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The Last Glacial Stage (the Devensian) in Northwest England

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Abstract

During the early Devensian, ice formed only in Cumbria. By 22,000 BP the northwest of England was covered by ice emanating from Scotland and the Lake District. The ice sheet was warmbased, with subglacial water movement within tunnel valleys. As the climate warmed the ice receded northwards, leaving moraines and stagnant ice features. During the later stages of recession, subglacial water began to move through the thick till bed, and deformation of this sediment into drumlins occurred. This process was aided by the marine inundation of the Irish Sea basin, forming a tidewater glacier margin, and causing rapid drawdown and calving of icebergs. After the main ice sheet had disintegrated, a cold snap led to the reformation of ice in the Pennines and Lake District.

Key words

Devensian, glaciation, Cheshire, Lancashire, Cumbria

Introduction

The northwest of England (Fig. 1) contains extensive evidence for glaciation and sea-level change during the last glacial stage (the Devensian, c. 118,000-10,000 BP). Reviews of the glaciation of different parts of this area were published in 1985 (Johnson 1985) and 1991 (Ehlers *et al.* 1991), and glaciation in parts of Cumbria was reviewed by Mitchell and Clark in 1994. However, a number of developments since then, including detailed mapping of selected areas and the application of new dating techniques, means that it is now possible to assess the evidence in relation to the more complete and detailed records provided by ice and marine cores.

In recent years, evidence from oxygen isotope, sediment and chemical records from ice cores and deep marine cores has shown that the Devensian was characterised by considerable variability in temperature, ice volume and sea level (Fig. 2). Linking these records to the terrestrial record of glaciation has proved difficult, as terrestrial records are not complete and difficult to date. Nevertheless, the rapid expansion of our knowledge of global climate change has allowed recognition of the intimate linkage between ocean circulation, sea-level and terrestrial ice sheet behaviour.

This paper reviews recent developments in understanding of the last glacial stage in northwest England. The area considered in this paper includes Cumbria, Lancashire, Cheshire, and parts of the western Pennines and Derbyshire (Fig. 1).

The Marine and Ice Record

Analysis of sedimentary, chemical and isotope content of marine and ice cores has provided much additional information on ice volume, temperature and marine and atmospheric circulation. In particular, analysis of ice-rafted debris (I.R.D.) layers in marine cores off the British Isles has provided information on the release and dispersal of icebergs from ice sheets around the north Atlantic (e.g. Robinson *et al.* 1995, Scourse *et al.* 2000, Richter *et al.* 2001). When combined with analysis of variability in oxygen isotope ^{18}O in marine cores, which can be related primarily to changes in ice volume, this record shows that ice sheet behaviour during the last glacial was closely linked to sea level and marine circulation (e.g. Bond *et al.* 1993).

Devensian Chronostratigraphy

The oxygen isotope ice core records have allowed the division of the Devensian into a number of interstadial and stadial events; the GRIP (Greenland Ice Core Project) Summit ice core shows 24 separate interstadial events from around 120,000 BP (Dansgaard *et al.* 1993). However, the poor preservation of deposits on land means that they cannot be correlated with this detailed record. Instead, the divisions suggested by the relatively low-resolution marine core record are used. In total, 4 oxygen isotope stages are recognised in the Devensian (Fig. 2). These can be grouped into three main phases, which can be related both to the terrestrial record seen in the northwest and the offshore marine record. The three divisions are summarised in Table 1, and discussed separately below.

