in the far south of Ireland and, in the northern ISB, deglaciation (19.2-19.7 cal ka) documented on the Co. Down coast (PU Clark *et al.*, 2004) appears to directly conflict a moraine age on the Scilly Isles (Scourse, 2006) and a preliminary OSL date from proglacial material in Co. Wexford (Thrasher *et al.*, 2008). Allowing for error bars, these sites could record total retreat of the ISB ice stream in as little as 100 years, requiring a retreat rate of ~4.6 km/yr. If this were the case, one would expect to see a substantial peak in sediment flux to cores on the Porcupine Seabight and Goban Spur, where Celtic Sea-derived material is known to have been deposited (Scourse *et al.*, 2000; Peck *et al.*, 2006, 2007). At 20-19 cal ka there is no such peak (Peck *et al.*, 2006). This either suggests there is a real conflict between the sets of dates, or the absence of a sediment signal reflects an alternative ice-rafting trajectory which 'misses' the core sites.

The minimum bounding polygons (or partial polygons) presented in Figure 10.23 enable some dates to be tentatively assigned to the retreat pattern presented in Chapter 9 (Figure 10.24). In turn, broad timings of the reconstructed relative stages in the ice sheet evolution can be speculated. A timing for the start of deglaciation is dependent on the timing of retreat through the ISB; it is suggested this stage occurs ~20 cal ka (exposure age from the Scilly Isles), but could be as early as 23-22 ka. By Stage VI, the ice sheet is almost everywhere confined to within the present-day coastline, and the reconstructed shape of the remnant ice masses at the start of Stage VI best matches the ~17-16 ka bounding polygon. Whilst there are some





Figure 10.23 Dates constraining deglaciation of the Irish Ice Sheet. With some caveats, uncertainties, and variably reliable date information, minimum bounding polygons, or partial polygons, can summarise a sequence of ice margin retreat. The broad sequence is incompatible with a suite of exposure dates presented by Bowen *et al.* (2002), which also has internal inconsistencies (large disparities in ages from closely nearby sites with comparable elevations), and it is suggested deglaciation from the continental shelf occurred following a maximum position at ~24 cal ka. Around the north and NE coasts, dates are of the 'event' type captured from sediment columns. The lowermost ages constrain initial deglaciation (main panel); the uppermost ages constrain final departure from these sites (b) after a period of margin oscillation and readvances. White & blue circles mark the final sites of decay, following this reconstruction. CB? denotes where it is unknown whether a core bottomed in glacigenic sediments.

uncertainties in bounding polygons for the 19 - 17 cal ka period, this timeframe largely fits the intervening Stage V. The reconstructed western margin during this stage should perhaps be





brought closer to the present-day coast, particularly around NW Co. Mayo, which would produce a more asymmetric ice sheet across a W-E transect but would better fit what dating information is available. The ice sheet likely undergoes complete decay by ~14.5 cal ka.

10.7.2.4 Absolute chronology: summary

Stages of the ice sheet reconstruction derived in this thesis are tentatively assigned absolute chronological timeframes according to the presently available dating information (Figure 10.25). It is suggested that the main onset of the last ice sheet to cover Ireland occurred at, or shortly after ~35 cal ka, and the ice sheet reached its maximum extent from ~28-24 cal ka. Different sectors of the ice sheet attained their maximum configuration at different times, the southern sector, in particular, likely lagging the northern and western sectors by approximately 3 ka. This is consistent with the relative chronology presented in the previous chapter. The deglacial pattern of the ice sheet remains unclear. There are internal contradictions between dates, different ages are minima or maxima, and the distribution of information is largely restricted to present-day coastal regions, which all hinder an attempt to correlate a relative with an absolute chronology for margin retreat. We can speculate that deglaciation of the ISB may have been extremely rapid, followed by a period of margin stabilisation and local oscillation around the north and east Irish coast whilst the central portions of the ice sheet unzipped into two remnant ice masses. The ice sheet pulsing, apparent during deglaciation in offshore cores, likely relates to periods of ice flushing below the spatial and temporal resolution considered here, but is entirely compatible with this reconstruction. It is likely that only small, terrestrialbased ice caps remained by ~15-14.5 cal ka.



Figure 10.25 All stages of the relative chronological ice sheet reconstruction, with tentative absolute timings. See also Map 4.

In the broad timings, and in the most general elements of flow patterns, there is some consistency between the new reconstruction and the most recent model of McCabe (2008 – Figure 10.26). Whilst the dates may constrain specific margin positions, and a detailed history of ice margin oscillations, the basis of the links invoked by McCabe between a marginal date and the evolution of the onshore flow geometry remains unclear. It is not clear which of the generalised flowlines are speculated (the earlier flow stages?) and which relate to specific



Figure 10.26 Age constraints upon a new model of Irish Ice Sheet history proposed by McCabe (2008).

landform patterns, or the basis for grouping any landform patterns into the stages to which they have been assigned. Although this new model proposed by McCabe is divided into several stages, it does appear that the interior flow geometry is relatively unchanging. The axes, domes or centres appear to be largely stable and the flow patterns broadly the same in each stage. The lack of clarity of the interior flow geometry in this model reflects the emphasis on marginal chronologies and generalised ice flowlines; clearly a way must be sought to better integrate marginal information with the ice sheet-scale spatial information which reveals the fundamental evolution of the ice sheet geometry.

10.8 Comparison with numerical modelling output

It was suggested in Chapter 2 that theoretical (modelling) approaches to ice sheet reconstruction are not yet sufficiently mature to warrant detailed comparison with evidence-based reconstructions. Notwithstanding the new reconstruction presented here which, since it offers an ice sheet-scale model with an explicit temporal component, will hopefully provide a better constraint upon numerical approaches, this is largely still the case. Two recent numerical approaches do, however, deserve brief consideration in light of this reconstruction. Boulton and Hagdorn (2006) take a glaciological modelling approach to explore the general glaciological characteristics and behaviour of the BIIS, rather than trying to precisely match specific geological data. Geometrically, several elements of their favoured ice sheet are not supported by this reconstruction (their target geometry appears to be a limited extent ice sheet, in southern Ireland at least), but since the aim of the modelling experiments was not to precisely simulate the ice sheet but to explore its behaviour this is not of too great a concern. These authors do reveal some interesting insights regarding the ice sheet glaciology: the importance of ice streams; and the emergence of 'unforced' margin oscillations, which are dynamic responses to internal glaciological processes rather than climate driven events.

Brooks *et al.* (2008) employ glacio-isostatic modelling to investigate the required geometry of the last Irish Ice Sheet to best fit the available relative sea level records from Ireland and proximal British sites. The earlier 'best fit' model of Shennan and colleagues (2006) is modified by Brooks *et al.* such that the ice model more closely predicts the observed RSL data from Ireland (Brooks and Edwards, 2006), not fully incorporated hitherto into GIA modelling of the British Isles. Their best fit ice sheet model (Figure 10.27) appears to present some strange geometric elements (the closed contours over Galway Bay and NW Mayo at their 24 and 21 cal ka timeslices), but reveals some interesting broad ice sheet configurations. In particular, they highlight the need for substantial loading of the Irish midlands and Irish Sea Basin during the maximum period of glaciation, which is consistent with the divide position reconstructed during Stage IV. Brooks *et al* also favour a final decay position towards Co. Leitrim.

10.9 A framework for research

This ice sheet reconstruction does not, and cannot, resolve every dynamic element of the ice sheet's history. A consequence of presenting a final ice sheet-wide reconstruction as a



Figure 10.27 The ice sheet history favoured by Brooks *et al.* (2008) to best fit a database of RSL observations from Irish and proximal British sites. 'Contours' show terrain corrected ice thicknesses, at timeslices in cal. ka. Whilst the ice surface geometry is potentially not always glaciologically plausible, the centres of ice loading (ice divides) over the Irish midlands and ISB during the maximum, and towards the west during deglaciation, are broadly consistent with the reconstruction presented in this thesis.

manageable number of timeslices is that local-scale intricacies of flow patterns, or lower-order behaviour of ice sheet sectors are necessarily generalised and condensed. However, by using as complete an initial dataset as possible, the process of generalisation can be sensitive to all the vital spatial, temporal and glaciodynamic information held by the full landform record of the ice sheet. It is therefore expected that all the key events, of at least a first-order significance, are captured in this reconstruction. The final reconstruction which is presented in Map 4 should be taken not as 11 discrete snapshots of the ice sheet geometry, but as a framework for the evolution of the ice sheet, comprising 6-7 phases of ice sheet activity which synthesise the behaviour of the ice sheet during these phases and hint at the manner of its evolution.

Throughout the above discussion reference has been made to numerous examples where specific local or regional dynamics can be incorporated into the broad framework of a first-order, ice sheet-wide reconstruction. Elements of lower-order behaviour have been reconstructed in this thesis: where flowlines have been revealed to fluctuate and migrate within an ice sheet sector;

where flowlines exhibit convergence and diverge at sub-flowset scales (see the regional ice sheet histories, Section 9.3, or the discussion of flowset classification and glaciodynamic interpretation, in Chapter 8). The literature, in particular, reveals a greater level of detail of the patterns and dynamics of ice behaviour at local scales. Margin oscillations are particularly prominent in the reported local-scale literature, both on and offshore (McCabe and Clark, 1998, 2003; McCabe et al., 1998, 2005, 2007b; Glanville, 1997; Delaney, 2002; Thomas and Summers, 1983; Thomas et al., 2004; Thomas and Chiverrell, 2007; Evans and O Cofaigh, 2003). Local interplay between different lobes of ice has been revealed in the sedimentological record of the south coast (Ó Cofaigh and Evans, 2001a,b, 2007), where it is suggested that the local extent of inland Irish ice is constrained by the buttressing effect of Celtic Sea ice. Retreat patterns, in particular, are frequently able to be reconstructed at a local scale to a greater level of detail than captured here. Finer-scale landform mapping than is feasible using a remote mapping approach, consideration of additional landform-sediment associations (e.g. deltas, outwash fans) and sedimentological and stratigraphical evidence provide this enhanced detail. Knight (2003b) proposes an 6-stage retreat pattern for ice in the Omagh Basin and Clogher/Tempo valleys, describing the thinning of ice, the uncoupling of local lobes around higher terrain, and the steady withdrawal of the margin towards the south-west (see Figure 10.17). Meehan (1999) reconstructs a pattern of retreat across Cos. Westmeath and Meath of a crenulated margin, characterised by local lobe division around higher terrain protruding through thinning ice (Slieve na Calliagh). The scale of ice margin behaviour, and the often sedimentological nature of the evidence it leaves behind, is such that many local margin dynamics cannot be recognised explicitly in the approach to ice sheet-wide reconstruction undertaken here. However, the geometry and behaviour of each of these examples have been found to be entirely compatible with the model of ice sheet evolution presented in this thesis. In this way, this ice sheet reconstruction provides a context for research focussed at different scales, and a framework of evolution to be examined, evaluated, refined or rejected as necessary by future research.

A notable outcome of this work is the revelation of dynamic ice sheet behaviour at a range of scales. A hierarchy of dynamic elements of the ice sheet can be conceptualised:

- 1. At the highest-order, this reconstruction depicts a major reorganisation of the overriding ice sheet structure part way through its evolution. The build-up and maximum stages are characterised by an overriding axis structure, which gives way to a multi-domed structure during the latter part of the ice sheet's history.
- 2. Within different overriding structures, ice divides clearly migrate, and ice flow geometry changes at the ice sheet sector level.
- 3. Ice sheet sectors display sub-stage variability in flow dynamics. The bedform record is dominated by time-transgressive, or incrementally inscribed flowsets, which record the continual evolution of the ice flow geometry. Within ice sheet sectors, spatial (lateral) variability of flow geometry and behaviour has been revealed, with parts of sectors at times drained by ice streams, and with the development of crenulated margins during retreat and the consequent sub-flowset level convergence or divergence of flowlines.

4. At a local scale, margins have been revealed to be highly dynamic. Whilst the ice sheet sector flow geometry, and any resulting bedform imprint, may remain relatively stable, margin oscillations punctuate the history of the ice sheet. Oscillations have been recorded in particular during deglaciation, but the offshore record additionally reveals the pulsing nature of the ice sheet throughout its evolution.

In this way, this reconstruction provides a framework for research focussed at different scales, and should provide a stimulus for future research and model refinement directed at the full range of scales of ice sheet behaviour and evolution.

10.10 Summary and conclusions

Comparison of the reconstruction with the existing literature is a mutually beneficial exercise: the literature supports and adds information to the new model, whilst this model of the ice sheet history sheds light on some debates which have long characterised the literature. A key advance is the recognition of, and untangling of a highly multi-temporal landform record of glaciation which is suggested to reveal elements of the full evolution of the ice sheet. Allowing different ice sheet sectors to evolve in their geometry and behaviour in different ways at different times has reconciled several competing ideas which have previously been set in vigorous competition by an assumption of contemporaneity. Relaxing this restriction resolves certain debates.

There are numerous remaining challenges in enhancing our understanding of the Irish Ice Sheet's history. Thus far only the interior of the ice sheet record has been considered; many dynamics and drivers of ice sheet behaviour may be associated with offshore margin positions (see Chapter 11), and a lot may be learnt by exploring the bathymetric record of palaeo-ice cover. A better chronology of events is fundamental to constraining the history of the last Irish Ice Sheet. Several regional flowset groups are currently positioned in the reconstruction by virtue of plausibility, and lack even a secure relative chronology. Higher resolution efforts (fieldwork or higher quality imagery) to document relative chronological relationships and constrain an absolute chronology are essential in exploring the security of this reconstruction. The volume and distribution of dated sites are currently far too meagre to adequately constrain any reconstruction in absolute time. The distribution is almost exclusively coastal, and an improved spatial coverage and variety of glaciodynamic contexts is necessary to better understand a chronology for ice sheet evolution. Furthermore, a well-constrained chronology for a dynamic ice sheet is fundamental to examining the role of and the interactions between this ice sheet and the wider Earth and climate system.

This chapter has explored the success of the new reconstruction in light of the existing Irish Ice Sheet literature, and looks forward to how the reconstruction can be evaluated, refined, and used to inform further research in the future. The following, penultimate chapter of this thesis explores the palaeo-glaciology of the ice sheet: the patterns of evolution, the potential drivers of the observed ice sheet dynamics, and the implications of the landform record and the ice sheet reconstruction for understanding the development of a composite record of Irish glaciation.

Chapter 11. Discussion: exploring the ice sheet palaeoglaciology

11.1 Introduction

Beyond simply deciphering an ice flow geometry, the reconstruction of the last Irish Ice Sheet which is presented in this thesis has yielded a number of insights regarding the patterns of ice sheet evolution and properties of the ice sheet's behaviour; in essence, its palaeo-glaciology as well as its palaeo-geography or geometry. Furthermore, implicit in the reconstruction process, insights have been yielded regarding the properties and palaeo-glaciological significance of the glacial landform record of Ireland. In a geomorphologically-driven ice sheet reconstruction, we learn something about both components of the inversion model: the ice sheet, and the geomorphological record. These two strands are explored in this chapter.

Not only may we gain specific insights into the manner of the ice sheet's evolution – the ways in which its geometry changes, or the degree to which ice streams dominate the flow behaviour – but an ice sheet reconstruction stimulates a wide range of questions concerning the implications for the ice sheet's role in the wider Earth system. What were the fundamental interactions and responses between the ice sheet component, the atmosphere, the ocean or the land? What were the primary drivers of ice sheet behaviour – the overriding climate, the ocean, internal glaciological dynamics? Do different drivers promote a response at different scales of ice sheet behaviour? How does the ocean, specifically the overturning circulation, respond to ice and meltwater fluxes from the ice sheet? How does (or indeed, can) the ice sheet perturb atmospheric circulation patterns or, more locally, precipitation patterns? What are the implications of the ice sheet reconstruction for isostatic loading and both eustatic and isostatic sea level change? How does the ice sheet interact with the underlying landscape? Can the landscape exert a control upon ice flow geometry or behaviour? What can we learn from the reconstruction process about the subglacial environment and geomorphological processes?

Many of the above are large-scale Earth system science questions and demand an Earth systems modelling approach to fully address their implications. However, models require data either for verification of model output or to drive the numerical process and, at a crude level, this evidence-based reconstruction can offer such information. The ice sheet reconstruction derived in this thesis therefore offers both specific insights regarding this ice sheet's behaviour and evolution, and should act as a stimulus for further exploration of Earth system implications. This chapter explores a range of ideas and insights which are stimulated by the ice sheet reconstruction. These encompass both the properties of the ice sheet system and properties of the geomorphological system.

11.2 Plausibility of the reconstruction

To draw meaningful insights from this reconstruction of the Irish Ice Sheet, it must first be ascertained that the reconstruction is plausible. There are two elements to the question of plausibility: is the reconstruction logically consistent with the physical evidence of glaciation, and is the reconstruction glaciologically plausible? In considering the compatibility of this reconstruction with evidence and models presented in the literature, Chapter 10 has largely addressed the first of these questions. Here, I briefly consider the latter. This reconstruction has been guided in a qualitative manner by glaciological and glacial geomorphological principles, and by modern ice sheet analogues. The following checks assess three key glaciological properties in a more quantitative manner.

11.2.1 Ice sheet surface profiles

Conceptualisations of the extent and dimensions of the last British and Irish Ice Sheets have varied like fashions over the century and a half of research into the nature of these ice sheets. Early workers presented a 'big ice' view of glaciation (e.g. Close, 1867; Hull, 1878; Geikie, 1894) in which ice covered the continental shelf of the British Isles in part or in entirety. A 'little ice' view of the last glacial maximum emerged through the middle of the 20th century (e.g. Synge, 1969, 1970; McCabe, 1985), with the ice limits confined to the present-day landmasses, and this idea still lingers (e.g. Bowen *et al.*, 2002; Knight *et al.*, 2004). In recent years a growing consensus is returning to the original view of continental shelf glaciation (e.g. Sejrup *et al.*, 2005; Hiemstra *et al.*, 2006; Stoker *et al.*, 2006b; Boulton and Hagdorn, 2006; Bradwell *et al.*, 2008 in press).

A simple analytical relationship for a steady state ice mass links the thickness of the ice body (on a horizontal bed) and the distance from the margin (hence the surface profile) of the ice sheet via the basal stress conditions (Equations 11.1 & 11.2; Paterson, 1994; Nye, 1952):

$$h = c\sqrt{x}$$
 Eq. 11.1

where h = ice thickness; x = distance from the ice margin;

and
$$c = \sqrt{\frac{2\tau}{\rho g}}$$
 Eq. 11.2

where τ = basal shear stress; ρ = density of ice; and g = acceleration due to gravity.

These relationships have been widely applied in a number of studies, to reconstruct or explore ice thicknesses, ice extent, surface slopes and driving stresses of palaeo-ice masses (e.g. Mathews, 1974; Reeh, 1984; Clark, 1992; Glasser and Sambrook Smith, 1999; Ballantyne *et al.*, 1998, 2007, 2008). The simple relationship between thickness and distance, modulated by the *c* value which determines the steepness of the surface profile, provides the opportunity to explore the question of ice sheet extent, and to explore the security of this reconstruction's depicted ice sheet geometries. All variables must fall within a plausible range of values in order to accept

this reconstruction; if values fall outside an acceptable range, an explanation must be sought or the reconstruction modified. To explore this problem, we require an estimation of ice sheet surface altitude, and either a range of basal shear stress values (τ) or a range of ice sheet profile index (c) values. The reconstruction provides the geometry to the problem: the distance between the divide and the ice margin, and the flowline which links the two.

Two alternative options could be pursued to analyse this problem: given a c value, is the resultant ice sheet height plausible?; or, conversely, given an ice sheet height is the ice surface profile realistic? An inherent limitation in this analysis is the poor constraint upon values for both of these unknowns; the following should therefore be taken simply as an exploration of plausibility rather than a critical test. The vertical extent of the last Irish Ice Sheet is not precisely known (see Chapter 2, Section 2.2.3.4) but the constraints upon its limits are becoming clearer (Rae *et al.*, 2004; Ballantyne *et al.*, 2006, 2007, 2008). Trimline evidence in the Wicklow mountains yields a minimum ice surface altitude of ~725 m (Ballantyne *et al.*, 2006); in Co. Donegal almost all high ground was overridden and a minimum ice divide elevation of ~700 m is proposed (Ballantyne *et al.*, 2007); and in western Ireland a minimum ice surface altitude of ~740 m (Ballantyne *et al.*, 2008). Using this information, the latter of the two potential approaches was taken. The following assumptions were employed:

- For most profiles an ice divide height of 1000 m was assumed. This takes the trimline altitudes as minima (after Ballantyne *et al.*, 2006, 2007, 2008), accounts for their location peripheral to, or branched from a main ice axis, and accounts for eustatic sea level change (although does not account for isostatic depression along the profile line).
- Where a divide height of 1000 m was not deemed appropriate, for example during a deglacial stage, the height was modified accordingly.
- As a first approximation each terminus is taken as 0 m elevation, which would imply a land-terminating ice margin. Three of the four selected profiles (see below) could potentially be (likely?) marine-terminating but with a relatively shallow water depth. C values are explored for these sectors using a 100 m ice cliff scenario.

The parabola index for the ice surface profile was compared to a range of c values for contemporary ice sheets gathered from the scientific literature (Figure 11.1).

Four profile lines, which are thought to be the least secure in terms of their ice surface profile, were selected (Figure 11.2) from the reconstruction of the ice sheet presented in this thesis. Using a selected divide height, the distance to the margin was calculated along a reconstructed flowline, and the required surface profile index value was determined. The results are annotated upon Figure 11.2.



Figure 11.1 Surface profiles in the literature have typically been described by high c values, ~4.5. Nye (1952) and Hollin (1962) base their values on single transect lines; Hollin's does not reach the ice divide since the parabola failed after 375 km from the margin. Had he followed the flowline to the divide, the true value would have been lower, possibly more aligned with the findings of Barr *et al.* (in prepn.), which are based on 10 profiles of each modern ice sheet extracted from digital elevation models.

Profile 1 considers an aspect of the plausibility of a Scottish ice 'invasion' of northern and central Ireland during reconstruction Stage I. Two sets of profiles have been examined. One set extends from the furthest margin to a Scottish source. The other set envisages that Scottish ice encroaches on Ireland but merges with and drives local ice towards the south-west, rather than Scottish ice itself being delivered all the way from the source to the margin. The profiles reaching all the way from Scotland yield very low c values (1.58), even with a divide height of 1000 m which is a likely overestimate for this early stage of glaciation. This flowline configuration is not considered plausible, since its profile lies outside the range of c values observed today. A mitigating factor which may often explain a low profile arises when fast flow induces drawdown of ice over a soft bed. However, this mechanism is most unlikely for this ice sheet sector, which is land terminating and must negotiate a varied subglacial topography along the length of the flowline. Profiles beginning over northern Ireland yield values more compatible with contemporary ice masses, although even these values suggest a shorter flowline would be more appropriate for a plausible at-an-instant geometry. These results support a contention that Stage I represents a time-transgressive stage in the ice sheet history, reflecting the advance of ice over Ireland and the coeval migration of the divide as it increasingly reflects the input from locally nourished ice caps (e.g. Figure 11.3).

Profiles 2 and 3 examine the reverse scenario to Profile 1: do these ice sheet sectors possess too steep a profile? That is, has the margin been reconstructed too close to the inferred ice divide position? The reconstruction of Profile 2 has been guided, in part, by the interpretation of the Quaternary stratigraphy of the south coast by Ó Cofaigh and Evans (2007). An inferred lack of offshore movement of Irish ice prior to a Celtic Sea incursion, would require a steep ice surface profile in Stage IIIb. Assuming an ice divide height of 1000 m, this ice surface profile (c value 3.26) lies firmly within the range observed on modern-day ice sheets (2.67 - 4.7). Indeed, if 1000 m is considered too thick an ice sheet in this peripheral sector, an even closer margin

would be required to maintain a suitable ice surface profile. In Connemara, a similarly steeply dipping sector is reconstructed (Profile 3) but this geometry occurs later in the relative chronology of events. The selected ice divide height is therefore lowered to reflect ice sheet thinning during deglaciation; 700 m yields suitable c values (3.56). If the divide height is kept at 1000 m, the surface profile (5.08) exceeds the range from contemporary ice sheets.



Figure 11.2 Ice surface profiles explored in terms of their glaciological plausibility, by comparison to contemporary ice sheet surface profiles. Values of an ice divide height were estimated and parabola index values were calculated along the appropriate reconstructed flowline to the margin. See text for further description and discussion of calculated *c* values.



Figure 11.3 Schematic model of how an incremental advance over Ireland during Stage I might be conceptualised. Profile lines will therefore be shorter and steeper than in Figure 11.2, more consistent with ice surfaces observed on contemporary ice sheets. Note that this illustration should not be taken as an assertion that ice specifically built up from the local areas depicted, this is merely a schematic illustration of the concept of a north-easterly ice lobe advance concurrent with local ice growth.

Profile 4 considers the much discussed Irish Sea ice stream. A flowline sourced at the head of the Irish Sea Basin and a margin position far into the Celtic Sea produce an exceptionally long flowline and, consequently, a very low ice surface profile. With an ice divide height of 1000 m, the *c* value of \sim 1.2 is well below the modern range of profiles. However, since ice streaming has been proposed along almost the entire length of this sector, there may be a dynamic reason for such a low profile. Fast flow over soft, deformable marine sediments would likely draw down ice from the interior of the ice sheet, having the effect of lowering the surface profile. Furthermore, in this context the basis for the parabolic relationship expressed in Eqn. 1 may be undermined; the relationship assumes a steady-state flow scenario, without dynamic elements such as ice streams. Ice streams bring about a deviation from steady-state and are somewhat of a mechanical anomaly, possessing very low driving stresses, low surface slopes, yet fast velocities. To accept the very low profile of this reconstruction as a plausible flow geometry, this flow route must be regarded as an ice stream.

These four sets of ice surface profiles represent the most extreme, or questionable of those ice sheet geometries reconstructed in this thesis. The results from Profile 1 reject a model of a single flowline extending from Scottish sources (either the Rannoch Moor area or the Southern Uplands) to the furthest margin reconstructed in Stage I. Rather, a model of advancing ice across central Ireland is more plausible. The other three profiles which have been examined, with some mitigating circumstances for the Irish Sea flow route, are all compatible with contemporary ice masses and these ice sheet geometries are accepted as plausible representations of the palaeo-ice sheet.

11.2.2 Flotation

Margins around the full extent of the ice sheet depicted in this reconstruction are located in present-day marine environments. These margins have been inferred based on the reconstructed onshore flow geometry, but their exact location is unclear and there is a lack of firm evidence on which to position margins with confidence; most margins are *not* based on offshore moraines.

An additional on the plausibility of the reconstruction presented in this thesis considers whether these ice sheet limits are viable grounded margins, or whether they have been positioned in locations simply too deep to allow a grounded margin of a plausible ice thickness.

The neatest solution to this problem would consider each reconstructed stage in light of the appropriate sea level for its time period, drawn from a global sea level curve (e.g. Bard *et al.*, 1990; Yokoyama *et al.*, 2000; Lambeck and Chappell, 2001), and determine whether each apparently marine terminating sector could physically remain grounded. However, in the absence of a secure absolute chronology for this reconstruction this route of analysis is not straightforward. Furthermore, the relative sea level history for the last glacial period around the British Isles reflects a complex interaction between eustatic and isostatic components, and there is limited information available beyond the Holocene and Late-Glacial (Shennan *et al.*, 2006; Brooks and Edwards, 2006). A full check on the viability of grounded ice margin positions from first principles is not possible but their likelihood can be explored for selected ice sheet sectors.

The most straightforward ice sheet sectors to assess are those which develop during the maximum phases of glaciation, since these phases can be associated with some confidence with a known global eustatic sea level fall of ~120-135 m (e.g. Bard *et al.*, 1990; Yokoyama *et al.*, 2000; Lambeck and Chappell, 2001). All four major ice sheet sectors at this time are suggested to have terminated in marine environments: the Porcupine shelf margin (up to 290 m below present-day sea level); the Donegal Bay shelf edge (~ -170 m); the Barra/Donegal Fan margin (~ -270 m); and the Celtic Sea margin (~ -135 m). A minimum ice thickness required to keep each of these margins grounded can be calculated on the basis of Equations 11.3 and 11.4 (Paterson, 1994; Benn and Evans, 1998):

$$w_f \approx 0.87h$$

where w_f = water depth required for flotation, and h = ice thickness;

$$i = h(\frac{\rho}{\rho'})$$
 Eq. 11.4

where i = depth of isostatic depression, h = ice thickness, $\rho = \text{density of ice, and } \rho' = \text{density}$ of rock. Given that ρ' can be taken as 3.7ρ (Paterson, 1994) Equation 11.4 can be rearranged as i = 0.27h. Eq. 11.4b

Assuming that isostatic adjustment is in equilibrium (the response is only to the immediate loading, there is no lasting response to the ice loading history) and there is no lateral component of lithospheric flexure (no response to the *surrounding* ice loading is considered), Equations 11.3 and 11.4b can be combined (Figure 11.4) to solve for the value of h:

$$w_f = w_e + i$$
 and thus $0.87h = w_e + 0.27h$ Eqs. 11.5a&b
where w_e = eustatic water depth (i.e. known from present-day bathymetry).



Figure 11.4 The necessary thickness of ice to maintain grounding of the ice sheet at a marine terminating margin can be estimated, and attempts to take account of isostatic depression. The water depth, accounting for the last glacial maximum eustatic minimum, can be ascertained at the reconstructed ice limit: w_e . Both the depth of isostatic depression and the maximum depth of water which could maintain grounding can be expressed in terms of ice thickness, and are mutually related by w_e . A minimum ice thickness which maintains grounding can therefore be resolved (Eq. 11.5a&b).

The minimum ice thickness required to keep the margin grounded at the reconstructed position, accounting for isostatic depression (in steady state), can be estimated (Table 11.1, Figure 11.5).

 Table 11.1
 Estimated minimum ice thicknesses required to maintain ice grounding at the reconstructed ice sheet limit.

 Thicknesses are calculated assuming two alternative custatic sea level histories.

Site (Figure 11.4)	Present-day depth	Palaeo-depth (eustatic fall 120m)	Palaeo-depth (eustatic fall 135m)	Required ice thickness (-120m)	Required ice thickness (-135m)	
1. Porcupine shelf	-290m	-170m	-155m	283m	258m	
2. Donegal Bay shelf	-170m	-50m	-35m	83m	58m	
3. Barra Fan	-270m	-150m	-135m	250m	225m	
4. Celtic Sea	-135m	-15m	0m	25m		





Table 11.1 presents the results of this analysis and it is suggested that none of these sectors raises any concern regarding the validity of the reconstructed extent as a grounded margin. The estimated ice thickness of ~200-300m required to maintain grounding is well within a plausible range of grounding line ice thicknesses. A calving ice cliff in excess of 500m would still be within the range depths of iceberg draughts discharged from modern-day and other palaeo-ice sheets (Dowdeswell et al., 1993; Polyak et al., 2001; Dowdeswell and Bamber, 2007). Furthermore, independent evidence supports grounded ice at the deepest reconstructed limits in the Porcupine and Barra Fan sectors. Sejrup et al. (2005) report well-developed moraines on the Porcupine Shelf, and the Barra Fan comprises glacigenic debris flows consistent with grounded shelf-edge glaciation (Knutz et al., 2002b). It is with some confidence, therefore, that the ice extents reconstructed in the maximum period ice sheet configuration are accepted as plausible limits of grounded ice. Indeed, site 4 could potentially have emerged above the eustatic global sea level. If this were the case, isostatic depression alone could never have depressed the subglacial surface such that the ice would have become buoyant. The converse to the question explored here is perhaps pertinent for this sector of the ice sheet: what water depth is required to induce calving? Celtic Sea ice is known to have discharged IRD to the Porcupine Seabight and Goban Spur (Scourse et al., 2000; Peck et al., 2006, 2007) and therefore this sector must have calved icebergs. The data presented here, albeit arising from a quick and crude analysis, suggests that ice at the terminus of the Celtic Sea sector of the ice sheet was not of a great thickness. For icebergs here to calve at this depth and float away to deposit IRD, ice thickness could only have been on the order of 25-30m. It is possible the margin extended further into slightly deeper waters than depicted in this reconstruction.

