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Deglacial chronology from County Donegal, Ireland: implications for deglaciation of the British–Irish ice sheet

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Abstract: In the north of Ireland ice advanced northwards onto the continental shelf from inland centres of dispersion at the last glacial maximum. We constrain the timing of three subsequent events by accelerator mass spectrometry ^{14}C dating of marine microfaunas from muds at Corvish, County Donegal. Early and rapid deglaciation of the continental shelf off northwestern Ireland occurred before 17.1 k ^{14}C years bp when marine muds formed in Trawbreaga Bay. Ice subsequently readvanced into the bay some time between 15.0 and 14.0 k ^{14}C years bp and compressed contemporary sea stacks and beach cobbles into a ridge at Ballycrampsey. Early deglacial muds were deformed during this ice readvance and redeposited with stratigraphically inverted ^{14}C ages between 16.0 and 15.2 k ^{14}C years BP. The deformed mud is overlain by undeformed laminae deposited during the final deglaciation of the area after 14.1 k ^{14}C years bp. The early deglaciation in the north at *c*. 17 k ^{14}C years bp is correlative with deglaciation recorded in the Irish Sea Basin, western Ireland and northeastern Scotland, indicating a response of the entire British–Irish ice sheet to early warming of the North Atlantic Ocean that resulted in a loss of up to two-thirds of its mass. Subsequent ice-sheet readvance between 15.0 and 14.1 k ^{14}C years bp in the north is part of a widespread response of the British–Irish ice sheet to Heinrich event 1 during the Killard Point Stadial. High relative sea levels that accompanied deglaciation at 17 k ^{14}C years bp and again at 14.1 k ^{14}C years bp indicate substantial loading and attendant isostatic depression by the British–Irish ice sheet.

Keywords: British Isles, ^{14}C, deglaciation, palaeoclimate.

Records from the northwestern European shelf identify abrupt changes in sea surface temperatures during the last deglaciation that are associated with rapid changes in the strength and location of North Atlantic deep-water formation (Koc Karpuz & Jansen 1992; Lehman & Keigwin 1992; Sejrup *et al*. 1994; Hafidason *et al*. 1995). Adjacent European ice sheets probably responded to these large and abrupt climate changes (McCabe & Clark 1998; McCabe *et al*. 1998) but to a large extent terrestrial records constraining ice-sheet variability and its relation to climate change remain poorly dated.

Marine microfaunas found in marine and glaciomarine sediments deposited during the last deglaciation of the British–Irish ice sheet (McCabe 1997) provide a robust means of dating these sediments and related ice-sheet fluctuations (McCabe & Clark 1998). Here we present a deglacial chronology for the northern sector of the British–Irish ice sheet. New accelerator mass spectrometry (AMS) ^{14}C dates on marine microfaunas in deglacial muds at Corvish, north Donegal, constrain early deglaciation and subsequent readvance of this ice-sheet sector. These dates, together with ages from other raised marine deposits in northern Britain, identify a high sensitivity of the British–Irish ice sheet to the abrupt climate changes that occurred during the last deglaciation.

In situ fossiliferous marine muds, dated by AMS ^{14}C, show that high relative sea levels occurred on the margins of the Irish Sea Basin during at least four phases of the last deglaciation (*c*. 17 k ^{14}C years bp; and before, during and after the Killard Point Stadial (*c*. 14 k ^{14}C years BP)) (McCabe & Clark 1998). Because the Irish Sea Basin occurs near the geometric centre of the former ice sheet and acted as its main drainage conduit, it is likely that marine downdraw influenced ice-sheet dynamics, much as interior seaways affected the Laurentide (Hughes 1987; Dyke *et al*. 2002) and Fennoscandian (Donner 1980) ice sheets. Such a marine influence is also marked by ice-directional indicators that record centripetal ice drainage into the basin from Ireland, Scotland, Wales and northern England. This model contrasts with other concepts of ice-sheet evolution based on undated subglacial deposits, especially on the eastern side of the basin (e.g. Hambrey *et al*. 2001). Eyles & McCabe (1989) recognized that subglacial deposits are an integral part of the glacial system in the Irish Sea Basin, but their presence does not refute the influence of marine and glaciomarine conditions on adjacent ice masses during deglaciation. The subglacial and glaciomarine concepts are not mutually exclusive and should be integrated into any hypothesis for a basin-wide ice-sheet system.

Ice-sheet limit at Ballycrampsey

The study area in County Donegal is the most northerly peninsula of Ireland exposed directly to the North Atlantic Ocean. Ice from lowland centres of ice dispersion and from the Donegal ice cap coalesced and advanced northwards across this part of County Donegal (Fig. 1). The areal patterns of erosion (Synge 1978) identify ice flow onto the continental shelf during the last glacial maximum (Dyke *et al*. 2002).

Within Trawbreaga Bay, basal till deposits on bay margins record the position of an ice lobe centred on the inner bay. Directional indicators including small-scale erosional forms and striae within the postulated ice limits (Fig. 1) show that the ice lobe advanced to the west and NW, crosscutting the northerly ice flow of the last glacial maximum.