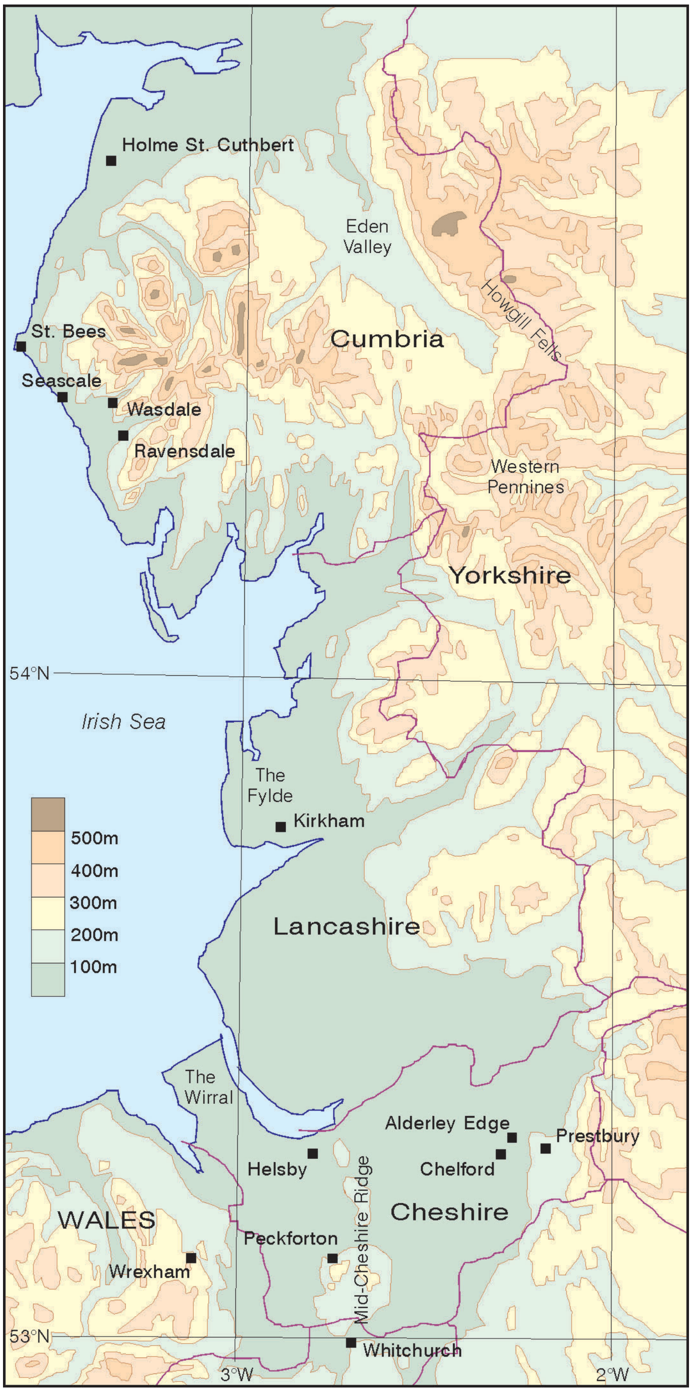

Figure 1: Map of northwest England, showing topography and the location of places mentioned in the text.

Table 1: Chronostratigraphy for the Devensian (after Merrit and Auton, 2000).

	Oxygen isotope stages	Years BP
Early Devensian	5d – 5a	118,000 – 75,000
Middle Devensian	4 – 3	75,000 – 26,000
Late Devensian	2	26,000 – 10,000

The Early Devensian Glaciation

Marine and Ice Records

The Devensian period commenced at the end of O.I. (oxygen isotope) stage 5e (c. 118,000 BP), when an initial cooling of climate occurred (Fig. 2). O.I. stage 5 is characterised by a series of interstadial and warmer periods, where climate in Britain varied between conditions seen in southern Scandinavia today and somewhat colder conditions (Lowe and Walker 1997). During these substages sea level varied between –60 and –12m O.D., due primarily to the expansion of ice sheets in North America (Shackleton 1987). This would have left the southern part of the Irish Sea basin at least as dry land. Offshore records of ice-rafted debris indicate that during O.I. stage 5 an ice stream was intermittently present in the Irish Sea basin (Richter *et al*. 2001). However, there is no evidence of regional ice onshore in the northwest.

Events on Land

On land, the only physical evidence for conditions during the first part of the Devensian occurs in the Cheshire area, where sediments indicate that this period was marked by dominantly cool but non-glacial conditions, interrupted by one warmer period, the Chelford interstadial. The deposits are best seen at Farm Wood and Oakwood Quarries near Chelford (Fig. 1, SJ 810730). The initial stages of cooling led to the deposition of extensive low-angle alluvial fan deposits, which contain intraformational frost cracks indicating a cold, arid climate (Boulton and Worsley 1965; Worsley 1966; Worsley *et al.* 1983; Rendell *et al.* 1991). Within these sands, a major paleochannel is partly infilled with organics containing a pollen assemblage dominated by birch, pine and spruce, indicating a climate similar to south-central Finland today (Worsley 1970). The fluvial and aeolian sands have been thermoluminescence dated to between 98.7 ± 12.0 ka and 21.04 ± 2.1 ka BP, with the interstadial occurring between 98.7 ka and 74.0 ± 8.1 ka BP. However, deposition of the fluvial sediments started before this, probably during the previous interglacial (O.I. stage 5e; Rendell *et al.* 1991; Rendell 1992). Uranium/Thorium series dating of the peats give a date of 86 ±26 ka BP, indicating that the interstadial corresponds to O.I. stage 5c (Heijnis and Van der Plicht 1992). The channel sediments are overlain at Chelford by coversands (wind-blown deposits formed around the edges of ice sheets), indicating a return to cold, arid conditions before the onset of glaciation (Rendell *et al.* 1991).

Mid- Devensian Glaciation

The Marine and Ice Record

The start of O.I. stage 4 is marked by an increase in ice volume globally, a reduction in temperatures, and a drop in sea level to below –60m (Shackleton 1987). This phase of cooling also marks the appearance of repeated cycles of decreasing ^{18}O within the marine and ice core records, indicating an initial abrupt warming followed by a gradual cooling in climate (Bond *et al.* 1992; Dansgaard *et al*. 1993; Figs. 2, 3). The cycles, termed Bond cycles, lasted between 10-15,000 years and contained a number of shorter cooling events, each lasting between 500-2,000 years, termed Dansgaard-Oeschger events (or interstadials), again with an abrupt start followed by gradual cooling of around 7°C (Fig. 3; Johnsen *et al.* 1992; Dansgaard *et al.* 1993).

The north Atlantic marine record shows a close relationship between the oxygen isotope record, sea surface temperature variations and ice-rafted debris records (Bond *et al.* 1992). In particular, the coldest part of each Bond cycle can be correlated with the presence of a rapidly deposited, I.R.D.-enriched Heinrich layer within marine sediments (Fig. 3). These layers are thought to have been formed by major discharges of icebergs from the ice sheets around the North Atlantic. Bond and others (1993) have suggested that this evidence for instability reflects a transition from terrestrial to glaciomarine ice margins as ice sheets expanded into deep water during cooling phases. As the ice margins floated, rapid calving occurred, drawing down more ice from the interior which in turn calved, leading to rapid retreat of the ice margin, a decrease in albedo as ice cover diminished, and a rapid warming in air temperatures. Recent work indicates that these iceberg discharges are likely to have initiated in the British-Irish and Fenno-scandian ice sheets, which in turn may have triggered instability in the Greenland and Laurentide ice sheets (Grousset *et al*. 2000; Snoeckx *et al.* 1999; Scourse *et al*. 2000). Heinrich events within O.I. stage 2 are discussed further below.