11.2.3 Ice sheet volume and sea level contribution

A final way of assessing the reliability of an aspect of this reconstruction is to examine whether the volume of ice captured in the reconstruction is consistent with other estimates of ice volume and/or sea level contribution (water volume) from this ice sheet. Clearly to accurately determine a volume of the ice sheet the ice surface must be well-constrained; in the absence of specific ice thickness information yielded by this flow geometry reconstruction, this exploration is more concerned with whether the reconstruction, and the ice thickness estimates used above, provide an estimate which is within the right 'ballpark' of previous estimates. To determine the evolution of the volume of the Irish Ice Sheet throughout its cycle would require too many assumptions of glaciological parameters and the absolute chronology of events. A crude estimate can be made, nonetheless, for the maximum period ice sheet.

To arrive at such an estimate, a Stage IV ice sheet (maximum) is divided into sectors (Figure 11.6a). For simplicity, each sector is assigned a divide height of 1000 m, a grounding line ice thickness of 100 m; a c value to describe the ice surface is deduced accordingly using Eqn 11.1. By integrating under the ice surface profile, an along flowline cross-sectional area may be derived (Figure 11.6b). Multiplying by an average sector width, a volume can be approximated for each sector of the ice sheet. The volume of the underlying topography is simply calculated

on the basis of the elevation and pixel size information of the British Isles and continental shelf Digital Elevation Model (Figure 11.6c), and subtracted from the full ice volume. This goes some way towards achieving a terrain correction, but for simplicity assumes a horizontal base level and no isostatic adjustment.

An ice volume of 119,817 km³, or ~0.3 m equivalent sea level, is estimated for the maximum phase of the last Irish Ice Sheet. This volume is reassuringly consistent with existing estimates of BIIS ice volume and sea level contribution. Hughes *et al.* (1981) place the volume of the *whole* BIIS at ~800,000 km³; Hagdorn (2003) estimates the BIIS volume to have been between ~250,000 and 800,000 km³ depending on the choice of climate driver of his numerical ice sheet model. Peltier, Shennan and colleagues express ice sheet volume as a sea level equivalent: the ICE-4G model of Peltier *et al.* (2002) suggests a BIIS sea level contribution of ~0.5 m whilst Shennan *et al.* (2006) revise this value to ~1 m sea level contribution under their 'thick ice' model. The values estimated here suggest the Irish Ice Sheet could contribute $\sim \frac{1}{2}$ of the total BIIS volume (though under a model of confluent ice from Ireland to Fennoscandia the notion of individual ice sheets and individual contributions becomes rather arbitrary). The reconstructed size of the Irish Ice Sheet, and the assumptions of ice thickness and surface profiles invoked in the above analysis appear to be consistent with other such reconstructions.





Figure 11.6 Estimating ice sheet volume for the maximum period. The ice sheet is split into 6 sectors, broadly defined by the major drainage basins (**a**). An average length and surface profile is determined for each sector, allowing a longitudinal cross-section area to be approximated for each (**b**). Multiplying the cross-section area by the sector's average width gives an approximate volume for each sector. Digital elevation data possesses an elevation value per pixel (of area xy - c), & thereby provides an estimate of the subglacial topography. Subtracting the topographic volume from the total volume under the ice surface gives an ice sheet volume.

11.2.4 Exploration of glaciological 'plausibility': summary

This section has considered three elements of glaciological plausibility in a more quantitative manner than the qualitative glaciological principles which initially guided the reconstruction. Although only an exploration of the reconstruction rather than a definitive confirmation (or otherwise) of its validity, these analyses largely support the reconstruction as far as the exploration permits. Those ice sheet profiles which visually appear to be the most questionable are accepted as legitimate reconstructions. Overall, profile values are towards the lower end of the range observed from contemporary ice sheets; this may be attributable to large marine sectors occupied by the last Irish Ice Sheet once it extended over the present-day coastline onto soft, deformable sediments and a subdued topography. Whilst a considerable proportion of the ice sheet was likely marine terminating during its maximum stages, water depths are not thought to be sufficient to induce buoyancy of the reconstructed limits, and these limits are accepted as plausible grounded ice margins. This is not to say ice shelves did not extend further seawards from these grounding lines. Potential marine ice limits during the stages of ice sheet build-up and decay are less easily evaluated in the absence of a secure chronology for the ice sheet's evolution and a detailed relative sea level history for the whole glacial period for the British Isles. Finally, the overall volume of the ice sheet which can be crudely estimated from the reconstructed flow geometry is entirely consistent with previously modelled ice sheet volumes and sea level contributions. Accepting these limited checks on the plausibility of the ice sheet reconstruction presented here, we can now more securely explore the palaeo-glaciological insights yielded by this reconstruction of the last Irish Ice Sheet.

11.3 Insights: ice dynamics & the pattern of Irish Ice Sheet evolution

The reconstruction of the Irish Ice Sheet presented in Chapter 9 of this thesis provides not only a geometric reconstruction of the ice sheet history, but has revealed a range of properties of the ice sheet which give us some insight into the ice sheet's dynamics and behaviour. The ice sheet likely underwent major changes in its overriding structure from the growth and maximum phases into the deglaciation. Ice divide migrations characterise all stages of the ice sheet's history. Ice streaming is a fundamental property of the maximum period of glaciation. The specific pattern of ice sheet evolution also reveals some interesting insights. Evolution was asymmetric: ice retreat did not mirror the pattern of ice sheet growth. The spatial evolution of the ice sheet was also asynchronous: western sectors expanded to their maximum extent prior to advance to the southern maximum. The manner of deglaciation was ice sheet fragmentation into residual ice caps and bodies. These observed properties lead us to question the drivers behind such ice sheet behaviour. What mechanisms may induce structural changes and ice divide migrations? What role do ice streams play in the observed patterns of ice sheet behaviour and evolution? Why was the spatial pattern of ice sheet evolution neither symmetric nor synchronous? The ice dynamic properties observed in the reconstruction and the questions these dynamics raise concerning the controls on ice sheet behaviour are explored in this section.

11.3.1 Structural changes and ice divide migrations: controls on ice sheet behaviour

A range of scales of ice sheet behaviour have been recognised in the Irish Ice Sheet and reconstructed in this thesis. These encompass changes in the overriding structure of the ice sheet occurring over major phases of the glaciation, through to small-scale oscillations and subtle fluctuations of the ice flow geometry. Short-term and abrupt changes in ice sheet geometry or behaviour demand and attract considerable attention since these are important indicators of ice sheet sensitivity to changes in their driving forces. The Irish Ice Sheet literature has speculated whether the shorter- to medium-timescale events (e.g. ice sheet readvances and margin oscillations) may have been driven by climate forcing (a regional D-O type cooling, or local precipitation regimes responding to the vigour of the Atlantic MOC, e.g. McCabe *et al.*, 2007b), sea level forcing (the interplay between isostatic loading, RSL and calving rates, e.g. Eyles and McCabe, 1989; McCabe *et al.*, 2007b), or dynamics internal to the glaciological system (e.g. Evans and Ó Cofaigh, 2003; Boulton and Hagdorn, 2006). At the other end of the scale, fundamental changes in the structure of the ice sheet are accompanied by major ice divide migrations – major movements (>100 km) of the centres of mass of the ice sheet. This section explores potential drivers behind some of these *major* changes in the configuration of the ice sheet throughout its evolution.

Two marked sequences of events occur from Stage II to IIIb – the eastwards migration of the main ice divide – and from Stage IV to V – the collapse of a linked British-Irish ice divide and the westwards movement of the remnant Irish axis. These sequences reflect major structural changes in the ice sheet geometry. These phases of change are additionally characterised by large ice streams in sectors of the ice sheet. Two hypotheses are put forward which could explain the large-scale changes in ice sheet configuration:

- 1. Ice divide configuration and migration has been driven, in these stages, primarily by glaciological dynamics, such as by ice streams.
- 2. Ice divide changes were a response to steady climate forcing.

These hypotheses are now explored.

11.3.1.1 An ice stream driver?

Ice streams can potentially discharge up to 90% of the mass of an ice sheet (Paterson, 1994; Bamber *et al.*, 2000). These fast flowing arteries are known to have an impact upon ice sheet geometry via draw-down mechanisms and surface profile lowering. The following analysis considers whether an ice stream can perturb the ice sheet geometry more fundamentally, by shifting the position of the ice divide. To consider this problem, I take a catchment-based approach. An ice divide is essentially an ice-shed between catchments, or ice sheet drainage basins. To effect the movement of a divide an ice stream must, logically, enlarge its catchment. This scenario could arise if the catchment was perturbed from a balanced state. If discharge from the catchment were to exceed accumulation over the catchment then, to maintain mass balance, further input is required; the catchment must enlarge and the divide must be driven headwards. This analysis explores the balance velocities of catchments which could be implicated in the ice divide migrations and re-configurations between Stages II-IIIb and IV-V.

A catchment balance velocity is estimated based on a number of conditions or assumptions:

an accumulation rate is assumed, consistent with modern ice sheet accumulation rates from

comparable climate settings. The Antarctic peninsula and the southern tip of Greenland both lie in maritime climatic settings at the limit of modern continental glaciation. Thomas *et al.* (2001) estimate that southern Greenland accumulates between 59.7-67.0 cm/yr, broadly consistent with Ohmura and Reeh (1991) although these latter authors suggest accumulation may exceed 1 m/yr in restricted parts of southern Greenland. Estimates for the Antarctic peninsula and its neighbouring catchments range from ~45-90 cm/yr (Giovinetto and Zwally, 2000; Rignot and Thomas, 2002). An accumulation rate of 80 cm/yr is selected as a plausible value for western Ireland, a slight depression of the modern precipitation rate for this region. Consistent with the modern west-east distribution of precipitation, an accumulation rate of 65 cm/yr is selected for eastern Ireland.

- accumulation is applied evenly over a whole catchment. This will over-estimate catchment mass gain but is the simplest assumption for the purposes of this exploration.
- mass loss occurs via discharge through a 'gate', positioned at the catchment terminus.
- a gate height, or ice thickness, is estimated based on the above exploration of grounding line positions and ice flotation.
- a catchment and catchment gate are drawn based on the reconstructed flow geometry.

Balance velocities are calculated, using appropriate values for the parameters outlined above, for the three catchments which are, under this hypothesis, implicated in the geometric changes of the ice sheet reconstructed between Stages II-IIIb and IV-V (Figure 11.7). These results are presented in Table 11.2.

Catchment	Gate height (m)	Gate area (km ²)	Catchment area (km ²)	Catchment accumulation (km³/yr)		Balance velocity (km/yr)	
Company and the explored he	a best in with the	the minimum man the		@ 65cm/yr	@ 80cm/yr	@ 65cm/yr	@ 80cm/yr
Western Bays (Stage I	I) 200	13.9	9917		7.93		0.57
(Stage I	IIa) 200	7.38	27,503		22.00		2.98
Irish Sea Basin	50	5.88	41,818	27.18		4.62	
North Channel (N.C. o	nly) 250	15.6	27,567	(17.92)	22.05	(1.15)	1.41
(Malin	Shelf) 250	21	42,484	and the second	33.99		1.62

Table 11.2 Estimated balance velocities for catchments displaying ice streaming during phases of ice sheet structural changes.

The balance velocities estimated for the Western Bays, the ISB and the North Channel catchments reveal that simply to export their catchment accumulation, ice streaming velocities are required. This is somewhat to be expected, since these flow geometries already depict strong flowline convergence: this is not an independent exploration of the effect of ice stream *initiation* on a catchment's geometry. However, it is still relevant to seek the impacts of *ongoing* ice streaming upon the structure of the ice sheet. The balance velocities are maximum estimates, since the assumption of equal accumulation everywhere is unlikely to hold. Furthermore, these velocities are not particularly remarkable in the context of the range of flow rates measured, modelled and reconstructed from both contemporary and palaeo-ice streams (Table 11.3). It remains feasible that the catchments considered here discharged ice at faster rates than they gained in mass, and thus an ice stream mechanism for catchment enlargement and ice divide



Figure 11.7 Ice streaming catchments implicated in ice divide migrations and structural changes of the ice sheet between Stages II-IIIb and Stages IV-Va. Balance velocities are calculated as outlined in text, using catchment area (green) and terminus gates (red.) Note that following the discussion of the maximum period of glaciation in Chapter 9, Section 9.4.2, both the North Channel and ISB routes may exhibit ice streaming throughout a time of ice divide movements north and south across the trough system. Configurations explored here are those which capture the likely largest extent of each ice stream system.

migration cannot be rejected. A stream in the Western Bays catchment could drive the main axis towards the east from Stages II-IIIb if it flowed faster than ~3 km/yr; an ice stream system is specifically reconstructed in Stage IIIa, lending support to this contention. Between Stages IV and V the main ice divide is driven from the Irish midlands and Irish Sea Basin, where it forms a saddle with the semi-independent British Ice Sheet, to a new position over western and northwestern Ireland. In Stage IV two ice streams operate in opposing directions from the ISB saddle, each capable of forcing headwards migration of the ice divide. The Irish Sea ice stream must flow at over 4 km/yr simply to discharge its catchment accumulation, but should the North

Table 11.3 Examples of ice stream velocities drawn from contemporary and palaeo-ice sheets. The above estimates of balance velocities from $\sim 1.5 - 4.5$ km/yr are well within a feasible range, and it remains plausible that an ice streaming catchment in excess of these estimated velocities could effect ice divide structural changes upon the Irish Ice Sheet.

Ice Stream	Context	Velocity	Reference		
Siple Coast (A-E)	contemporary	100-800 m/yr	(Joughin and Tulaczyk, 2002)		
Jakobshavn Isbrae	contemporary	>12 km	(Joughin et al., 2004)		
Norwegian Channel palaeo		~2.7 km/yr	(Nygård et al., 2007)		
Hudson Strait	palaeo	~4 km/yr	(Dowdeswell et al., 1995)		

Channel route surpass ~ 1.5 km/yr its catchment would encroach into that drained by the ISB. It remains plausible that competition for ice from both the northern and southern sides of the ISB saddle caused its collapse, driving the remnant Irish ice divide westwards.

11.3.1.2 A climate driver?

An alternative hypothesis to an ice stream mechanism for ice divide migration is that the change in structure is a simple response to climate forcing of the ice sheet. As accumulation and ablation zones of the ice sheet shift, the geometry and structure of the ice mass must adapt accordingly. For such a climate driver to force an ice divide migration, accumulation at the 'new' divide site must raise the ice surface altitude to exceed that at the initial divide position.

From Stage II to Stage IIIb, for example, the main axis of the ice sheet is suggested to have swung approximately 140 km from the west towards the east of Ireland (60 km between Stages IIIa-b). This sequence occurs during an overall period of ice sheet growth and, therefore, not only must the Stage IIIb divide exceed the height of the Stage II divide, but it must approach the maximum ice surface altitude attained by this ice sheet. The position of the axis in Stage IIIb lies virtually at the limit of glaciation in the earlier Stage II. If the eastern portion of the ice sheet gained in altitude at a rate of 65cm/yr (accumulation rate used in Section 11.3.1.1, above), without any redistribution of mass and whilst the west received no net accumulation, it would take over 1500 years to accumulate sufficient ice to raise the IIIb ice divide to a height of 1000 m. This represents a minimum response time to a climate signal and requires that the rest of the ice sheet system effectively stands still whilst accumulation gathers in the east. Configuration change via this mechanism would take a considerably longer time than this estimate.

Furthermore, the distribution of accumulation required for relative height gain in the east counters the expected west-east precipitation gradient. Both the proximity to the moisture source and the (initially) higher ice surface altitude in the west would be expected to reinforce western sites of accumulation. Eastern sectors should be relatively more starved of precipitation, in the 'rain shadow' of high elevation to the west and due to a strong west-east continentality gradient. Model experiments find that a west-east continentality gradient across the British-Irish Ice Sheet must be extremely strong in order to produce a 'realistic' ice sheet geometry and evolutionary pattern (Boulton and Hagdorn, 2006). Not simply the weakening, but the *reversal* of this gradient would be most unexpected. These arguments suggest that a climate driver is not the most likely candidate for stimulating a major ice divide migration towards the east of the ice sheet.

11.3.1.3 Summary: drivers of structural changes

Neither climate drivers nor ice streaming can be rejected as mechanisms of ice structure changes. Both hypotheses remain plausible but, given the demands for dramatic switches in precipitation gradients under a climate driver framework, an ice streaming interpretation is favoured here. The landform evidence, reconstructed flow geometries and balance velocities are

consistent with ice streaming in each of the implicated catchments, and velocities in excess of those required for mass balance would drive a geometric change in ice sheet properties.

Clark and Meehan (2001) describe a westwards divide migration which is broadly consistent with the changes observed here between Stages IV and V (see Sections 10.3.1, 10.7.1). They speculate this shift reflects an ice sheet response to a moisture deficit in the east and enhanced accumulation nearer the source of moisture in the west. Although it is argued here that climate forcing would not explain the earlier, eastwards divide movement, for the sequence of events described by Clark and Meehan, their climatic interpretation is logical. However, it would be remarkable should the two large, competing ice streams which divided the British from the Irish Ice Sheet have had no structural impact. The North Channel and the ISB ice streams each individually have the power to effect a migration of their ice divide. Operating at the same time but in opposition to each other, the potential for ice divide collapse and the resultant structural change is strong. To further evaluate the relative roles of climatic or dynamic drivers of major changes in ice sheet geometry we should appeal to numerical modelling as a tool to explore the sensitivity of the ice sheet at a range of scales to its potential forcing functions.

11.3.2 The pattern of ice sheet evolution

Not only does the ice sheet reconstruction reveal certain types of behaviour, such as ice divide migrations or ice stream operation, as explored above, but it also raises interesting questions of the specific *spatial pattern* of events, of the specific pattern of ice sheet evolution. In particular, the reconstruction indicates both an asymmetry and a lack of synchroneity across ice sheet sectors in the evolution of the ice sheet throughout its cycle. These patterns are explored here.

11.3.2.1 Asymmetric evolution

The incursion of ice from Scotland onto the north and east Irish coasts has long been discussed (e.g. Charlesworth, 1939; Synge and Stephens, 1960; Stephens *et al.*, 1975; McCabe and Hoare, 1978; Hoare, 1991; McCabe *et al.*, 1999). Independent evidence described in this thesis supports and extends this ice flow movement; a substantial movement of ice from the north-east is evident across much of northern and central Ireland early in the glacial record. It is suggested this flow pattern operated during the initiation of the last Irish Ice Sheet (Sections 9.4.1, 11.2.1) and the major centre of ice accumulation, and ice sheet inception, must have been located over western Scotland. The Irish Ice Sheet does not, however, decay following the same pattern as that with which it grew. This reconstruction, and other models of ice sheet evolution presented in the literature (e.g. Clark and Meehan, 2001; Delaney, 2002; Knight, 2003a,b; Brooks *et al.*, 2008), reveals that in the final stages of glaciation, ice withdrew to western Ireland. Ice sheet evolution was therefore asymmetric in its geometry (Figure 11.8).

This reconstruction reveals that the Irish Ice Sheet became semi-independent of the British Ice Sheet soon after initiation. Whilst undoubtedly confluent, the Irish Ice Sheet displays its own dynamic behaviour and is not simply a passive appendage to the larger British Ice Sheet.

Furthermore, the geography of the British Isles, divided by the deep troughs of the North Channel and Irish Sea Basin, lends itself to supporting two semi-independent ice bodies. This trough zone is the line of connectivity of the two ice sheets and the manner of ice behaviour through this zone is likely to be fundamental to the overall geometry of the ice sheets' evolution. It was proposed above (Section 11.3.1.1) that two competing ice streams through the North Channel – ISB trough system could induce collapse of the saddle which links the British to the Irish Ice Sheet (Stage IV). If both streams, operating in opposing directions, drained a sufficiently large volume of ice such that their natural tendency was to drive their ice divide headwards, competition for ice supply could induce both collapse of the saddle and collapse of one or both of the ice streams. In so doing, this would effectively break the tie between the two ice sheets, and they would become dynamically independent. A model of retreat to the west of Ireland is then easily accommodated, the remnant divide driven westwards by the collapse of the saddle, and towards where moisture supplies could maintain the nourishment of the ice sheet during its deglaciation. This model indicates that whilst climate (via the ELA) may be a fundamental driver of ice sheet nucleation, and may dictate the final sites of ice sheet decay, the glaciological dynamics of the ice sheet take over, such that the sites of initiation and disintegration are not the same. Ice sheet evolution is thus asymmetric.



Figure 11.8 a) Schematic conceptualisation of the time-space evolution of the last Irish Ice Sheet, across a west-east transect (b). Growth and decay is revealed to be asymmetric, following the general trend shown in panel **a**, **inset** (red line). It is speculated this asymmetry is a product of the glaciological system itself. Red dots mark the intersection of the ice margin with the transect, black dots mark the divide position; D = ice divide; S = ice saddle.

11.3.2.2 Asynchronous evolution

Whilst the ice sheet displays asymmetric evolution from west to east, it also displays asynchronous evolution from the north/west to the south. The reconstruction suggests a swift expansion of ice onto the western and northern continental shelves, where it attains its maximum extent (from Stage IIIb) prior to the advance of ice through the ISB to the southern maximum, likely towards the end of Stage IV (Figure 11.9). It was suggested in Chapter 10 the time lag between the western and southern maxima may be on the order of ~3 ka. The ice

stream system in the ISB is again implicitly implicated in the asynchronous behaviour of these ice sheet sectors. It rapidly delivers ice well beyond the limit of the Stage III ice sheet, and well beyond the limit over terrestrial sectors of the British Ice Sheet.





11.3.2.3 Dynamic controls on asymmetry and asynchroneity?

Ice streams in the North Channel and Irish Sea Basin have been implicated both in driving the asymmetric pattern of ice sheet evolution and accounting for the asynchronous pattern of ice sheet behaviour at the first order scale. This zone of ice flow between the British and Irish Ice Sheets appears to have exerted a fundamental control on the growth and decay of the whole ice body. This zone connects the ice sheets from the time of their initiation, and flow is funnelled through this system in both directions from a relatively early stage. This begs the question why the system might have collapsed at the time that it has been observed to do so; if the North Channel and ISB systems operate against each other, how did the maximum ice sheet ever build up? The implication is that system did not always have such power to drive its own collapse: one or both ice streams were not 'turned on' at an early stage.

It was speculated in Chapter 9 that the North Channel funnels ice out of the central portions of the BIIS from the earlier stage. It has also been suggested in previous literature that the Irish Sea advance was rapid, unstable and short-lived, occurring later in the glaciation than western and northern maxima. The implication is that the North Channel ice flow route was the more stable and long-lasting, and the ISB advance destabilises the system and induces self-destruction. The controls on the timing of the ISB advance may only be speculated: a relative sea level rise and drawdown mechanism?; a critical thickness or driving stress reached?; the removal of some control that had earlier pinned back the tendency of funnelled flow to advance out of the inner basin?; a surge-type mechanism? There must clearly be some mechanism which

inhibits the development of this route as an ice stream capable of such a massive advance earlier in the period of ice sheet evolution.

11.3.3 Further implications of ice streaming: meltwater fluxes to the North Atlantic

Ice streams have been implicated, above, as potentially powerful drivers of major changes in ice sheet structure and geometry. They appear to have been capable of driving significant ice divide migrations which were not necessarily consistent with the likely pattern of climate forcing, and are strongly implicated in driving an overall asymmetry and asynchronous pattern of ice sheet evolution. Beyond their potential impacts on the ice sheet system itself, these arteries of fast ice flow are routes of concentrated ice, sediment and meltwater export from the ice sheet to the ocean system. Much recent research has been directed at understanding the oceanographic (and, consequently, climatic) effects of ice and meltwater delivery to the oceans (e.g. Broecker, 1994; Rahmstorf, 1995; Seidov and Maslin, 1999; Weaver et al., 2003; Tarasov and Peltier, 2005; Jennings et al., 2006; Hall et al., 2006; Death et al., 2006). Whilst the BIIS is small and its volumetric contribution to the ocean far less than the larger Laurentide or Fennoscandian Ice Sheets, its proximity to sites of deep water formation demand that ice and meltwater delivery to the ocean from the BIIS is taken into consideration. Assessing the significance of the BIIS in this way requires knowledge of the ice sheet history, likely sites of delivery and, importantly, fluxes via these gateways. This section considers what the Irish Ice Sheet reconstruction can contribute towards these requirements. Gateways and fluxes identified here are being used in ongoing modelling experiments (R.C. Levine & G.R. Bigg) which are examining the role of NW European ice sheets in perturbing ocean convective processes in the North Atlantic.

Two approaches may be undertaken in order to estimate ice discharge to the ocean. A catchment-based approach is the primary one, which envisages that ice streams will be the major vehicles for rapid and punctuated delivery of ice and meltwater. The alternative is a more broad-brush approach, which simply states that the whole volume of the maximum period ice sheet must be delivered to the ocean during deglaciation. These are both explored here.

11.3.3.1 A catchment-based approach

The major catchments, or drainage basins, which likely contributed ice and meltwater to the ocean in a spatially focussed manner are the Western Bays catchment, the ISB, the North Channel – Malin Shelf catchment, and the Clare catchment (Figure 11.10). While the exact geometry and the behaviour of each of these catchments is temporally variable, each are relatively stable features of the broad ice sheet structure. Three of these four have been inferred to carry ice streams at some time during their history, and have been considered above in the context of dynamic controls upon ice sheet structure. The Clare catchment has not been reconstructed or discussed as a potential ice stream, but the landform evidence clearly reveals this was a major flow route to a margin located some distance offshore; it is considered here, therefore, as a potential route of focussed ice delivery. Balance fluxes from the three former

catchments have been calculated in Section 11.3.1. Estimates of ice fluxes from the Clare catchment are calculated in the same way, and presented in Table 11.4.



Figure 11.10 Major catchments through which ice export to the ocean is considered here.

 Table 11.4
 Estimated fluxes from major Irish Ice Sheet catchments, using the accumulation balance approach outlined above,

 Section 11.3.1, and exploring fluxes through the same gate at a range of flow velocities. For the Clare catchment, a gate height of 200m is used, and an accumulation rate of 80 cm/yr. This estimate is subject to the same caveats and assumptions outlined above.

Catchment	Gate height	Balance flux (km ³ /yr)	Flux (km ³ /yr) at velocities:			
	(m)		0.5 km/yr	2 km/yr	6 km/yr	12 km/yr
Western Bays	200	22.00	3.69	14.76	44.28	88.56
ISB	50	27.18	2.94	11.76	35.28	70.56
North Channel	250	22.05	7.8	31.2	93.6	187.2
(Malin Shelf)		(33.99)	(10.5)	(42)	(126)	(252)
Clare	200	14.59	5.98	23.92	71.76	143.52

The estimated catchment fluxes are small compared to those calculated for major streams, from both contemporary and palaeo contexts. At velocities of ~4 km/yr the Hudson Strait and M'Clure Strait ice streams are suggested to have exported 312 km³/yr and in excess of 400 km³/yr respectively (Dowdeswell *et al.*, 1995; Clark and Stokes, 2001; Stokes *et al.*, 2005). The Norwegian Channel ice stream, flowing at ~2.7 km/yr, would likely have discharged ice at 135 km³/yr (Nygård *et al.*, 2007). Joughin and Tulaczyk (2002) estimate that the flux from the Siple Coast ice streams totals approximately 72 km³/yr, more comparable to the Irish estimates. The North Channel – Malin Shelf system is the most likely candidate for delivering significant volumes of ice and meltwater to the ocean from the Irish Ice Sheet, having a large gate area and a context highly conducive to ice streaming at high velocities (topographic constraint, funnelled flow and deformable marine sediments). Whilst fluxes from the Irish Ice Sheet are generally minor, their location may render their fluxes significant, delivering icebergs more readily into the key regions of ocean overturning in the NE Atlantic. The sites and discharges calculated here are therefore relevant for exploration of the sensitivity of the glacial ocean to meltwater delivery from circum-North Atlantic ice sheets.

Whilst modelling experiments reveal insights of the sensitivity of the different components of the ice sheet - ocean - climate system, and are able to advance our understanding of the physical mechanisms involved, the actual evidence of punctuated changes in the system is revealed in both ice cores and marine cores. The sites of focussed ice delivery to the ocean which are identified here may also be relevant to deciphering the record of ice-rafted debris from the continental slopes. Ocean cores from the western British Isles (e.g. Hall and McCave, 1998; Scourse et al., 2000; Kroon et al., 2000; Richter et al., 2001; Knutz et al., 2001, 2002a, 2007; Peck et al., 2006, 2007) document a continuous record of BIIS-related ice-rafted sedimentation. The increasing capabilities for tracing the provenance of ice-rafted material may yield not only the ice sheet from which material has been delivered, but from which specific outlet the associated icebergs were discharged (e.g. Walden et al., 2007; Knutz et al., 2007; Peck et al., 2007). The identification of likely outlets from the onshore record is clearly pertinent to this effort. Whilst the ice dynamic implications of an IRD signature are, as yet, poorly understood (Marshall and Koutnik, 2006; McCabe et al., 2007b; Scourse et al., 2008), such IRD 'fingerprinting' will contribute to a better understanding of the roles and periodicities of different ice sheets in circum-North Atlantic events.

11.3.2.2 Full ice sheet volume

In order to investigate the impact of focussed, punctuated delivery of icebergs and meltwater to the ocean, a catchment-based approach to estimating ice fluxes is likely the more appropriate. However, the total volume of ice held within the ice sheet must, eventually, be delivered to the ocean during deglaciation. In Section 11.2.3, above, an estimate of ~120,000 km³ ice was put forward for the maximum period ice sheet. Rapid deglaciation over a period of ~5ka (e.g. Shennan *et al.*, 2006; Brooks *et al.*, 2008) would require the loss of ~24 km³ of ice per year; over a longer timeframe the annual requirement of ice loss would be even less. This flux is of the same order as that which a single ice stream could deliver without any other loss from the ice sheet system. Of course these estimates assume there is no mass gain during deglaciation, and to take this into account would raise the required annual flux. Nonetheless, we must conclude that ice streams could not have been particularly active once deglaciation was underway; if they had been, the ice sheet would have ceased to exist in an even shorter timescale. This is consistent with the evidence-based reconstruction which recognises maximum phase ice streams, but likely only small outlet glaciers operating during ice sheet decay.