Close to the postulated ice limit a narrow (20–40 m across),

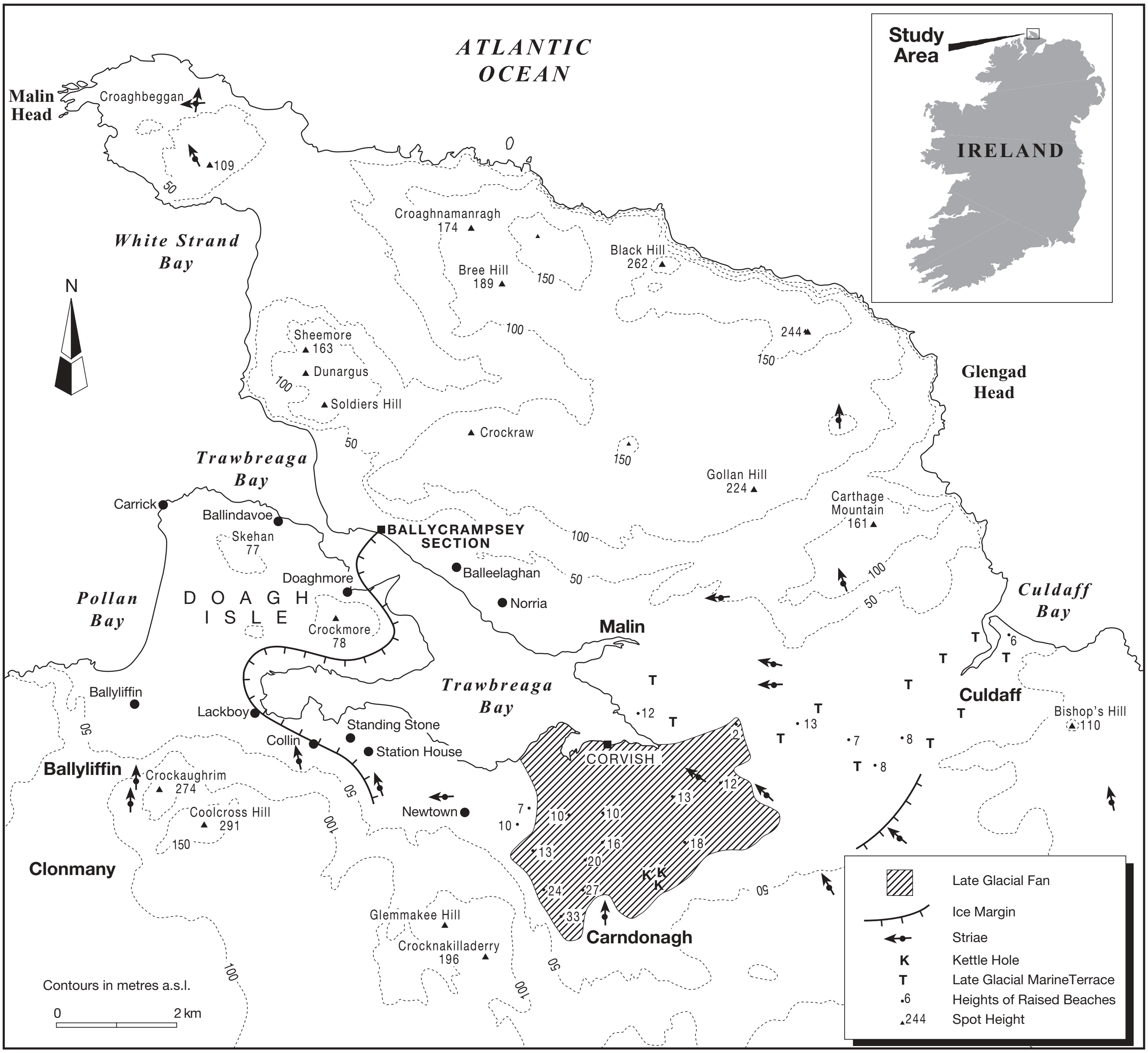

Fig. 1. Location of study area in north County Donegal, Ireland, and sites referred to in the text. Ice limits, directional data, the deglacial fan at Carndonagh and surveyed sites of raised beaches are shown. All heights and contours in metres above Irish datum. Inset shows the study area located in the northern part of the Inishowen peninsula.

flat-topped ridge is located across the mouth of the inner bay at Ballycrampsey and continues across the floor of the bay, resulting in a narrowing of the bay seawards (Fig. 1). Exposures in the ridge reveal two main facies: glaciotectonized schist and cobble gravel. At the base of the exposure slabs of schist are thrust together on a metre scale and consistently dip 40–50° to the SE (Fig. 2). Planes of schistosity within adjacent thrust slabs generally exhibit sharp, angular junctions with no obvious cataclastic deformation. Some junctions between thrust slabs are also marked by isolated well-rounded cobbles and pebbles of quartzite. This pattern is accompanied by isolated vertical pockets and narrow (5–20 cm) inclusions of unimodal, well-rounded cobbles between the slabs (Fig. 2). In both cases the *ab* planes or long axes of the cobbles are often aligned parallel to that of the junctions of the enclosing schist slabs. The upper surfaces of the schist slabs are irregular on a metre scale with individual slabs (0.5 m across) projecting upwards into the main part of the cobble facies. These slabs dip southeastwards at slightly steeper angles (*c.* 65°) than the schist below, suggesting a curved suite of listric shear surfaces flattening towards the SE (Fig. 2). Isolated, disaggregated slabs of schist float within the cobbles but maintain the same fabric as the remainder of the schist. A planar pervasive fabric is also present within about 80% of the cobble facies. The cobble facies is massive and shows variable texture between openwork and bimodal mixes of cobbles and coarse sand. Cobbles are well rounded, 8–15 cm in diameter and predominantly (95%) locally derived schist and quartzite. Locally, small disharmonic folds are present but the dominant feature is the pervasive shear fabric present throughout the deposits and its abrupt truncation at the top of

