Marine geophysical evidence for Late Pleistocene ice sheet extent and recession off northwest Ireland

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Colm Ó Cofaigh[1*], Paul Dunlop[2] and Sara Benetti[2]

[1] *Department of Geography, Durham University, Durham DH1 3LE, UK*
[2] *School of Environmental Sciences, University of Ulster, Coleraine, BT52 1SA Northern Ireland*

** Corresponding author: colm.o'cofaigh@durham.ac.uk*

Abstract

Multibeam swath bathymetry data collected through the Irish National Seabed Survey provides direct evidence for extensive glaciation of the continental shelf off NW Ireland. Streamlined subglacial bedforms on the inner shelf record former offshore-directed ice flow. The major glacial features, however, consist of well developed, nested arcuate moraines which mark the retreat of a former ice sheet margin(s) across the shelf. Distal to these moraines on the outermost shelf prominent zones of iceberg-ploughmarks give way into a well developed system of gullies and canyons which incise the continental slope. The large-scale, nested, arcuate moraines record the episodic retreat, probably punctuated by minor readvances or oscillations, of a grounded ice sheet lobe across this sector of the continental shelf during regional deglaciation. Initial retreat from the outer shelf was associated with an episode of ice sheet break-up and calving as recorded by extensive zones of iceberg ploughmarks distal to the outermost moraine. It is conceivable that this could have been driven by rising sea level. The data indicate a major reorganisation of the Irish Ice Sheet on the NW shelf during deglaciation; an initial elongate ice sheet configuration extending along the shelf edge changed to a pronounced lobate form during retreat. Consideration of dated, marine stratigraphic records from the wider NW margin suggests that ice sheet advance to the shelf edge likely occurred at about 29-27 ka BP, but that retreat from this shelf edge position did not take place until after 24 cal ka BP. Large-scale contrasts in continental margin morphology west of Ireland, from trough mouth fans in the north to gully/canyon systems further to south, reflects a combination of factors including spatial variations in sediment flux related to palaeo-glaciology.

Keywords: Irish Ice Sheet; North-West Ireland; continental shelf; marine geophysics; last glacial maximum; moraines; Donegal Bay

Introduction

The NW European continental margin is characterised by a range of submarine features related to the expansion and contraction of Pleistocene ice sheets across the continental shelf and the associated transfer of glacigenic sediments to the deep ocean (Fig. 1). These features include submarine fans deposited at the mouths of cross-shelf bathymetric troughs by fast-flowing ice streams, submarine slides formed by the failure of unstable accumulations of glacigenic and marine sediments, and moraines and streamlined subglacial lineations recording the former presence of grounded ice (e.g., Nygård et al., 2004; Sejrup et al., 2005, 2009; Ottesen et al., 2005; Graham et al., 2007, Bradwell et al., 2008). Although the large-scale morphology of the NW European margin is increasingly well known (e.g., Weaver et al., 2000; Sejrup et al., 2005), the precise extent and timing of shelf glaciation(s) remains controversial, in large part due to the fragmentary nature of the evidence in many areas (e.g., Bowen et al., 2002; Boulton and Hagdorn, 2006; Ó Cofaigh and Evans, 2007; Ballantyne et al., 2007; Bradwell et al., 2008). This is particularly the case on the continental shelf west of Ireland. Terrestrial glacial geomorphological and sedimentological evidence points to a dynamic Irish Ice Sheet which flowed onto the continental shelf on probably more than one occasion (Synge, 1978; Knight and McCabe, 1997; C. Clark and Meehan, 2001; Ballantyne et al., 2007). However, the offshore record of glaciation in terms of its maximum extent, its geomorphological record, and the nature of ice sheet retreat remain largely unknown due to the fact that existing submarine data on ice flow across the shelf (King et al., 1998) are spatially limited and of a reconnaissance nature.