11.3.4 Ice dynamics: summary

The reconstruction of flow geometry and ice sheet configuration deciphered in this thesis reveals a range of insights regarding the palaeo-glaciology of the Irish Ice Sheet. Some of these relate specifically to the dynamics of the ice sheet system and have been explored here; some are more intricately linked with the nature of the geomorphological system, and are considered in Section 11.4, below. At the ice sheet-scale, significant changes in structure and geometry have been observed throughout the ice sheet's evolution, and the overall pattern of evolution displays both asymmetry and asynchroneity. Common to both of these large-scale dynamic

insights is the implication of the role of ice streams. The reconstruction suggests the ice sheet was drained by large ice streams particularly through its maximum period. Climate drivers of ice sheet evolution are clearly a fundamental control, but the exploration in the above sections suggests that ice streams may have been sufficiently powerful to exaggerate, accentuate or even detach the ice sheet behaviour from the overriding climate signal. Ice streams were potentially capable of independently driving reorganisations of the ice sheet geometry. Furthermore, their implication in the asymmetric evolution of the ice sheet via the destruction of the North Channel – Irish Sea Basin suture line between the British and Irish Ice Sheets suggests also that by instigating its own collapse this ice stream system was a key driver of deglaciation.

What controls the timing and consequences of ice streaming upon the ice sheet are fundamental questions in glaciology which remain poorly understood. How does the North Channel – ISB system evolve as a competing system and what controls the point at which it destroys its source saddle and induces collapse along the suture zone of the BIIS? Major ice streams have not been reconstructed during deglacial stages, once the ice has retreated to the present-day land; what causes an ice stream system to stop? Do ice streams typically operate during all periods of growth, maximum and decay of ice sheets? Numerical modelling tools are best equipped to explore such questions in a rigorous manner, as well as the fundamental balance of climatic, ocean and internal ice dynamic controls upon ice sheet behaviour and evolution. Modelling experiments are also key to exploring the wider significance of the ice sheet and the Earth system implications of this reconstruction, such as the questions raised earlier in this chapter, Section 11.1. Towards this end, estimates of fluxes from this reconstructed ice sheet contribute to an ongoing model exploration of the impacts of ice and meltwater delivery from NW European ice sheets on ocean convection and overturning in the North Atlantic.

11.4 Insights: glacial geomorphology

A geomorphologically driven ice sheet reconstruction inevitably generates two lines of understanding: something is learnt about the ice sheet, and something is learnt about the geomorphology. Our drive to understand each of these aspects of the palaeo-glaciological system is complementary. In particular, an improved picture of the ice sheet, its behaviour and its evolution, both raises questions of and sheds some light on our interpretation of the geomorphological record. Three key aspects of the Irish geomorphological record merit further comment and discussion in light of the new ice sheet reconstruction. How is the reconstruction underpinned by geomorphic process models; in particular, what are the implications for models of ribbed moraine genesis? What are the implications of this multi-temporal landform record for landform generation and preservation? Finally, how can we better characterise the geomorphological record for palaeo-glaciological interpretation at the ice sheet-scale?

11.4.1 Models of ribbed moraine genesis

A fundamental assumption of the landform inversion model adopted in this thesis is that ribbed

moraine are part of a suite of landforms generated under a deforming bed process framework. An alternative model of ribbed moraine formation (Hättestrand, 1997; Kleman and Hättestrand, 1999) predicts that ribbed moraine are a product of thermally induced fracturing of the till sheet. This alternative proposes that at a transition from cold- to warm-based ice, an extensional flow regime will promote fracture of the sediment substrate into tabular-like ridges. The development of this theory of genesis notes that there is often a geographical coincidence between ribbed moraine distribution and the core areas of ice sheets. Furthermore, the distribution and disposition of ribbed moraine in Sweden closely follows the deglacial ice sheet configuration, rather than any previous ice sheet geometry (Hättestrand, 1997). On this basis it has been inferred that ribbed moraine fields are generated time-transgressively near the core of an ice sheet, at a retreating frozen-thawed boundary which accompanies retreat of the ice margin. Lineation overprinting is interpreted as a product of the ongoing thermal phase change to a warm-based subglacial environment. Such landform assemblages have thereby been used as indicators with which to reconstruct ice sheet core zones and frozen beds.

Explored here are the implications for the Irish ice sheet reconstruction if a thermal fracturing model, set in a deglacial context, was adopted. Since the development of the theory had a strong geographical basis – the disposition of ribbed moraine in relation to ice sheet geometry – it is interesting to explore whether the geography of the Irish Ice Sheet and its geomorphological record supports or challenges the thermal fracture model. Could a model of concentric retreat to the zone of ribbed moraine be applied to the Irish landform record, whilst maintaining the rules of inversion which the interpretation of lineations must obey? If so, an alternative (likely significantly different) ice sheet history to the reconstruction presented in this thesis could be equally viable. The large swath of ribbed moraine across northern and central Ireland, and the associated lineation record, are interrogated with three key questions. Do the ribbed moraine and their inferred flow directions broadly form a concentric pattern? If so, can any other evidence support or reject a model of concentric ice margin retreat to the core zone characterised by ribbed moraine?

Figure 11.11 addresses these questions. A concentric arrangement of ribbed moraine could, potentially, be interpreted (Figure 11.11a). To do so would require that some complex ribbed moraine morphologies and arrangements, possibly cross-cutting arrangements (starred in Figure 11.11a), should be ignored, but these could be explained as minor anomalies which do not invalidate the larger-scale model. Lineations which overprint the ribbed moraine broadly form a radial arrangement from this core zone. Furthermore, they impinge on all but the central part of the ribbed moraine zone (marked in Figure 11.11b); this could more accurately pinpoint the final site of deglaciation. However, one key component of the lineation record leads to an argument that this model of, and context for, ribbed moraine formation cannot be supported by the landform evidence observed in Ireland (Figure 11.11c). To adhere to the 'false divide' rule (Section 9.2.1) the lineation flowsets east and west of the ribbed moraine zone cannot be

considered contemporaneous. Ice divide positions which are required by these flowsets are markedly different. Furthermore, and a critical test, independent deglacial evidence produces a retreat pattern which does not correlate with the ribbed moraine distribution (see Figure 9.22). The final sites of ice sheet decay have been reconstructed in the mountain groups of the west coast, rather than the central lowlands occupied by ribbed moraine. A model of ribbed moraine genesis via thermally induced fracturing of the sediment substrate *during the period of deglaciation* therefore does not receive support from the Irish landform record.



Figure 11.11 Exploration of the thermal fracture and deglacial model for ribbed moraine genesis, and its implications for the Irish Ice Sheet reconstruction. A concentric zone of ribbed moraine could perhaps be interpreted if some cross-cutting anomalies are ignored (a). Lineation patterns are also broadly radial from an inner zone (b). However, these lineations cannot be considered as a product of deglaciation to accompany ribbed moraine formation behind a shrinking cold-based zone. They do not display deglacial glaciodynamic contexts, and their contemporaneity is rejected following the 'false divide rule' for landform inversion (c).

The model outlined above largely falls apart in the Irish context by assigning the ribbed moraine and all associated landform suites to a *deglacial* context. The ribbed moraine underlie virtually all major lineation flowset groups, which would suggest all the intricacies of these flowsets must be incorporated into a steady deglacial pattern. However, could a thermal fracture model for landform genesis still apply without invoking an attendant margin retreat context? Could a thermal fracturing model and a cross-cutting flowset model be compatible?

If it is glaciologically plausible that a cold-bedded core zone of an ice sheet could evolve independent of margin behaviour, this could be so. The necessary extensional regimes could then be thermally generated but without forcing contemporaneity of formation and a deglacial context upon the whole ribbed moraine record and the overprinted lineations. Figure 11.12 illustrates this concept. In stage (a), ribbed moraine is generated by an inner cold zone which shrinks as the stage progresses. The margin and flow geometry is, however, unchanging. Lineations are overprinted, governed by the same ice flow geometry, as the transition from cold-to warm-based ice progresses (b). If, following a geometric reorganisation of the ice sheet (c), the same sequence of thermal regime change took place, then a multi-temporal ribbed moraine record could be generated, with associated lineation superimposition. The resultant ice sheet
model would differ only in its thermal properties to the reconstruction derived in this thesis; the geometries would be comparable.



Figure 11.12 Thermal fracturing model without the constraint of a deglacial context. (a) ribbed moraine are generated at the coldwarm transition; (b) cold zone shrinks, independent of any ice sheet geometric change, and as warm zone expands lineations overprint ribbed moraine; (c) an ice geometry change and thermal regime evolution renews ribbed moraine generation, which crosscuts and fractures earlier formed ridges.

This conceptual model would depend on whether repeated growth and decline of an inner coldbased zone is plausible, whether its dynamics could operate independently of the ice sheet margin, and whether this evolution of the spatial zonation of thermal regime could accompany overall changes in ice sheet configuration. This model would also depend on the likelihood of repeated fracturing of a till sheet in multiple directions. Repeated fracture would produce smaller and smaller remnant ridges, yet Ireland has possibly the largest ribbed moraine in the world (Clark and Meehan, 2001; Dunlop and Clark, 2006). Nonetheless, repeated fracturing could explain the unusual planform morphometries and the apparent cross-cutting yet lack of superimposition that has been observed (Section 7.5.2.3).

The question of ribbed moraine genesis and its palaeo-glaciological significance remains to be resolved. The geography of the geomorphic record in Ireland presents a challenge to the model of ridge formation by thermally induced extension and fracture of the till substrate, specifically with regard to its assertion of a deglacial context. If this contextual constraint can be relaxed, then both a 'pure' bed deformation model and a thermal fracture model could satisfactorily explain the ribbed moraine record, and would not require significant modification to the *geometry* of the ice sheet reconstruction presented in this thesis. An interesting avenue for research would be to explore this problem using a numerical ice sheet modelling approach. Could a thermo-mechanical ice sheet model, tuned to simulate all the lineation flowsets in the manner of their reconstruction, generate significant regions of cold-based ice given the relatively warm and wet climatic regime of Ireland? If cold-based ice is found to be persistent, how does its distribution relate to that of the main ribbed moraine fields? This exploration would present an interesting test of competing models of ribbed moraine genesis.

11.4.2 Landform generation and preservation

The reconstruction presented in this thesis stimulates three main points for discussion, in many ways interlinked, which relate to questions of landform generation and preservation:

- What mechanisms could preserve the landform legacy of a previous ice sheet configuration under a new geometry?
- Eskers and bedforms rarely align; why might there be a disparity between the bedform record and the deglacial landform record?
- What are the implications of the geomorphic record for the subglacial thermal regime?

11.4.2.1 Landform preservation under an evolving ice sheet

Although subglacial bedforms are thought to be transient morphological features of the subglacial system, the widespread occurrence of palimpsest patterns across many palaeo-ice sheet beds suggests that the power of ice sheets to completely reorganise their beds is overestimated. As has been widely found elsewhere, landform patterns of large sectors of the Irish Ice Sheet must be preserved through geometric changes in ice flow patterns of a variety of scales. Since the demand for widespread preservation was first realised (e.g. Boulton and Clark, 1990a,b; Kleman, 1992, 1994) several mechanisms have been proposed which could satisfy the requirement. Clark (1999) synthesises the range of possible conditions for landform and landscape preservation under ice sheets:

- Low velocity zones (ice divides). A lack of geomorphic activity has been attributed to core areas of an ice sheet on the basis that basal ice velocity is virtually nil underneath an ice divide (Boulton and Clark, 1990b; Boulton, 1996). Ice should therefore be incapable of moulding its bed, and would preserve any existing landscape underneath an ice divide.
- Cold-based ice. A number of workers invoke a frozen subglacial thermal regime to explain landscape preservation (e.g. Kleman, 1992, 1994; Kleman et al., 1994; Sollid and Sorbel, 1994; Kleman and Hättestrand, 1999; Hattestrand and Stroeven, 2002; Stroeven et al., 2002; Hall and Glasser, 2003; Kleman and Glasser, 2007). 'Cold ice', below the pressure melting point and frozen to its bed, would preclude either basal sliding or bed deformation, and geomorphic activity is thought to be minimal. Cold-based ice and ice divide mechanisms are not mutually exclusive, and in large-scale reconstructions of the Laurentide and Fennoscandian ice sheets it has been suggested that the ice sheets are cored by cold-bedded zones (Kleman and Hättestrand, 1999; Kleman and Glasser, 2007).
- Reduction of deformation. A soft sediment substrate requires a critical range of boundary conditions in order to deform, and thereby (under a bed deformation model of genesis) create or modify landforms. Deformation is crucially dependent on subglacial hydrology the presence and arrangement of water at the bed. Where till is well-drained it stiffens, and till mirrors a rigid bed scenario: till is not conducive to bed deformation and ice can neither generate nor modify subglacial bedforms.

These potential mechanisms are explored with regard to the likelihood of their explanation of the preservation of a multi-temporal landform record in Ireland. To consider the potential role of

ice divides and cold-based ice, the zones of influence of these mechanisms are mapped either according to the reconstruction (ice divides) or our expectation of their distribution (frozenbed). These zones can be compared to the distribution of bedforms which require preservation, in order to make a qualitative assessment of how well the proposed mechanism could satisfy the preservation requirement (Figure 11.13a,b). It is revealed that throughout the full sequence of the reconstruction very few sites are characterised by a long-term ice divide position. A divide could undoubtedly provide some protection for various flowsets at various times, but the





Figure 11.13 Exploration of potential mechanisms for preservation of the multitemporal landform record in Ireland. (a) Ice divides are thought to protect the underlying landscape due to low basal velocities. Divide positions for each stage of the ice sheet history have been buffered to $\sim 20\%$ of the ice sheet span (yellow bands). Also for each stage, the regions of bedforms which require preservation have been identified. The cumulative area which requires preservation under the subsequent ice flow geometry is outlined at each interval (dark blue). Many bedform patches can, at an individual level, be accounted for by ice divide protection at various stages and, given the degree of ice divide migration, much of the former ice sheet bed lay underneath an ice divide at some point (see composite panel, left). However, *persistent* ice divide preservation is minimal ('high frequency' in left panel). <1% of the area offered protection by ice divide cover persists through the 7 major stages. Conversely, many areas are susceptible to bed reorganisation much of the time.



(b) The likely coverage of cold-based patches is estimated (blue patches) according to (i) a maximum cold-based end-member (ribbed moraine as thermal fracture products) and (ii) a minimum cold-based end-member (ribbed 'pure' moraine as bed deformation landforms, and cold ice restricted to high ground and regions of dominant lateral meltwater drainage). As above, the dark blue outline represents the cumulative area of the ice sheet bed which requires preservation. Neither a cold-based nor an ice divide mechanism can successfully explain the full bedform record which requires preservation through the glacial cycle.

reconstructed mobility of the divides is such that the preservation of few, if any landform assemblages could be *solely* attributed to an ice divide position. Two 'end-member' views of the distribution of persistent cold-based ice are presented in Figure 11.13b, according to whether ribbed moraine are interpreted as an independent indicator of frozen-bed conditions. Again, there are numerous bedform regions whose preservation throughout the ice sheet's evolution cannot be explained exclusively by cold ice preservation. Several regions which were potentially persistently cold-based display little bedform evidence; there may be a causal relationship between these two observations, but frozen-bed conditions cannot exclusively explain the preservation of a substantial proportion of the bedform record.

Different degrees of modification and preservation likely affect the landform record over different timescales. In several ice sheet sectors throughout Ireland landforms display evidence of continual reworking and smudging due to subtle fluctuation of the flow geometry (timetransgressive flowsets). For the duration of these ice sheet sectors, a mechanism is required which can allow overprinting, weak modification and partial preservation of a pre-existing landform pattern. However, once the ice sheet undergoes a change in overall configuration, and this sector ceases to operate in the same way, full preservation seems to be required. Different timescales of preservation required by different components of the landform record make it difficult to unravel the mechanisms which could satisfy these requirements. However, a mixed preservation history, both spatially and temporally, is most likely the case.

An important implication of these observations is that for a range of timescales, both within sector (time-transgressive, smudged records) and across different ice sheet stages (overprinted isochronous flowsets), some degree of preservation under a warm-based regime is required. A mechanism must be called upon which can continually rework and manipulate the bed and its bedforms, but without total destruction of the initial or pre-existing form of the substrate. Warm-based ice cannot pervasively eradicate pre-existing landform imprints.

To reconcile a warm-based regime with incomplete reorganisation of the bed we must appeal to a range of potential factors which could determine the degree of deformation:

- Total basal uncoupling via very high porewater pressures would preserve a bedform imprint, although the impact of re-coupling should be considered.
- Very low porewater pressures would stiffen the till substrate and inhibit deformation.
- A thin deformation layer could be incapable of modifying the full depth of the sediment column. Only the upper layers of the bed would be eroded or modified, but landforms of an amplitude greater than this depth would still, in essence, be preserved. This idea captures a subtle distinction between pure surface preservation and landform preservation (Clark, 1999).
- A short duration time of the secondary ice flow regime could be insufficient to totally remould the earlier substrate form.

The ice – bed 'mosaic' model of Piotrowski and colleagues (e.g. Piotrowski *et al.*, 2004) provides a useful context for this discussion (Figure 11.14). This model proposes that, through the variety of factors outlined above, bed deformation is likely spatially and temporally heterogeneous. The final geological record is a composite product which can reveal a preservation history of sediments generated and reworked under a warm-based, soft substrate subglacial regime. This model has been stimulated by finer-scale sedimentological observations; it should be considered whether the model can scale-up to explain the partial preservation of subglacial bedforms under similar regimes.



Figure 11.14 Mosaic model of a deforming bed, from Piotrowski *et al.* (2004). Patches of the substrate conducive to deformation are spatially (both vertically through the sediment column, and horizontally) and temporally heterogeneous. In a warm-based subglacial environment, sediment moulding regimes and preservation regimes can co-exist as a mosaic of deforming and 'stable' patches. Piotrowski *et al.* (2004) infer deformation may take place only in a thin till layer at the ice – bed interface; could the depth of deformation under such a model be sufficient to explain bedform partial preservation in the same way?

This discussion has likely raised more questions than it has solved. A future line of enquiry could draw upon numerical modelling techniques applied to questions of both ice sheet and landscape evolution. How extensive a region can an ice divide protect? How does the thermal regime of this (and other) ice sheet(s) evolve and where, and for how long, can frozen patches persist? What is the nature of ice flow – sediment transport coupling in the Irish context? What substrate conditions are required to yield only a shallow deforming layer, and how does its depth evolve spatially and temporally? It would be interesting to explore, either in the numerical (model) domain or via GIS overlay operations, how the different potential mechanisms combine to account for the generation and preservation of today's composite glacial landform record. Careful observations in this thesis have shown that overprinting and landform preservation are widespread, and provides a challenge to our process understanding.

11.4.2.2 The disparity between eskers and bedforms

Interpretation of the retreat pattern of the ice sheet is a special case of the landform preservation

question addressed above. The presence of eskers indicates a warm-based retreat regime, but the lack of association and alignment (Figure 11.15), in places, between eskers and bedforms suggests that bedforming was not always active in the areas of esker formation during ice margin retreat. This disparity is in stark contrast to other ice sheet beds such as the Laurentide, where eskers are almost always aligned with the ice flow directions yielded by bedforms (e.g. Prest *et al.*, 1968; Boulton *et al.*, 1985; Clark and Walder, 1994). Eskers are typically interpreted, for palaeo-glaciological reconstruction, as a product of incremental sedimentation behind a retreating ice margin (Kleman and Borgström, 1996; Kleman *et al.*, 1997, 2006). Aligned bedforms are, by association, interpreted as deglacial. Applying this interpretative template in Ireland implies that bedforming during ice margin retreat was far from ubiquitous.



Figure 11.15 Eskers are typically interpreted as a product of sedimentation behind a retreating ice margin (\mathbf{a} – from Kleman *et al.*, 2006) and their alignment with bedforms is taken to indicate that the bedforms are similarly deglacial (\mathbf{b} – from the Glacial Map of Canada (Prest *et al.*, 1968). However, in several locations in Ireland (\mathbf{c} , \mathbf{d}) eskers and bedforms display a lack of alignment, suggesting that deglaciation was not widely accompanied by bedform generation. Scale in $\mathbf{c} \& \mathbf{d}$: gridmarks at 20 km.

Two potential explanations can be put forward to account for this unexpected lack of association between the two landform types. Either, our interpretative model of eskers is wrong: their orientation does not exclusively reveal the pattern of the final ice margin retreat. Alternatively, the lack of bedforming during the retreat of several ice sheet sectors is a real result; in which case why was bedform generation not widespread during (warm-based) deglaciation?

Clark *et al.* (2000) invoked the former explanation to account for eskers of an anomalous direction in the Québec – Labrador sector of the Laurentide Ice Sheet. Rather than recording the final stages of margin retreat, Clark *et al.* speculate that the anomalous eskers may in fact have been deposited in an englacial environment during an earlier ice sheet phase with a different flow geometry and surface slope direction to that of the final ice sheet configuration. A switch of englacial thermal regime to a cold environment would have preserved these stringers of sediment, to be laid down onto the ground surface during melt and margin retreat from a different direction to that of the former ice surface slope. Bedforms generated during retreat would therefore not be aligned with the trend of the eskers. If this mechanism were invoked in Ireland, the anomalous esker systems should be interpreted as a product of an earlier stage ice sheet, leaving bedforms and other landform assemblages to form the basis of a retreat pattern.

The alternative interpretation of the Irish record is that the absence of bedforming in many sectors during final deglaciation is real. Why, then, are so few bedforms inscribed during warmbased margin retreat? Many of the 'anomalous' eskers in question form well-developed and often dendritic networks. They suggest that the hydrology of their associated ice sheet sector during the period of their genesis was characterised by a well-developed, channelised drainage system. Channelised drainage will act upon the subglacial system to draw water from sediment pore spaces and smaller drainage pathways (higher water pressure) into progressively larger channels (lower water pressure) (Röthlisberger, 1972; Walder and Fowler, 1994). The substrate would consequently be well-drained, raising the effective pressure and stiffening the till substrate to the extent that it was potentially no longer conducive for bed deformation (Paterson, 1994; Hooke, 2005). Esker systems could thereby develop in the absence of bedforms.

The question now becomes: why could esker development have inhibited bedforming in Ireland, but they are found in widespread conjunction across the beds of the Laurentide and Fennoscandian Ice Sheets, where there are widespread deglacial bedform patterns? Why is the Irish landform record so strikingly different to others? Notwithstanding these outstanding questions, the latter explanation of the Irish record is favoured here: the lack of bedforms relates to the low capacity for bed deformation. An anomaly between esker and bedform orientations is not an isolated occurrence, but a property of several spatially separated landform assemblages. To interpret all such cases under a model of cold ice entrapment, reorganisation and subsequent melt-out would produce a far more intricate and involved solution to the reconstruction problem, and the scenario of minimum complexity is favoured. Furthermore, regardless of timing – pre-deglacial or deglacial – an ice flow geometry is still required to explain these eskers. Several systems, in particular the NE flowing eskers across northern Ireland (Figure 11.15d), would be difficult to incorporate at any other time with a realistic ice sheet geometry. A lack of bedforming during final deglaciation, associated with a well-drained bed and inhibited

deformation, is therefore the favoured model of interpretation. Inappropriate conditions for bedforming would also help to explain certain reconstructed retreat patterns, such as the northwards margin retreat over Cos. Clare and Galway, which are demanded by the ice sheet configuration but present little direct evidence for their occurrence.

11.4.2.3 Implications of the landform record for the subglacial thermal regime

Thermal regime has been proposed as a key mechanism determining the degree of landform generation and preservation. A 'frozen' bed will preserve earlier 'wet-bed' glacial landscapes, non-glacial (pre-glacial) landscapes, and will be incapable of generating new subglacial landforms (e.g. Kleman, 1992, 1994; Kleman *et al.*, 1994; Sollid and Sorbel, 1994; Kleman and Hättestrand, 1999; Hattestrand and Stroeven, 2002; Stroeven *et al.*, 2002; Hall and Glasser, 2003; Kleman and Glasser, 2007). In the absence of a clear, physically-based understanding of subglacial thermal spatial organisation (Sugden, 1977; Hooke, 2005) preserved landform patterns, preserved non-glacial landscapes and an absence of a bedform record have been used as key indicators of palaeo-frozen bed regions of an ice sheet.

Whilst landform preservation is undoubtedly required, and an absence of bedforming is observed in some sectors, it is argued here that there is a lack of independent evidence for a cold-based regime. Landsystems typical of such a regime are not commonly observed in Ireland. Lateral meltwater channels, used elsewhere as a key indicator of cold-based ice (Dyke, 1993; Kleman and Borgström, 1996; Kleman *et al.*, 1997, 2006; Hättestrand and Clark, 2006b), are scarce, and the interpretation of ribbed moraine in terms of thermal regime is contentious. It has been argued above that the landform record in Ireland presents inconsistencies with the Swedish deglacial model of ribbed moraine genesis via thermally induced fracturing (Hättestrand, 1997; Hättestrand and Kleman, 1999). If thermal organisation of the ice sheet bed can evolve in similar timescales to ice sheet configuration changes then the growth and reduction of cold-based core zones could be interpreted from the swath of ribbed moraine across northern and central Ireland. However, lineation overprinting throughout much of the ribbed moraine zone requires the transition to warm ice. Therefore, even if the body of ribbed moraine can be interpreted as a cold ice signature, frozen conditions were not lasting.

Moreover, it is suggested that a warm-based regime was both widespread and persistent through several ice sheet sectors at different stages in the ice sheet's history. Subglacial landforms, both bedforms and meltwater features, are almost ubiquitous in the composite 'end product' of landform generation and preservation. Bedforms are restricted to the northern and central sectors of Ireland, but subglacial meltwater channels are more evenly distributed across the whole landmass (Chapter 6, and Section 8.2.1.1). The range of bedform morphologies observed, and their spatial and temporal arrangements, also support an often warm-based ice sheet. Bedforms display complex morphologies rather than 'classic', easily categorised landforms, and time-transgressive flowset interpretations dominate over clean, isochronous snapshots of the bedform record. It is suggested that partial reworking and remoulding is more typical in the

bedform record of Ireland than pristine preservation.

Cold-based ice beneath the Irish Ice Sheet was likely a transient property, or highly restricted. Little evidence suggests prolonged frozen-bed conditions, except perhaps confined to the higher reaches of mountain areas around the periphery of Ireland. A plethora of landform assemblages require warm-based conditions for both their generation and their 'smudging' (partial preservation) under evolving ice flow geometries. The Irish Ice Sheet was situated in a maritime climatic zone, was small and likely sensitive to external and internal glaciodynamic forcing, and likely responded with high ice flow velocities. These factors all contribute to maintaining a warm-based thermal regime. This context contrasts with colder, more continental climate regimes over the larger Laurentide and Fennoscandian Ice Sheets which would enhance the advection of cold ice to the bed of the ice sheet. Models of thermal regime built from observations and palaeo-glaciological reconstructions of these larger, continental ice sheets may be less applicable to smaller, lowland ice sheets such as the Irish.

11.4.3 Characterisation of the geomorphological record

One of the final contributions of this effort towards ice sheet reconstruction is the advancement in our approach to conceptualising the geomorphic record for palaeo-glaciological interpretation. The mapping programme of this research revealed some particularly complex landform arrangements which could not be satisfactorily untangled or synthesised using existing models (Clark, 1999; Kleman *et al.*, 1997, 2006) for bedform spatial summary (flowsets) and glaciodynamic interpretation (Chapters 7 & 8, particularly Section 8.2.2). New interpretative templates are required by the Irish landform record and their implications are now discussed.

11.4.3.1 Irish flowset palaeo-glaciology: the significance of time-transgressive landform records

The basis for interpreting the palaeo-glaciological significance of a flowset is an interpretative template. However, having derived a population of flowsets which spatially synthesise the Irish subglacial bedform record (Chapter 7), a substantial proportion of flowsets could not be satisfactorily interpreted using existing models of flowset palaeo-glaciology (Section 8.2.2.2, Figure 8.8). These existing templates were found to provide inadequate or inappropriate descriptions of a number of flowsets. New interpretative models were required to capture what appeared to be highly 'smudged' ice flow signatures.

Smudged landform patterns are inherently time-transgressive. Two new interpretative models of time-transgressive flowsets were proposed to better capture the landform evidence displayed in Ireland: smudging in response to *flowline migration*, or fluctuation, driven either by a shifting divide or a shifting outlet position; and smudging due to *ice thinning*, revealing the increasing control of the topographic shape upon the flowline and bedforming direction. These models were found to be better descriptors of several flowsets in Ireland which reveal a transition in flow geometry rather than discrete end products of a stabilised ice sheet configuration. With

these additional templates all but the smallest or most sparsely populated flowsets were interpreted in terms of their formative context.

The dominance of time-transgressive flowsets in Ireland is indicative of the timescales of ice flow behaviour associated with their formation. The scale of ice flow behaviour which manifests itself in smudged landform patterns is different from that which is encapsulated in major ice sheet-wide movements of the centres of mass of the ice sheet. At this first-order, ice sheet-scale, the timescales of the flow behaviour are long in relation to the timescales of bedforming. However, smudged records, and the interpretation of *transitions* in flow geometry which are echoed in the bedform imprint, suggest that in time-transgressive flowsets the timescales of ice flow behaviour are of a similar order to the timescales of bedform genesis and shaping.

These initial insights can be developed in two ways. Firstly, time-transgressive flow signatures have implications for mechanisms of landform generation and preservation, discussed above. For the duration of the overall flowset the bed is repeatedly or even continually manipulated. A mechanism is therefore required which will weakly modify existing landforms according to a subsequent flow geometry, but without erasing either the first or the intermediate patterns in the progression of the ice flowline to a final configuration. Furthermore, the pattern of such modification is rarely consistent or ubiquitous across the whole flowset. Such a mechanism must therefore either impart or respond to a spatial heterogeneity of controlling factors.

Secondly, this documentation of widespread time-transgressive bedform genesis and associated short timescale flow behaviour reinforces intuitive notions of an ice sheet which is highly responsive to various ice dynamic forcing mechanisms. If the timescales of ice flow behaviour are comparable to those of bedform genesis or remoulding, then this has important implications for the speeds with which an ice sheet sector's flow geometry may change. A decadal timescale for bedforming (Hindmarsh, 1998a; Smith *et al.*, 2007) could imply that ice sheet changes associated with a time-transgressive flowset would occur equally rapidly. Stage Va-c, for example, which describes the fragmentation of the Irish Ice Sheet into two component ice bodies, could potentially proceed very rapidly: over a decadal – centennial time period.

11.4.3.2 Complex bedform assemblages in relation to the ice divide structure: branching ice divides and triple junctions

A key characteristic of the build-up and maximum phases of the reconstruction is an ice divide structure comprising branched sub-divides which meet the main axis at 'triple junctions'. Such a configuration has been inferred throughout Stages II – IV. Sub-divides (hence triple junctions) have largely been invoked to account for convergent flow patterns which cannot be separated in time. A triple junction arrangement broadly fits the geomorphological record, but the ice dynamics revealed by some landforms are not always as straightforward as their encapsulation in a single ice sheet phase may suggest. Two sites, in particular, reveal a record which is less straightforward to interpret: Omagh Basin and the Slieve Aughtys. This section justifies and

explains the inclusion of these landform arrangements within a single ice sheet phase. It asks whether we can learn anything about bedforming immediately downstream of triple junctions and, in turn, whether we can thereby learn something about the triple junction system itself.