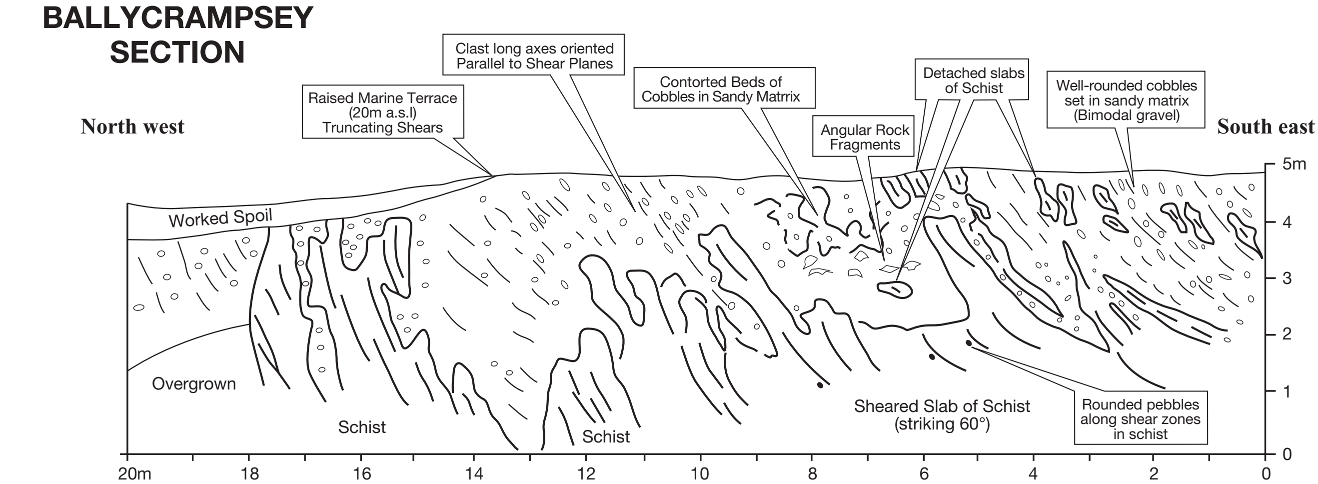

Fig. 2. Field sketch of section exposed at Ballycrampsey, County Donegal, Ireland [Grid reference: C437517]. The sketch is to scale and consists of slabs of schist and well-rounded pebbles compressed by ice action into a ridge (kilometre scale) that may be traced across Trawbreaga Bay, which causes a narrowing of the bay. All of the shear planes, tectonic lineations and *ab* planes of the cobbles dip consistently southeastwards. It should be noted that the shear structures are abruptly truncated at the top of the section. Towards the base of the section slabs of schist are thrust together with rounded quartzite cobbles located along tectonic junctions. Towards the top of the section isolated slabs of schist occur entirely within the cobble facies and both have a similar sense of shear.

the section (Fig. 2). The average dip of the fabric is *c*. 65° to the SE.

At Ballycrampsey the pervasive deformation is well marked by stacked, listric shear planes resembling an imbricate thrust system (e.g. Park 1983). The pattern of thrusts and aligned cobbles was generated by an overriding shear to the NW imparted by an overlying ice sheet (Fig. 2). This sense of overriding shear is further recorded across the bay by the ridge convexity facing NW. The kilometre scale of this feature evidenced from ridge continuity and models of thin-skinned tectonics (Park 1983) suggests that the high-angle listric shear patterns at Ballycrampsey flatten downwards into a common detachment or décollement at depth within the upper part of the schist bedrock. The truncated sharp planar upper surface of the complex probably represents the position of the glacier sole. Williams *et al*. (2001) described the glaciotectonic structures at St. Bees, Cumbria, in terms of a mechanical model of glacier bed deformation based on the frictional critical Coulomb wedge theory. Glaciotectonic thrust structures were considered by Williams *et al*. (2001) to be controlled by key elements such as the material strength and cohesion of the glacier bed, properties of the detachment surface and pore fluid pressure. Many studies (e.g. van der Wateren 1985; Benn & Evans 1998) have assumed that this type of glaciotectonics is proglacial. However, the listric thrust geometries together with imbricated bedrock point to a subglacial origin (see Wateren *et al*. 2001). There is no support from the section for a dual event involving proglacial thrusting and stacking followed by ice overriding because the continuity of the ridge would have been disrupted. The occurrence of till only within the suggested ice limits (Fig. 1) also suggests that the ridge, glaciotectonics and till are part of the same subglacial system associated with an ice lobe centred on the inner part of Trawbreaga Bay.

It is unusual for glaciotectonically sheared cobble gravel and schist bedrock slabs to occur jointly within a glaciotectonic imbricate system although this is adequately explained if the basal detachment occurred within the upper part of the schist bedrock. In particular, a central issue is explanation of how well-rounded and well-sorted cobbles occur in juxtaposition with angular slabs of schist prior to ice advance. One possible analogy occurs on the low (2–5 m above sea level (a.s.l.)) raised Holocene beach platform immediately west of Malin village (Fig. 1). This upper shoreface setting consists of detached sea stacks (3–4 m high) separated by swash gullies and cobble beach flats and ridges. Loosened slabs from the stacks together with the cobbles provide the appropriate facies for glaciotectonic compression during an ice advance across an upper shoreface setting. This interpretation means that relative sea level was the same as at present, or slightly higher, some time after the last glacial maximum but immediately before the last ice advance into Trawbreaga Bay. It is also likely that relative sea level was stable for a period long enough either to cut a new platform or to retrim an older feature. These observations indicate that many geomorphologically complex shore platforms in northwestern Britain that developed between the last glacial maximum and subsequent ice-sheet advances may be different in age, composite in origin and not necessarily solely attributable to erosion during the Younger Dryas or other restricted time intervals.

Corvish section

Immediately north of Carndonagh a late-glacial outwash surface (5 km^2) slopes northwards from around 30 to 7 m a.s.l. (Fig. 1). Limited fluvial erosion (>20 m) shows that the southern part of this spread consists of poorly sorted cobble to boulder gravel within stacked channels. Kettle holes on the surface NE of Carndonagh suggest that the southern part of the gravelly outwash is ice proximal and records sedimentation when the ice margin was pinned on solid rock at Carndonagh village following final ice withdrawal out of Trawbreaga Bay (Fig. 1).