High-resolution, multibeam swath bathymetric records of seafloor morphology and associated shallow acoustic stratigraphic records collected by the Irish Government since 1999 as part of the Irish National Seabed Survey (INSS) and Integrated Mapping for the Sustainable Development of Ireland's Marine Resource (INFOMAR) programmes provide a superb opportunity to investigate offshore ice sheet limits and large-scale glacier influenced sedimentation on the Irish continental margin. We focus here on the continental shelf off NW Ireland for two reasons. First, spatial data coverage for this region of the continental shelf is extensive and allows glacially-related seafloor features to be imaged and mapped at high resolution from the swath bathymetric data. Second, some reconstructions of ice sheet history in this region have argued for a highly dynamic Irish Ice Sheet which underwent repeated large-scale oscillations, the most extensive of which may have pre-dated the last glacial maximum (LGM; globally defined as 26.5-19 ka BP, Clark et al., 2009) (Bowen et al., 2002; McCabe et al. 2007). This contrasts with more recent work which argues for ice sheet advance through Donegal Bay and onto the continental shelf at the LGM (Greenwood and Clark, 2009). All these reconstructions have been based on terrestrial data and, with one exception (King et al., 1998), the offshore record of glaciation on the NW shelf is unknown. Understanding the former extent and flow dynamics of the Irish Ice Sheet is important because of the ice sheet's location bordering the North Atlantic and its potential impact on the thermohaline circulation through the delivery of iceberg and meltwater fluxes.

In this paper we present new marine geophysical data on seafloor morphology and shallow acoustic stratigraphy from a 30,000 km^2 area of the continental shelf offshore of NW Ireland (Fig. 1). Our aims in the paper are twofold: (1) to describe the glacial geomorphology of the continental shelf in this region; (2) to use these data to reconstruct the former dynamics and extent of the Irish Ice Sheet in its NW sector.

Methods

This study uses marine geophysical data acquired by the Marine Institute and the Geological Survey of Ireland on the northwest Irish continental margin under the auspices of the INSS. The aim of the INSS and INFOMAR is to map Ireland's Exclusive Economic Zone (EEZ) and collected data primarily consist of multibeam swath bathymetry, backscatter, sub-bottom profiler and magnetometric records. The interpretations presented in this paper are based mainly on the multibeam swath bathymetric data and on some key tracklines of seismic data. The continental shelf area was surveyed in the period 2002-2008 by the *RV Celtic Explorer* and *RV Celtic Voyager*. Multibeam data were acquired using a hull-mounted Simrad EM1002S and EM3002 on the Celtic Voyager and an EM1002 on the Celtic Explorer with decimetric vertical and horizontal accuracy that varies from 10-50 cm according to water depth. Seismic data were acquired with a SES Probe 5000 sub-bottom profiler with a hull-mounted transducer array, using CODA DA200 data acquisition and processing system. The pinger was operated at 3.5 kHz frequency. Penetration is up to 50 m below the seabed depending on the nature of the sub-sea floor sediments, with approximately 0.5 m vertical resolution. Multibeam swath bathymetric data on the continental slope and rise were acquired by the *SV Siren* with an EM1002 multibeam system and by the *SV Blight* with an EM120 multibeam system. The multibeam data were gridded at a cell size of 10, 15 or 20 m on the continental shelf (between 40 and 230 m water depth) and at 50 or 100 m on the continental slope and rise (below 200 m water depth) according to data quality, using CARIS HIPS and SIPS hydrographic software package version 6.0. The multibeam data were interpreted using shaded relief images created in Leica Geosystems ERDAS Imagine 9.2 and 3D views generated in IVS3D Fledermaus v6.7 software. To avoid the problem of azimuth biasing (Clark and Meehan, 2001; Smith et al., 2001) various shaded renditions of the bathymetric data, including non-azimuth images, were consulted during the mapping process. All landforms identified on the data were digitised on-screen directly into a Geographic Information System using ESRI ArcGIS v9.2.

3. Seafloor morphology and acoustic stratigraphy: description and interpretation

3.1 Transverse/arcuate ridges

The major geomorphological features on the multibeam swath bathymetric record from the continental shelf are a sequence of large arcuate ridges which extend from the centre of Donegal Bay to the outermost shelf some 90 km from the most westerly point of County Donegal (Figs. 2 and 3). In general, the ridges become sharper and narrower with distance inshore from the outermost shelf (Figs. 2 and 4). The major set of ridges is aligned northeast-southwest and individual ridges step back from the shelf break towards mainland Donegal. A second set of smaller ridges extend in a stepped sequence northwards from the entrance of Killala Bay to the centre of Donegal Bay (the 'Killala Bay moraines' in Fig. 3). Here the majority of ridges are aligned east-west, but the two northernmost ridges in the centre of Donegal Bay have a slight northeast-southwest orientation. A third set of ridges are isolated in the northwest of the study area approximately 55 km northwest of Tory Island (~55° 37´ N 9° 01´ W) and have a northwest-southeast alignment. Here we summarise the main morphometric and morphological features of each set.