Omagh Basin presents a complex record of ribbed moraine. The morphology of individual ridges is erratic and far from consistent; ridges appear to be arranged, in places, almost perpendicularly to their neighbours; and across the basin landforms display a range of sizes (see Map 2, and Section 7.5.2.3). In Chapter 7, these landforms were summarised as two flowsets, one flowing from NE to SW, the other almost perpendicularly from the SE. Over Lower Lough Erne, these flow patterns appear to merge, and take on a more westerly flow direction (Figure 11.16a). Downstream of Omagh Basin, lineation flowsets converging around Donegal Bay from different directions cannot be separated in time, and are interpreted as part of a larger, contemporaneous ice stream tributary system feeding through Donegal Bay and the other bays of the north-west coast of Ireland. To drive this system, a branching ice divide structure is reconstructed, with a triple junction located to the north-east of Omagh Basin (Stage III). Omagh Basin therefore becomes situated in the crux point of this triple junction. Could the complex ribbed moraine record be a signature of repeated flowline deflection and competition between the two opposing branch divides?



Figure 11.16 A triple junction and sub-divide arrangement is thought to best characterise the landform assemblages in Omagh Basin and western Cos. Fermanagh and Donegal (a) and over the Slieve Aughty uplands and Cos. Clare and Galway (b). Potentially the smudged landforms reflect the alternation of directions from which the dominant flowline is sourced.

In Cos. Galway and Clare a large, yet smudged (flowline migration) flowset (*lins fs6*) passes offshore, flowing NE-SW through the low ground between the Burren and the Slieve Aughtys. This is overprinted by a small flowset (*lins fs7*) which records ice flow west *over* the Slieve Aughtys. To invoke an independent ice sheet geometry, temporally separate from that which produces the main Galway-Clare flowset and which, most significantly, would require an ice divide so far south and east, would be a very surprising result. The two flowsets, *fs6* and *fs7*, have therefore been encapsulated into a branching ice divide model, under which the flowlines emanating from each branch compete for 'dominance' (Figure 11.16b).

Both the north and south triple junctions of the main ice axis have therefore been implicated in a

potential regime in which the dominant control over the regional flowline switches between one sub-divide and the other. This raises a question of what we might *expect* to find in the landform record immediately downstream from a divide triple junction. This question has implications for the geomorphic record, and also for how triple junction arrangements operate and fluctuate. It is suggested here that there is landform evidence of pulsing, or competition for 'dominance' from one side then the other. The way in which dominance could be achieved would be flowline deliverance directly (i.e. perpendicularly) rather than obliquely from the divide. A flowline will emanate in the former manner if the ice divide is flat, i.e. it has a constant elevation (Figure 11.17a); if a divide is dipping, flowlines will emanate obliquely towards the direction of dip (Figure 11.17b). It is speculated that where the landform record suggests repeated fluctuation of the dominant flowline direction (Figure 11.17c), this may reflect the relative raising and dipping of one or more ice divides or sub-divides.



Figure 11.17 Conceptualisation of the effect of ice divide dip on the direction of ice flow emanating from the divide. If a divide undergoes vertical movements, i.e. it dips and rises, a cross-cutting or smudged landform imprint may result. Where two such divides discharge flowlines into a zone of convergence (c) the imprint will be particularly difficult to decipher.

To return to the reconstructed ice divide structure in Stages III-IV, what does this conceptualisation imply? The ribbed moraine of Omagh Basin have been attributed to Stage IIIa. Following this triple junction interpretative model, the Donegal branch and the main ice divide are speculated to fluctuate in elevation, repeatedly dipping and growing, but neither divide gaining a long-lasting dominance. In Stage IIIb, the main axis discharges flowlines which dip towards the south, suggesting the northern triple junction has a higher ice surface altitude than the southern, and that the dominant source or dome of the ice sheet at this stage lies in the north. This could be considered consistent with 'hingeing' of the divide in the north whilst it swings from west to east at its southern end (Section 9.4.2). The sequence of events over the Slieve Aughtys in Stage IV suggest an earlier regional flowline sourced from the western subdivide. Smudging of the bedform record could be associated with subtle vertical movements of the divide. Subsequently, the south-eastern branch of the divide triple junction takes on a more powerful role, potentially reflecting thickening of this part of the ice sheet and a diminishing slope of the ice divide, which delivers ice more directly west and WSW across the Slieve Aughty uplands. This pattern of behaviour would be consistent with the progression of the ice sheet through its maximum period, and the enhanced growth of the southern ice sheet sectors at this time. On reflection, an additional mechanism could be added to the conceptualisation of

time-transgressive (smudged) flowsets: ice thinning (role of topography); flowline migration (outlet switches); flowline migration (*spatial* migration of ice divide); flowline migration (*vertical* movement of ice divide).

11.4.4 Implications for geomorphology: summary

This research yields a variety of implications for our understanding of ice – geomorphology links and interactions, in relation to this ice sheet and in more general terms:

- The Irish landform record presents a challenge to the model of ribbed moraine genesis which favours fracturing of the substrate in response to a thermally induced extensional flow regime, in a deglacial context. The major challenge lies in the inappropriate deglacial context of the model, and the fracture model is not ruled out as a mechanism specifically of generating transverse till ridges.
- A mixed preservation history likely accounts for the composite, multi-temporal landform record. Neither ice divides nor cold-based ice can account for the preservation of the full record. An abundance of sectors require preservation under subsequent warm-based conditions, suggesting a preservation mechanism must be intrinsic to the operation of a deforming bed.
- The relation between complex landform assemblages and ice divide structure may indicate that smudged landform records may be generated not only by lateral (spatial) migrations of a divide, but vertical movement also.
- The plethora of time-transgressive flowsets in Ireland has implications for interpreting timescales of bedforming and timescales of changes in ice flow geometry. It is suggested timescales for these two processes may be of a comparable order, with implications for very rapid geometric changes in the organisation of the ice sheet.

Beyond these immediate implications of the geomorphic record and its interpretation, common to all the themes explored above is the way in which the Irish landform record and its implications differs from other ice sheets. The distribution of ribbed moraine does not mirror the sites of final deglaciation. No significant cold-based zones have been identified. There is widespread demand for warm-based landform preservation - almost the entire bedform record must be preserved at different times. Time-transgressive flowsets dominate in terms of abundance over isochronous landform imprints. We do not see 'classic' imprints of ice streams. Perhaps one of the biggest surprises is that a bedform record of deglaciation appears to be largely lacking and, indeed, esker systems are not spatially extensive. Each of these observed characteristics of the Irish record differs from palaeo-ice sheet beds such as the Laurentide or Fennoscandian, where core areas coincide with both ribbed moraine and cold-based interpretations and where, in particular, bedforms and eskers are closely aligned and there is an extensive landform record of deglaciation. Why, then, is the Irish record so different? We can speculate about a number of potential reasons or factors: ice sheet size/thickness?; its maritime location?; its basin setting?; its periphery dominated by large marine sectors (and only a relatively small terrestrial-based core)? Our interpretative models of palaeo-ice sheets and their

geomorphic records have been developed from large, continental-scale ice sheets. Perhaps these models simply do not scale well to a small, thin, lowland, maritime ice sheet. Numerical modelling could clearly assist our understanding of this discord. What are the differences between the glaciological parameters and boundary conditions needed to successfully model the Laurentide or Fennoscandian Ice Sheets and those needed to simulate the Irish?

11.5 Stimuli for future research

Our understanding of the geometry and behaviour of the last Irish Ice Sheet is still incomplete. However, an inversion approach based on the geomorphological record has yielded a broad framework for its evolution, has identified the fundamental elements of the ice sheet history at a range of spatial and temporal scales, and has revealed a range of insights into the wider palaeoglaciology of the ice sheet. The most powerful route of further enquiry will be to combine geological and numerical approaches (cf Andrews, 1982). The integration of both approaches should ultimately yield a more secure reconstruction and a more complete picture of the threedimensional evolution of the ice sheet. A modelling approach will also provide the opportunity to explore a range of ice sheet scenarios, their sensitivities to their boundary conditions and controlling forces, and their implications for the ice sheet's role in the wider Earth system.

This ice sheet reconstruction for Ireland represents a documentation of the observational record of glaciation, with a particular emphasis upon its flow geometry, which can serve as a critical test for numerical ice sheet models. To reconstruct as well as explore sensitivity, numerical models must be well-constrained by the available evidence of palaeo-glaciation. Ice sheet model outputs have typically been compared to static ice sheet properties, such as generalised images of an 'LGM' ice sheet extent. Here, by contrast, the reconstruction offers an evolving sequence of ice sheet geometries rather than a static 'target' configuration, and it offers information about the *internal* flow patterns and configuration, in addition to a margin position. In these ways a multi-temporal reconstruction such as that derived here for the Irish Ice Sheet can offer a better route of comparison with the inherently multi-temporal output from numerical models. Promising developments towards this end are explored by Napieralski and colleagues (2006, 2007a,b; Li et al., 2007) who outline and test GIS approaches to numerical model - inversion model comparison and verification. Their methods test numerical model output against inversion model margin positions, flowset locations and directions and, importantly, flowset sequencing. In so doing, a range of geological and geomorphological proxies test modelled ice sheets. Such automated methods are a more appropriate, objective and useful route of enquiry than current 'eye-balling' approaches to judging numerical model performance, and will ultimately yield a more secure and informative description of the geometry and behaviour of palaeo-ice sheets.

Whilst simulation is essential for an accurate reconstruction of past ice sheet – climate systems, ice sheet models additionally offer the opportunity to explore the behaviour of an ice sheet, its sensitivity to potential forcing mechanisms and, in turn, the sensitivity of other Earth system

components to ice sheet forcing. A modelling approach could explore in a rigorous manner the questions considered rather more brutally in this chapter, and further Earth system implications which the ice sheet reconstruction stimulates. What drivers are required to achieve the 'right' ice sheet? How sensitive is the ice sheet geometry to activation and deactivation of ice streams, or sea level change, or a changing distribution of climate input fields? Does climate forcing or dynamic forcing produce an asymmetric ice sheet evolution? What are the dominant controls upon ice sheet fragmentation? What potential effects would the ice sheet have upon ocean structure or iceberg drift and, consequently, what would be the resultant climate effects?

Finally, links between the ice sheet and its geomorphological legacy have been explored in this chapter but likely pose more questions than have been answered. An interesting exploration would examine whether a thermomechanical ice sheet model could generate significant and persistent regions of cold-based ice under the mild and wet climate regime of Ireland. The thermal evolution of the ice sheet has implications both for models of bedform genesis and for landscape preservation. The question of preservation remains puzzling and, in this case, coupled ice sheet – landscape evolution models may shed some light on the role of different potential preservation mechanisms. It is clear, however, that a dichotomy of pervasive preservation versus pervasive generation (i.e. an absolute 'on-off switch') is an inappropriate conceptualisation of the subglacial geomorphological system. Warm-based preservation mechanisms are a clear requirement of the Irish landform record, which suggests considerable spatial and temporal heterogeneity of bed deforming and bed moulding regimes. If processes and environments of bedform genesis are better known, this understanding can feed back into assessing and improving the security of the ice sheet reconstruction, enabling us to draw more accurate conclusions regarding the palaeo-glaciology of the ice sheet.

12.1 Thesis summary

The motivation which stimulated this thesis was twofold. Firstly, existing research into Irish glacial history had not hitherto yielded a reconstruction of the ice sheet which adequately described its full geometry, behaviour and evolution. Basic properties, such as the main centres of mass of the ice sheet, were poorly known or fiercely contested and, it is argued, debate had hindered rather than propelled efforts towards reaching an understanding of the palaeo-geography and palaeo-glaciology of the ice sheet. The Irish Ice Sheet was therefore an unresolved problem which warranted a fresh approach to its reconstruction. Secondly, capture of dynamic ice sheet behaviour is a key challenge for numerical ice sheet modelling. It was anticipated that the small, maritime Irish Ice Sheet would have exhibited a sensitive and dynamic relationship between the ice mass, the ocean and the climate forcing. Its evidence-based reconstruction, therefore, presents a critical test for ice sheet modellers. If a model can successfully capture the dynamics revealed by the physical legacy of glaciation, this will enable a comprehensive exploration of the drivers of ice sheet dynamics and consequently advance our understanding of the wider Earth system.

The aim of this thesis was to employ a geomorphologically-driven inversion approach to yield a palaeo-glaciological reconstruction of the last Irish Ice Sheet, revealing its extent, its centres of dispersal, its flow configuration, flow behaviour, retreat pattern, and a chronology for the attainment of and changes in each of these properties. Four specific objectives were outlined:

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

It is argued that these objectives have been achieved within this thesis.

Rather than adopting an incremental and field-based approach to documenting the full suite of glacial geomorphological evidence in Ireland, which has hitherto underpinned, but somewhat ironically hindered a consensus of ice sheet-wide properties, an ice sheet-scale, top-down approach was favoured by this thesis. An approach using remotely sensed landscape imagery and derived topographic products enabled a rigorous and countrywide mapping programme to be undertaken. At a range of data resolutions, to capture a range of geomorphic scales, landscape imagery facilitated systematic and consistent mapping of subglacial bedforms, meltwater landforms and moraines throughout Ireland. A repeat-pass procedure ensured that the resulting landform maps are as complete as possible with the available imagery. The mapping

programme yields the first major product of this thesis (objective 1): glacial geomorphological maps for Ireland comprising over 39,000 landforms.

Subglacial bedforms are the most comprehensively and securely mapped component of the mapping programme, are the most abundant and well-distributed across Ireland, and are the primary ingredients of a reconstruction of the flow configuration of the Irish Ice Sheet. Interpretative models for subglacial bedforms additionally draw upon landform associations with meltwater and morainic features, whilst these other landforms also form the basis for reconstructing the ice sheet retreat pattern. Ancillary lines of information, beyond the primary mapping output, were assimilated in order to support the palaeo-glaciological inversion (objective 2). Literature which has reported meltwater feature and moraine mapping was incorporated into the GIS framework to support the primary mapping, and other sources of ice flow information, such as erratic transport and sediment dispersal data were also explored. It was found that sediment dispersal patterns provide a powerful new layer of information – subglacial bedforms, meltwater features, moraines and sediment dispersal patterns – formed the basic ingredients into the inversion model procedure.

Existing interpretative templates (e.g. Boulton and Clark, 1990a,b; Clark, 1997, 1999; Kleman and Borgström, 1996; Kleman et al., 1997, 2006) were employed and developed to extract the spatial, temporal and glaciodynamic information which is held by the glacial geomorphological record: a 'flowset' approach. How do the spatial properties of individuals and groups of landforms reveal discrete ice flow events of the ice sheet? Where, within the ice sheet, was a particular landform assemblage located? At what stage in the ice sheet's development? What is the glaciological, or ice dynamic context which would most likely have led to the inscription of this assemblage in the landscape: steady sheet flow, ice streaming, ice margin retreat, a warm or cold-based subglacial thermal regime? Using such a characterisation of each package of landform information, in conjunction with a set of principles and 'rules' to which any inversion output must adhere, this model of analysis has yielded a new reconstruction of the history of the last Irish Ice Sheet. This new model is unlikely to be a unique solution but, it is argued, best fits the wealth of evidence which underpins it (objective 3). Six to seven broad stages of ice sheet development, which describe the geometry, structure, flow configuration and surface form of the ice sheet, are revealed by the landform legacy of glaciation. Palaeo-glaciological insights of the reconstruction and potential drivers of ice sheet behaviour have been explored (objective 4).

12.2 Key outcomes

In the pursuit of a new reconstruction of the Irish Ice Sheet, this thesis yields a number of important outcomes in addition to, and stimulated by the final proposed solution.

Glacial geomorphological maps of Ireland. Maps 2 and 3 document the products of a consistent and systematic mapping programme for glacial geomorphology throughout Ireland.

All landform types relevant to ice sheet-wide reconstruction are captured. An important advance upon earlier glacial maps (e.g. Synge, 1979) is the true representation of individual landforms (their sizes, shapes and arrangements) without recourse to a schematised representation of generalised patterns. These maps reveal an extended distribution of subglacial bedforms, in particular ribbed moraine, and reveal a complex array of landform associations. Maps 2 and 3 have been used in this thesis for inversion of the geomorphological record to yield an ice sheet reconstruction. However, the landform data presented in thesis Section B should stand alone as a product of rigorous observation and documentation of evidence, and will be published as such (Greenwood and Clark, in prepn.), separate from the interpretations laden upon them in subsequent thesis Sections C and D. In further potential routes of enquiry, the landform data documented here hold great potential for assessing genetic models in glacial geomorphology.

A multi-temporal geomorphological record. Cross-cutting is revealed to be prevalent throughout the landform record rather than simply observed as local anomalies, both amongst bedforms and amongst meltwater features. A highly multi-temporal record of landform inscription has thus been preserved. Models of ice history which assume synchroneity of evidence and generalise flow patterns are invalidated accordingly.

Significance of sediment dispersal information. Analysis in this thesis has yielded a new dataset of the major sediment dispersal patterns in Ireland. These patterns largely confirm those revealed by other landform assemblages and, in places, reveal additional information not otherwise evident. Sediment dispersal patterns may therefore provide information for sectors or stages where subglacial bedforming was absent or has not been subsequently preserved.

Advances in flowset interpretative templates. Flowsets summarise a group of glacial landforms interpreted as a spatially and temporally coherent assemblage representative of a discrete ice flow event. A well-established suite of diagnostic criteria (e.g. Clark, 1999; Kleman and Borgström, 1996; Kleman *et al.*, 2006) facilitate the palaeo-glaciological interpretation of flowsets either as clean imprints of interior ice sheet or stream flow (isochronous) or as smudged imprints of margin retreat (time-transgressive). The Irish record was challenging to interpret under these existing templates, and it demands new interpretative models to synthesise a complex arrangement of landforms. 'Smudged' records in contexts unrelated to margin retreat appear to be prevalent. New templates of time-transgressive bedforming have been conceptualised, reflecting short timescale minor fluctuations of the primary ice flowline. Minor, local readjustments may be a response to fluctuating ice source locations, shifting outlet positions, or ice sheet thinning and enhanced topographic control of the flowline geometry. An interesting concept worthy of further exploration is the impact of *vertical* fluctuations of an ice divide, which would serve to emit ice at more or less oblique angles to the divide as it falls or gains in elevation.

A full flow configuration and retreat pattern reconstruction for the Irish Ice Sheet. A

fundamental outcome of this work is the first full (ice sheet-wide) reconstruction of the flow configuration of the Irish Ice Sheet and its evolution, and a description of the pattern of ice margin retreat across Ireland to its final sites of disintegration. These models and the main conclusions they stimulate are outlined below.

12.2.1 A reconstruction of the Irish Ice Sheet

The inversion model employed in this thesis yields seven broad stages of ice sheet history, which appear to best fit all the available landform evidence, sediment dispersal patterns and dating constraints (Map 4, Figure 12.1). Evidence is consistent with the following key features of ice sheet history:

- An early incursion of ice from Britain, and ensuing build-up from the NE of Ireland together with local centres of ice dispersal. Fragmented evidence suggests the incremental advance of ice from the NE over much of the Irish midlands, presumed to be early in the last glaciation.
- The ice sheet expanded swiftly onto the western continental shelf, a likely product of an ice divide positioned over western Ireland during a build-up phase of the ice sheet.
- The period from build-up to maximum is characterised by a branching ice axis structure to the ice sheet, and a large migration (up to 140 km) of this main axis from west to east.
- The maximum extent is attained first on the western continental shelf, followed by the maximum extent of southern sectors. There is potentially a time-lag of ~3 ka between these two episodes.
- The maximum period ice sheet is structured around a main divide lying across the Irish
 midlands and the Irish Sea Basin. It is logical to assume an ice divide saddle would lie
 across the connected troughs of the North Channel and ISB the suture line of the British
 and Irish Ice Sheets.
- Ice streaming dominates the maximum period of glaciation, through the major bays of the NW Irish coast, and likely through both the North Channel and the ISB. Large ice streams, conversely, do not appear to characterise deglaciation, likely due to the recession of the ice margin back into a terrestrial environment, thereby eliminating the calving mechanism for rapidly exporting mass and drawing down ice through streams from the ice sheet interior.
- A hiatus appears in the landform record between the maximum stage and the first identifiable record of deglaciation. Between these periods, the saddle linking the BIIS has been broken, and retreat ensues towards a divide lying over the west of Ireland. The first coherent signal of ice margin retreat records withdrawal from a position across southern Ireland approximately coincident with the apparent line of the Southern Irish End Moraine. The supposed moraine, however, as a continuous feature across Ireland, has not been replicated by the mapping programme of this thesis and its existence is therefore not supported.
- Two end member alternative trajectories through deglaciation can be accommodated by the landform record: a model of steady margin retreat, or a model of large-scale retreat and readvance (following the 'Drumlin Readvance' model of Synge, 1969, and the Killard Point



319

readvance model of McCabe and Clark, 1998; McCabe *et al.* 1998). Neither end member provides a wholly satisfactory model for deglaciation. It is most likely the pattern of retreat is situated between these two end members. A model is favoured which describes a relatively steady retreat, punctuated by repeated minor margin oscillations or pulsing.

- Ice sheet fragmentation must occur whichever deglacial model is favoured. The British and Irish Ice Sheets split from one another to decay independently, and the remnant Irish Ice Sheet likely 'unzipped' into two component ice masses along a suture line from Sligo Bay across the central-western lowlands to the main Offaly esker systems.
- Final retreat ensues towards centres of ice dispersal over western mountain groups: towards Connemara (from Killala Bay and Co. Mayo, and from the central eskers and southernmidlands counties); towards Co. Leitrim (from Co. Sligo, and from northern Ireland); and from the north and west shores towards a final ice cap over Co. Donegal.

Comparison of this model with the Irish glacial literature both sheds light on existing literature debates and reveals a good level of support from recent regional models of glacial history:

- The recognition of a multi-temporal glacial landform record explains a number of debates which have hitherto dominated the literature:
 - the dichotomy of an axis versus a multi-domed structure is explained by allowing the ice sheet structure to evolve and change through the ice sheet history;
 - debated ice axis locations are explained by recognising ice divide migrations;
 - the SIEM-type limit is interpreted as a recessional ice limit during deglaciation rather than a maximum position – this limit lacks a continuous moraine but is characterised by ice-marginal landsystems across its full length;
 - complex individual landform morphologies, such as those in Clew Bay, are interpreted as composite features remoulded under a sequence of ice flow events.
- Traditional single configuration ice sheet models for Ireland (i.e. Close, 1867; Hull, 1878; Warren, 1992; McCabe, 1985) are rejected. These models cannot account for the observed multi-temporal geological and geomorphological record of glaciation. The demand for a multi-temporal ice sheet reconstruction is consistent with recent lines of argument (e.g. McCabe and Clark, 1998; Knight, 1999; Clark and Meehan, 2001; Ó Cofaigh and Evans, 2007).
- Information reported in the literature has been incorporated into the inversion procedure with efforts to detach good observations from the interpretation laden upon them by previous workers. The good level of consistency between the new reconstruction and recent regional models of ice sheet history is therefore an encouraging validation of the security of the reconstruction. The flow patterns and relative chronology of events for the eastern midlands of Ireland outlined by both McCabe *et al.* (1999) and by Clark and Meehan (2001) are recognised in their proposed sequences by this reconstruction. The model for ice flow history and for ice sheet decay over Omagh Basin (Knight, 2003a,b, 2006a) can be largely accommodated by the new reconstruction, with some minor adjustments to both this model

and Knight's description of events. The reconstruction presented in this thesis enables the regional models identified by previous workers to be set in an ice sheet-wide context.

Replication of earlier findings is a reassuring outcome of both the initial mapping programme and the ice sheet reconstruction which is yielded, and lends support to the new model as an appropriate representation of the ice sheet events which characterised the last glacial period in Ireland. One model for which the evidence gathered in this thesis does *not* find convincing support is that of a large-scale and ice sheet-wide readvance which punctuates deglaciation (McCabe and Clark, 1998; McCabe *et al.*, 1998). The landform evidence documented here can accommodate a readvance scenario, but does not explicitly require such a model for its satisfactory explanation. Indeed, a more convoluted ice sheet history must be invoked if a readvance model is imposed upon this reconstruction. Furthermore, the interpretations postulated by McCabe and others are not found to be grounded in a secure, logical basis. Whilst readvance stratigraphies and their chronologies are well-constrained at numerous coastal sections, the spatial scale of any readvance has not been well-demonstrated. A model of repeated but relatively minor margin oscillations during overall ice sheet retreat can explain the stratigraphic and chronological evidence equally successfully. An ice sheet-wide readvance model is not rejected, but little support for its occurrence has been found.

12.2.2 Palaeo-glaciology of the ice sheet

The reconstruction of the last Irish Ice Sheet derived in this thesis reveals a range of insights and opens several avenues for future exploration of its wider implications. What have we learnt about the palaeo-glaciology, as well as the palaeo-geography of the ice sheet? What may have been the main drivers of the observed ice sheet behaviour and patterns of evolution? What effect did the ice sheet, in turn, have upon other Earth system components: the ocean, or the underlying landscape? Some such questions were explored in Chapter 11 of this thesis. Two overriding insights into the palaeo-glaciology of this ice sheet are summarised here.

12.2.2.1 Asymmetric and asynchronous evolution

Two main properties of the pattern of ice sheet growth and decay reveal a spatial asymmetry to the evolution of the ice sheet:

- growth is dominated by flow from the north-east, with a significant contribution from Britain, but the ice sheet decays to the west;
- maximum extent is attained first in the west, and later in the south.

It is suggested that asymmetric evolution might largely be a product of the glaciological system itself. We can speculate that, at times, the ice sheet responds more strongly to its own internal dynamic drivers than the climate forcing which initiated ice sheet development. Ice streams of the Irish Ice Sheet have been shown to have the potential to perturb their associated ice sheet geometry from a steady state configuration by driving ice divide migrations; in such a way they have the power to drive ice sheet change which is unrelated to climate control. We can explore the idea that ice stream location and behaviour is key to the asymmetry of the (British-) Irish Ice Sheet evolution. The detachment of the British from the Irish Ice Sheet after the maximum period of glaciation prohibits ice sheet decay back towards the initial main sites of nucleation. Ice streams operating in the North Channel and Irish Sea Basin are implicated in the severance of the two ice masses. Operating in opposing directions from the same ice saddle, each with a tendency to drive a headwards migration of the saddle, the competition between the two ice streams could feasibly lead to total collapse of the divide and its drawdown into the ice stream system. Meanwhile, the southern maximum extent of glaciation is likely achieved via a rapid advance of ice from the ISB far to the south of the ice limit over the rest of the British Isles. Such a rapid, ice dynamic-driven event likely exaggerates the overriding climate control on ice sheet expansion to its maximum extent. The drivers of ice streams themselves are still poorly constrained, but it is clear these dynamic elements of an ice sheet possess the potential to drive ice sheet evolution in a manner partially detached from the primary climate forcing.

Symmetry, or otherwise, of ice sheet evolution has both spatial and temporal components. At the scale of an individual ice sheet, such as the Irish, its *spatial* pattern of evolution may be modulated, as described above, by dynamic ice sheet elements. In the *temporal* domain and at a global scale, ice sheet evolution (and interrelated Earth system components – climate patterns, sea level change) is also known to be asymmetric: ice sheets are typically believed to grow slowly but undergo rapid decay; sea level falls slowly but its rise may be both rapid and non-monotonic. Without a better constrained absolute chronology for the Irish Ice Sheet further comment on the temporal asymmetry of its evolution is limited. The available chronological information leads us to speculate that expansion of the ice sheet may in fact have been rather rapid. Nonetheless, in both the temporal and spatial domains, a growing body of evidence suggests that ice sheets evolve in neither a steady nor symmetrical manner.

12.2.2.2 Time-transgressive bedforming and rates of ice sheet behaviour

A multi-temporal landform record is an important observation, but a multi-stage ice sheet history is not a surprising outcome; this is a fundamental property of the modern era of palaeoice sheet reconstructions and should be expected. The dominance throughout Ireland of timetransgressive imprints of individual flow patterns is, however, a more important revelation. Smudged imprints of single ice flow events reveal a far more 'fluid' evolution of the ice flow geometry of the Irish Ice Sheet than previously captured by ice sheet reconstructions elsewhere. Rather, we can observe systematic changes in the local ice flow geometry which serve to smear the landform imprint; rather than seeing two end states of a geometric change, we can observe the *transition* from one state to another. Note that this presents a fundamental cartographic problem for representation of the ice sheet reconstruction, which is mitigated as best as possible by recognising and outlining sub-stages, or even sub-sub-stages of ice sheet history.

These observations have important implications for understanding the processes of subglacial landform generation, remoulding and partial preservation; for conditions and properties of the

subglacial environment; and for the thermal regime of the ice sheet. They also lead us to recognise different scales and rates of change in the fundamental geometric properties of the ice sheet. Whilst at a large scale (ice sheet-scale) the ice sheet structure may steadily evolve, within this overriding context flowline instability and repeated fluctuations at a regional or local scale dominate. Ice flowlines are in a state of continual readjustment to outlet positions, to subtle first-order ice sheet structure changes, to subglacial topography or other subglacial properties which cause flowlines to be deflected or funnelled at a local scale. Such continual readjustments may likely be the case for all ice sheets. The fact that these readjustments and fluctuations are recorded in the geomorphological in Ireland record suggests that the timescales of these ice dynamics must be close to the timescales of bedform generation and moulding.

12.3 Implications for palaeo-glaciology, research approaches and future work

12.3.1 The importance of scale

The prevalence of time-transgressive landform imprints at a sub-ice sheet sector level reveals the importance of recognising different scales of ice sheet behaviour. It also reveals that the spatial and temporal domains of ice sheet behaviour are intrinsically linked. At an ice sheetwide spatial scale, the overriding structure is relatively stable, i.e. it possesses (relatively) slow timescales of evolution. At a local or regional spatial scale, individual landform assemblages indicate repeated or continual reworking of the substrate under subtly different or evolving ice flow regimes, i.e. they record (relatively) fast timescales of activity. A hierarchy of scales, or orders of ice sheet behaviour can be conceptualised with reference to the Irish Ice Sheet:

- 1st order. *Ice sheet structure*. The overriding structure of the ice sheet switches from an axis controlled structure to a multi-domed ice sheet at the temporal scale of major evolutionary phases of the ice sheet, i.e. axis controlled during growth and maximum, multi-domed during deglaciation.
- 2. Ice divide migration and associated ice sheet geometry evolution. At this spatial scale, six or seven broad phases of ice sheet evolution are recognised. These are distinguished by major changes (order ~10-100 km) in ice divide positions.
- 3. Ice flowline fluctuations and readjustments. Within each of the 6-7 main stages, more rapid and more local geometric changes are observed (order ~1-10 km)
- 4. *Margin oscillations*. Of a similar spatial scale to flowline fluctuations (~1-10 km), but the spatial changes are in a longitudinal rather than lateral direction. Oscillations are short-lived, and are captured within the higher order framework for ice sheet geometry.