An exposure near Corvish on the distal or north end of the outwash surface reveals mainly mud and sand (Fig. 3). We identify four main facies on the basis of vertical position in the section, textural changes, degree of interbedding and lamination, degree

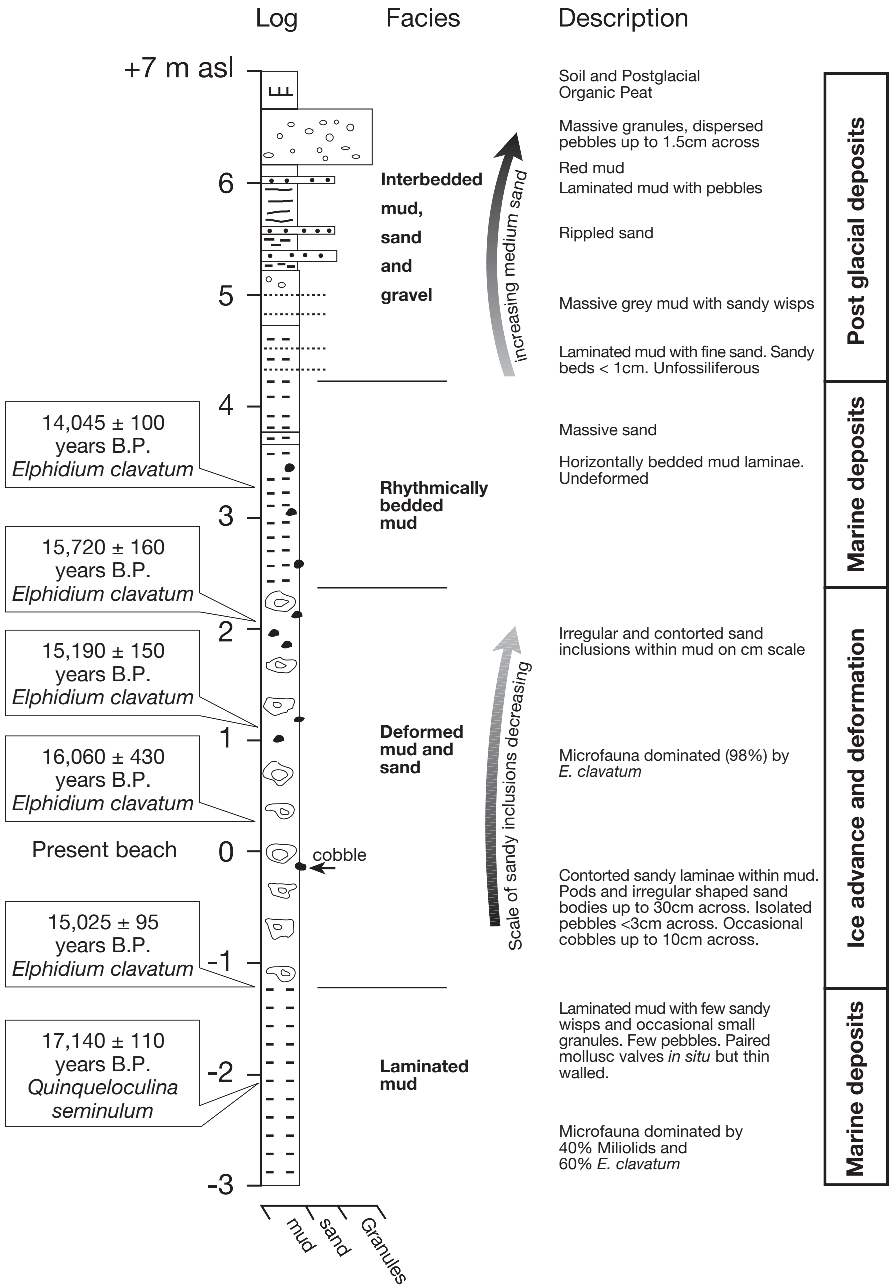

Fig. 3. Stratigraphic log from Corvish [Grid reference: C473482] at the distal end of the late-glacial spread at Carndonagh. All of the AMS ^{14}C dates are uncalibrated but have been corrected (−400 years) for an assumed sea-water effect. Flat lamination shows that the lower and upper parts of the section are undisturbed by ice advance. The ^{14}C dates from the middle part of the section are consistently older than the date obtained from the top of the underlying undeformed mud. This pattern is consistent with ice deformation and shearing of muddy sediment across the site prior to deposition of undeformed rhythmically bedded marine mud at the top of the succession.

of sediment deformation, changes in marine microfaunal assemblages and AMS ^{14}C dating of marine microfaunas (Fig. 3).

Laminated mud

The oldest unit recovered by hand coring from below present beach level consists of at least 3 m of finely laminated light grey muds containing only occasional small pebbles (<1 cm). Thin-walled, paired mollusc shells were too fragile for sampling. Marine microfaunas consisted of 60% *Elphidium clavatum* and 35% miliolids. Fragile species of foraminifera (*Pseudopolymorphina novangliae*, *Legena clavata*, *Oolina*/*Fissurina* spp.) and articulated valves of *Cytheropteron* species with a range of juveniles show that the fauna is *in situ*. Large numbers of polymorphinids, *Lagena*, miliolids (*Pyrgo williamsoni*, *Quinqueloculina seminulum)* suggest that the association is marine rather than glaciomarine. The fauna contains distinctly cold-water species, including *Cytheropteron dimlingtonense* and *C. montrosiense*, which are restricted to cold or very cold waters (Whatley & Masson 1980). Another member of the ostracode fauna, *Roundstonia globulifera*, has a circum-Arctic distribution (Lord 1980). A monospecific sample of *Q. seminulum* was AMS dated to 17 140 ± 110 years bp (AA33832) at −2.2 m a.s.l. and a sample of *E. clavatum* to 15 025 ± 95 years bp (AA33831) at −1.2 m a.s.l.

Deformed mud and sand

The second unit found immediately above beach level consists of deformed laminated sand and mud containing clasts up to 10 cm across. Most clasts (90%) are 1–2 cm across. At beach level the rhythmically bedded laminae are 0.5–1.0 cm thick but are deformed into rounded to irregularly shaped pods up to 30 cm across. Upwards the deformation becomes more intense with a decrease in bed continuity, the presence of irregularly shaped sandy inclusions within finer beds, small-scale (centimetre-scale) shears and disarticulated sandy beds. Small-scale parallel folds with wavelengths of up to about 10 cm and amplitudes of 3–4 cm are found in some parts of the deformed muds whereas recumbent folds occur in adjacent beds. Slickenside striations are common within these folds and because of their disharmonic nature it is difficult to determine any regular sense of fold vergence. In general, bed continuity becomes more difficult to trace towards the top of this division and the sand bodies become very irregular in outline and distinctly lenticular. It is likely that much of the deposit is pervasively sheared.