Closer to the northwest, I.R.D. records from the Atlantic margin west of Ireland indicate that an ice stream existed in the Irish Sea basin during ^{18}O stage 4, and intermittently during O.I. stage 3 (Richter *et al*. 2001; Knutz *et al*. 2001). I.R.D. from Ireland is not seen during this phase, although Scottish-derived I.R.D. is present in cores off NW Scotland, indicating that the ice sheet was confined to the

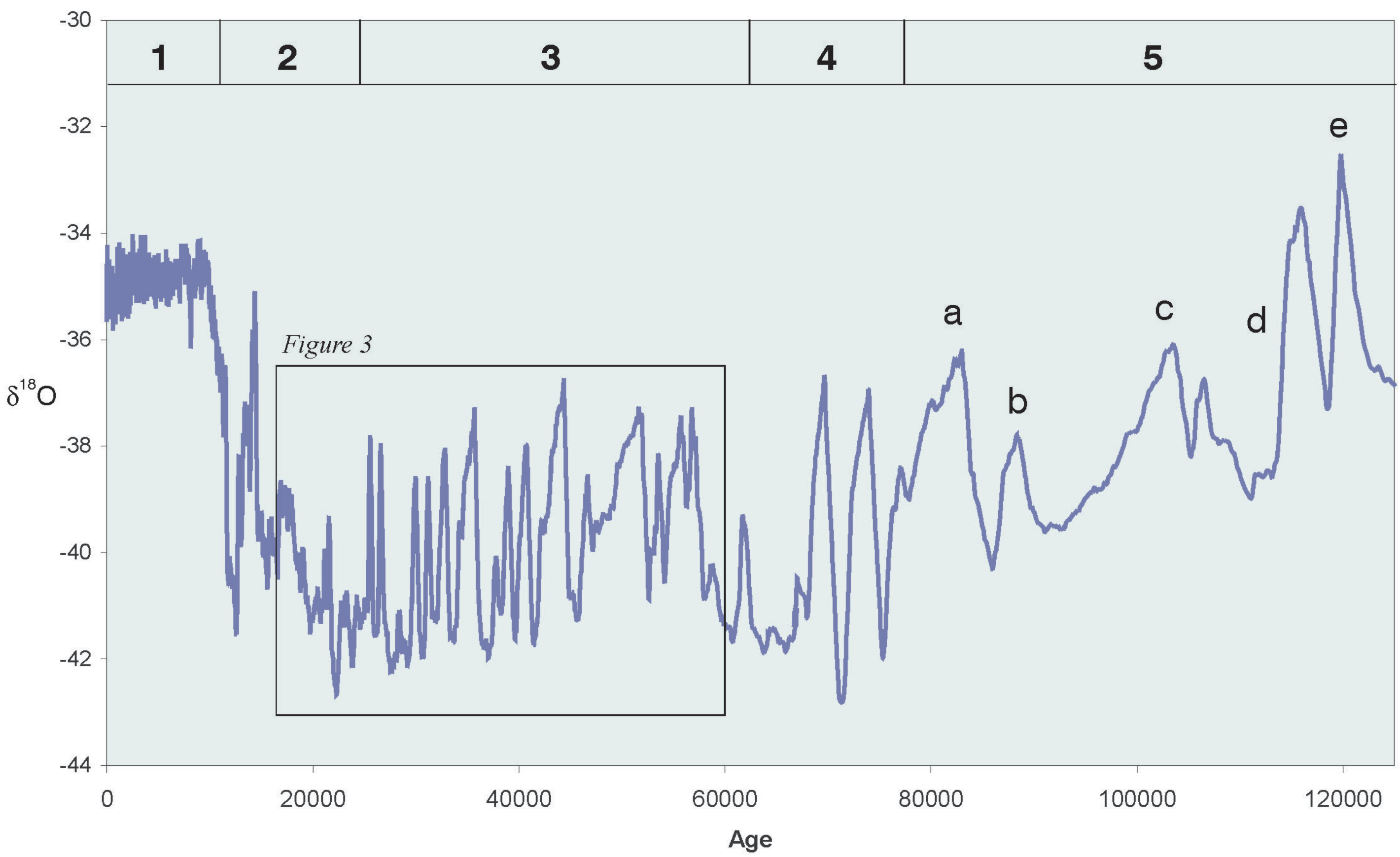

Figure 2: The oxygen isotope record from the GRIP ice core, showing marine oxygen isotope stages (after Lowe and Walker, 1997).

northern British Isles. However, this is at odds with ^{36}Cl dates obtained by Bowen *et al*. (2002), which indicate that an ice sheet covered all of Ireland during O.I. stage 3, but had retreated between 37,500 and 25,100 BP. This divergence of opinion is also reflected in views on glaciation in the northwest.

Events on land

Although earlier workers suggested otherwise (Wills 1937; 1952; Shotton 1967), it has been generally accepted that glaciation did not occur on the Cheshire lowlands between the start of the Devensian and the last glacial maximum (LGM, O.I. stage 2). This view is supported by the thermoluminescence dates from Chelford, which indicate that glacial deposits are not found in this area until after 21,000 BP (Rendell *et al*. 1991, Rendell 1992). However, recently Bowen *et al*. (2002) have suggested that an earlier phase of glaciation may have occurred prior to O.I. stage 2. This interpretation is based on unpublished amino acid ratios from shells below tills in the Birmingham area, which give a 5e stage age, and indicate an advance of Irish Sea ice in this area. If this is the case, the ice sheet must have been of extremely limited width, as otherwise evidence for its existence would be found at Chelford and other Cheshire interstadial sites. In the absence of other evidence, the interpretation of Bowen and his co-workers seems unlikely.