Observed orders of ice sheet behaviour have implications for the scales at which we, as palaeoglaciologists, direct research to unravel ice sheet histories. Work directed at the local scale will better constrain the 3rd and 4th order systems; research directed at the ice sheet-scale, as in this thesis, will yield reconstructions of higher order systems, and may reveal the broad nature but less precisely reconstruct 3rd or 4th order behaviour. All scales of focus are essential in acquiring a more complete knowledge and understanding of the ice sheet's history. An ice sheet-wide framework provides a wider context which may help explain local patterns; meanwhile it is difficult to assess the sensitivity of the ice sheet to various controlling factors without considering the local scale, at which dynamic responses are more likely to be evident. Research must be directed to a scale appropriate to the questions posed. Questions of ice sheet-wide and global ice sheet – Earth system interactions should not be expected to be resolved without an ice sheet-wide framework in which to situate local scale observations.

12.3.2 'Uniqueness' of the Irish Ice Sheet?

In many ways this reconstruction of the last Irish Ice Sheet echoes findings from other palaeoice sheet reconstructions. The bed reveals a multi-temporal landform record, we are able to recognise discrete landform assemblages relating to specific ice flow episodes, we are able to piece together a relative time-stack of events and provide a framework for ice sheet evolution. Our interpretative models developed from other ice sheets have been applied to the Irish Ice Sheet and they largely survive intact. However, in many ways the Irish Ice Sheet presents anomalies, or differences with the palaeo-glaciology of other ice sheets. The landform record comprises a wide range of bedform morphologies, revealing many which are difficult to classically categorise. The Irish Ice Sheet inscribed the largest known ribbed moraine in the world (Dunlop and Clark, 2006). Ice stream imprints are not the 'classic', 'rubber-stamped' imprints such as those observed in Canada (Stokes and Clark, 1999, 2001). Existing interpretative models for landform assemblages have required development in light of the Irish record. A prevalence of time-transgressive assemblages has been found. There is a notable lack of persistent cold-based zones. Perhaps most surprising from an apparently highly dynamic ice sheet, there is little imprint of a deglacial landform record, in striking contrast to the bed of the Laurentide or Fennoscandian ice sheets, for example (e.g. Prest et al., 1968).

Why might the Irish Ice Sheet differ in its palaeo-glaciological record to other Quaternary ice sheets? Because it is small? Thin? Has a maritime setting? Perhaps, due to these properties, the ice sheet is less likely to ever reach a steady state, unlike larger ice sheets, and therefore its behaviour and its landform record reflect a different palaeo-glaciology. A powerful mechanism has created mega ribbed moraine, yet there is no strong deglacial landform signal; is this because the ice sheet was well-drained in deglaciation? However, the Laurentide was arguably very well-drained given the abundance of eskers, yet these are associated with widespread bedforming. Perhaps our interpretative models for ice sheet-wide geomorphology and palaeo-glaciology simply do not scale particularly well from large, thick continental-scale ice sheets to small, thin, lowland and maritime counterparts? In scaling up or down perhaps some critical thresholds for landform genesis and for ice sheet behaviour are passed? Numerical modelling experiments offer the best opportunity to explore these discordances and address these questions. How do the drivers of and responses in ice sheet behaviour differ between continental-scale ice sheets and contexts such as that of the Irish Ice Sheet?

12.3.3 An holistic approach

To better understand and evaluate questions such as those stimulated above, and to better address the full range of scales at which an ice sheet operates, research must encompass the full range of tools, or techniques available to the palaeo-glaciologist. Different techniques reveal different lines of information and, importantly, at different scales. Sedimentology, for example, yields point data which may unravel the ice history of a local site and, critically, can provide chronological control on this history. Geomorphology can provide a wider spatial scale but may be limited by a lack of process information which sedimentology may supplement. Numerical approaches explore ice sheet-wide questions but are typically limited by the coarse resolution of relatively large computational cell sizes. The applicability of a single tool or approach tends to be limited to a single scale of the system of interest. Furthermore, none alone can expect to solve the range of questions which any reconstruction will stimulate. To advance both our palaeo-reconstruction and our understanding of its wider significance, the most profitable route of investigation will be to employ numerical techniques fully grounded in evidence-based data. Techniques must be applied in an holistic and integrated manner to more fully advance our understanding of the whole ice sheet system.

This thesis set out to reconstruct, and ask questions of the Irish Ice Sheet at ice sheet-scale. The landform record offers the greatest potential for evidence-based research at this scale, since its spatial component can link information across the full extent of the ice sheet. Whilst based primarily, therefore, upon the glacial geomorphological record, the research approach of this thesis has attempted to integrate as much other information as possible within the framework of an inversion model: sediment dispersal patterns, stratigraphic relationships, the available chronological information and other such point data previously reported in the literature. This thesis recognises and reconstructs ice sheet behaviour at 1st, 2nd and 3rd order scales. As such, the new reconstruction presents a framework for future exploration, evaluation, refinement and/or rejection of the model using evidence-based or numerical techniques directed at the full range of scales of ice sheet behaviour.

12.3.4 Future directions and further questions

12.3.4.1 Refining the reconstruction

The new reconstruction of the last Irish Ice Sheet provides a framework for and should stimulate a range of further work to improve the model at the full range of scales of ice sheet behaviour. This reconstruction can direct such further work to three key aspects:

- A greater wealth of **absolute chronological information** with which to constrain the ice sheet history. A far improved spatial and temporal coverage of data is required, particularly inland from the present-day coast, to enable tight constraints to be placed upon individual moraines, margin positions and ice flow geometries throughout the ice sheet's evolution.
- Offshore mapping. It is likely that important ice dynamics left a record of their activity in peripheral (offshore) areas of the ice sheet for which data has not been available in this research. Ice streams, in particular, have largely been inferred to be most well-developed in

offshore sectors of the ice sheet. Imaging of the surface bathymetry, and resources such as 2d and 3d seismic data will open avenues to explore the surface and buried landform record in present-day offshore sectors, and tie such information to a regional stratigraphy or chronology of ice sheet events and behaviour.

• Enhancements to the onshore reconstruction model. It is argued that this mapping programme and ice sheet reconstruction have captured the major ice sheet significant flow events of the last Irish Ice Sheet. The interpretative security of the reconstruction varies, however, across different ice sheet sectors and phases. The reconstruction should be tested and refined with future, higher resolution work at sites which have been revealed to be critical to understanding the sequence and pattern of ice sheet evolution. Two such regions demand specific attention: *central Co. Galway*, and the *Lough Neagh* area. Each of these regions lies at the crux of at least four separate ice flow sequences, and deciphering the relative chronology of these sequences is crucial to assessing the security of the reconstruction presented here. The interaction between an independent ice cap over the Kerry/Cork mountains and the main ice sheet also remains enigmatic. Given the interpretation of an ice covered southern Ireland favoured here and in recent years by other workers, the role of local ice centres within a larger ice mass must be revisited through higher resolution (local scale) documentation and interpretation of the glacial record.

12.3.4.2 Integration with modelling

The integration of geological and numerical approaches will be the most powerful route towards a full understanding of the evolution of the last Irish Ice Sheet, and towards an exploration of its palaeo-glaciological and Earth system implications. The physical evidence of glaciation is not a complete record of the ice sheet history and its inscription is governed by spatially and temporally variable processes within the subglacial system. A comprehensive reconstruction of the ice sheet from the available physical legacy does, however, provide a critical test of whether a climate-driven numerical ice sheet model has captured the full description of all the relevant glaciological processes and boundary conditions which govern the system. A numerical model which can successfully simulate an evidence-based reconstruction can then add information to the model of ice sheet history and set the evidence of glaciation in its full three-dimensional and evolutionary context. An holistic approach, integrating all palaeo-glaciological tools, will thus yield the most complete knowledge and understanding of the palaeo-ice sheet system. The reconstruction of the last Irish Ice Sheet presented in this thesis should serve as a framework for further evidence-based testing and refinement, and should stimulate efforts towards numerical model - data integration, comparison and mutual improvement. The digital nature of the data presented here facilitates such an initiative.

12.3.4.3 Exploring wider implications

The discussion and conclusions drawn from the reconstruction presented in this thesis largely focus upon the 'immediate' palaeo-glaciological insights drawn from the Irish Ice Sheet. Future work, explored with an holistic approach, should consider the wider implications and role of the

BIIS in the Earth system. What is the effect of ice delivery and ice sheet disintegration upon the North Atlantic overturning circulation? What are the driving mechanisms and ice sheet responses to the observed Heinrich and D-O type cycles in North Atlantic palaeo-records? Does the growth of the ice sheet perturb or modulate local atmospheric circulation or precipitation patterns? What are the eustatic and isostatic sea level implications of the reconstructed ice sheet? How does sea level feedback upon the ice sheet system as a control on ice sheet stability and ice flow drawdown? What are the implications of relative sea level reconstructions for questions of a Britain-to-Ireland landbridge, and therefore postglacial migration of species between the two present-day landmasses? A combined evidence-based and numerical modelling approach is best suited to address such questions.

12.4 Conclusions

This thesis yields glacial geomorphological maps for the whole of Ireland, further develops existing interpretative models for their palaeo-glaciological inversion, and yields a new reconstruction of the palaeo-geography and palaeo-glaciology of the last Irish Ice Sheet The reconstruction reveals two primary palaeo-glaciological properties of the Irish Ice Sheet. Short timescale ice flow behaviour is prevalent across the ice sheet and throughout its evolution. Timescales of ice flow adjustments and readjustments to forcing are comparable to the timescales of bedforming. Secondly, the overriding pattern of ice sheet evolution is both spatially asymmetric and asynchronous. The internal dynamics of the glaciological system are implicated in these patterns, which potentially have the capacity to 'detach' the manner of ice sheet evolution from the principal climate forcing. This new model acts as a framework for understanding the ice sheet's evolution and directing continued investigation into its geometry and behaviour. It provides an effective foundation for exploration of geomorphological and glaciological processes, and improvement of ice sheet and Earth system modelling.

- Agassiz L (1838). Upon glaciers, moraines and erratic blocks: being the address delivered at the opening of the Helvetic Natural History Society, Neuchatel, on the 24th of July 1837, by its President, M L Agassiz. *Edinburgh New Philosophical Journal* 24: 364-383.
- Agassiz L (1840). Etudes sur les glaciers. Jent & Gassman; Neuchatel.
- Agassiz L (1842). Glaciers, and the evidence of their having once existed in Scotland, Ireland, and England. Proceedings of the Geological Society of London 3: 327-332.
- Ahlberg K, Almgren E, Wright HE, Ito E and Hobbie S (1996). Oxygen-isotope record of Late-Glacial climatic change in western Ireland. *Boreas* 25 (4): 257-270.
- Andersen BG (1981). Late Weichselian ice sheets in Eurasia and Greenland. In Denton GH and Hughes TJ (ed.) The Last Great Ice Sheets. Wiley; New York. pp 1-65.
- Aylsworth JM and Shilts W (1989). Bedforms of the Keewatin Ice Sheet, Canada. Sedimentary Geology 62: 407-428.
- Andrews JT (1982). On the reconstruction of Pleistocene ice sheets: a review. *Quaternary Science Reviews* 1: 1-30.
- Ballantyne CK, McCarroll D, Nesje A, Dahl SO and Stone JO (1998). The last ice sheet in North-West Scotland: reconstruction and implications. *Quaternary Science Reviews* 17: 1149-1184.
- Ballantyne CK, McCarroll D and Stone JO (2006). Vertical dimensions and age of the Wicklow Mountains ice dome, Eastern Ireland, and implications for the extent of the last Irish ice sheet. *Quaternary Science Reviews* 25 (17-18): 2048-2058.
- Ballantyne CK, McCarroll D and Stone JO (2007). The Donegal ice dome, northwest Ireland: dimensions and chronology. *Journal of Quaternary Science* 22 (8): 773-783.
- Ballantyne CK, Stone JO and McCarroll D (2008). Dimensions and chronology of the last ice sheet in Western Ireland. *Quaternary Science Reviews* 27 (3-4) 185-200.
- Bamber JL (2006). Remote sensing in glaciology. In Knight PG (ed.) Glacier science and environmental change. Blackwell; Oxford. pp 370-382.
- Bamber JL, Vaughan DG and Joughin I (2000). Widespread Complex Flow in the Interior of the Antarctic Ice Sheet. *Science* (5456): 1248-1249.
- Bard E, Hamelin B and Fairbanks RG (1990). U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. *Nature* **346**: 456-458.
- Barr ID, Ng F, Clark CD (In preparation). Surface profiles of modern ice masses: a tool for glacial reconstruction
- Belderson RH, Kenyon NH and Wilson JB (1973). Iceberg plough marks in the Northeast Atlantic. Palaeogeography, palaeoclimatology, palaeoecology 13: 215-224.
- Bell RE, Studinger M, Shuman CA, Fahnestock MA and Joughin I (2007). Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. *Nature* 445: 904-907.
- Benn DI and Evans DJA (1998). Glaciers and Glaciation. Arnold; London.
- Benn DI and Evans DJA (2006). Subglacial megafloods: outrageous hypothesis or just outrageous? In Knight PG (ed.) *Glacier science and environmental change*. Blackwell; Oxford. pp 42-46.
- Bindschadler R and Choi H (2007). Increased water storage at ice-stream onsets: a critical mechanism? Journal of Glaciology 53: 163-171.
- Bouchard MA (1989). Subglacial landforms and deposits in central and northern Quebec, Canada, with emphasis on Rogen moraines. *Sedimentary Geology* 62: 293-308.
- Boulton GS (1987). A theory of drumlin formation by subglacial sediment deformation. In Menzies J and Rose J (ed.) *Drumlin Symposium*. Balkema; Rotterdam. pp 25-80.

- Boulton GS (1996). Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. *Journal of Glaciology* **42**: 43-62.
- Boulton GS and Clark CD (1990a). A highly mobile Laurentide Ice Sheet revealed by satellite images of glacial lineations. *Nature* 346: 813-817.
- Boulton GS and Clark CD (1990b). The Laurentide ice sheet through the last glacial cycle: the topology of drift lineations as a key to the dynamic behaviour of former ice sheets. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 81: 327-347.
- Boulton GS and Hagdorn MKM (2006). Glaciology of the British Ice Sheet during the last glacial cycle: form, flow, streams and lobes. *Quaternary Science Reviews* **25** (23-24): 3359-3390.
- Boulton GS and Hindmarsh RCA (1987). Sediment deformation beneath glaciers: rheology and sedimentological consequences. *Journal of Geophysical Research* 92 (B9): 9059-9082.
- Boulton GS, Jones AS, Clayton KM and Kenning MJ (1977). A British ice-sheet model and patterns of glacial erosion and deposition in Britain. In Shotton FW (ed.) *British Quaternary Studies, Recent Advances*. Clarendon Press; Oxford. pp 231-246.
- Boulton GS, Smith GD, Jones AS and Newsome J (1985). Glacial geology and glaciology of the last mid-latitude ice sheets. *Journal of the Geological Society, London* 142: 447-474.
- Boulton GS, Peacock JD and Sutherland DG (1991). Quaternary. In Craig GY (ed.) Geology of Scotland. 3rd edition. The Geological Society; London. pp 503-543.
- Boulton GS, Dongelmans P, Punkari M and Broadgate M (2001). Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weichselian. *Quaternary Science Reviews* 20: 591-625.
- Bowen DQ (ed.) (1999). A Revised Correlation of Quaternary Deposits in the British Isles. Geological Society Special Report No. 23. Geological Society Publishing House; Bath.
- Bowen DQ and Sykes GA (1988). Correlation of marine events and glaciations on the northeast Atlantic margin. *Philosophical Transactions of the Royal Society of London, B* **318**: 619-635.
- Bowen DQ, Rose J, McCabe AM and Sutherland DG (1986). Correlation of Quaternary Glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews* 5: 299-340.
- Bowen DQ, Phillips FM, McCabe AM, Knutz PC and Sykes GA (2002). New data for the Last Glacial Maximum in Great Britain and Ireland. *Quaternary Science Reviews* 21 (1-3): 89-101.
- Bradwell T, Stoker MS and Larter R (2007). Geomorphological signature and flow dynamics of The Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science* 22 (6): 609-617.
- Bradwell T, Stoker MS, Golledge NR, Wilson C, Merritt J, Long D, Everest JD, Hestvik O, Stevenson A, Hubbard A, Finlayson A, Mathers H (2008 in press). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth Science Reviews*.
- Broecker WS (1994). Massive iceberg discharges as triggers for global climate change. *Nature* 372: 421-424.
- Brooks AJ and Edwards RJ (2006). The development of a sea-level database for Ireland. Irish Journal of Earth Sciences 24: 13-27.
- Brooks AJ, Bradley SL, Edwards RJ, Milne GA, Horton B and Shennan I (2008). Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. *Journal of Quaternary Science* 23 (2): 175-192.
- Brown EJ, Rose J, Coope RG and Lowe JJ (2007). An MIS 3 age organic deposit from Balglass Burn, central Scotland: palaeoenvironmental significance and implications for the timing of the onset of the LGM ice sheet in the vicinity of the British Isles. *Journal of Quaternary Science* 22 (3): 295-308.
- Carolan J (2006). An evaluation of the last glacial-deglacial cycle and evidence for lower than present sea levels, Clew Bay, Ireland. (Abstract). IQUA Spring Meeting, Belfast.
- Carr SJ, Holmes R, van der Meer JJM and Rose J (2006). The Last Glacial Maximum in the North Sea Basin: micromorphological evidence of extensive glaciation. *Journal of Quaternary Science* 21 (2): 131-153.

- Carvill Lewis H (1894). The glacial geology of Great Britain and Ireland. Longmans, Green & company; London.
- Charlesworth JK (1924). The glacial geology of the north-west of Ireland. *Proceedings of the Royal* Irish Academy 36B: 174-314.
- Charlesworth JK (1928a). The glacial geology of North Mayo and West Sligo. Proceedings of the Royal Irish Academy 38: 100-115.
- Charlesworth JK (1928b). The Glacial Retreat from Central and Southern Ireland. Quarterly Journal of the Geological Society of London 84: 293-344.
- Charlesworth JK (1929). The Glacial Retreat in Iar Connacht. Proceedings of the Royal Irish Academy 39B: 95-106.
- Charlesworth JK (1939). Some observations on the glaciation of north-east Ireland. Proceedings of the Royal Irish Academy 45B: 255-295.
- Charlesworth JK (1953). The Geology of Ireland. Oliver and Boyd; Edinburgh.
- Charlesworth JK (1957). The Quaternary Era: with special reference to its glaciation. Arnold; London.
- Charlesworth JK (1973). Stages in the dissolution of the last ice-sheet in Ireland and the Irish Sea region. *Proceedings of the Royal Irish Academy* **73B**: 79-86.
- Clapperton CM (1968). Channels formed by the superimposition of glacial meltwater streams, with special reference to the East Cheviot Hills, North-East England. *Geografiska Annaler* **50A**: 207-220.
- Clapperton CM (1971). The location and origin of glacial meltwater phenomena in the Eastern Cheviot Hills. *Proceedings of the Yorkshire Geological Society* **38** (3): 361-380.
- Clark CD (1993). Mega-scale glacial lineations and cross cutting ice-flow landforms. *Earth Surface Processes and Landforms* 18: 1-29.
- Clark CD (1994). Large-scale ice-moulding: a discussion of genesis and glaciological significance. Sedimentary Geology 91: 253-268.
- Clark CD (1997). Reconstructing the evolutionary dynamics of former ice sheets using multitemporal evidence, remote sensing and GIS. *Quaternary Science Reviews* 16: 1067-1092.
- Clark CD (1999). Glaciodynamic context of subglacial bedform generation and preservation. *Annals* of Glaciology 28: 23-32.
- Clark CD and Meehan RT (2001). Subglacial bedform geomorphology of the Irish Ice Sheet reveals major configuration changes during growth and decay. *Journal of Quaternary Science* **16** (5): 483-496.
- Clark CD and Stokes CR (2001). Extent and basal characteristics of the M'Clintock Channel Ice Stream. *Quaternary International* 86 (1): 81-101.
- Clark CD and Stokes CR (2003). Palaeo-ice stream landsystem. In Evans DJA (ed.) Glacial landsystems. Arnold; London. pp 204-227.
- Clark CD, Knight JK and Gray JT (2000). Geomorphological reconstruction of the Labrador Sector of the Laurentide Ice Sheet. *Quaternary Science Reviews* 19: 1343-1366.
- Clark CD, Evans DJA, Khatwa A, Bradwell T, Jordan CJ, Marsh SH, Mitchell WA and Bateman MD (2004). Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas* 33: 359-375.
- Clark CD, Greenwood SL and Evans DJA (2006). Palaeo-glaciology of the last British-Irish Ice Sheet: challenges and some recent developments. In Knight PG (ed.) *Glacier Science and Environmental Change*. Blackwell; Oxford. pp 248-264.
- Clark CD, Greenwood SL and Hughes ALC (In preparation). Shape and size characteristics of a large sample of drumlins and discovery of a scale-dependent upper elongation limit.
- Clark PU (1992). Surface form of the southern Laurentide Ice Sheet and its implications to ice-sheet dynamics. *Geological Society of America Bulletin* **104**: 595-605.

- Clark PU and Walder JS (1994). Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. *Geological Society of America Bulletin* 106: 304-314.
- Clark PU, McCabe AM, Mix AC and Weaver AJ (2004). Paleoclimate: Rapid Rise of Sea Level 19,000 Years Ago and Its Global Implications. *Science* **304** (5674): 1141-1143.
- Clarke GK, Leverington DW, Teller JT, Dyke AS and Marshall SJ (2005). Fresh arguments against the Shaw megaflood hypothesis. A reply to comments by David Sharpe on "Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event". *Quaternary Science Reviews* 24 (12-13): 1533-1541.
- CLIMAP (1976). The surface of the Ice-Age Earth. Science 191: 1131-1137.
- Close MH (1867). Notes on the general glaciation of Ireland. Journal of the Royal Geological Society of Ireland 1: 207-242.
- Colhoun EA (1970). On the nature of the glaciation and final deglaciation of the Sperrin Mountains and adjacent areas in the North of Ireland. *Irish Geography* 6 (2): 162-185.
- Colhoun EA (1971). The glacial stratigraphy of the Sperrin Mountains and its relation to the glacial stratigraphy of North-West Ireland. *Proceedings of the Royal Irish Academy* **71B**: 37-52.
- Colhoun EA, Dickson JH, McCabe AM and Shotton FW (1972). A Middle Midlandian freshwater series at Derryvree, Maguiresbridge, County Fermanagh, Northern Ireland. Proceedings of the Royal Society of London, B 180: 273-292.
- Colhoun EA and Synge FM (1980). The cirque moraines at Lough Nahanagan, County Wicklow, Ireland. *Proceedings of the Royal Irish Academy* 80B: 25-45.
- Coxon P (1993). Irish Pleistocene Biostratigraphy. Irish Journal of Earth Sciences 12: 83-105.
- Coxon P and Browne P (1991). Glacial deposits and landforms of central and western Ireland. In Ehlers J, Gibbard PL and Rose J (ed.) *Glacial Deposits in Great Britain and Ireland*. Balkema; Rotterdam. pp 355-365.
- Culleton EB (1978). Limits and directions of ice movements in South County Wexford. Journal of Earth Sciences, Royal Dublin Society 1: 33-39.
- Dardis GF (1985). Till facies associations in drumlins and some implications for their mode of formation. *Geografiska Annaler* 67A: 13-22.
- Dardis GF (1987). Sedimentology of late-Pleistocene drumlins in south-central Ulster, Northern Ireland. In Menzies J and Rose J (ed.) *Drumlin Symposium*. Balkema; Rotterdam. pp 215-224.
- Dardis GF, McCabe AM and Mitchell WI (1984). Characteristics and origins of lee-side stratification sequences in Late Pleistocene drumlins, Northern Ireland. Earth Surface Processes and Landforms 9: 409-424.
- Davis T, MacCarthy IAJ, Allen AR and Higgs B (2006). Late Pleistocene-Holocene buried valleys in the Cork syncline, Ireland. *Journal of Maps* 2006: 79-93.
- De Angelis H (2007). *Palaeo-ice streams in the north-eastern Laurentide Ice Sheet*. Unpublished PhD thesis. Physical Geography and Quaternary Geology; University of Stockholm.
- De Angelis H and Kleman J (2005). Palaeo-ice streams in the northern Keewatin sector of the Laurentide ice sheet. Annals of Glaciology 42 (1): 135-144.
- De Angelis H and Kleman J (2007). Palaeo-ice streams in the Foxe/Baffin sector of the Laurentide Ice Sheet. *Quaternary Science Reviews* 26 (9-10): 1313-1331.
- De Angelis H and Skvarca P (2003). Glacier surge after ice shelf collapse. Science 299: 1560-1562.
- Death R, Siegert MJ, Bigg GR and Wadley MR (2006). Modelling iceberg trajectories, sedimentation rates and meltwater input to the ocean from the Eurasian Ice Sheet at the Last Glacial Maximum. *Palaeogeography, palaeoclimatology, palaeoecology* 236 (1-2): 135-150.
- Delaney C (2001a). Esker Formation and the Nature of Deglaciation: the Ballymahon Esker, Central Ireland. North West Geography 1: 23-33.
- Delaney C (2001b). Morphology and sedimentology of the Rooskagh esker, Co. Roscommon. Irish Journal of Earth Sciences 19: 5-22.

Delaney C (2002). Sedimentology of a glaciofluvial landsystem, Lough Ree area, Central Ireland: implications for ice margin characteristics during Devensian deglaciation. Sedimentary Geology 149 (1-3): 111-126.

Denton GH and Hughes TJ (eds.) (1981). The Last Great Ice Sheets. Wiley; New York.

- Diefendorf AF, Patterson WP, Mullins HT, Tibert N and Martini A (2006). Evidence for highfrequency late Glacial to mid-Holocene (16,800 to 5500 cal yr B.P.) climate variability from oxygen isotope values of Lough Inchiquin, Ireland. *Quaternary Research* 65 (1): 78-86.
- Domack E, Amblas D, Gilbert R, Brachfeld S, Camerlenghi A, Rebesco M, Canals M and Urgeles R (2006). Subglacial morphology and glacial evolution of the Palmer Deep outlet system, Antarctic Peninsula. *Geomorphology* 75 (1-2): 125-142.
- Dowdeswell JA and Bamber JL (2007). Keel depths of modern Antarctic icebergs and implications for sea-floor scouring in the geological record. *Marine Geology* 243: 120-131.
- Dowdeswell JA, Villinger H, Whittington RJ and Marienfeld P (1993). Iceberg scouring in Scoresby Sund and on the East Greenland continental shelf. *Marine Geology* **111** (1-2): 37-53.
- Dowdeswell JA, Maslin MA, Andrews JT and McCave IN (1995). Iceberg production, debris rafting, and the extent and thickness of Heinrich layers (H-1, H-2) in North Atlantic sediments. *Geology* 23 (4): 301-304.
- Dunlop P (2004). The characteristics of ribbed moraine and assessment of theories for their genesis. Unpublished PhD thesis. Department of Geography; University of Sheffield. pp363.
- Dunlop P and Clark CD (2006). The morphological characteristics of ribbed moraine. *Quaternary* Science Reviews 25 (13-14): 1668-1691.
- Dupont TK and Alley RB (2005). Assessment of the importance of ice-shelf buttressing to ice-sheet flow. *Geophysical Research Letters* **32**: L04503.
- Dyke AS (1993). Landscapes of cold-centred Late Wisconsinan ice caps, Arctic Canada. Progress in Physical Geography 17 (2): 223-247.
- Dyke AS and Morris TF (1988). Canadian Landform Examples 7: Drumlin fields, dispersal trains, and ice streams in Arctic Canada. *Canadian Geographer* 32: 86-90.
- Dyke AS and Prest VK (1987). Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. Geographie Physique et Quaternaire 41: 237-263.
- Dyke AS, Moore A and Robertson L (2003). Deglaciation of North America. Geological Survey of Canada, Open File 1574.
- Edwards KJ, Baillie MGL, Pilcher JR, Hirons KR and Thompson R (1985). Chronology. In Edwards KJ and Warren WP (ed.) *The Quaternary History of Ireland*. Academic Press; London. pp 279-308.
- Ehlers J and Gibbard PL (eds.) (2004). Quaternary Glaciations Extent and Chronology. Part 1: Europe. Developments in Quaternary Science 2. Elsevier; Amsterdam.
- Ehlers J and Wingfield R (1991). The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. Journal of Quaternary Science 6: 313-326.
- Ehlers J, Gibbard PL and Rose J (eds.) (1991). Glacial deposits in Great Britain and Ireland. Balkema; Rotterdam.
- Engelhardt H and Kamb B (1997). Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations. *Journal of Glaciology* **43**: 207-230.
- Evans DJA and Ó Cofaigh C (2003). Depositional evidence for marginal oscillations of the Irish Sea ice stream in southeast Ireland during the last glaciation. *Boreas* 32: 76-101.
- Evans DJA and Rea BR (2003). The surging glacier landsystem. In Evans DJA (ed.) Glacial landsystems. Arnold; London. pp 259-288.
- Everest JD, Bradwell T and Golledge NR (2005). Subglacial landforms of the Tweed palaeo-ice stream. *Scottish Geographical Journal* 121 (2): 163-173.

- Everest JD, Bradwell T, Fogwill CJ and Kubik PW (2006). Cosmogenic 10BE Age Constraints for The Wester Ross Readvance Moraine: Insights Into British Ice-Sheet Behaviour. *Geografiska* Annaler Series A 88 (1): 9-17.
- Eyles N and McCabe AM (1989). The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. *Quaternary Science Reviews* 8: 307-351.
- Fairbanks RG, Mortlock RA, Chiu T-C, Cao L, Kaplan A, Guilderson TP, Fairbanks TW and Bloom AL (2005). Marine Radiocarbon Calibration Curve Spanning 0 to 50,000 Years B.P. Based on Paired ²³⁰Th / ²³⁴U / ²³⁸U and ¹⁴C Dates on Pristine Corals. *Quaternary Science Reviews* 24: 1781-1796.
- Farrell A, McCarron S and Coxon P (2005). The Quaternary Geology of Central Western Ireland. In Coxon P (ed.) The Quaternary of Central Western Ireland: Field Guide. Quaternary Research Association; London. pp 7-24.
- Farrington A (1934). The glaciation of the Wicklow mountains. Proceedings of the Royal Irish Academy 42B: 173-209.
- Farrington A (1936). The glaciation of the Bantry Bay district. Scientific Proceedings of the Royal Dublin Society 21: 345-361.
- Farrington A (1947). Unglaciated areas in southern Ireland. Irish Geography 1 (4): 89-97.
- Farrington A (1954). A note on the correlation of the Kerry-Cork glaciations with those of the rest of Ireland. *Irish Geography* 3: 47-53.
- Farrington A (1965). The Last Glaciation in the Burren, Co. Clare. Proceedings of the Royal Irish Academy 64B: 33-39.
- Finch TF (1977). Guidebook for Excursion C16: Western Ireland. INQUA; Norwich.
- Finch TF and Ryan P (1966). Soils of County Limerick. An Foras Taluntais; Dublin.
- Finch TF and Synge FM (1966). The drifts and soils of West Clare and the adjoining parts of Counties Kerry and Limerick. *Irish Geography* 5 (2): 161-172.
- Finch TF and Walsh M (1973). Drumlins of County Clare. Proceedings of the Royal Irish Academy 73B: 405-413.
- Flint RF (1930). The origin of the Irish "eskers". Geographical Review 20: 615-630.
- Flint RF (1943). Growth of the North American ice sheet during the Wisconsinan age. *Geological* Society of America Bulletin 54: 325-362.
- Flint RF (1947). Glacial geology and the Pleistocene Epoch. Wiley; New York.
- Fowler AC (1987). Sliding with cavity formation. Journal of Glaciology 33: 255-267.
- Fricker HA, Scambos TA, Bindschadler R and Padman L (2007). An active subglacial water system in West Antarctica mapped from space. *Science* **315**: 1544-1548.
- Gallagher C (1998). A reconstruction of Pleistocene ice sheet limits in Slieve Bloom using heavy minerals. *Irish Geography* 31 (2): 100-110.
- Gallagher C and Thorp M (1997). The age of the Pleistocene raised beach near Fethard, County Wexford, using infra red stimulated luminescence (IRSL). *Irish Geography* 30 (2): 68-89.
- Gallagher C, Thorp M and Steenson P (1996). Glacier Dynamics around Slieve Bloom, Central Ireland. Irish Geography 29 (2): 67-82.
- Gallagher C, Sutton G and Bell T (2004). Submerged ice marginal forms in the Celtic Sea off Waterford Harbour, Ireland. Irish Geography 37 (2): 145-165.
- Geikie J (1894). The Great Ice Age and its relation to the antiquity of man. 3rd edition. Edward Stanford; London.
- Gibson PJ (1993). Geological and Geomorphological Applications of Low-Angle Illumination Satellite Imagery in Northern Ireland. Irish Geography 26 (1): 58-64.
- Giovinetto MB and Zwally HJ (2000). Spatial distribution of net surface accumulation on the Antarctic ice sheet. Annals of Glaciology 31: 171-178.