The marine microfauna from the deformed mud and sand is similar to that in the undeformed mud below beach level. The three AMS ^{14}C dates ($16\,060 \pm 430$ ^{14}C years bp; $15\,190 \pm 150$ ^{14}C years bp; $15\,720 \pm 160$ ^{14}C years bp) (AA45966; AA45967; AA45968) from the deformed unit are consistently older than the date ($15\,025 \pm 95$ ^{14}C years bp) obtained from the top of the laminated mud. Because these dates are stratigraphically inverted with respect to those from the undisturbed laminated mud below it is argued that the deformed muds record reworking of the lower laminated mud by an ice advance over the site.

Rhythmically bedded mud

The deformed mud is overlain by 1.8 m of undeformed, rhythmically bedded mud (Fig. 3). Laminae are up to 0.7 cm thick and show occasional normal grading patterns although most laminae are massive. Discontinuous wisps of fine sand several grains thick emphasize the laminations. Small clasts (<1 cm) are occasionally present. The microfauna is dominated (98%) by *E. clavatum*, although most of the other species recorded from the underlying muds are present in smaller numbers. An AMS ^{14}C date of $14\,045 \pm 100$ years bp (AA32315) was obtained from a monospecific sample of *E. clavatum.*

Interbedded mud sand and gravel

The finely laminated muds are overlain by 2 m of sand and gravel, which contains beds of unfossiliferous laminated pebbly mud. This division contains organic deposits that are post-glacial in age.

Regional correlations and implications

Early deglaciation

Last glacial maximum ice advanced onto the outer shelf north of Ireland, probably near the shelf edge (Bowen *et al*. 2002), although the exact location and age of the ice limit is not known with certainty. Marine muds at Corvish record deglaciation of Trawbreaga Bay by 17 k ^{14}C years bp following retreat of last glacial maximum ice from the shelf. The fully marine microfauna and the general paucity of ice-rafted detritus (IRD) in the muds indicate that the ice margin had retreated well inland by this time. Raised marine indicators on the margins of Trawbreaga Bay (Fig. 4) suggest that this deglaciation was associated with a marine limit around 30 m a.s.l.

Early deglaciation of the British–Irish ice sheet recorded from Corvish has also been documented by AMS and conventional ^{14}C dates on marine microfaunas at sites in northeastern Scotland (Hall & Jarvis 1989), the Irish Sea Basin (McCabe & Clark 1998) and western Ireland (McCabe *et al*. 1986) (Fig. 5). In Ireland, deposits related to this event have been grouped into the Cooley Point Interstadial (McCabe & Haynes 1996; McCabe & Clark 1998). The widely spaced locations of the sites indicate an ice-sheet-wide response that resulted in a decrease in ice-sheet size by about two-thirds from the last glacial maximum limits on the continental shelf at *c*. 21 cal ka bp (McCabe *et al*. 1998; Bowen *et al*. 2002).

In Ireland, terrestrial evidence provides information on the nature of this deglaciation, but we do not yet know the final position of the ice margin following retreat. In southeastern and eastern Ireland, there are no large end morainic complexes located on land other than the South of Ireland End 'Moraine' (Fig. 5) (Charlesworth 1928), which may represent a terrestrial

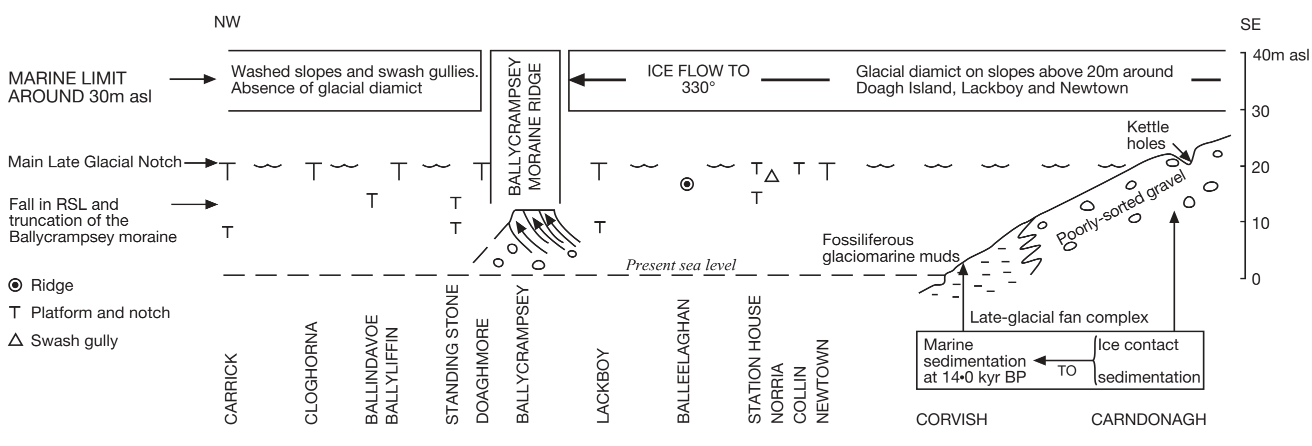

Fig. 4. Diagram illustrating possible relationships between sea-level changes, ice advance to the Ballycrampsey limit and the late-glacial spread at Carndonagh. Poorly drained soils within this ice limit are developed on basal diamict, which is absent to the NW (outside) of the ice limit at Ballycrampsey. High marine limits around 30 m a.s.l. are found only outside the Ballycrampsey moraine, suggesting their removal from the head of the bay during the final ice advance to Ballycrampsey. The main late-glacial strandline seems to be contemporaneous with part of the late-glacial spread at Carndonagh and is higher than the marine muds dated to 14.1 k ^{14}C years bp. All heights were surveyed by Trimble 4200 GPS.