Concrete evidence for glaciation during the mid-Devensian is found only in the Lake District. Here, new evidence from boreholes indicate that valley glaciers formed in Wasdale and other valleys and at Wasdale advanced periodically into a proglacial lake in the Ravensdale, Seascale and Lower Wasdale area (Fig. 1; Merrit and Auton 2000). These lake sediments are rhythmically laminated and lamination counts indicate that the lake may have existed for over 2,000 years. The upper part of the sequence contains marine microfossils, indicating that a marine transgression occurred after 60,000 BP, when sea level rose to above –20m O.D. (Merrit and Auton 2000). As global sea levels appear to have been lower during this period (Shackleton 1987), this probably reflects isostatic depression in the Lake District.

Last Glacial Maximum

The Ice and Marine Record

Global ice volumes were at their maximum during O.I. stage 2. However, the ice core record indicates that there was considerable variability in temperature, and Bond cycles, Dansgaard-Oeschger cycles and Heinrich events all continued during this stage (Fig. 3). This is also the period with the most extensive terrestrial record of ice sheet extent and behaviour.

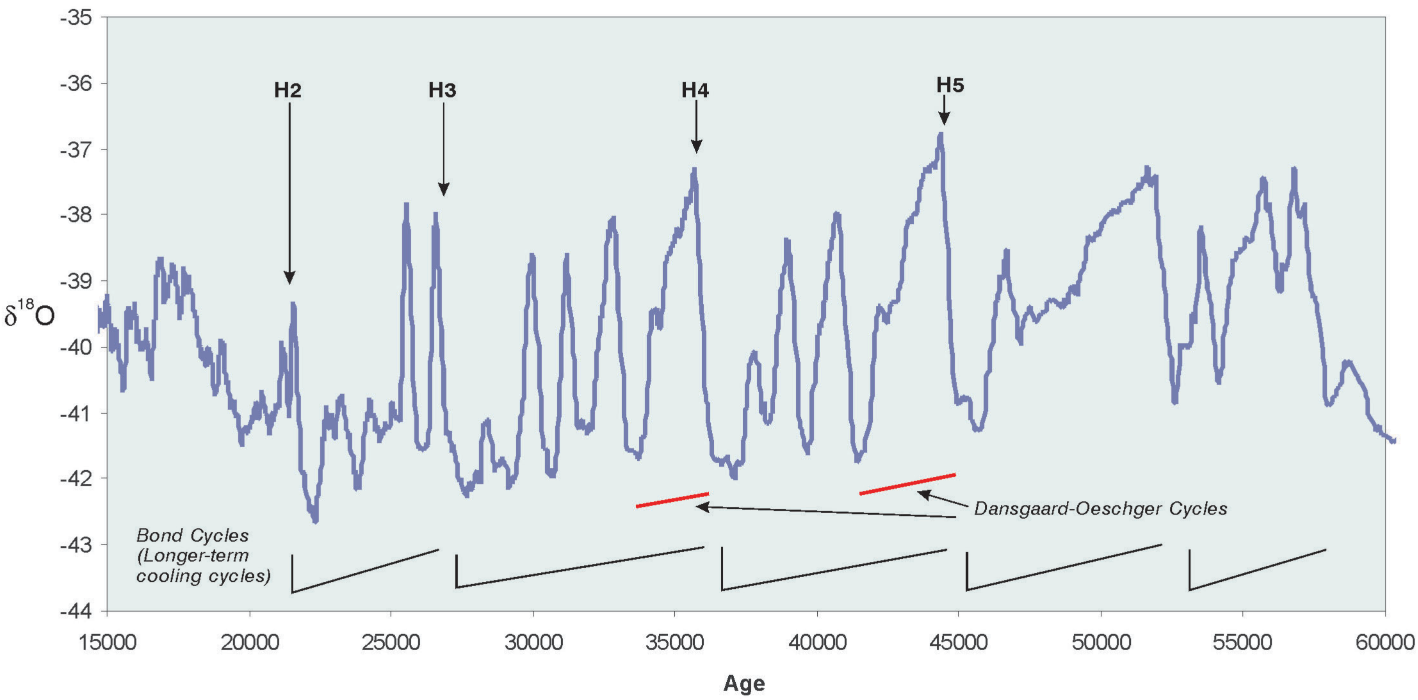

Figure 3: Part of the oxygen isotope record from the GRIP ice core, showing long-term (Bond) and short-term (Dansgaard-Oeschger) cooling cycles, and the position of Heinrich events (after Bond et al. *1993).*

Offshore around the British Isles, deep marine cores show an increase in the amount of I.R.D. during this period. Heinrich events are recorded in cores from off the continental shelf to the south, west and north of the islands, indicating that icebergs from the Laurentide and Greenland ice sheets traversed most of the Atlantic before melting (Heinrich 1988). Recent analyses of one of these Heinrich layers (H2, 20-21,000 14C years BP) indicates that this iceberg discharge was preceded by a release of I.R.D. from the British and Irish Ice sheet (Scourse *et al.* 2000). These Heinrich layers and other, smaller I.R.D. peaks have recently been related to events onland in Ireland and in northwest Britain (Eyles and McCabe 1989, McCabe 1996, McCabe and Clark 1998; see below)

Events on land

In the northwest, extensive glacigenic deposits are associated with this main phase of glaciation. Thermo-luminescence dating from Chelford indicates that ice from the Irish Sea basin and Lancashire covered this area after 21ka BP (Rendell *et al*. 1991; Rendell 1992), after the glacial maximum at c. 22,000 BP, and extended as far south as the Whitchurch end moraine (Fig. 4; Boulton and Worsley 1965; Earp and Taylor 1986; Thomas 1989). Erratic contents, till fabrics and drumlin orientations indicates the ice radiated outwards and extended southwards through Lancashire from local accumulation centres in the Lake District and western Pennines, while a major ice stream moved down the Irish Sea Basin from Scotland, penetrating south-eastwards into the Cheshire Plain. Ice also formed in the Welsh Mountains and moved eastwards to coalesce with the Irish Sea ice on the western side of the Cheshire Plain.