- Glanville C (1997). Glaciolacustrine and glaciofluvial deposits defining the margins of uncoupling ice lobes in the southeastern midlands of Ireland. *Quaternary Science Reviews* 16: 685-703.
- Glasser NF and Sambrook Smith GH (1999). Glacial meltwater erosion of the Mid-Cheshire Ridge: implications for ice dynamics during the Late Devensian glaciation of northwest England. *Journal of Quaternary Science* 14 (7): 703-710.
- Glasser NF, Etienne JL, Hambrey MJ, Davies JR, Waters RA and Wilby PR (2004). Glacial meltwater erosion and sedimentation as evidence for multiple glaciations in west Wales. *Boreas* 33: 224-237.
- Gluckert G (1973). Two large drumlin fields in central Finland. Fennia 120.
- Golledge NR (2007). An ice cap landsystem for palaeoglaciological reconstructions: characterizing the Younger Dryas in western Scotland. *Quaternary Science Reviews* 26: 213-229.
- Graham AGC, Lonergan L and Stoker MS (2007). Evidence for Late Pleistocene ice stream activity in the Witch Ground Basin, central North Sea, from 3D seismic reflection data. *Quaternary Science Reviews* 26 (5-6): 627-643.
- Gray JM and Coxon P (1991). The Loch Lomond Stadial glaciation in Britain and Ireland. In Ehlers J, Gibbard PL and Rose J (ed.) *Glacial deposits in Great Britain and Ireland*. Balkema; Rotterdam. pp 89-105.
- Greenwood SL and Clark CD (In preparation). Subglacial bedforms of the Irish Ice Sheet. Journal of Maps.
- Greenwood SL, Clark CD and Hughes ALC (2007). Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: application to the British Ice Sheet. *Journal of Quaternary Science* 22 (6): 637-645.
- Gregory JW (1920). The Irish Eskers. *Philosophical Transactions of the Royal Society of London, B* **210**: 115-151.
- Guilcher A (1965). Drumlin and spit structures in the Kenmare River, south-west Ireland. Irish Geography 5 (2): 7-19.
- Haflidason H, King EL, Kristensen DK, Helland E, Duffy M, Scourse JD, Austin WEN and Sejrup HP (1997). Marine geological/geophysical cruise report on the western Irish margin: Donegal Bay, Clew Bay, Galway Bay, Irish shelf and Rockall Trough. Department of Geology, University of Bergen; Bergen.
- Hagdorn MKM (2003). Reconstruction of the Past and Forecast of the Future European and British Ice Sheets and Associated Sea-Level Change. Unpublished PhD thesis. School of Geosciences; University of Edinburgh. pp175.
- Hall AM and Glasser NF (2003). Reconstructing the basal thermal regime of an ice stream in a landscape of selective linear erosion: Glen Avon, Cairngorm Mountains, Scotland. Boreas 32 (1): 191-207.
- Hall AM, Peacock JD and Connell ER (2003). New data for the Last Glacial Maximum in Great Britain and Ireland: a Scottish perspective on the paper by Bowen et al. (2002). Quaternary Science Reviews 22 (14): 1551-1554.
- Hall IR and McCave IN (1998). Late Glacial to Recent accumulation fluxes of sediments at the shelf edge and slope of NW Europe, 48-50°N. In Stoker MS, Evans D and Cramp A (ed.) *Geological Processes on Continental Margins: Sedimentation, Mass-Wasting and Stability*. Geological Society; London. pp 339-350.
- Hall IR, Moran SB, Zahn R, Knutz PC, Shen C-C and Edwards RL (2006). Accelerated drawdown of meridional overturning in the late-glacial Atlantic triggered by transient pre-H event freshwater perturbation. *Geophysical Research Letters* 33: L16616.
- Hallissy T (1914). Clare Island Survey: Geology. Proceedings of the Royal Irish Academy 31: 1-22.
- Hanvey PM (1987). Sedimentology of lee-side stratification sequences in late-Pleistocene drumlins, north-west Ireland. In Menzies J and Rose J (ed.) *Drumlin Symposium*. Balkema; Rotterdam. pp 241-253.

- Harrison S and Anderson E (2002). Glaciation of the Reeks and Glenavy Stadial advance moraines.
 In Harrison S and Mighall TM (ed.) *The Quaternary of South West Ireland. Field Guide*.
 Quaternary Research Association; London. pp 35-46.
- Hättestrand C (1997). Ribbed moraines in Sweden distribution pattern and palaeoglaciological implications. *Sedimentary Geology* 111: 41-56.
- Hättestrand C (1998). The glacial geomorphology of central and northern Sweden. Sveriges Geologiska Undersökning Ser. Ca 85: 47 pp.
- Hättestrand C and Clark CD (2006a). The glacial geomorphology of the Kola Peninsula and adjacent areas in the Murmansk Region, Russia. *Journal of Maps* **2006**: 30-42.
- Hättestrand C and Clark CD (2006b). Reconstructing the pattern and style of deglaciation of Kola Peninsula, northeastern Fennoscandian Ice Sheet. In Knight PG (ed.) *Glacier Science and Environmental Change*. Blackwell; Oxford. pp 199-201.
- Hättestrand C and Kleman J (1999). Ribbed moraine formation. *Quaternary Science Reviews* 18: 43-61.
- Hättestrand C and Stroeven AP (2002). A relict landscape in the centre of Fennoscandian glaciation: Geomorphological evidence of minimal Quaternary glacial erosion. *Geomorphology* 44 (1-2): 127-143.
- Haynes JR, McCabe AM and Eyles N (1995). Microfaunas from Late Devensian glaciomarine deposits in the Irish Sea Basin. Irish Journal of Earth Sciences 14: 81-103.
- Hegarty S (2002a). Pathways and processes of Late Pleistocene subglacial meltwater flows, County Kilkenny. Unpublished PhD thesis. Department of Geography; University College, Dublin. pp377.
- Hegarty S (ed.) (2002b). *The Quaternary of Kilkenny*. Irish Quaternary Association Field Guide No 24. Irish Quaternary Association; Dublin.
- Hegarty S (2004). Limits of Midlandian glaciation in south-eastern Ireland. Irish Geography 37 (1): 60-76.
- Heijnis H, Ruddock J and Coxon P (1993). A uranium-thorium dated Late Eemian or Early Midlandian organic deposit from near Kilfenora between Spa and Fenit, Co. Kerry, Ireland. Journal of Quaternary Science 8 (1): 31-43.
- Hiemstra JF, Evans DJA, Scourse JD, McCarroll D, Furze MFA and Rhodes E (2006). New evidence for a grounded Irish Sea glaciation of the Isles of Scilly, UK. *Quaternary Science Reviews* 25 (3-4): 299-309.
- Hill AR (1970). The relationship of drumlins to the directions of ice movement in north Co. Down. In Stephens N and Glasscock RE (ed.) *Irish Geographical Studies, in honour of E. Estyn Evans.* The Queen's University of Belfast; Belfast. pp 53-59.
- Hill AR (1971). The internal composition and structure of drumlins in North Down and South Antrim, Northern Ireland. *Geografiska Annaler* 53A: 14-31.
- Hill AR (1973). The distribution of drumlins in County Down, Ireland. Annals of the Association of American Geographers 63 (2): 226-240.
- Hill AR and Prior DB (1968). Directions of ice movement in North-East Ireland. *Proceedings of the Royal Irish Academy* **66B**: 71-84.
- Hindmarsh RCA (1998a). Drumlinization and drumlin-forming instabilities: viscous till mechanisms. Journal of Glaciology 44: 293-314.
- Hindmarsh RCA (1998b). The stability of a viscous till sheet coupled with ice flow, considered at wavelengths less than ice thickness. *Journal of Glaciology* 44: 288-292.
- Hindmarsh RCA (1999). Coupled ice-till dynamics and the seeding of drumlins and bedrock forms. Annals of Glaciology 28: 221-230.
- Hoare PG (1991a). Late Midlandian glacial deposits and glaciation in Ireland and the adjacent offshore regions. In Ehlers J, Gibbard PL and Rose J (ed.) *Glacial Deposits in Great Britain and Ireland*. Balkema; Rotterdam. pp 69-78.
- Hoare PG (1991b). The glacial stratigraphy and deposits of Eastern Ireland. In Ehlers J, Gibbard PL and Rose J (ed.) *Glacial Deposits in Great Britain and Ireland*. Balkema; Rotterdam. pp 367-375.
- Hollin JT (1962). On the glacial history of Antarctica. Journal of Glaciology 4: 173-195.
- Hooke RL (2005). Principles of Glacier Mechanics, 2nd edition. Cambridge University Press; Cambridge.
- Hooke RL and Jennings CE (2006). On the formation of the tunnel valleys of the southern Laurentide ice sheet. *Quaternary Science Reviews* 25: 1364-1372.
- Hubbard A (1999). High-Resolution Modeling of the Advance of the Younger Dryas Ice Sheet and its Climate in Scotland. *Quaternary Research* 52: 27-43.
- Hubbard A, Bradwell T and Stoker MS (2007). Modelling the dynamical response of the last British Ice Sheet. (Abstract). QRA ADM - The Growth, Maximum Extent and Deglaciation of the last British and Irish Ice Sheet. St. Andrews.
- Hull E (1878). Physical Geology and Geography of Ireland. Edward Stanford; London.
- Huuse M and Lykke-Andersen H (2000). Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. *Quaternary Science Reviews* 19: 1233-1253.
- IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (ed.). Cambridge University Press, Cambridge, pp996.
- Jansson KN, Kleman J, Marchant DR (2002). The succession of ice-flow patterns in north-central Québed-Labrador, Canada. *Quaternary Science Reviews* 21: 503-523.
- Jennings AE, Hald M, Smith M and Andrews JT (2006). Freshwater forcing from the Greenland Ice Sheet during the Younger Dryas: evidence from southeastern Greenland shelf cores. *Quaternary Science Reviews* 25 (3-4): 282-298.
- Jessen K, Andersen ST and Farrington A (1959). The interglacial deposit near Gort, Co. Galway, Ireland. *Proceedings of the Royal Irish Academy* 60B: 1-77.
- Jorgensen F and Sandersen PBE (2006). Buried and open tunnel valleys in Denmark--erosion beneath multiple ice sheets. *Quaternary Science Reviews* **25** (11-12): 1339-1363.
- Jordan CJ (1997). Quaternary Geology Mapping in the Republic of Ireland how much can be achieved through satellite remote sensing? Twelfth International Conference and Workshops on Applied Geologic Remote Sensing. Denver, Colorado.
- Jordan CJ (2002). An holistic approach to mapping the Quaternary Geology and reconstructing the last glaciation of West County Mayo, Ireland, using satellite remote sensing and 'conventional' mapping techniques. Unpublished PhD thesis. Queen Mary, University of London.
- Joughin I and Tulaczyk S (2002). Positive mass balance of the Ross Ice Streams, West Antarctica. Science 295: 476-480.
- Joughin I, Tulaczyk S, Bindschadler R and Price S (2002). Changes in West Antarctic ice stream velocities: observation and analysis. *Journal of Geophysical Research* 107 (B11): 2289.
- Joughin I, Tulaczyk S, MacAyeal DR and Engelhardt H (2004). Melting and freezing beneath the Ross ice streams, Antarctica. *Journal of Glaciology* **50** (168): 96-108.
- Kamb B (1987). Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *Journal of Geophysical Research* 92: 9083-9100.
- Kilfeather AA (2004). *Glaciation, deformation and till porosity: County Laois, Ireland*. Unpublished PhD thesis. Department of Geography; Queen Mary, University of London.
- Kilroe JR (1888). Directions of ice-flow in the North of Ireland, as determined by the observations of the Geological Survey. *Quarterly Journal of the Geological Society of London* 44: 827-833.
- Kinahan GH and Close MH (1872). The General Glaciation of lar-Connaught and its neighbourhood, in the Counties of Galway and Mayo. Hodges, Foster, and Co.; Dublin.

- King CAM and Gage M (1961). Note on the extent of glaciation in part of West Kerry. Irish Geography 4: 202-208.
- Kjaer KH, Houmark-Nielsen M and Richardt N (2003). Ice-flow patterns and dispersal of erratics at the southwestern margin of the last Scandinavian Ice Sheet: signature of palaeo-ice streams. *Boreas* 32: 130-148.
- Kleman J (1992). The palimpsest glacial landscape in northwestern Sweden. Geografiska Annaler 74A: 305-325.
- Kleman J (1994). Preservation of landforms under ice sheets and ice caps. Geomorphology 9: 19-32.
- Kleman J and Borgström I (1996). Reconstruction of palaeo-ice sheets: the use of geomorphological data. *Earth Surface Processes and Landforms* **21**: 893-909.
- Kleman J and Glasser NF (2007). The subglacial thermal organisation (STO) of ice sheets. Quaternary Science Reviews 26: 585-597.
- Kleman J and Hättestrand C (1999). Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum. *Nature*: 63-65.
- Kleman J, Borgström I and Hättestrand C (1994). Evidence for a relict glacial landscape in Quebec-Labrador. *Palaeogeography, palaeoclimatology, palaeoecology* 111: 217-228.
- Kleman J, Hättestrand C, Borgström I and Stroeven AP (1997). Fennoscandian palaeoglaciology reconstructed using a glacial geological inversion model. *Journal of Glaciology* **43**: 283-299.
- Kleman J, Hättestrand C, Stroeven AP, Jansson KN, De Angelis H and Borgström I (2006). Reconstruction of paleo-ice sheets - inversion of their geomorphological record. In Knight PG (ed.) *Glacier Science and Environmental Change*. Blackwell; Oxford. pp 192-199.
- Knies J, Vogt C, Matthiessen J, Nam S-I, Ottesen D, Rise L, Bargel T and Eilertsen RS (2007). Readvance of the Fennoscandian Ice Sheet during Heinrich Event 1. *Marine Geology* 240: 1-18.
- Knight J (1997). Morphological and morphometric analyses of drumlin bedforms in the Omagh Basin, north central Ireland. *Geografiska Annaler* **79A**: 255-266.
- Knight J (1999). Problems of Irish drumlins and Late Devensian ice sheet reconstructions. *Proceedings of the Geologists' Association* **110**: 9-16.
- Knight J (2001). Glaciomarine deposition around the Irish Sea basin: some problems and solutions. Journal of Quaternary Science 16 (5): 405-418.
- Knight J (2002). Bedform patterns, subglacial meltwater events, and Late Devensian ice sheet dynamics in north-central Ireland. *Global and Planetary Change* 35: 237-253.
- Knight J (2003a). Geomorphic and sedimentary evidence for patterns of late Midlandian ice retreat in the Tempo Valley, north-central Ireland. *Irish Geography* **36** (2): 127-144.
- Knight J (2003b). Geomorphic evidence for patterns of late Midlandian ice advance and retreat in the Omagh Basin. *Irish Geography* 36 (1): 1-22.
- Knight J (2003c). Evaluating controls on ice dynamics in the north-east Atlantic using an event stratigraphy approach. *Quaternary International* **99-100**: 45-57.
- Knight J (2006a). Geomorphic evidence for active and inactive phases of Late Devensian ice in north-central Ireland. *Geomorphology* **75** (1-2): 4-19.
- Knight J (2006b). Sub-ice shelf deposition during the late Devensian glaciation in western Ireland. *Marine Geology* 235: 229-240.
- Knight J and McCabe AM (1997a). Drumlin evolution and ice sheet oscillations along the NE Atlantic margin, Donegal Bay, western Ireland. *Sedimentary Geology* 111: 57-72.
- Knight J and McCabe AM (1997b). Identification and significance of ice-flow-transverse subglacial ridges (Rogen moraines) in north central Ireland. *Journal of Quaternary Science* 12 (6): 519-524.
- Knight J, McCarron SG and McCabe AM (1999). Landform modification by palaeo-ice streams in east-central Ireland. *Annals of Glaciology* 28: 161-167.

- Knight J, Coxon P, McCabe AM and McCarron SG (2004). Pleistocene glaciations in Ireland. In Ehlers J and Gibbard PL (ed.) Quaternary Glaciations - extent and chronology. Part 1: Europe. Elsevier; Amsterdam. pp 183-191.
- Knutz PC, Austin WEN and Jones EJW (2001). Millennial-scale depositional cycles related to British Ice Sheet variability and North Atlantic paleocirculation since 45 kyr B.P., Barra Fan, U.K. margin (Paper 1999PA000483). Paleoceanography 16 (1): 53-64.
- Knutz PC, Hall IR and Zahn R (2002a). Multidecadal ocean variability and NW European ice sheet surges during the last deglaciation. *Geochemistry, Geophysics, Geosystems* **3** (12): 1077.
- Knutz PC, Jones EJW, Austin WEN and van Weering TCE (2002b). Glacimarine slope sedimentation, contourite drifts and bottom current pathways on the Barra Fan, UK North Atlantic margin. *Marine Geology* 188: 129-146.
- Knutz PC, Zahn R and Hall IR (2007). Centennial-scale variability of the British Ice Sheet: Implications for climate forcing and Atlantic meridional overturning circulation during the last deglaciation. *Paleoceanography* 22: PA1207.
- Kroon D, Shimmield G, Austin WEN, Derrick S, Knutz PC and Shimmield T (2000). Century- to millennial-scale sedimentological-geochemical records of glacial-Holocene sediment variations from the Barra Fan (NE Atlantic). *Journal of the Geological Society, London* 157: 643-653.
- Laberg JS, Eilertsen RS, Salomonsen GR and Vorren TO (2007). Submarine push moraine formation during the early Fennoscandian Ice Sheet deglaciation. *Quaternary Research* 67 (3): 453-462.
- Lafferty B, Quinn R and Breen C (2006). Subglacial imprints associated with the isolation and decay of an ice mass in the Lower Lough Erne basin, Co. Fermanagh, NW Ireland. Journal of the Geological Society, London 163: 421-430.
- Lamb AL and Ballantyne CK (1998). Palaeonunataks and the altitude of the last ice sheet in the south-west Lake District, England. *Proceedings of the Geologists Association* 109: 305-316.
- Lambeck K (1993a). Glacial rebound of the British Isles 1. Preliminary model results. *Geophysical Journal International* 115: 941-959.
- Lambeck K (1993b). Glacial rebound of the British Isles II. A high-resolution, high-precision model. *Geophysical Journal International* 115: 960-990.
- Lambeck K (1995). Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society, London* 152: 437-448.
- Lambeck K (1996). Glaciation and sea-level change for Ireland and the Irish Sea since Late Devensian/Midlandian time. *Journal of the Geological Society, London* 153: 853-872.
- Lambeck K and Chappell J (2001). Sea level change through the last glacial cycle. *Science* **292**: 679-686.
- Lewis CA (1967). The glaciation of the Behy Valley County Kerry. Irish Geography 5 (2): 293-301.
- Lewis AR, Marchant DR, Kowalewiski DE, Baldwin SL and Webb LE (2006). The age and origin of the Labyrinth, western Dry Valleys, Antarctica: Evidence for extensive middle Miocene subglacial floods and freshwater discharge to the Southern Ocean. *Geology* 34 (7): 513-516.
- Li YK, Napieralski JA, Harbor J and Hubbard A (2007). Identifying patterns of correspondence between modeled flow directions and field evidence: an automated flow direction analysis. *Computers and Geosciences* 33: 141-150.
- Lliboutry (1968). General theory of subglacial cavitation and sliding of temperate glaciers. *Journal* of Glaciology 7: 21-58.
- Lowe JJ, Walker MJC, Scott EM, Harkness DD, Bryant CL and Davies SM (2004). A coherent high-precision radiocarbon chronology for the Late-glacial sequence at Sluggan Bog, Co. Antrim, Northern Ireland. *Journal of Quaternary Science* 19 (2): 147-158.
- Lundqvist J (1969). Problems of the so-called Rogen moraine. Sverige Geologiske Undersoegelse Series C: 648.

- Mannerfelt CM (1949). Marginal drainage channels as indicators of the gradients of Quaternary ice caps. *Geografiska Annaler* **31**: 194-199.
- Mardia KV and Jupp PE (2000). Directional Statistics. Wiley; Chichester.
- Marshall SJ and Koutnik MR (2006). Ice sheet action versus reaction: Distinguishing between Heinrich events and Dansgaard-Oeschger cycles in the North Atlantic. *Paleoceanography* 21: PA2021.
- Marshall SJ, Tarasov L, Clarke GKC and Peltier WR (2000). Glaciological reconstruction of the Laurentide Ice Sheet: physical processes and modelling challenges. *Canadian Journal of Earth Sciences* 37 (5): 769-793.
- Mathews WH (1974). Surface profiles of the Laurentide Ice Sheet in its marginal areas. Journal of Glaciology 13: 37-43.
- McCabe AM (1972). Directions of Late Pleistocene ice-flows in eastern Counties Meath and Louth, Ireland. Irish Geography 6: 443-461.
- McCabe AM (1985). Glacial Geomorphology. In Edwards KJ and Warren WP (ed.) The Quaternary History of Ireland. Academic Press Inc.; London. pp 67-93.
- McCabe AM (1987). Quaternary Deposits and Glacial Stratigraphy in Ireland. Quaternary Science Reviews 6: 259-299.
- McCabe AM (1991). The distribution and stratigraphy of drumlins in Ireland. In Ehlers J, Gibbard PL and Rose J (ed.) *Glacial Deposits in Great Britain and Ireland*. Balkema; Rotterdam. pp 421-435.
- McCabe AM (1993). The 1992 Farrington Lecture: Drumlin Bedforms and Related Ice-Marginal Depositional Systems in Ireland. Irish Geography 26 (1): 22-44.
- McCabe AM (1996). Dating and rhythmicity from the last deglacial cycle in the British Isles. Journal of the Geological Society, London 153 (4): 499-502.
- McCabe AM (1997). Geological constraints on geophysical models of relative sea-level change during deglaciation of the western Irish Sea Basin. Journal of the Geological Society, London 154 (4): 601-604.
- McCabe AM (1998). Striae at St. Mullin's Cave, County Kilkenny, southern Ireland: their origin and chronological significance. *Geomorphology* 23: 91-96.
- McCabe AM (2005). AMS ¹⁴C chronology and an ice sheet model for western Ireland. In Coxon P (ed.) *The Quaternary of Central Western Ireland: Field Guide*. Quaternary Research Association; London. pp 25-34.
- McCabe AM (2008). Glacial Geology and Geomorphology: The Landscapes of Ireland. Dunedin Academic Press, Edinburgh.
- McCabe AM and Clark PU (1998). Ice-sheet variability around the North Atlantic Ocean during the last deglaciation. *Nature* **392**: 373-377.
- McCabe AM and Clark PU (2003). Deglacial chronology from County Donegal, Ireland: implications for deglaciation of the British-Irish Ice Sheet. Journal- Geological Society London 160 (6): 847-856.
- McCabe AM and Dardis GF (1989). A geological view of drumlins in Ireland. Quaternary Science Reviews 8: 169-177.
- McCabe AM and Dardis GF (1994). Glaciotectonically induced water-throughflow structures in a Late Pleistocene drumlin, Kanrawer, County Galway, western Ireland. *Sedimentary Geology* **91**: 173-190.
- McCabe AM and Dunlop P (2006). The Last Glacial Termination in Northern Ireland. Geological Survey of Northern Ireland; Belfast.
- McCabe AM and Haynes JR (1996). A late Pleistocene intertidal boulder pavement from an isostatically emergent coast, Dundalk Bay, eastern Ireland. *Earth Surface Processes and Landforms* 21: 555-572.

- McCabe AM and Hoare PG (1978). The Late Quaternary history of east-central Ireland. *Geological Magazine* **115** (6): 397-413.
- McCabe AM and Ó Cofaigh C (1994). Sedimentation in a subglacial lake, Enniskerry, eastern Ireland. Sedimentary Geology 91: 57-95.
- McCabe AM and Ó Cofaigh C (1996). Upper Pleistocene facies sequences and relative sea-level trends along the south coast of Ireland. *Journal of Sedimentary Research* 66 (2): 376-390.
- McCabe AM, Mitchell GF and Shotton FW (1978). An inter-till freshwater deposit at Hollymount, Maguiresbridge, Co. Fermanagh. *Proceedings of the Royal Irish Academy* **78B**: 77-89.
- McCabe AM, Dardis GF and Hanvey PM (1984). Sedimentology of a Late Pleistocene submarine moraine complex, County Down, Northern Ireland. *Journal of Sedimentary Research* 54: 716-730.
- McCabe AM, Haynes JR and MacMillan NF (1986). Late-Pleistocene tidewater glaciers and glaciomarine sequences from north County Mayo, Republic of Ireland. *Journal of Quaternary Science* 1 (1): 7-84.
- McCabe AM, Knight J and McCarron SG (1998). Evidence for Heinrich event 1 in the British Isles. Journal of Quaternary Science 13 (6): 549-568.
- McCabe AM, Knight J and McCarron SG (1999). Ice-flow stages and glacial bedforms in north central Ireland: a record of rapid environmental change during the last glacial termination. *Journal of the Geological Society, London* **156**: 63-72.
- McCabe AM, Clark PU and Clark J (2005). AMS ¹⁴C dating of deglacial events in the Irish Sea Basin and other sectors of the British-Irish ice sheet. *Quaternary Science Reviews* 24 (14-15): 1673-1690.
- McCabe AM, Clark PU and Clark J (2007a). Radiocarbon constraints on the history of the western Irish ice sheet prior to the Last Glacial Maximum. *Geology* **35** (2): 147-150.
- McCabe AM, Clark PU, Clark J and Dunlop P (2007b). Radiocarbon constraints on readvances of the British-Irish Ice Sheet in the northern Irish Sea Basin during the last deglaciation. *Quaternary Science Reviews* 26: 1204-1211.
- McCarroll D (2001). Deglaciation of the Irish Sea Basin: a critique of the glaciomarine hypothesis. Journal of Quaternary Science 16 (5): 393-404.
- McCarroll D (2002). Amino-acid geochronology and the British Pleistocene: secure stratigraphical framework or a case of circular reasoning? *Journal of Quaternary Science* 17 (7): 647-652.
- McCarroll D and Ballantyne CK (2000). The last ice sheet in Snowdonia. Journal of Quaternary Science 15 (8): 765-778.
- McCarroll D, Knight J and Rijsdijk KF (2001). Introduction: The glaciation of the Irish Sea basin. Journal of Quaternary Science 16 (5): 391-392.
- McManus J (1967). The influence of Pleistocene glaciation on the geomorphology of eastern Murrisk, Co. Mayo. Scientific Proceedings of the Royal Dublin Society **3A**: 17-31.
- Meehan RT (1999). Directions of ice flow during the last glaciation in counties Meath, Westmeath and Cavan. *Irish Geography* **32** (1): 26-51.
- Meehan RT (2004). Evidence for several ice marginal positions in east central Ireland, and their relationship to the Drumlin Readvance Theory. In Ehlers J and Gibbard PL (ed.) Quaternary Glaciations Extent and Chronology. Part 1: Europe. Elsevier; Amsterdam. pp 193-194.
- Meehan RT (2006a). Glacial readvances: self-promulgating theories or science-based reality? In Knight PG (ed.) *Glacier Science and Environmental Change*. Blackwell; Oxford. pp 264-266.
- Meehan RT (2006b). Parent material / subsoil mapping. In EPA Soil and Subsoil Mapping outline procedure document, Version 1.2. Teagasc, Dublin.
- Menzies J (1987). Towards a general hypothesis on the formation of drumlins. In Menzies J and Rose J (ed.) Drumlin Symposium. Balkema; Rotterdam. pp 9-24.

- Menzies J (1989). Drumlins products of controlled or uncontrolled glaciodynamic response. Quaternary Science Reviews 8: 151-158.
- Mitchell FJG and Delaney C (ed.) (1997). The Quaternary of the Irish Midlands. Field Guide No. 21. Irish Association for Quaternary Studies; Dublin.
- Mitchell GF (1976). The Irish Landscape. Collins; London.
- Mitchell GF and Ryan M (1998). Reading the Irish Landscape. Town House; Dublin.
- Mix AC, Bard E and Schneider R (2001). Environmental processes of the ice age: land, oceans, glaciers (EPILOG). *Quaternary Science Reviews* 20: 627-657.
- Munro MJ and Shaw J (1997). Erosional origin of hummocky terrain, Alberta, Canada. *Geology* 25: 1027-1030.
- Napieralski JA, Li YK and Harbor J (2006). Comparing predicted and observed spatial boundaries of geologic phenemena: Automated Proximity and Conformity Analysis (APCA) applied to ice sheet reconstructions. *Computers and Geosciences* **32**: 124-134.
- Napieralski JA, Harbor J and Li YK (2007a). Glacial geomorphology and geographic information systems. *Earth Science Reviews* 85: 1-22.
- Napieralski JA, Hubbard A, Li YK, Harbor J, Stroeven AP, Kleman J, Alm G and Jansson KN (2007b). Towards a GIS assessment of numerical ice sheet model performance using geomorphological data. *Journal of Glaciology* 53: 71-83.
- Nielsen T, De Santis L, Dahlgren KIT, Kuijpers A, Laberg JS, Nygård A, Praeg D and Stoker MS (2005). A comparison of the NW European glaciated margin with other glaciated margins. *Marine and Petroleum Geology* 22: 1149-1183.
- Nye JF (1952). A method of calculating the thickness of the ice-sheets. Nature 169: 529-530.
- Nye JF (1976). Water flow in glaciers: jökulhlaups, tunnels and veins. Journal of Glaciology 17: 181-207.
- Nygård A, Sejrup HP, Haflidason H, Cecchi M and Ottesen D (2004). Deglaciation history of the southwestern Fennoscandian Ice Sheet between 15 and 13 ¹⁴C ka BP. *Boreas* 33 (1): 1-17.
- Nygård A, Sejrup HP, Haflidason H, Lekens WAH, Clark CD and Bigg GR (2007). Extreme sediment and ice discharge from marine-based ice streams: New evidence from the North Sea. *Geology* **35** (5): 395-398.
- Ó Cofaigh C and Evans DJA (2001a). Deforming bed conditions associated with a major ice stream of the last British ice sheet. *Geology* 29 (9): 795-798.
- O Cofaigh C and Evans DJA (2001b). Sedimentary evidence for deforming bed conditions associated with a grounded Irish Sea glacier, southern Ireland. Journal of Quaternary Science 16 (5): 435-454.
- Ó Cofaigh C and Evans DJA (2007). Radiocarbon constraints on the age of the maximum advance of the British-Irish Ice Sheet in the Celtic Sea. *Quaternary Science Reviews* 26 (9-10): 1197-1203.
- Ohmura A and Reeh N (1991). New precipitation and accumulation maps for Greenland. Journal of Glaciology 37: 140-148.
- Orme AR (1967). Drumlins and the Weichsel Glaciation of Connemara. Irish Geography 5: 262-274.
- Ottesen D, Dowdeswell JA, Rise L, Rokoengen K and Henriksen S (2002). Large-scale morphological evidence for past ice-stream flow on the mid-Norwegian continental margin. In Dowdeswell JA and Ó Cofaigh C (ed.) Glacier-influenced sedimentation on high-latitude continental margins. Geological Society of London Special Publication, 203. pp 245-258.
- Ottesen D, Dowdeswell JA and Rise L (2005). Submarine landforms and the reconstruction of fastflowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57° – 80° N). Geological Society of America Bulletin 117 (7): 1033-1050.