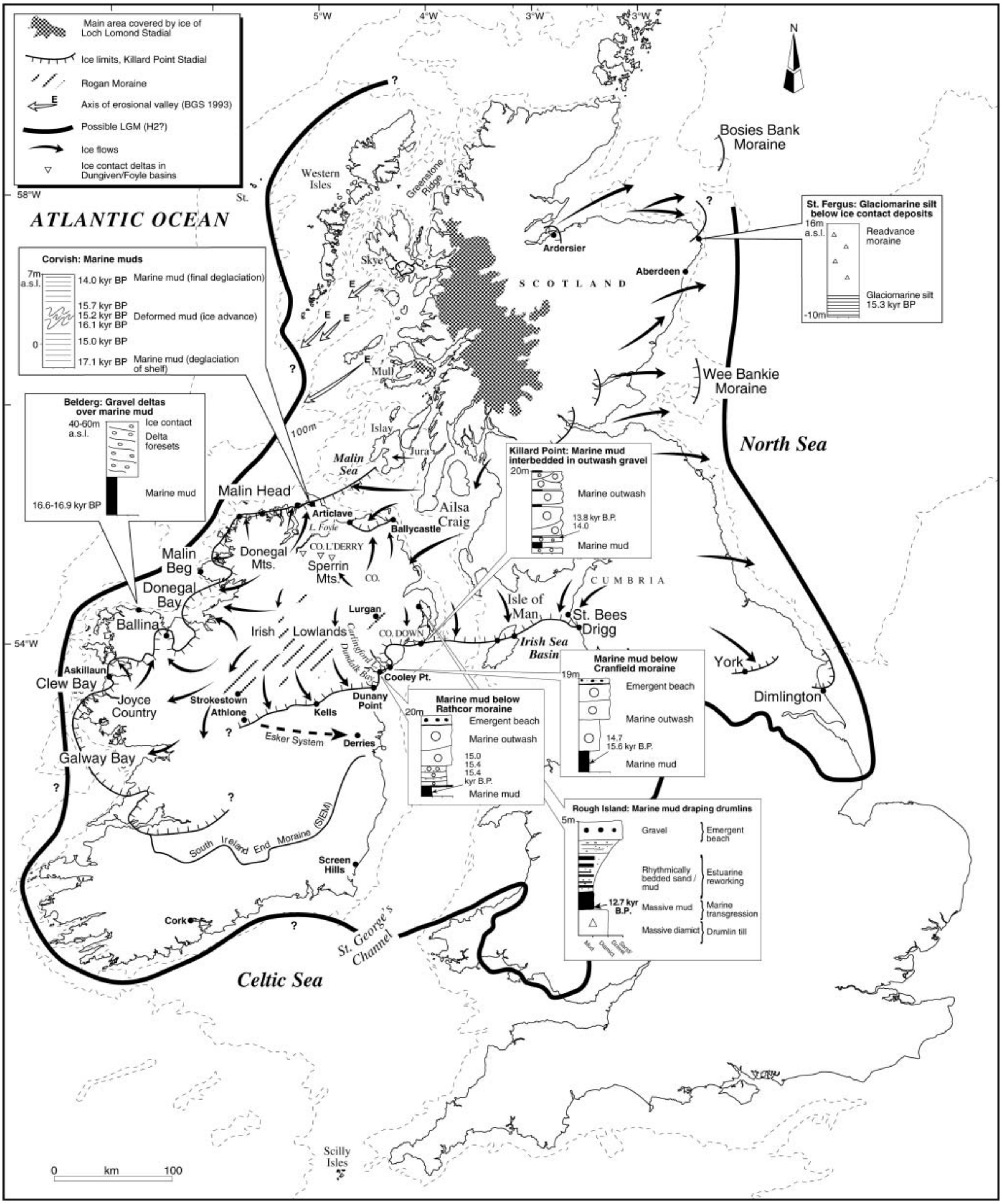

Fig. 5. Possible ice limits around the British Isles, sites referred to in the text and some generalized ice flows. Simplified stratigraphic logs together with uncalibrated AMS ^{14}C age determinations from widely spaced sites around the decaying ice sheet are shown. Data from St. Fergus in NE Scotland are from Hall & Jarvis (1989). The remainder of the dates are from McCabe *et al*. (1986) and McCabe & Clark (1998). All age-constrained marine muds demonstrate conclusively that marine conditions accompanied ice-sheet margins during and after deglaciation and contributed to ice-sheet collapse following Heinrich event 2.

last glacial maximum glaciofluvial feature. Their absence suggests that the ice margin continued to retreat once it withdrew from the continental shelf onto land. Withdrawal from the Celtic Sea is recorded by muds and diamicts on the south coast of Ireland, which may represent deposition associated with grounded ice margins (O'Cofaigh & Evans 2001). The raised succession of beachface gravel and marine sand west of Cork Harbour (Wright & Muff 1904), which overlie directly a glaciated shore platform (McCabe & O'Cofaigh 1996), probably formed in an Arctic setting after ice vacated this coastal zone. The closely spaced (metre-scale) erosional furrows on this platform record unidirectional subglacial meltwaters moving southwards and may be the subglacial signal for the initiation of deglaciation. A slightly later phase of deglaciation occurred when the ice margin retreated north into St. George's Channel, forming the raised ice contact delta at the Screen Hills, which prograded southwards into high relative sea level (Eyles & McCabe 1989).

Widespread successive ice marginal esker and outwash deposits between The Derries and Athlone (Fig. 5) indicate continuous ice recession westwards across the central plain of Ireland (Delaney 2002). In the central Irish Lowlands, transverse subglacial (Rogen) moraines occur in a zone 10–30 km in width stretching from Lurgan in the NE to Strokestown in the SW (Fig. 5). The main area of transverse ridges is only remoulded at its margins by ice-margin readvance during the subsequent Killard Point Stadial, when bed reorganization and drumlinization occurred in the northern parts of Ireland (McCabe & Clark 1998). This relationship suggests that the area of transverse moraines formed below the ice mass that remained in north–central Ireland following early deglaciation.