The ice left behind a range of sedimentary assemblages, which can be divided into four different areas. On the lowlands south of the Kirkham end moraine, the deposits consist of multiple beds of waterlain sediment and diamictons unsorted masses of sediment), formed into a mosaic of till plains, hummocky moraine, small end moraines, eskers, kettle holes and outwash fans (Boulton and Worsley 1965; Earp and Taylor 1986; Thomas 1989; Wilson and Evans 1990; Glasser *et al.* 2001). Drainage channels cut into bedrock are common on higher ground, and appear to be both ice-marginal and subglacial in origin (Earp and Taylor 1986; Sambrook Smith and Glasser 1998; Glasser and Sambrook Smith 1999). Large tunnel valleys underlie much of this area, and indicate that subglacial waters drained roughly south and southeastwards from the Irish Sea basin and from the West Pennines (Fig. 4; e.g. King 1976).

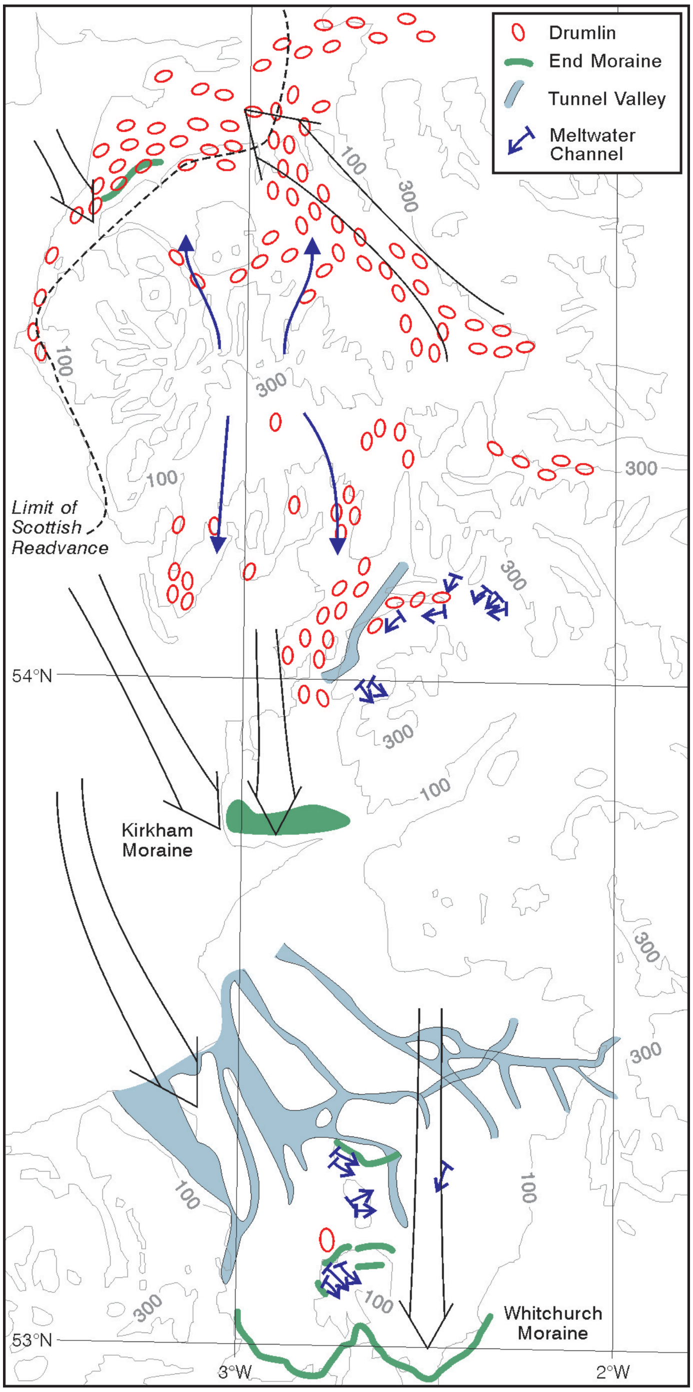

Figure 4: General direction of ice movement during the late Devensian and location of major glacial features in the northwest (From: King 1976, Arthurton and Wadge 1981, Johnson 1985, Earp and Taylor 1986, Wilson and Evans 1990, Boardman 1996, Brandon et al. 1998).

The Kirkham end moraine is one of the few moraines to be oriented transverse to the regional direction of ice flow, and marks a major change in the nature of the glacigenic deposits (Fig. 4). The complex interbedding of sand and gravel and diamicton is no longer important. Instead, north Lancashire is dominated by two till types which occur side by side and contain two different suites of erratics (Brandon *et al.* 1998). To the east, a grey till contains locally derived clasts only, while to the west on the Lancashire plain, it is overlapped by a reddish brown till containing Lake District erratics with very occasional Scottish granite erratics, indicating a minor input from the Irish Sea ice stream (Longworth 1985; Brandon *et al.* 1998). Some eskers occur in the southern part of the area, and buried tunnel valleys occur, but the topography is dominated by drumlins which indicate that ice moved both northwards and southwards out of the Lake District and the Western Pennines during deglaciation (Fig. 4; Mitchell and Clark 1994, Wilson and Evans 1990).