3.1.1 Northeast-southwest aligned nested ridges

The most conspicuous landforms on the northwest Irish shelf are the sequence of very large northeast-southwest oriented ridges that step back from the shelf break towards the centre of Donegal Bay. Most are arcuate in planform, however, some of the longer ridges consist of beaded sections that have a much straighter profile (Fig. 3). The largest of this sequence are the two broad anastomosing ridges that lie buttressed against one another close to the shelf break ~ 90 km from the west coast of Donegal. The outermost of the two ridges is by far the longest in the entire sequence and stretches discontinuously near the shelf break for ~125 km (Fig. 3). In plan-view the ridge has a variable morphology. It is widest in its northwestern section being up to 11 km wide and 14 m high. In the central and southeastern parts it is much narrower and lower in height, being approximately 0.5 km wide and 6 m high. Nestled directly behind this ridge is another of similar dimensions. At its widest part this second ridge measures 11 km and is up to 6 m high. At its western end it bifurcates into a sequence of finger-like ridges that are much narrower than the main ridge and range from 0.5-2 km in width and up to 7 km in length (Fig. 3). Immediately to the south (54° 52´ N 10° 03´ W) the ridge becomes narrower and more fragmented. Individual sections are straight to arcuate in planform and range from 2.5-25 km in length, 1-1.5 km in width and 1-2 m in height.

The sequence of ridges continues 18 km further to the east, where a prominent suite of closely nested ridges can be traced eastwards across the shelf towards Donegal Bay (Figs. 2 and 3). The outermost ridges in this sequence are lobate features that can be traced for 40-70 km across the shelf. These nested ridges are much narrower than those on the outermost shelf (see above) and vary in width from 0.2-3.5 km. They are generally lower, ranging from 1-4 m in height (Fig. 2), and are off-lapped by acoustically transparent sediment lenses bounded by acoustically stratified sediment (Fig. 4a and b). The most prominent ridge in the sequence occurs at the mouth of Donegal Bay (between 54° 44´ and 54° 27´ N, and along 9° 2´ W) (Figs. 2 and 4a). This ridge extends continuously across the floor of Donegal Bay for ~35 km and ranges from 1-2.5 km in width and is up to 15 m in height. Generally in the central and southern parts of the bay the ridge is sharp crested with a steeper eastward (landward) face and gentler westward side (Fig. 4a). However, further to the north the ridge has a much broader, flatter profile. Sub-bottom profiler records show that the ridge is draped by about 0.5 m of acoustically stratified sediment but beneath this surficial drape internal reflectors are absent (Fig. 4a). The final ridge in this sequence is located ~5 km to the east of this ridge in the centre of Donegal Bay (54° 28´ N 8° 57´ W). It is 16 km in length, 1 km in width and 3-5 m in height.

This pattern of northeast-southwest aligned ridges is repeated in two other locations off the northwest coast of Donegal. The first is located just 13 km northeast of the prominent ridge at the mouth of Donegal Bay. Here, up to twenty ridges can be seen closely nested in a similar fashion as the larger ridges to the south (Fig. 3; series of ridges 15 km southwest of Arranmore Island), however, they are not as prominent and are much smaller. They have a similar plan-view morphology to the neighbouring ridges in outer Donegal Bay and range from 1.5-9 km in length, 1-3.5 km in width and are 1-5 m in height. The other set of ridges is located 5 km further to the northeast. These ridges have a similar alignment and again are found in a nested sequence, but they are more widely spaced. They are straight to arcuate in planform and are much thinner than all the other ridges with a north/south alignment. They range from 1.5-13 km in length, 0.1-1 km in width and are 0.6-3 m in height. The two inner ridges (54° 59´ N 8° 40´ W) are clearly superimposed on top of the local bedrock which suggests they are depositional features.

3.1.2 Northwest-southeast aligned ridges

In the Malin Sea region, 40 km northwest of Tory Island, several coalescing ridges make up a large prominent northwest-southeast oriented sinuous ridge that can be traced for 45 km between 95 and 125 m water depth (ridge centre located at 55° 34´ N 8° 59´ W)(‘Scottish moraine’ in Fig. 3). The longest continuous section of the ridge is 30 km in length, 2.5 km in width and up to 5 m in height. The smaller sections of the ridge vary in length and range from 0.4-2.5 km in width and 4-8 m in height. The ridge has an asymmetric cross-sectional profile with a gentle eastern slope and much steeper western slope. The surface texture of the eastern side has a smooth streamlined appearance which the backscatter returns show is not caused by a draping of fine sediments. A further 8 km to the southwest there is another northwest/southeast orientated ridge, 12 km in length and 1.2 km in width, and situated close to the shelf edge.