- Parent M, Paradis SJ and Boisvert E (1995). Ice-flow patterns and glacial transport in the eastern Hudson Bay region: implications for the late Quaternary dynamics of the Laurentide Ice Sheet. Canadian Journal of Earth Sciences 32: 2057-2070.
- Parent M, Paradis SJ and Doiron A (1996). Palimpsest glacial dispersal trains and their significance for drift prospecting. *Journal of Geochemical Exploration* 56: 123-140.
- Paterson WSB (1994). The Physics of Glaciers. Pergamon; Oxford.
- Payne AJ (1999). A thermomechanical model of ice flow in West Antarctica. *Climate Dynamics* 15: 115-125.
- Payne AJ and Sugden DE (1990). Topography and ice sheet growth. Earth Surface Processes and Landforms 15: 625-639.
- Payne AJ, Vieli A, Shepherd AP, Wingham DJ and Rignot E (2004). Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. *Geophysical Research Letters* 31: L23401.
- Peck VL, Hall IR, Zahn R, Elderfield H, Grousset F, Hemming SR and Scourse JD (2006). High resolution evidence for linkages between NW European ice sheet instability and Atlantic Meridional Overturning Circulation. *Earth and Planetary Science Letters* 243: 476-488.
- Peck VL, Hall IR, Zahn R, Grousset F, Hemming SR and Scourse JD (2007). The relationship of Heinrich events and their European precursors over the past 60 ka BP: a multi-proxy ice-rafted debris provenance study in the North East Atlantic. *Quaternary Science Reviews* 26 (7-8): 862-875.
- Peltier WR (1994). Ice age paleotopography. Science 265 (5169): 195-201.
- Peltier WR, Shennan I, Drummond R and Horton B (2002). On the postglacial isostatic adjustment of the British Isles and the shallow viscoelastic structure of the Earth. *Geophysical Journal International* 148: 443-475.
- Piotrowski JA (1994). Tunnel-valley formation in northwest Germany geology, mechanisms of formation and subglacial bed conditions for the Bornhöved tunnel valley. *Sedimentary Geology* 89: 107-141.
- Piotrowski JA (1997). Subglacial hydrology in north-western Germany during the last glaciation: groundwater flow, tunnel valleys and hydrological cycles. *Quaternary Science Reviews* 16: 169-185.
- Piotrowski JA, Larsen NK and Junge FW (2004). Reflections on soft subglacial beds as a mosaic of deforming and stable spots. *Quaternary Science Reviews* 23 (9-10): 993-1000.
- Polyak L, Edwards MH, Coakley BJ and Jakobsson M (2001). Ice shelves in the Pleistocene Arctic Ocean inferred from glaciogenic deep-sea bedforms. *Nature* **410**: 453-456.
- Praeg D (2003). Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin high resolution from low-frequencies. *Journal of Applied Geophysics* 53: 273-298.
- Prest VK (1969). Retreat of Wisconsinan and Recent Ice in North America. Geological Survey of Canada Map 1257A.
- Prest VK, Grant DR and Rampton VN (1968). Glacial Map of Canada. Geological Survey of Canada Map 1253A.
- Price RJ (1960). Glacial meltwater channels in the Upper Tweed drainage basin. Geographical Journal 126: 483-489.
- Price RJ (1963). A glacial meltwater drainage system in Peeblesshire, Scotland. Scottish Geographical Magazine 79: 133-141.
- Rae AC, Harrison S, Mighall T and Dawson AG (2004). Periglacial trimlines and nunataks of the Last Glacial Maximum: the Gap of Dunloe, southwest Ireland. *Journal of Quaternary Science* 19 (1): 87-97.
- Rahmstorf S (1995). Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle. *Nature* **378**: 145-149.

- Reeh N (1984). Reconstruction of the glacial ice covers of Greenland and the Canadian Arctic islands by three-dimensional, perfectly plastic ice-sheet modelling. *Annals of Glaciology* **5**: 115-121.
- Retzlaff R and Bentley CR (1993). Timing of stagnation of Ice Stream C, West Antarctica, from short-pulse radar studies of buried surface crevasses. *Journal of Glaciology* **39**: 553-561.
- Richter TO, Lassen S, van Weering TCE and de Haas H (2001). Magnetic susceptibility patterns and provenance of ice-rafted material at Feni Drift, Rockall Trough: implications for the history of the British-Irish ice sheet. *Marine Geology* **173**: 37-54.
- Rignot E and Thomas RH (2002). Mass balance of polar ice sheets. Science 297: 1502-1506.
- Rignot E, Casassa G, Gogineni P, Krabill W, Rivera A and Thomas R (2004). Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters* 31: L18401.
- Roberts DH, Chiverrell RC, Innes JB, Horton BP, Brooks AJ, Thomas GSP, Turner S and Gonzalez S (2006). Holocene sea levels, Last Glacial Maximum glaciomarine environments and geophysical models in the northern Irish Sea Basin, UK. Marine Geology 231: 113-128.
- Roberts DH, Dackombe RV and Thomas GSP (2007). Palaeo-ice streaming in the central sector of the British-Irish Ice Sheet during the Last Glacial Maximum: evidence from the northern Irish Sea Basin. *Boreas* 36: 115-129.
- Rose J (1987). Drumlins as part of a glacier bedform continuum. In Menzies J and Rose J (ed.) Drumlin Symposium. Balkema; Rotterdam. pp 103-116.
- Rose J and Letzer JM (1977). Superimposed drumlins. Journal of Glaciology 18: 471-480.
- Röthlisberger H (1972). Water pressure in intra- and sub-glacial channels. *Journal of Glaciology* 11: 177-203.
- Röthlisberger H and Lang H (1987). Glacial Hydrology. In Gurnell AM and J CM (ed.) Glaciofluvial sediment transfer: an alpine perspective. John Wiley & sons; Chichester. pp 207-284.
- Scourse JD (1991). Glacial deposits of the Isles of Scilly. In Ehlers J, Gibbard PL and Rose J (ed.) Glacial deposits in Great Britain and Ireland. Balkema; Rotterdam. pp 291-300.
- Scourse JD (ed.) (2006). The Isles of Scilly: Field Guide. Quaternary Research Association; London.
- Scourse JD and Furze MFA (2001). A critical review of the glaciomarine model for Irish sea deglaciation: evidence from southern Britain, the Celtic shelf and adjacent continental slope. Journal of Quaternary Science 16 (5): 419-434.
- Scourse JD, Robinson E and Evans C (1991). Glaciation of the central and southwestern Celtic Sea. In Ehlers J, Gibbard PL and Rose J (ed.) Glacial Deposits in Great Britain and Ireland. Balkema; Rotterdam. pp 301-310.
- Scourse JD, Hall IR, McCave IN, Young JR and Sugdon C (2000). The origin of Heinrich layers: evidence from H2 for European precursor events. *Earth and Planetary Science Letters* 182 (2): 187-195.
- Scourse JD, Peck VL, Haapaniemi A, Austin WEN, Colmenero-Hidalgo E and Hall IR (2008). Iceocean-climate interaction in the NE Atlantic during marine isotope stages 2 and 3. (Abstract). QRA ADM - Quaternary of the British Isles and adjoining seas. RGS, London.
- Seidov D and Maslin M (1999). North Atlantic deep water circulation collapse during Heinrich events. *Geology* 27 (1): 23-26.
- Sejrup HP, Haflidason H, Aarseth I, King E, Forsberg CF, Long D and Rokoengen K (1994). Late Weichselian glaciation history of the northern North Sea. *Boreas* 23: 1-13.
- Sejrup HP, Larsen E, Haflidason H, Berstad IM, Hjelstuen BO, Jonsdottir HE, King EL, Landvik J, Longva O, Nygård A, Ottesen D, Raunholm S, Rise L and Stalsberg K (2003). Configuration, history and impact of the Norwegian Channel Ice Stream. *Boreas* 32 (1): 18-36.
- Sejrup HP, Hjelstuen BO, Torbjorn Dahlgren KI, Haflidason H, Kuijpers A, Nygård A, Praeg D, Stoker MS and Vorren TO (2005). Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology* 22 (9-10): 1111-1129.

- Shannon RJ (2006). *Reconstructing the configuration of the last Irish Ice Sheet*. Unpublished Masters thesis. School of Environmental Sciences; University of Ulster.
- Shaw J (1983). Drumlin formation related to inverted meltwater erosional marks. Journal of Glaciology 29: 461-479.
- Shaw J (1989). Drumlins, subglacial meltwater floods and ocean responses. Geology 17: 853-856.
- Shaw J (2006). A glimpse at meltwater effects associated with continental ice sheets. In Knight PG (ed.) *Glacier science and environmental change*. Blackwell; Oxford. pp 25-33.
- Shaw J and Freschauf RC (1973). A kinematic discussion of the formation of glacial flutings. *Canadian Geographer* 17: 19-35.
- Shaw J and Kvill D (1984). A glaciofluvial origin for drumlins of the Livingstone Lake area, Saskatchewan. Canadian Journal of Earth Sciences 12: 1426-1440.
- Shennan I, Peltier WR, Drummond R and Horton B (2002). Global to local scale parameters determining relative sea-level changes and the post-glacial isostatic adjustment of Great Britain. *Quaternary Science Reviews* 21: 397-408.
- Shennan I, Bradley S, Milne G, Brooks A, Bassett S and Hamilton S (2006). Relative sea-level changes, glacial isostatic modelling and ice-sheet reconstructions from the British Isles since the Last Glacial Maximum. *Journal of Quaternary Science* **21** (6): 585-599.
- Shilts WW (1980). Flow patterns in the central North American ice sheet. Nature 286: 213-218.
- Shilts WW (1993). Geological Survey of Canada's contributions to understanding the composition of glacial sediments. *Canadian Journal of Earth Sciences* **30**: 333-353.
- Shipp S, Anderson J and Domack E (1999). Late Pleistocene-Holocene retreat of the West Antarctic Ice Sheet system in the Ross Sea: Part 1 - Geophysical results. *Geological Society of America Bulletin* 111 (10): 1486-1516.
- Shreve RL (1972). Movement of water in glaciers. Journal of Glaciology 11: 205-214.
- Shreve RL (1985). Esker characteristics in terms of glacier physics, Katahdin esker system, Maine. Geological Society of America Bulletin 96: 639-646.
- Siegert MJ, Dowdeswell JA, Gorman MR and McIntyre NF (1996). An inventory of Antarctic subglacial lakes. *Antarctic Science* 8: 281-286.
- Siegert MJ, Carter S, Tabacco I, Popov S and Blankenship DD (2005). A revised inventory of Antarctic subglacial lakes. *Antarctic Science* 17: 453-460.
- Simms MJ (2005). Glacial and karst landscapes of the Gort lowlands and Burren. In Coxon P (ed.) *The Quaternary of Central Western Ireland: Field Guide*. Quaternary Research Association; London. pp 39-63.
- Sissons JB (1958). Subglacial stream erosion in southern Northumberland. Scottish Geographical Magazine 74: 164-174.
- Sissons JB (1960). Some aspects of glacial drainage channels in Britain. Part 1. Scottish Geographical Magazine 76 (3): 131-146.
- Sissons JB (1961). Some aspects of glacial drainage channels in Britain. Part 2. Scottish Geographical Magazine 77: 15-36.
- Sissons JB (1964). The Glacial Period. In Watson JW and Sissons JB (ed.) The British Isles: a systematic geography. Nelson; London. pp 131-151.
- Sissons JB (1967). The evolution of Scotland's scenery. Oliver & Boyd; Edinburgh.
- Smalley IJ and Unwin DJ (1968). The formation and shape of drumlins and their distribution and orientation in drumlin fields. *Journal of Glaciology* 7: 377-390.
- Smith AG and Goddard IC (1991). A 12 500 year record of vegetational history at Sluggan Bog, Co. Antrim, N. Ireland (incorporating a pollen zone scheme for the non-specialist). New Phytologist 118: 167-187.

- Smith AM, Murray T, Nicholls KW, Makinson K, Aðalgeirsdóttir G, Behar AE and Vaughan DG (2007). Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic ice stream. *Geology* 35 (2): 127-130.
- Smith MJ (2003). Technical Developments for the Geomorphological Reconstruction of Palaeo Ice Sheets from Remotely Sensed Data. Unpublished PhD thesis. Department of Geography; University of Sheffield. pp297.
- Smith MJ, Dunlop P and Clark CD (2006). An overview of sub-glacial bedforms in Ireland, mapped from digital elevation data. In Knight PG (ed.) Glacier science and environmental change. Blackwell; Oxford. pp 384-387.
- Sollas WJ (1896). A map to show the distribution of eskers in Ireland. Scientific Transactions of the Royal Dublin Society 5 (2): 785-822.
- Sollid JL and Sorbel L (1994). Distribution of glacial landforms in southern Norway in relation to the thermal regime of the last continental ice sheet. *Geografiska Annaler* 76A (1-2): 25-35.
- Stephens N and Synge FM (1965). Late-Pleistocene shorelines and drift limits in North Donegal. Proceedings of the Royal Irish Academy 64B: 131-153.
- Stephens N, Creighton JR and Hannon MA (1975). The Late-Pleistocene period in North-Eastern Ireland: an assessment. Irish Geography 8: 1-23.
- Stoker MS and Bradwell T (2005). The Minch palaeo-ice stream: NW sector of the British-Irish Ice Sheet. Journal- Geological Society London 162 (3): 425-428.
- Stoker MS, Bradwell T, Wilson C, Harper C, Smith D and Brett C (2006a). Pristine fjord landsystem revealed on the sea bed in the Summer Isles region, NW Scotland. Scottish Journal of Geology 42 (2): 89-99.
- Stoker MS, Long D, Bulat J and Davison S (2006b). Seismic geomorphology and Pleistocene ice limits off NW Britain. In Knight P (ed.) Glaciology and Earth's changing environment. Blackwell; pp.
- Stokes CR and Clark CD (1999). Geomorphological criteria for identifying Pleistocene ice streams. Annals of Glaciology 28: 67-75.
- Stokes CR and Clark CD (2001). Palaeo-ice streams. Quaternary Science Reviews 20 (13): 1437-1457.
- Stokes CR and Clark CD (2003). Laurentide ice streaming on the Canadian Shield: A conflict with the soft-bedded ice stream paradigm? *Geology* **31** (4): 347-350.
- Stokes CR, Clark CD, Darby DA and Hodgson DA (2005). Late Pleistocene ice export events into the Arctic Ocean from the M'Clure Strait Ice Stream, Canadian Arctic Archipelago. Global and Planetary Change 49 (3-4): 139-162.
- Stone JO and Ballantyne CK (2006). Dimensions and deglacial chronology of the Outer Hebrides Ice Cap, northwest Scotland: implications of cosmic ray exposure dating. *Journal of Quaternary Science* 21 (1): 75-84.
- Stroeven AP, Fabel D, Hättestrand C and Harbor J (2002). A relict landscape in the centre of Fennoscandian glaciation: cosmogenic radionuclide evidence of tors preserved through multiple glacial cycles. Geomorphology 44: 145-154.
- Sugden DE (1977). Reconstruction of the morphology, dynamics and thermal characteristics of the Laurentide ice sheet at its maximum. Arctic and Alpine Research 9 (1): 21-47.
- Sugden DE and John BS (1976). Glaciers and landscape: a geomorphological approach. Arnold; London.
- Sutherland DG (1984). The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews* 3 (2-3): 157-254.
- Synge FM (1950). The glacial deposits around Trim, county Meath. Proceedings of the Royal Irish Academy 53: 99-110.
- Synge FM (1963). The Glaciation of the Nephin Beg Range, County Mayo. Irish Geography 4 (6): 397-403.

Synge FM (1968). The Glaciation of West Mayo. Irish Geography 5: 372-386.

- Synge FM (1969). The Würm ice limit in the West of Ireland. In Wright HE (ed.) *Quaternary Geology and Climate*. National Academy of Sciences; Washington DC. pp 89-92.
- Synge FM (1970). The Irish Quaternary: Current views 1969. In Stephens N and Glasscock RE (ed.) Irish Geographical Studies, in honour of E. Estyn Evans. The Queen's University of Belfast; Belfast. pp 34-48.
- Synge FM (1977). Introduction. In Lewis CA (ed.) Guidebook for Excursion A15: South and South West Ireland. INQUA; Norwich. pp 4-8.
- Synge FM (1979). Glacial landforms. In Haughton JP (ed.) Atlas of Ireland. Royal Irish Academy; Dublin. pp 21.
- Synge FM and Stephens N (1960). The Quaternary Period in Ireland an assessment. Irish Geography 4: 121-130.
- Tarasov L and Peltier WR (2005). Arctic freshwater forcing of the Younger Dryas cold reversal. *Nature* 435: 662-665.
- Thomas GSP and Chiverrell RC (2006). A model of subaqueous sedimentation at the margin of the Late Midlandian Irish Ice Sheet, Connemara, Ireland, and its implications for regionally high isostatic sea-levels. *Quaternary Science Reviews* 25 (21-22): 2868-2893.
- Thomas GSP and Chiverrell RC (2007). Structural and depositional evidence for repeated icemarginal oscillation along the eastern margin of the Late Devensian Irish Sea Ice Stream. *Quaternary Science Reviews* 26: 2375-2405.
- Thomas GSP and Summers AJ (1983). The Quaternary stratigraphy between Blackwater Harbour and Tinnaberna, County Wexford. *Journal of Earth Sciences, Royal Dublin Society* 5: 121-134.
- Thomas GSP, Chiverrell R and Huddart D (2004). Ice-marginal depositional responses to readvance episodes in the Late Devensian deglaciation of the Isle of Man. *Quaternary Science Reviews* 23: 85-106.
- Thomas R, Csatho B, Davis C, Kim C, Krabill W, Manizade S, McConnell J and Sonntag J (2001). Mass balance of higher-elevation parts of the Greenland ice sheet. *Journal of Geophysical Research* 106 (D24): 33707-33716.
- Thrasher IM, Mauz B, Chiverrell RC and Lang A (2008). A lithofacies-based approach to OSL dating of ice-proximal sandar on the margins of the Irish Sea ice-stream. (Abstract). QRA ADM Quaternary of the British Isles and adjoining seas. RGS, London.
- van der Meer JJM and Warren WP (1997). Sedimentology of Late Glacial Clays in Lacustrine Basins, Central Ireland. *Quaternary Science Reviews* 16 (7): 779-792.
- Vernon P (1966). Drumlins and Pleistocene ice flow over the Ards peninsula/Strangford Lough area, County Down, Ireland. *Journal of Glaciology* **6**: 401-409.
- Vieli A, Payne AJ, Clark CD, Evans DJA and Ó Cofaigh C (2007). Arising issues from modelling the British-Irish Ice Sheet. (Abstract). QRA ADM - The Growth, Maximum Extent and Deglaciation of the last British and Irish Ice Sheet. St. Andrews.
- Walden J, Wadsworth E, Austin WEN, Peters C, Scourse JD and Hall IR (2007). Compositional variability of ice-rafted debris in Heinrich layers 1 and 2 on the northwest European continental slope identified by environmental magnetic analyses. *Journal of Quaternary Science* 22 (2): 163-172.
- Walder JS and Fowler AC (1994). Channelized subglacial drainage over a deformable bed. Journal of Glaciology 40: 3-15.
- Warren WP (1977). North East Iveragh. In Lewis CA (ed.) Guidebook for Excursion A15: South and South West Ireland. INQUA; Norwich. pp 37-45.
- Warren WP (1985). Stratigraphy. In Edwards KJ and Warren WP (ed.) The Quaternary History of Ireland. Academic Press; London. pp 39-65.
- Warren WP (1988). The Pleistocene Geology and Geomorphology of Glen Behy, Co. Kerry. Irish Geography 21: 1-10.

- Warren WP (1991a). Fenitian (Midlandian) glacial deposits and glaciation in Ireland and the adjacent offshore regions. In Ehlers J, Gibbard PL and Rose J (ed.) *Glacial Deposits in Great Britain and Ireland*. Balkema; Rotterdam. pp 79-88.
- Warren WP (1991b). Glacial deposits of southwest Ireland. In Ehlers J, Gibbard PL and Rose J (ed.) Glacial Deposits in Great Britain and Ireland. Balkema; Rotterdam. pp 345-353.
- Warren WP (1992). Drumlin orientation and the pattern of glaciation in Ireland. Sveriges Geologiska Undersökning 81: 359-366.
- Warren WP and Ashley GM (1994). Origins of the ice-contact stratified ridges (eskers) of Ireland. Journal of Sedimentary Research A64 (3): 433-449.
- Watts WA (1985). Quaternary Vegetation Cycles. In Edwards KJ and Warren WP (ed.) The Quaternary History of Ireland. Academic Press; London. pp 155-185.
- Weaver AJ, Saenko OA, Clark PU and Mitrovica JX (2003). Meltwater Pulse 1A from Antarctica as a Trigger of the Bølling-Allerød Warm Interval. *Science* 299: 1709-1713.
- Weertman (1972). General theory of water flow at the base of a glacier or ice sheet. Reviews of Geophysics and Space Physics 10: 287-333.
- Wellner JS, Heroy DC and Anderson JB (2006). The death mask of the Antarctic ice sheet: Comparison of glacial geomorphic features across the continental shelf. *Geomorphology* 75 (1-2): 157-171.
- Wingham DJ, Siegert MJ, Shepherd A and Muir AS (2006). Rapid discharge connects Antarctic subglacial lakes. *Nature* 440: 1033-1036.
- Winsborrow MCM, Clark CD and Stokes CR (2004). Ice streams of the Laurentide Ice Sheet. Geographie Physique et Quaternaire 58 (2-3): 269-280.
- Wright WB (1914). The Quaternary Ice Age. Macmillan; London.
- Yokoyama Y, Lambeck K, De Deckker P, Johnston P and Fifield LK (2000). Timing of the Last Glacial Maximum from observed sea-level minima. *Nature* 406: 713-715.
- Zwally HJ, Abdalati W, Herring T, Larson K, Saba J and Steffen K (2002). Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow. *Science* 297: 218-221.

Appendix: Dates constraining the Irish Ice Sheet.

Onshore dates documented from published literature to constrain the last Irish Ice Sheet history. Note that dates were compiled from a thorough, but not exhaustive literature search, and the list may not be complete. Irish National Grid x and y coordinates are given (units = metres) and are as accurate as the source publication provided. All radiocarbon dates have been calibrated independently using Fairbanks (2005), which provides the longest time scale, to ensure internal consistency throughout the dataset and enable inter-date comparisons. For calibrations provided by the original authors, refer to the source publication. Laboratory codes are given, where provided, or the Figure/Table number from the source publication is given. Refer to the thesis text (e.g. Chapter 7 & Chapter 10) for a full description of the compilation and use of the data listed here.

ID	Reference	x	Y	Date_ka	Error_1sd	Scale	Technique	Calibration	Cal_error	Material
1	Ahlberg et al 1996	163843	140674	11.880	0.080	14C	14C AMS	13.717	0.076	seed
2	Ballantyne et al 2006	317900	210300	19.100	1.200	cal.	10Be cosmogenic	19.100	1.200	vein quartz
3	Ballantyne et al 2006	312500	203400	18.200	1.200	cal.	10Be cosmogenic	18.200	1.200	vein quartz
4	Ballantyne et al 2006	313400	201600	18.500	1.200	cal.	10Be cosmogenic	18.500	1.200	vein quartz
5	Ballantyne et al 2007	181500	432300	18.600	1.400	cal.	10Be cosmogenic	18.600	1.400	granite boulder
6	Ballantyne et al 2007	189500	431800	16.300	1.200	cal.	10Be cosmogenic	16.300	1.200	granite boulder
7	Ballantyne et al 2007	151100	384300	15.900	1.000	cal.	10Be cosmogenic	15.900	1.000	erratic boulder
8	Ballantyne et al 2007	152100	385500	16.600	1.100	cal.	10Be cosmogenic	16.600	1.100	bedrock (quartz)
9	Ballantyne et al 2008	87700	301600	17.200	1.100	cal.	10Be cosmogenic	17.200	1.100	quartzite outcrop
10	Ballantyne et al 2008	60800	307500	24.000	1.600	cal.	10Be cosmogenic	24.000	1.600	vein quartz
11	Ballantyne et al 2008	60800	307500	23.100	1.700	cal.	10Be cosmogenic	23.100	1.700	vein quartz
12	Ballantyne et al 2008	80100	265100	15.100	1.000	cal.	10Be cosmogenic	15.100	1.000	sandstone
13	Ballantyne et al 2008	79300	267600	13.200	0.800	cal.	10Be cosmogenic	13.200	0.800	sandstone
14	Ballantyne et al 2008	98900	282200	16.700	1.000	cal.	10Be cosmogenic	16.700	1.000	vein quartz
15	Ballantyne et al 2008	57300	305900	14.500	0.900	cal.	10Be cosmogenic	14.500	0.900	vein quartz, roche moutonnee
16	Ballantyne et al 2008	58100	305800	11.700	0.700	cal.	10Be cosmogenic	11.700	0.700	quartzite
17	Ballantyne et al 2008	57900	305700	15.000	1.000	cal.	10Be cosmogenic	15.000	1.000	vein quartz
18	Ballantyne et al 2008	90300	303200	61.600	4.000	cal.	10Be cosmogenic	61.600	4.000	quartzite outcrop
19	Ballantyne et al 2008	90300	303200	36.000	2.300	cal.	10Be cosmogenic	36.000	2.300	quartzite outcrop
20	Ballantyne et al 2008	80300	268300	43.200	2.800	cal.	10Be cosmogenic	43.200	2.800	sandstone outcrop
21	Ballantyne et al 2008	87700	301600	17.100	1.100	cal.	10Be cosmogenic	17.100	1.100	quartzite outcrop
22	Bowen et al 2002	259515	179893	37.500	1.500	cal.	36CI cosmogenic	37.500	1.500	
23	Bowen et al 2002	263292	148331	36.500	3.600	cal.	36CI cosmogenic	36.500	3.600	
24	Bowen et al 2002	317104	213567	36.000	13.000	cal.	36Cl cosmogenic	36.000	13.000	
25	Bowen et al 2002	200048	416947	31.000	17.000	cal.	36CI cosmogenic	31.000	17.000	
26	Bowen et al 2002	239793	459432	25.100	1.100	cal.	36CI cosmogenic	25.100	1.100	
27	Bowen et al 2002	259907	131261	23.600	2.800	cal.	36Cl cosmogenic	23.600	2.800	
28	Bowen et al 2002	321231	182493	22.300	2.000	cal.	36Cl cosmogenic	22.300	2.000	
29	Bowen et al 2002	314667	312612	17.300	0.600	cal.	36Cl cosmogenic	17.300	0.600	
30	Bowen et al 2002	308711	200009	17.100	0.900	cal.	36Cl cosmogenic	17.100	0.900	
31	Bowen et al 2002	59927	307375	18.000	4.000	cal.	36Cl cosmogenic	18.000	4.000	
32	Bowen et al 2002	319363	321083	16.700	1.000	cal.	36Cl cosmogenic	16.700	1.000	
33	Bowen et al 2002	317063	215236	15.700	1.100	cal.	36Cl cosmogenic	15.700	1.100	
34	Bowen et al 2002	57998	305016	21.600	5.300	cal.	36Cl cosmogenic	21.600	5.300	

ID	Setting	Context	Elevation	Ref code	Comments
1	lowest date from bog core (unknown if bottomed)	ice free	247	Table1-f CAMS-2193	
2	near mountain summits	exposure	725	DJ-01	assumes no erosion and no inheritance
3	near mountain summits	exposure	523	KAN-01	assumes no erosion and no inheritance
4	near mountain summits	exposure	600	SCA-01	assumes no erosion and no inheritance
5	Story of a constant in Carlo Carl 2005	exposure - deglacial	75	BF-01	man pice internet
6	Children of the South and Description of the South State of the South	exposure - deglacial	70	BF-02	
7	Contradid a Summer (BCC)	exposure - deglacial	82	MAL-03	12.230
8	Construction Statute Physics and Statute Physics	exposure - deglacial	31	MAL-05	10 10 10 10 10 10 10 10 10 10 10 10 10 1
9	below glacial limit	exposure - deglacial thinning	440	CM-05	
10	below glacial limit	exposure - deglacial	269	CH-01	
11	below glacial limit	exposure - deglacial	269	CH-02	
12	below glacial limit	exposure - deglacial	305	MWR-02	
13	below glacial limit	exposure - deglacial thinning	650	MWR-05	
14	below glacial limit	exposure - deglacial	125	FAH-04	
15	mouth of corrie	exposure - interp YD	287	LACOR-03	
16	boulder on moraine	exposure - interp YD	190	LACOR-06	
17	boulder on moraine	exposure - interp YD (inheritance)	198	LACOR-09	
18	above glacial limit	exposure - nunatak	716	CM-06	
19	above glacial limit	exposure - nunatak	710	CM-07	
20	above glacial limit	exposure - nunatak	790	MWR-07	
21	below glacial limit	exposure - deglacial thinning	440	CM-04	
22		exposure	244	Table1-1	St Molan's Cave - mislocated?
23		exposure	75	Table1-2	Rathpatrick Cross - mislocated?
24		exposure	213	Table1-3	
25		exposure	70	Table1-5	
26		exposure	55	Table1-6	
27		exposure	245	Table1-7	Hatton farm - mislocated?
28		exposure	250	Table1-8	
29		exposure	243	Table1-16	windy gap mislocated?
30		exposure	450	Table1-17	
31		exposure	5	Table1-14	exact same location as table1-18
32		exposure	354	Table1-19	mislocated?
33		exposure	420	Table1-20	
34		exposure	190	Table1-9	exact same site as table1-22