We consider climate and sea level as the two most likely mechanisms for early deglaciation of the British–Irish ice sheet. The timing of deglaciation shows a close correspondence to increased meridional overturning of the Atlantic thermohaline circulation and attendant warming of the North Atlantic Ocean immediately after the last glacial maximum (Clark *et al*. 2002). The atmosphere would respond rapidly to rising sea surface temperatures, and the signal would be transmitted 'downwind' from the areas of ocean warming (Rind & Peteet 1985; Hostetler *et al*. 1999). The location of the British–Irish ice sheet immediately adjacent to the North Atlantic Ocean would make the ice sheet particularly vulnerable to this early warming.

Deglaciation of the British–Irish ice sheet began before the first major rise in global sea level at *c*. 19 cal ka bp (Yokoyama *et al*. 2000), but changes in relative sea level driven by glacial isostasy may have provided an additional mechanism for deglaciation (Eyles & McCabe 1989; Andrews 1998). Because of its extended marine margins (Fig. 5), the British–Irish ice sheet would have been most sensitive to sea-level change when it was at its maximum extent around 21 cal ka bp. Raised marine sediments and marine limits up to 80 m a.s.l. in north County Mayo attest to substantial isostatic depression by the British–Irish ice sheet prior to early deglaciation (McCabe *et al*. 1986; McCabe 1997). Given a characteristic time scale of <3 ka for marginal isostatic loading (Andrews & Peltier 1989), we infer that such loading may have destabilized extended marine ice margins. Ice-sheet drawdown associated with high relative sea level, combined with deglacial warming from the North Atlantic Ocean, may thus have contributed to widespread deglaciation.

Indicators of high relative sea level from the west coast of Ireland (McCabe *et al*. 1986) and the Irish Sea Basin (McCabe 1997; McCabe & Clark 1998) are in direct conflict with geophysical models of post-glacial sea level in the British Isles, which predict relative sea level at or below present for all but northernmost Ireland during the last deglaciation (Lambeck 1996; Lambeck & Purcel 2001). The evidence for high relative sea level is based not solely on interpretation of glaciogenic deposits as glaciomarine (e.g. Hambrey *et al*. 2001), but also on direct evidence of raised marine landforms and marine muds dated by AMS ^{14}C that occur well above relative sea level predicted by these models. We attribute some of this discrepancy to the fact that the models have not accounted for the rapid spatial and temporal evolution of the British–Irish ice sheet that occurred during the last deglaciation.

Ballycrampsey readvance

Our new data document a significant ice-sheet readvance into Trawbreaga Bay between 14 and 15 k ^{14}C years bp that postdates the last glacial maximum but predates the Loch Lomond Stadial in northwestern Britain. The ice flow indicators associated with the ice limit at Ballycrampsey are related to an ice-sheet readvance that moved WNW into the depression between Trawbreaga Bay and Culdaff Bay (Fig. 1). Much of this depression is filled with raised marine terraces recording high relative sea levels following retreat from the Ballycrampsey ice limit (Stephens & Synge 1965), indicating ice loading and isostatic depression associated with the Ballycrampsey readvance (Fig. 4).

Regional ice-flow indicators and moraine orientation suggest that the ice-sheet limit at Ballycrampsey is part of the same readvance system as recorded by the Armoy moraine along the coastal fringe of northern Ireland between Ballycastle and Articlave (Fig. 5). Flow indicators such as the distribution of Ailsa Craig microgranite erratics westward along the northern Irish coast indicate that the main centres of ice dispersion for this readvance were located in the highlands of western Scotland (Fig. 5). Coarse Gilbert-type deltas with north-dipping foresets located in north-facing valleys in County Londonderry and in Lough Foyle were deposited in extensive lakes dammed by this southerly ice advance across the north coast of Ireland. The presence of these lakes requires that the ice mass centred in the Irish lowlands had vacated the north coast lowlands and begun to retreat prior to the advance of ice from western Scotland (McCabe *et al*. 1998). These relations suggest that the maximum extent of ice from Scotland occurred when Irish ice had retreated for at least 40 km southward around the eastern and western flanks of the Sperrin Mountains.

Within the uncertainties of ^{14}C dating, the ice-sheet readvance to Ballycrampsey is correlative with a readvance of the Irish ice-sheet margin elsewhere in Ireland during the Killard Point Stadial (McCabe & Clark 1998). In the Irish Sea Basin at Killard Point, marine muds interbedded with coarse-grained outwash were deposited around 14 k ^{14}C years bp (McCabe & Clark 1998). The ice contact outwash at Killard Point occurs 1–6 km down-ice from the main drumlin field in County Down and thus may represent debris flux towards the ice-sheet margin during widespread drumlinization of the north–central Irish lowlands (Fig. 5). A similar pattern occurs on the northern margins of the Irish Sea Basin, where regional flowlines reconstructed from drumlins are also bounded by limiting moraines on the Isle of Man and along the Cumbrian coast. McCabe & Clark (1998) suggested that this regional pattern of ice flow into the northern Irish Sea Basin points to renewed ice-sheet activity from centres of ice dispersion in southern Scotland and northern England. An ice margin terminating in a high relative sea level at this time means that the ice sheet could have made a contribution to ice-rafted debris transport southward along the Irish Sea Basin.

Further evidence for ice margin readvance at this time comes from Cranfield Point, where an outer ridge deposited by an ice lobe centred on Carlingford Lough overlies marine mud dated by AMS to 14.7 and 15.6 k ^{14}C years bp (McCabe & Clark 1998). The younger date provides a limiting age for the end of the Cooley Point Interstadial, and the presence of the raised marine muds provides further evidence that relative sea level in the Irish Sea Basin was higher than at present prior to ice readvance.

Further south, the southern margin of an ice lobe in Dundalk Bay is marked by a large ridge at Dunany Point composed primarily of muddy glaciomarine sediment that was deformed into a large ridge during a marginal oscillation of the ice lobe (McCabe *et al*. 1987). Sedimentary variability and deformation within the ridge suggests that the ice was advancing into its own outwash at a time of high relative sea level. Muds dated to 15.4 and 15.0 k ^{14}C years bp are overlain by an intertidal boulder pavement that predates this ice readvance (McCabe & Haynes 1996). These field relationships thus indicate that relative sea level rose some time after 15 k ^{14}C years bp and prior to the ice-sheet advance before 14 k ^{14}C years bp.