A further change in the nature of the glacial deposits and landforms is seen in the lowland areas around the western and northern side of the Lake District. Here, there is a return to the complex sediment sequences seen further south, with multiple sorted sediment and diamictic beds present in boreholes (e.g. Merrit and Auton 2000). Morainic landforms skirt the edge of the highland area, and deltaic sediments are common in the valleys leading out onto the lowland areas. This is in contrast to the Lake District itself, which is dominated by erosional landforms including cirques, glacial troughs and smaller streamlined bedforms. Landform orientation and distribution of erratics show that ice radiated outwards from the mountains and interacted with both the Scottish and the Irish Sea ice sheets (e.g. Taylor *et al.* 1971; Merrit and Auton 2000).

Discussion

The complex pattern of sediments and landforms seen in the northwest has provoked much debate, and has led to the development of a number of conflicting models of ice sheet behaviour. In particular, two features of the glacial assemblages have given rise to debate; two questions arise. First, how was the complex sequence of sorted and diamictic sediments generated? Second, how were the drumlins formed and what conditions do they reflect?

1. Generation of stratified sediment/diamicton sequences. The formation of these complex sequences was one of the first issues to be addressed. Boulton and others initially suggested that the sedimentary sequence was formed in a terrestrial ice-marginal area, with diamictons formed as basal lodgement or deformation tills, meltout tills, and flow tills and debris flows reflecting resedimentation of material at a stagnating ice margin (e.g. Boulton 1965). Waterlain sediments are interpreted as subglacial, ice marginal and pro-glacial outwash and glaciolacustrine deposits.

However Eyles and others (Eyles and Eyles 1984, Eyles and McCabe 1989, Eyles and McCabe 1991) proposed a new model for the interpretation of the Irish Sea Basin deposits. They suggested that during the early deglaciation of the basin after 22,000 BP, rising sea-level due to early melting of ice sheets elsewhere caused inundation of the isostatically depressed southern Irish Sea basin and rapid northward retreat of the Irish Sea glacier, due to iceberg calving along its tidewater (shallow marine) terminus (Eyles and McCabe 1989). Consequently, they reinterpreted the stacked diamictic/stratified sediment sequences seen in lowland areas along the Wirral, Lancashire and Cumbrian coastlines as glaciomarine in origin. According to this model, lenses of diamicton formed from a combination of sediment gravity flows along the ice margin, while more widespread diamictic sheets reflect deposition of large quantities of mud by salt flocculation from suspension, combined with the dumping of a wide range of sediment from iceberg rafting. Stratified sediments formed at the point of exit of efflux jets along the tidewater margins of the ice sheet while deformation structures within the sediment reflect resedimentation of unstable piles of material due primarily to gravity. Moraines were inter-preted as tidewater morainal banks, formed at the marine grounding line of the ice sheet, while higher level deltas along the Welsh mountains and in Cumbria are thought to have formed at the isostatically depressed margin where freshwater discharged into the marine basin. Foraminifera and mollusca within the sediments are interpreted as *in situ* fauna. The presence of a glaciomarine margin dominated by iceberg calving is also thought to have implications for drawdown of ice from further inland and drumlin formation (see below).

The reinterpretation of terrestrial sequences as glaciomarine in origin, and the associated implications of significant isostatic depression have provoked considerable response. A number of researchers have pointed out major flaws in this interpretation, and have pointed out that evidence from the northwest tends not to support this model in its entirety. Firstly, deltas in Cumbria and North Wales which Eyles and McCabe suggested formed at sea level, are located at a wide range of heights from 30m to 152m O.D., and are inconsistent with the relatively smooth uplift associated elsewhere with isostatic rebound (Huddart 1994; McCarroll 2001). Thomas (1985, 1989) found no evidence of glaciomarine deposition in the Welsh borders, and concluded that deltaic and finegrained laminated sediments in this area were formed in fresh water ponded between the ice margin and the Welsh Hills, while Huddart (1994) re-interpreted as some of the Cumbrian deltas as proglacial outwash plain.

Sediment successions along the coasts of Lancashire and Cumbria are also inconsistent with glaciomarine deposition. Huddart (1994) re-examined sediments at Holme St. Cuthbert, which Eyles and McCabe interpreted as a tidewater morainal bank, and has suggested that they are more consistent with formation as a glaciolacustrine Gilbert delta. More recently, Glasser and others (2001) have shown that deformation structures in diamictons exposed along the Wirral coastline are consistent with formation by subglacial deformation, rather than by soft-sediment gravity deformation, and that the sediment sequence can be best explained by a combination of subglacial deposition and supraglacial sedimentation processes.

Finally, deposits containing marine microfossils which can be related to water depth indicate that sea level was considerably lower than postulated by Eyles and McCabe during deglaciation. Intertidal and shallow marine deposits from the Irish Sea bed between the Isle of Man and Cumbria indicate that sea level was probably below present levels immediately after the removal of ice (Pantin 1977; Thomas 1985). Onshore, deposits from the Isle of Man indicate that relative sea level was at between 2-15m O.D. at 15,150 BP (Thomas 1985; Dackombe and Thomas 1991), while further north at St. Bees, a transition from glaciolacustrine to cold marine deposition occurred at a height of around 4m O.D. shortly before 11,780 BP, while the evidence suggests that marine conditions reached no higher than 10-15m O.D. in western Cumbria during this period.

Given this evidence, it appears that marine flooding did not occur within the Irish Sea Basin until late in deglaciation, and that much of the sedimentary sequence in the northwest can be attributed to deposition from a terrestrial ice sheet, with subglacial deforming bed conditions superseded by ice marginal stagnation and high levels of meltwater generation. The glaciomarine model for breakdown of the Irish Sea Ice Stream may only have applied towards the end of the deglacial period in the northern part of the area, as the rate of sea level rise overtook the rate of isostatic rebound.