ID	Reference	X	Y	Date_ka	Error_1sd	Scale	Technique	Calibration	Cal error	Material
35	Bowen et al 2002	96619	64084	181.000	29.000	cal.	36CI cosmogenic	181.000	29.000	
36	Bowen et al 2002	96337	63755	22.000	3.400	cal.	36CI cosmogenic	22.000	3.400	
37	Bowen et al 2002	90622	41949	21.300	1.300	cal.	36CI cosmogenic	21.300	1.300	
38	Bowen et al 2002	81558	154591	20.300	1.800	cal.	36CI cosmogenic	20.300	1.800	
39	Bowen et al 2002	87090	159469	15.300	1.000	cal.	36CI cosmogenic	15.300	1.000	
40	Bowen et al 2002	63826	317873	32.900	5.100	cal.	36CI cosmogenic	32.900	5.100	
41	Bowen et al 2002	59927	307375	17.000	2.100	cal.	36 CI cosmogenic	17.000	2.100	
42	Bowen et al 2002	57692	305772	11.800	0.600	cal.	36CI cosmogenic	11.800	0.600	
43	Bowen et al 2002	57998	305016	13.600	0.600	cal.	36CI cosmogenic	13.600	0.600	
44	Bowen et al 2002	103218	220907	20.900	2.700	cal.	36CI cosmogenic	20.900	2.700	
45	Clark et al 2004 (in McCabe et al 2005)	331000	313500	16.970	0.190	14C	14C AMS	19.696	0.214	foram
46	Clark et al 2004 (in McCabe et al 2005)	331000	313500	16.540	0.070	14C	14C AMS	19.268	0.100	foram
47	Clark et al 2004 (in McCabe et al 2005)	331000	313500	16.640	0.070	14C	14C AMS	19.364	0.093	foram
48	Clark et al 2004 (in McCabe et al 2005)	331000	313500	16.760	0.130	14C	14C AMS	19.478	0.140	foram
49	Clark et al 2004 (in McCabe et al 2005)	331000	313500	16.750	0.160	14C	14C AMS	19.469	0.167	foram
50	Colhoun & Synge 1980	308000	198800	11.500	0.550	14C	14C conventional	13.360	0.562	
51	Colhoun & Synge 1980	308000	198800	11.600	0.260	14C	14C conventional	13.450	0.256	
52	Colhoun et al 1972	236381	339185	30.500	1.170	14C	14C conventional	35.888	1.172	
53	Craig 1978	295448	122917	12.470	0.155	14C	14C conventional	14.416	0.270	
54	Craig 1978	266168	103889	12.235	0.260	14C	14C conventional	14.088	0.339	
55	Cwynar & Watts 1989	320364	225993	12.540	0.080	14C	14C conventional	14.554	0.166	twig
56	Diefendorf et al 2006	127750	189570	16.175	0.245	cal.	14C	16.175	0.245	bulk macrofossil
57	Dresser 1980	82488	282970	10.010	0.170	14C	14C conventional	11.529	0.309	
58	Gallagher & Thorp 1997	280400	106300	161.785	18.462	cal.	IRSL	161.785	18.462	
59	Gallagher & Thorp 1997	280400	106300	128.610	16.795	cal.	IRSL	128.610	16.795	
60	Godwin & Willis 1959	280975	298893	14.367	0.300	14C	14C conventional	16.926	0.514	
61	Godwin & Willis 1964	360768	366025	12.110	0.190	14C	14C conventional	13.926	0.208	
62	Harkness & Wilson 1979	280980	352020	46.600	0.000	14C	14C conventional			
63	Harkness & Wilson 1979	280980	352020	46.450	0.000	14C	14C conventional			
64	Heijnis et al 1993	76630	114960	118.000	5.000	cal.	U-Th	118.000	5.000	peat
65	Lowe et al 2004	309900	392100	12.295	0.050	14C	14C conventional	14.096	0.086	humic
66	Lowe et al 2004	309900	392100	12.430	0.085	14C	14C AMS	14.337	0.183	humin
67	McCabe & Clark 1998 (in McCabe et al 2005)	327300	310100	14.705	0.130	14C	14C AMS	16.805	0.231	foram
68	McCabe & Clark 1998 (in McCabe et al 2005)	349500	368900	12.740	0.095	14C	14C AMS	14.176	0.160	foram
69	McCabe & Clark 1998 (in McCabe et al 2005)	360400	343300	13.785	0.115	14C	14C AMS	15.578	0.164	foram
70	McCabe & Clark 1998 (in McCabe et al 2005)	360400	343300	13.995	0.105	14C	14C AMS	15.819	0.158	foram
71	McCabe & Clark 1998 (in McCabe et al 2005)	327300	310100	15.605	0.140	14C	14C AMS	18.416	0.207	foram
72	McCabe & Clark 2003 (in McCabe et al 2005)	247300	448200	14.045	0.100	14C	14C AMS	15.877	0.158	foram
73	McCabe & Clark 2003 (in McCabe et al 2005)	247300	448200	15.720	0.160	14C	14C AMS	18.548	0.184	foram
74	McCabe & Clark 2003 (in McCabe et al 2005)	247300	448200	15.190	0.150	14C	14C AMS	17.686	0.326	foram
75	McCabe & Clark 2003 (in McCabe et al 2005)	247300	448200	16.060	0.430	14C	14C AMS	18.827	0.449	foram
76	McCabe & Clark 2003 (in McCabe et al 2005)	247300	448200	15.025	0.095	14C	14C AMS	17.357	0.220	foram
77	McCabe & Clark 2003 (in McCabe et al 2005)	247300	448200	17.140	0.110	14C	14C AMS	19.882	0.147	mollusc
78	McCabe & Haynes 1996 (in McCabe et al 2005)	321900	305100	15.020	0.110	14C	14C AMS	17.358	0.249	foram
79	McCabe & Haynes 1996 (in McCabe et al 2005)	321900	305100	15.390	0.110	14C	14C AMS	18.082	0.251	foram

ID	Setting	Context	Elevation	Ref_code	Comments
35	NAME AND A DEPARTMENT OF AN ADDRESS OF A DESCRIPTION	exposure	36	Table1-0	12.335 1.751 1.563
36	Machine is a rest	exposure	30	Table1-10	
37	Manual et al 1994	exposure	152	Table1-11	ALL MARKED AND AND AND AND AND AND AND AND AND AN
38	The Cable of all NVIK (in MCCable of all 2008)	exposure	120	Table1-13	10.020 0.127 Incluses
39		exposure	66	Table1-21	A LOS AND A
40		exposure	20	Table1-4	
41	And the set of the set	exposure	5	Table1-18	exact same location as table1-14
42	Marchen et al. 201	exposure	200	Table1-23	A STREET SCHERE MANAGE
43	Reviewe & Martin	exposure	190	Table1-22	exact same location as table1-9
44	Michigher and Michie	exposure	30	Table1-12	10.001 0.000 employ
45	channel infill	event: post-deglacn RSL rise	1.3 440	CAMS-89688	kilkeel steps
46	channel infill	event: post-deglacn RSL rise		CAMS-89686	kilkeel steps
47	channel infill	event: post-deglacn RSL rise		CAMS-89686	kilkeel steps
48	channel infill	event: post-deglacn RSL rise	105	AA22351	kilkeel steps
49	channel infill	event: post-deglacn RSL rise	140	AA22352	kilkeel steps
50	organic lake mat bulldozed into moraine ridge	event: YD		Birm-320	
51	organic lake mat bulldozed into moraine ridge	event: YD		Birm-321	
52	freshwater organic silts between 2 tills	ice free: pre-Late Dev		Birm. 166	1sd +1.170 -1030
53	deepest/oldest date from basin	ice free	50	Coolteen 71E D-109	
54	deepest/oldest date from basin	ice free	33	Belle Lake D-110	
55	deepest/oldest sample from bog	ice free	1.141	BA 457	VERY POORLY LOCATED
56	base of core bottomed in till	ice free	25	LINC-1 AA56896	CARL REAL CARLS
57	beach exposure, org material under gl till	event: pre-YD?		D-136F	Lab dating list, subm by GF Mitchell
58	beach deposit	event: pre-Devensian			
59	beach deposit	event: pre-Devensian	145		
60	lake sediments	discard		Q-16	hardwater contamination - too old
61	infill of interdrumlin hollow	ice free		Q-360	Lab dating list, same(?) section dated by Belfast?
62	lignite under 'boulder clay'	discard		SRR-716	infinite date. Lab date list, subm WI Mitchell
63	lignite under 'boulder clay'	discard		SRR-717	infinite date. Lab date list, subm WI Mitchell
64	stratig between 2 raised beach deps	event: pre-Devensian			11 samples, contam dates discarded
65	lowest sample from peat bog bottomed in till	ice free	60	SLG-1 SRR-6427	A CARLES AND A CARLES A
66	lowest sample from peat bog bottomed in till	ice free	60	SLG-1 AA-34265	
67	marine mud below outwash	event: ice free prior to readvance		AA56700	cranfield point moraine
68	marine mud drapes drumlin	event: RSL rise	10.110	AA21822	rough island
69	marine mud interbedded w/ morainic seds	event: ice sheet readvance		AA22820	killard point
70	marine mud interbedded w/ morainic seds	event: ice sheet readvance	1	AA22821	killard point
71	marine mud below outwash	event: ice free prior to readvance	1	AA21819	cranfield point moraine
72	marine mud above deformed layers	event: RSL rise post readvance	3	AA32315	
73	deformed muds	event: readvance	2	AA45968	
74	deformed muds	event: readvance	1	AA45967	
75	deformed muds	event: readvance		AA45966	
76	base of deformed muds	event: immed prior to readvance?	-1	AA33831	
77	muds beneath deformed section	event: ice free (high RSL) prior to readvance	-2	AA33832	
78	marine mud below outwash	event: ice free prior to readvance	140	AA17693	cooley point
79	marine mud below outwash	event: ice free prior to readvance	1	AA17694	cooley point

ID	Reference	X	Y	Date_ka	Error_1sd	Scale	Technique	Calibration	Cal_error	Material
80	McCabe & Haynes 1996 (in McCabe et al 2005)	321900	305100	15.400	0.140	14C	14C AMS	18.095	0.291	foram
81	McCabe et al 1978	315000	289200	41.500	0.000	14C	14C conventional	-	-	
82	McCabe et al 1986	315000	289200	16.540	0.120	14C	14C AMS	19.269	0.134	foram
83	McCabe et al 1986 (in McCabe et al 2005)	349500	368900	16.970	0.100	14C	14C AMS	19.688	0.123	mollusc
84	McCabe et al 2005	315000	289200	14.157	0.069	14C	14C AMS	16.006	0.129	foram
85	McCabe et al 2005	315000	289200	14.250	0.130	14C	14C AMS	16.136	0.201	foram
86	McCabe et al 2005	235791	340126	15.928	0.067	14C	14C AMS	18.735	0.080	mollusc
87	McCabe et al 2005	98912	341382	15.989	0.074	14C	14C AMS	18.786	0.086	mollusc
88	McCabe et al 2005	100682	341158	16.430	0.130	14C	14C AMS	19.167	0.141	mollusc
89	McCabe et al 2005	307200	296200	16.580	0.120	14C	14C AMS	19.307	0.133	mollusc
90	McCabe et al 2005	316302	305616	16.227	0.083	14C	14C AMS	18.987	0.102	foram
91	McCabe et al 2005	98912	341382	18.275	0.099	14C	14C AMS	21.181	0.155	mollusc
92	McCabe et al 2007a	98912	341382	26.930	0.160	14C	14C AMS	31.803	0.228	shell fragments
93	McCabe et al 2007a	98912	341382	24.380	0.120	14C	14C AMS	28.711	0.188	shell fragments
94	McCabe et al 2007a	98912	341382	29.660	0.220	14C	14C AMS	34.679	0.263	shell fragments
95	McCabe et al 2007a	98912	341382	21.920	0.090	14C	14C AMS	25.872	0.155	shells
96	McCabe et al 2007a	98912	341382	21.130	0.220	14C	14C AMS	24.737	0.323	forams
97	McCabe et al 2007a	106753	340180	23.630	0.090	14C	14C AMS	27.868	0.173	shells
98	McCabe et al 2007a	106753	340180	33.550	0.340	14C	14C AMS	38.545	0.372	shells
99	McCabe et al 2007a	106753	340180	27.200	0.130	14C	14C AMS	32.093	0.206	shells
100	McCabe et al 2007a	106628	339834	27.380	0.170	14C	14C AMS	32.285	0.240	shells
101	McCabe et al 2007a	106628	339834	23.530	0.110	14C	14C AMS	27.608	0.186	forams
102	McCabe et al 2007a	106628	339834	23.400	0.110	14C	14C AMS	27.755	0.187	forams
103	McCabe et al 2007a	106628	339834	23.740	0.110	14C	14C AMS	27.992	0.187	forams
104	McCabe et al 2007a	106628	339834	24.630	0.130	14C	14C AMS	28.991	0.190	shells
105	McCabe et al 2007a	106628	339834	34.470	0.390	14C	14C AMS	39.441	0.415	shells
106	McCabe et al 2007a	106628	339834	39.540	0.490	14C	14C AMS	43.975	0.463	shells
107	McCabe et al 2007b	106628	339834	15.450	0.045	14C	14C AMS	18.208	0.154	foram
108	McCabe et al 2007b	106628	339834	16.040	0.550	14C	14C AMS	18.779	0.620	foram
109	McCabe et al 2007b	106628	339834	13.125	0.070	14C	14C AMS	14.826	0.114	foram
110	McCabe et al 2007b	106628	339834	15.190	0.085	14C	14C AMS	17.682	0.223	foram
111	McCabe et al 2007b	106628	339834	15.300	0.090	14C	14C AMS	17.904	0.229	foram
112	Mitchell 1976, 1981	161266	109168	33.500	1.200	14C	14C conventional	38.873	1.189	bone
113	O Cofaigh & Evans 2007	295779	102597	29.805	0.350	14C	14C AMS	35.336	0.359	shell fragment
114	O Cofaigh & Evans 2007	295779	102597	36.605	0.440	14C	14C AMS	41.901	0.421	shell fragment
115	O Cofaigh & Evans 2007	295779	102597	43.585	1.100	14C	14C AMS	-	-	shell fragment
116	O Cofaigh & Evans 2007	295779	102597	47.175	1.600	14C	14C AMS	-	-	shell fragment
117	O Cofaigh & Evans 2007	220751	80132	32.745	0.290	14C	14C AMS	38.268	0.327	shell fragment
118	O Cofaigh & Evans 2007	220751	80132	20.185	0.070	14C	14C AMS	24.216	0.095	shell fragment
119	O Cofaigh & Evans 2007	220751	80132	20.775	0.080	14C	14C AMS	25.000	0.145	shell fragment
120	O Cofaigh & Evans 2007	220751	80132	25.495	0.130	14C	14C AMS	30.820	0.184	shell fragment
121	O Cofaigh & Evans 2007	220751	80132	43.680	0.000	14C	14C AMS	-		shell fragment
122	O Cofaigh & Evans 2007	220751	80132	39.675	1.200	14C	14C AMS	44.554	1.062	shell fragment
123	O Cofaigh & Evans 2007	220751	80132	23.835	0.150	14C	14C AMS	28.689	0.214	shell fragment
124	O Cofaigh & Evans 2007	220751	80132	22.555	0.140	14C	14C AMS	27.244	0.207	shell fragment

ID	Setting	Context	Elevation	Ref_code	Comments
80	marine mud below outwash	event: ice free prior to readvance		AA17695	cooley point
81	organic silts between 2 tills	discard		Birm. 309	infinite date
82	marine mud	event: tidewater proximal seds - deglacn		SSR-2713	
83	mud drape	event: high RSL		SSR-2714	
84	mud below pushed moraine	event: ice free prior to readvance		AA56700	linns, dundalk bay
85	marine mud below moraine deposits	event: ice free prior to readvance		AA56701	rathcor bay
86	diamictic mud, top of deglacial section	event: distal rain out - deglacn		AA56707	
87	diamictic mud, deglacial section	event: distal rain out - deglacn		AA56706	
88	diamictic mud, deglacial section	event: distal rain out - deglacn		AA56704	
89	diamictic mud, deglacial section	event: tidewater proximal seds - deglacn		AA53589	
90	laminated mud & sand, density underflows	event: tidewater proximal seds - deglacn		AA56703	
91	diamictic mud, deglacial section	event: distal rain out - deglacn		AA56705	anomalous date - potentially earlier degl phase
92	gravels. Interp as reworked shells from prev event	event: max age for deglacn	80	CAMS115272	interp: shells from high RSL pre-advance
93	gravels. Interp as reworked shells from prev event	event: max age for deglacn	80	CAMS115273	interp: shells from high RSL pre-advance
94	gravels. Interp as reworked shells from prev event	event: max age for deglacn	80	CAMS115274	interp: shells from high RSL pre-advance
95	gravels > mud > diamict. shells interp reworked.	event: max age for deglacn	80	CAMS115268	interp: shells from high RSL pre-advance
96	marine mud, below gravels, above diamict	event: deglaciation	80	AA56702	interp: in situ forams - high RSL immed post-advan
97	diamict < mud < gravels. shells interp reworked	event: ice mmt over coast	80	CAMS105065	interp: shells from high RSL pre-advance
98	gravels > mud > diamict. shells interp reworked.	event: max age for deglacn	80	CAMS115267	interp: shells from high RSL pre-advance
99	gravels > mud > diamict. shells interp reworked.	event: max age for deglacn	80	CAMS115066	interp: shells from high RSL pre-advance
100	gravels > mud > diamict. shells interp reworked.	event: max age for deglacn	80	CAMS115266	interp: shells from high RSL pre-advance
101	marine mud, below gravels, above diamict	event: deglaciation	80	CAMS111595	interp: in situ forams - high RSL immed post-advan
102	marine mud, below gravels, above diamict	event: deglaciation	80	CAMS111594	interp: in situ forams - high RSL immed post-advan
103	marine mud, below gravels, above diamict	event: deglaciation	80	CAMS105068	interp: in situ forams - high RSL immed post-advan
104	diamict < mud < gravels. shells interp reworked	event: ice mmt over coast	80	CAMS115271	interp: shells from high RSL pre-advance
105	diamict < mud < gravels. shells interp reworked	event: ice mmt over coast	80	CAMS115269	interp: shells from high RSL pre-advance
106	diamict < mud < gravels. shells interp reworked	event: ice mmt over coast	80	CAMS105067	interp: shells from high RSL pre-advance
107	marine mud included in till	event: ice free (marine) prior to readvance		CAMS105063	dunany port, correlate w/ cooley pt prior to readv
108	marine mud included in till	event: ice free (marine) prior to readvance		CAMS105064	dunany port, correlate w/ cooley pt prior to readv
109	marine mud drapes drumlin	event: RSL rise		AA68680	rough island
110	marine mud included in till	event: ice free (marine) prior to readvance		AA68976	dunany port, correlate w/ cooley pt prior to readv
111	marine mud included in till	event: ice free (marine) prior to readvance		AA68975	dunany port, correlate w/ cooley pt prior to readv
112	cave	ice free: pre-Late Dev	100	D-122	details found in 14C list Dresser & McAulay 74
113	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Poz-15803	Kilmore Quay. Corr'd for marine reservoir 525yrs
114	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222311	Kilmore Quay. Corr'd for marine reservoir 525yrs
115	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222312	Kilmore Quay. Corr'd for marine reservoir 525yrs
116	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222313	Kilmore Quay. Corr'd for marine reservoir 525yrs
117	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-215770	Ardmore Bay. Corr'd for marine reservoir 525yrs
118	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-215771	Ardmore Bay. Corr'd for marine reservoir 525yrs
119	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-215772	Ardmore Bay. Corr'd for marine reservoir 525yrs
120	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-215773	Ardmore Bay. Corr'd for marine reservoir 525yrs
121	ISB till, under glaciolac seds, under inland till	discard	a management	Beta-215774	Ardmore Bay. infinite date.
122	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Poz-15804	Ardmore Bay. Corr'd for marine reservoir 525yrs
123	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222302	Ardmore Bay. Corr'd for marine reservoir 525yrs
124	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance	and the second	Beta-222303	Ardmore Bay. Corr'd for marine reservoir 525yrs

ID	Reference	X	Y	Date_ka	Error_1sd	Scale	Technique	Calibration	Cal error	Material
125	O Cofaigh & Evans 2007	220751	80132	21.135	0.130	14C	14C AMS	25.470	0.201	shell fragment
126	O Cofaigh & Evans 2007	220751	80132	20.295	0.120	14C	14C AMS	24.324	0.137	shell fragment
127	O Cofaigh & Evans 2007	216087	77444	45.080	0.000	14C	14C AMS	-		shell fragment
128	O Cofaigh & Evans 2007	216079	80114	38.585	0.600	14C	14C AMS	43.603	0.547	shell fragment
129	O Cofaigh & Evans 2007	216079	80114	23.025	0.150	14C	14C AMS	27.777	0.219	shell fragment
130	O Cofaigh & Evans 2007	216079	80114	41.125	0.640	14C	14C AMS	45.823	0.596	shell fragment
131	O Cofaigh & Evans 2007	214369	77439	45.580	0.000	14C	14C AMS			shell fragment
132	O Cofaigh & Evans 2007	214369	77439	36.045	0.420	14C	14C AMS	41.410	0.407	shell fragment
133	O Cofaigh & Evans 2007	200413	67628	47.475	3.000	14C	14C AMS			shell fragment
134	O Cofaigh & Evans 2007	200413	67628	22.075	0.090	14C	14C AMS	26.697	0.152	shell fragment
135	O Cofaigh & Evans 2007	200413	67628	41.845	0.900	14C	14C AMS	46.447	0.804	shell fragment
136	O Cofaigh & Evans 2007	200413	67628	26.725	0.190	14C	14C AMS	32.146	0.255	shell fragment
137	O Cofaigh & Evans 2007	200413	67628	42.525	0.830	14C	14C AMS	47.032	0.739	shell fragment
138	O Cofaigh & Evans 2007	200413	67628	50.000	0.000	14C	14C AMS	-	-	shell fragment
139	O'Connell et al 1999	153700	143300	16.870	0.000	cal.	NOT DATED - correlation	16.870	0.000	
140	Page 1972	322966	-145560	21.200	0.900	14C	14C conventional	25.395	1.159	
141	Page 1972	322966	-145560	22.200	0.400	14C	14C conventional	26.690	0.484	
142	Pearson 1979	285300	430700	12.175	0.090	14C	14C conventional	13.960	0.105	A. C.
143	Pearson 1979	224500	371700	11.440	0.185	14C	14C conventional	13.293	0.191	
144	Scourse (ed) 2006	321229	-146402	24.490	0.960	14C	14C	29.370	1.181	humin
145	Scourse (ed) 2006	321229	-146402	21.500	0.890	14C	14C	25.778	1.137	humin
146	Scourse (ed) 2006	322019	-148745	113.000	0.000	cal.	10Be cosmogenic	113.000	0.000	granite tor
147	Scourse (ed) 2006	318952	-141772	25.100	2.200	cal.	OSL	25.100	2.200	
148	Scourse (ed) 2006	318952	-141772	22.700	0.900	cal.	OSL	22.700	0.900	
149	Scourse (ed) 2006	317665	-141976	19.800	0.000	cal.	10Be cosmogenic	19.800	0.000	boulder
150	Scourse 1991	322966	-145560	26.680	1.410	14C	14C	31.916	1.573	humin
151	Scourse 1991	322966	-145560	33.050	0.960	14C	14C	38.434	0.966	humin
152	Scourse 1991	322032	-141424	34.500	0.885	14C	14C	39.853	0.866	humin
153	Scourse 1991	322032	-141424	25.670	0.560	14C	14C	30.842	0.674	humin
154	Scourse 1991	319182	-150878	24.550	0.500	14C	14C	29.417	0.658	humin
155	Scourse et al 2004, (ed) 2006	322966	-145560	82.000	5.000	cal.	OSL	82.000	5.000	
156	Scourse et al 2004, (ed) 2006	322966	-145560	112.000	17.000	cal.	OSL	112.000	17.000	
157	Scourse et al 2004, (ed) 2006	324288	-142045	49.000	3.000	cal.	OSL	49.000	3.000	
158	Scourse et al 2004, (ed) 2006	324288	-142045	82.000	5.000	cal.	OSL	82.000	5.000	
159	Scourse et al 2004, (ed) 2006	324288	-142045	130.000	7.000	cal.	OSL	130.000	7.000	
160	Scourse et al 2004, (ed) 2006	324288	-142045	108.000	7.000	cal.	OSL	108.000	7.000	
161	Shotton et al 1969	266207	98331	38.000	0.000	14C	14C conventional	-		
162	Shotton et al 1974	328300	238400	12.040	0.110	14C	14C conventional	13.845	0.103	
163	Simms 2005	108500	201600	53.000	0.000	cal.	U-Th	53.000	0.000	flowstone
164	Simms 2005	108500	201600	38.000	0.000	cal.	U-Th	38.000	0.000	flowstone
165	Smith & Goddard 1991	309900	392100	12.470	0.125	14C	14C conventional	14.416	0.233	particulate matter
166	Smith et al 1971	364000	365800	11.390	0.160	14C	14C conventional	13.240	0.173	
167	Wintle 1981	321229	-146402	26.550	0.700	14C	14C conventional	31.818	0.775	
168	Wintle 1981	321229	-146402	20.630	0.480	14C	14C conventional	24.638	0.622	
169	Wintle 1981	321229	-146402	18.600	3.700	cal.	TL	18.600	3.700	sand

ID	Setting	Context	Elevation	Ref_code	Comments
125	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222304	Ardmore Bay. Corr'd for marine reservoir 525yrs
126	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222305	Ardmore Bay. Corr'd for marine reservoir 525yrs
127	ISB till, under glaciolac seds, under inland till	discard		Beta- 215775	Whiting Bay. infinite date
128	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-215776	Whiting Bay. Corr'd for marine reservoir 525yrs
129	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222306	Whiting Bay. Corr'd for marine reservoir 525yrs
130	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222307	Whiting Bay. Corr'd for marine reservoir 525yrs
131	ISB till, under glaciolac seds, under inland till	discard		Beta-215777	Whiting Bay. infinite date
132	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222314	Whiting Bay. Corr'd for marine reservoir 525yrs
133	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Poz-15807	Garryvoe. Corr'd for marine reservoir 525yrs
134	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-215778	Garryvoe. Corr'd for marine reservoir 525yrs
135	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-215779	Garryvoe. Corr'd for marine reservoir 525yrs
136	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222308	Garryvoe. Corr'd for marine reservoir 525yrs
137	ISB till, under glaciolac seds, under inland till	event: max age for ISB advance		Beta-222309	Garryvoe. Corr'd for marine reservoir 525yrs
138	ISB till, under glaciolac seds, under inland till	discard		Beta-222310	Garryvoe. infinite date.
139	top of outwash gravel/sand	ice free	30		
140	organic mat btw s&g (under) + breccia (overlies)	event: pre-ISB ice advance		GaK-2471	cited in Scourse et al 2006. 1sd error +.96
141	organic mat btw s&g (under) + breccia (overlies)	event: pre-ISB ice advance		T-833	cited in Scourse et al 2006
142	kettle hole infill	ice free	30	UB-2013	Lab date list
143	bog	ice free	215	UB-2142	Lab dating list
144	organic mat in Porthloo Breccia fm	event: pre-ISB ice advance		Q-2356	1sd errors +.9686
145	organic mat in Porthloo Breccia fm	event: pre-ISB ice advance		Q-2358	1sd errors +.898
146	tor outside hypo'd limit	exposure			
147	outwash interbedded w/ solifluction lobes	event: ISB ice advance		X1261	method probs - treat with caution
148	outwash interbedded w/ solifluction lobes	event: ISB ice advance		X1262	method probs - treat with caution
149	boulder moraine	exposure			(prelim). W/drawal / emplacement of ISB max limit
150	organic mat btw s&g (under) + breccia (overlies)	event: pre-ISB ice advance		Q-2362/2407	cited in Scourse et al 2006
151	organic mat btw s&g (under) + breccia (overlies)	event: pre-ISB ice advance		Q-2360/2408	cited in Scourse et al 2006
152	org material in Porthloo Breccia fm	event: pre-ISB ice advance		Q-2410	cited in Scourse et al 2006
153	org material in Porthloo Breccia fm	event: pre-ISB ice advance		Q-2366/2409	cited in Scourse et al 2006
154	org material in Porthloo Breccia fm	event: pre-ISB ice advance		Q-2370/2412	cited in Scourse et al 2006
155	raised beach s&g, base of Quat seq	event: RSL pre-glacn		X1260	Tech concerns re date - caution
156	raised beach s&g, base of Quat seq	event: RSL pre-glacn		X1261	Tech concerns re date - caution
157	top of Porthloo Breccia fm	event: pre-ISB ice advance		X1244	
158	shear zone in Scilly Till	discard		X1248	glaciotectonised - not age of emplacement
159	shear zone in Scilly Till	discard		X1248	glaciotectonised - not age of emplacement
160	shear zone in Scilly Till	discard		X1251	glaciotectonised - not age of emplacement
161	organic mat under Ballyvoyle till	discard		Birm-89	infinite date
162	peat btw 2 calcareous tills	event: pre-YD??		Birm-458	Lab dating list, subm by GF Mitchell
163	flowstone stratig below NW-derived till	ice free: pre-Mid/Early Dev			SPEC ice free, depends on conditions for flowstone
164	flowstone stratig between 2 tills	ice free: pre-Late Dev			SPEC ice free, depends on conditions for flowstone
165	deepest date from bog	ice free	50	UB-229F	
166	infill of interdrumlin hollow	ice free	2	UB-401A	Lab dating list
167	organic beds w/in breccia fm	event: pre-ISB ice advance		Q-2176	cited in Scourse et al 2006
168	organic beds w/in breccia fm	event: pre-ISB ice advance		Q-2177	cited in Scourse et al 2006
169	overlies Porthloo Breccia	event: loess correl w/ ISB ice advance		QTL-1f	cited in Scourse et al 2006





EXF

Part 4a summarises as flowsets the lineations and ribbed moraine presented in Map 2. These flowsets are the building blocks of an inversion model which extracts the spatial, temporal and glaciodynamic information of glacial landforms, employs a set of principles and rules for ice sheet reconstruction, and yields a model of the history of the last Irish Ice Sheet: Part 4b. Seven broad stages of ice sheet history are recognised.

In Part 4b solid black lines are ice divides, the outer line is the proposed ice sheet lineit, flowlines joing the divide to the margin and formlines ('contours') help to define the shape of the ice sheet. Underneath the 'ice sheet' lineation flowsets are shown as boxes, ribbed moraine as flowlines, erratics as flowlines (arrows), meltwater channels, eskers and moraines as blue, green and brown lines respectively. Over Britain, the ice sheet is represented by long dashed lines since the nature of the connection is unknown. Short dashed lines, used during the period of ice sheet retreat (Stages V-VII), indicate sequential margin positions during deglaciation. Note that these reconstruction diagrams represent ice sheet-wide interpretations of the individual data presented in Maps 2 and 3. They are somewhat abstracted from the individual data and they necessarily smooth and stylise more detailed interpretations. Note also that several phases of ice sheet history represent a period of evolution, rather than a snapshot in time. There is therefore a fundamental cartographic problem in representing this behaviour. There may consequently be subtle discordancies between flowlines and the underlying evidence, a full discussion of ice sheet stages and all caveats associated with their representation.