Coherent ice-flow lines reconstructed from bedforms across the Irish lowlands indicate contemporaneity of drumlinization and moraine building in eastern and western Ireland (Fig. 5). As discussed above, this phase of ice readvance in the west occurred during the Killard Point Stadial when ice overprinted subglacial bedforms that developed during the last glacial maximum or subsequent early deglaciation phase. At the head of Clew Bay, last glacial maximum bedforms recording westward ice flow onto the continental shelf were overprinted by ice readvance flowing to the NW (McCabe *et al*. 1998). These different flow lines reflect a change from a last glacial maximum ice-dispersal centre that was located to the NE of Clew Bay to an ice-dispersal centre during the Killard Point Stadial that was located at least 80 km to the south in Joyce Country (Fig. 5). These major shifts in ice-dispersal centres identify large-scale reorganization of ice-sheet dispersal centres on millennial time scales.

A notable signature of the ice-sheet readvance during the Killard Point Stadial was the subglacial transfer of large volumes of detritus to tidewater margins. For example, one of the resulting sediment aprons deposited on the southern margin of the Clew Bay ice lobe at Askillaun consists of 45 m of stacked, texturally variable diamict beds dipping consistently westwards (Fig. 5). Similar phases marked by extensive glaciogenic sediment output also occurred at about this time into the Forth and Tay estuaries in eastern Scotland (McCabe *et al*. 1998). These observations imply that terrestrial records of significant ice-sheet activity and sea-level change between the last glacial maximum and the Loch Lomond Readvance may well be contained within the thick glaciogenic and marine sediments found along the coast of eastern Scotland (e.g. Peacock 1999). In contrast, the ice-sheet margin in western Scotland advanced southwestwards into the north Irish lowlands and onto the Hebridean shelf, as indicated by a distinct IRD peak attributed to ice advance around 16–17 cal ka bp (Knutz *et al*. 2001). This evidence indicates that most of the isolated 'morainic' ridges on the margins of the western Highlands of Scotland represent at most minor deglacial events following ice retreat from the continental shelf rather than significant readvances (e.g. Wester Ross; Benn 1997).

Deglaciation after the Ballycrampsey readvance

The rhythmically bedded muds towards the top of the Corvish site that date to 14.0 k ^{14}C years bp record quiet sedimentation at the head of Trawbreaga Bay with little evidence of ice rafting. The field setting around the head of Trawbreaga Bay suggests that both ice contact deposition at Carndonagh and marine sedimentation at the distal (northern) end of the late-glacial outwash fan occurred at about the same time. Terraces and notches around bay margins indicate a marine limit at 20 m a.s.l. within the Ballycrampsey readvance limits (Fig. 4).

Regional mapping inland from these ice limits has not identified any well-defined moraines or other morphological feature that would indicate subsequent ice margin readvances in the north of Ireland. Restricted outwash fans occur in many valleys within the Donegal mountains but these simply record sediment deposition into the valleys during ice-sheet decay. These field relations thus suggest that the ice-sheet readvance to Ballycrampsey was followed by stagnation zone retreat. Stratigraphic evidence supported by AMS ^{14}C dates suggests that a similar pattern of ice retreat following the Killard Point Stadial also occurred in the north Irish Sea Basin at about the same time as in County Donegal (McCabe & Clark 1998). This phase of rapid ice decay from coastal fringes is also indicated from cores in the Bay of Biscay by a decrease in sedimentation rates and continental sediment supply from 14.4 to 13 k ^{14}C years bp (Zaragosi *et al*. 2001).

Conclusions

Well-dated records at Corvish, County Donegal, indicate that the deglacial model established for the Irish Sea Basin and adjacent areas (McCabe & Clark 1998) also applies to the northwestern sector of the Irish ice sheet, identifying ice-sheet-wide responses to climate and sea-level forcing. These data identify early deglaciation by 17 k ^{14}C years bp during the Cooley Point Interstadial that resulted in the British–Irish ice sheet losing over two-thirds of its mass. We suggest that this massive deglaciation occurred in response to some combination of early warming of the adjacent North Atlantic Ocean and high relative sea levels caused by ice-sheet loading that destabilized overextended marine margins. High relative sea levels on the western coast of Ireland and the eastern coast of the Irish Sea Basin associated with early deglaciation are in direct conflict with sea levels predicted by geophysical models (Lambeck 1996; Lambeck & Purcel 2001). We attribute at least some of this discrepancy to the large and rapid changes in ice mass associated with early deglaciation that are not captured by the models. Additionally, these models are constrained only by Holocene sea-level data, which do not reveal the magnitude of isostatic depression during maximum glacial loading.

Massive deglaciation may have released large volumes of sediment onto the shelf during high relative sea level, suggesting that increased IRD flux onto the shelf at this time resulted from ice-sheet collapse rather than an ice-sheet advance (see Scourse *et al*. 2000). This observation suggests that sequences of IRD on the European shelf should be investigated in greater detail regarding their provenance, mechanisms of delivery and release onto shelf areas before conclusions are reached regarding their climatic significance.

Our data from Corvish also identify readvance of the northern margin of the Irish ice sheet that, within uncertainties of radiocarbon dating, is correlative with readvance of other margins of the ice sheet in western Ireland and the Irish Sea Basin during the Killard Point Stadial (14–15 k ^{14}C years bp). We attribute this readvance to climate change caused by Heinrich event 1 and associated cooling of the North Atlantic Ocean (McCabe & Clark 1998). Flow-transverse Rogen moraines that formed by residual ice masses remaining after early deglaciation were subsequently overprinted by ice-margin readvance during this event. Marine ice margins that readvanced into high relative sea levels may have generated an IRD signal that represents just the opposite glaciological behaviour to that generated during early deglaciation, again indicating that caution is needed in interpreting the IRD record as a proxy for ice-margin fluctuations (e.g. Scourse *et al*. 2000).

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