2. *The formation of drumlins.* Drumlins occur extensively in the Western Pennines, in the Lancashire lowlands, and in the lowlands of the Eden Valley and northern Cumbria (Fig. 4). Isolated examples also occur further south, in particular around the mid-Cheshire ridge at Peckforton (Earp and Taylor 1986). Superimposed drumlins are common in the western Pennines and the Eden valley, and are thought to indicate changes in ice flow direction over time, reflecting the shifting of ice divides (Rose and Letzer 1977; Mitchell 1994). Recent work on ice flow and ice streams in modern glacial systems suggests that the drumlins are formed due to deformation of a basal till layer, which in turn is associated with rapid ice flow, and is commonly associated with ice streams (e.g. Alley *et al*. 1986; O'Cofaigh *et al*. 2002). Eyles and McCabe (1989) have suggested that the drumlins reflect rapid drawdown of ice towards a calving marine margin during deglaciation, while Mitchell (1994) has suggested that drumlins in the Western Pennines area may have formed under faster flowing ice streams within the main ice sheet, again reflecting drawdown. McCabe (1996) and McCabe and Clark (1998) have linked these drawdown events to Heinrich layers in marine sediments offshore, and have suggested that the drumlins formed as part of a circum-Atlantic chain of events, controlled by the interaction between the ice sheets and rising sea level. Work on satellite imagery in Ireland has shown that up to eight phases of drumlin formation can be identified in the northern half of Ireland, indicating rapidly shifting ice divides during this period and suggesting that drumlin formation was more continuous than suggested by McCabe originally (McCabe *et al*. 1998; Clark and Meehan 2001). However, the exact sequence of events is not clear, as dating methods do not yet provide the necessary resolution to link the terrestrial and oceanic records.

The Nature of the Late Devensian Deglaciation

From the above it can be seen the changing sediments and landforms indicate a change in ice dynamics and in the impact of sea-level changes as deglaciation progress during the Late Devensian. On the lowlands of Cheshire and Lancashire, evidence for a single advance and retreat only is found. Basal tills indicate that deforming bed conditions occurred in some places, indicating a fast-moving, warmbased ice sheet (Earp and Taylor 1986; Glasser *et al*. 2001). Ice also extended out onto the lowlands from the Welsh Mountains. At its maximum, the ice sheet was up to 400m thick, covering the mid-Cheshire ridge at Peckforton (Earp and Taylor 1986). Underneath the ice cover, there is evidence of large-scale water movement towards the ice margin along large tunnel valleys (Johnson 1985). Smaller scale subglacial and ice marginal channels also developed along the edges of the ice sheet in the Pennines and north Wales, following local bedrock topography, while further small subglacial chutes developed on bedrock highs, indicating a highly permeable ice sheet (Johnson 1985; Thomas 1985; Glasser and Hambrey 1998; Leviston 2001).

However, the subglacial deposits are secondary in importance to ice-marginal and proglacial sediments. Along the Welsh borders extensive proglacial lakes were ponded against the hills and against the Welsh ice, leaving a series of deltas and glaciolacustrine deposits in the Wrexham area (Thomas 1985; 1989). On the Cheshire plain, periodic halts in ice recession resulted in the formation of till-cored end-moraines, often concentrated around bedrock highs such as the mid-Cheshire ridge (Earp and Taylor 1986; Sambrook Smith and Glasser 1998; Glasser and Sambrook Smith 1999). In between masses of stagnant ice were left as the ice sheet receded northwards. These decayed, leaving complex sequences of supraglacial deposits and glaciofluvial and glaciolacustrine sediments, forming till plains, hummocky moraine and small eskers and containing kettle holes marking the site of buried ice blocks (Boulton and Worsley 1965; Earp and Taylor 1986; Thomas 1989). Eastwards towards the Pennines, hummocky moraine around Alderley Edge and Prestbury probably reflects the movement of sediment into the supraglacial zone due to compressive ice flow against the Pennines (Johnson 1985). On exposed bedrock highs, ice-marginal drainage channels formed, draining the ice margin (Earp and Taylor 1986; Sambrook Smith and Glasser 1998; Glasser and Sambrook Smith 1999). At Helsby these channels form an extensive integrated network from which water fed back into the ice sheet, indicating a highly porous ice sheet, with plentiful meltwater (Sambrook Smith and Glasser 1998).

Most of the glacial succession in South Lancashire is buried below Flandrian coastal sediments. To the north, there is a gradual transition from supraglacial and ice marginal glacial land systems to a dominantly subglacial landsystem. The lowland area of the Fylde is dominated by the Kirkham end moraine complex, formed from a complex of subglacial and supraglacial deposits (Wilson and Evans 1990). In the past, this moraine has been correlated with the Bride moraine in the Isle of Man, and the Drumlin Readvance Moraine in Ireland, both of which have been used to indicate a major readvance during the latter part of the last glaciation (e.g. Huddart *et al.* 1977, Thomas 1985). However, no evidence has been found which indicates a significant initial recession of ice or a readvance, suggesting that the Kirkham moraine is more likely to mark a temporary halt in ice recession, or a local readvance, rather than a major event. Kettle holes infilled with glacio-lacustrine and postglacial sediments occur throughout this area, indicating stagnation of the ice during recession. Radiocarbon dates indicate that meltout of this ice was underway by c. 12,200 at the latest (Wilson and Evans 1990).

North of the Kirkham end moraine the extensive drumlin fields indicate the widespread occurrence of subglacial deforming bed conditions, indicating a change in subglacial water drainage and reflecting faster flow. This change in flow conditions does not initially appear to be due to rising sea-level, but later reorientation of drumlins is likely to reflect the impact of marine inundation in the Irish Sea Basin and the drawdown of ice. The dominance of subglacial rather than ice marginal deposits in this area indicates that recession of the ice sheet was probably rapid, and with few still stands, leaving little evidence of ice marginal conditions. The lowland areas were fed by ice radiating outwards from the Lake District and Western Pennines, with the Lake District continued to act as an independent ice dome, deflecting ice flowing from further north (e.g. Taylor et al. 1971; Merrit and Auton 2000). In the southwest of the Lake District, nunataks perforated the ice sheet, indicating an ice thickness of up to 870m (Lamb and Ballantyne 1998). Along the west coast, ice from the mountains met the Irish Sea ice stream, and was deflected southwards during the main glaciation (Merrit and Auton 2000). As the Lake District ice retreated an ice-marginal lake formed between the two separating ice sheets, while later on as marine inundation reached the northern part of the Irish Sea Basin, glaciomarine sediments were deposited, indicating a sea level c. 5m above present O.D. (Merrit and Auton 2000). From this point the ice sheet had a tidewater margin, and changing flow patterns and local readvances were intimately connected with variation in sea-level and associated Heinrich events in the North Atlantic.

Evidence for a readvance of ice, known as the Scottish Readvance, into northern Cumbria and along the west Cumbrian coastal fringe has been debated for some time (Fig. 4; e.g. Huddart 1994; Pennington 1978; Thomas 1985; see Merrit and Auton 2000 for further discussion). Huddart and others have suggested that a major readvance took place as far as the northern fringes of the Lake District, depositing an upper till over outwash sediments. However, the extent of recession prior to readvance is unknown, and Thomas (1985) suggested that rather than a single major readvance, ice recession was marked by a series of local, minor oscillations. Recently Merrit and Auton have suggested that in western Cumbria at least two readvances occurred. The first, major event involved readvance of both the Irish Sea ice stream and local ice from the Lake District. This was followed by several minor oscillations, including the Scottish Readvance (Merrit and Auton 2000). This interpretation is consistent with recent evidence from Ireland, where repeated evidence of minor oscillations of the ice margin is found (e.g. Meehan 1999; Delaney 2002).

The final deglaciation in Western Cumbria is followed by marine inundation to a height of up to 15m O.D. (Merrit and Auton 2000).

The Loch Lomond Stadial

Evidence for the interruption of climatic warming and the occurrence of stadial conditions towards the end of the last glaciation is seen in the lake sediments in the Lake District. Interpretations based on the presence or absence of the full Late-Glacial sequence within corrie lakes suggest that corrie glaciers reformed at altitudes above 476m between 11,000 – 10,000 BP (Pennington 1978). The number of glaciers has been disputed by Sissons (1980) on the basis of morainic evidence and a number of authors have suggested that some of these corrie glaciers were more extensive than previously thought (e.g. Evans 1994; Evans and Cox 1995; Wilson and Clark 1998, 1999). However, as these moraines have not been related to the stratigraphic evidence, it is unclear whether they are simply recessional moraines formed during the retreat of the main glacier, or readvance moraines associated with the Loch Lomond Stadial.

McDougall (2001) re-examined the extent of ice on plateau areas above corries which contained glaciers securely dated to the Loch Lomond stadial. He noted that in valleys on either side of the Thunacar Knott-High Raise and Great Gable-Brandreth plateaux in the central Lake District, recessional moraines indicated that backwasting took place towards summits, rather than into corries or lower passes, indicating that a plateau ice field must have existed across this area during their formation. The stratigraphic sequence from corrie basins indicates that this ice formed during the Loch Lomond Stadial. The presence of a plateau ice field indicates that precipitation must have reached a minimum of 2000-2500mm during this period.

Finally, evidence from western Cumbria suggests that sea level fell from c. 15m O.D. to –30m O.D. during the final stages of the Devensian, due to isostatic rebound (Merrit and Auton 2000).

Conclusions

The glacial record from the northwest is dominated by sediments and landforms laid down during the deglaciation of the main Devensian ice sheet. While early and mid-Devensian deposits exist, they are commonly confined to borehole records, and indicate that much of the region outside the Lake District was dominated by cold, stadial conditions with a relatively arid climate. Only towards the Late Devensian, after 25,000 BP, does ice cover the entire region. Ice moving from the Lake District and Western Pennines interacted with an ice stream in the Irish Sea basin along the western and southern fringes of the region. The sedimentary record is dominated by evidence of a warm-based, fast-moving, wet ice sheet during this period. While highland areas are dominated by erosion, in valleys and lowland areas much of the base of the ice sheet is likely to have been underlain by a deforming bed of water saturated sediment, which would have facilitated rapid ice flow and adjustment to changing mass balance and ice marginal conditions. This layer of basal sediment was easily sculpted by ice flow, resulting in multiple phases of drumlin formation. Towards the ice margins, extensive tunnel valleys and meltwater channels indicates that considerable quantities of water were flushed from the system, depositing extensive outwash deposits beyond the ice margin. Where the two major ice sheets separated along the western fringes of the area, extensive proglacial lake sediments were deposited.

During deglaciation, initial recession appears to have been relatively steady, with a margin characterised by ice stagnation. However, towards the end of the main glaciation, recession became increasingly unsteady, and repeated oscillations of the ice margin occurred in the north. The later oscillations are associated with marine inundation into the Irish Sea Basin and then onland. A final readvance of ice occurred in the Lake District, when small ice fields reformed on some plateaux. Some corrie glaciation may also have occurred in the Western Pennines.

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