3.1.3 East-west aligned ridges north of Killala Bay

Another set of strongly nested ridges extend southwards from the centre of Donegal Bay towards the mouth of Killala Bay ~8 km off the north Mayo coast (‘Killala Bay moraines’ in Fig. 3). They are straight to arcuate in planform and range from 0.7-3 km in length, 0.1-0.7 km in width and 2.5-5 m in height. Most of the ridges have a strong east-west alignment and the only exceptions are the final few in the sequence in the central parts of Donegal Bay which have a slight southeast-northwest orientation. At this point they coincide with the prominent sharp crested ridge that cuts across the outer bay at 54° 31´ N 9° 6´ W (Fig. 3). Analysis of the multibeam data reveals that the east-west ridges are superimposed on top of the prominent ridge at the mouth of Donegal Bay and three other northeast-southwest aligned sinuous ridges that occur at the month of Killala Bay (54° 21´ N 9° 12´ W)(Fig. 3), indicating they were deposited after formation of the northeast-southwest aligned ridges.

Based on their morphology and nested, arcuate pattern (Figs. 2 and 3), we interpret the large northeast-southwest and northwest-southeast ridges described above (sections 3.1.1 and 3.1.2) as recessional moraines recording former ice sheet presence at the shelf edge and subsequent retreat inshore. The east-west aligned Killala Bay ridges record ice retreat southwards from Donegal Bay into Killala Bay. Based on the pattern of the moraines retreat in all cases appears to have been in form of lobate ice masses that occupied different parts of the continental shelf off the coast of Donegal and North Mayo. The nested pattern of the moraine ridges west of Donegal Bay implies repeated stillstands of the ice sheet margin during retreat across the shelf, punctuated by occasional minor readvances or oscillations (cf. Shipp et al., 2002; Nygård et al., 2004; Ó Cofaigh et al., 2008; Dowdeswell et al., 2008). Acoustically transparent sediment lenses that offlap the moraines on the outer shelf (Fig. 4a and b) are interpreted as debris flow lenses recording downslope remobilization of morainic sediment, either when the ice sheet was positioned at the ridge and/or following subsequent withdrawal. Acoustically stratified sediment drapes record suspension settling in an ice distal and/or postglacial setting.

3.1.4 East-west aligned ridges on the upper continental slope

On the upper continental slope of the Porcupine Bank, in the southern part of the study area, a series of ridges is observed in water depths of 300 to 400 m. They are 3-13 km in length, 0.5-1.5 km in width and up to 7 m in height. In planform, they are straight to sinuous and they are oriented at 50-60°. Based on their shape and size, these ridges are also interpreted as moraines. Unlike the other moraines in the study area, however, they are overprinted by furrows interpreted as iceberg scours (cf. section 3.2 below; Fig. 5).

3.1.5 Streamlined features

In the northeastern sector of the study area, 5 km northwest of Tory Island, a field of 275 well defined elongate mounds are clearly visible on the multibeam data (Fig. 6a; 55° 18´ N 8° 21´ W). The mounds range in height from 1-5.5 m, are generally closely spaced together and the long axis of the landforms have the same northwest-southeast orientation (~ 270°-290°). Generally, they have a blunt steep face on their eastern side and a tapering lee on the western side which gives them and the surrounding sea bed a streamlined appearance. A swarm of 59 similarly shaped landforms is located on the seabed 17 km to the southeast, 5 km northwest of Arranmore Island (Fig. 6b; 55° 1´ N 8° 39´ W). Although smaller in scale than the mounds off Tory Island, they have a similar elongate morphology and all have the same northwest-southeast orientation (~290°-310°) which gives the seabed a streamlined appearance in this locality. Statistical measures of the mounds show they have a mean length of 657 m, a mean width of 350 m and a mean elongation ratio of 2.8 (Fig. 6c). The majority of them tend to be 100-1200 m in length, 100-600 m in width and 1.5 to 5 times longer than they are wide (Fig. 6c). Both the morphology and scale of these landforms are consistent with descriptions of other streamlined features described as drumlins or drumlinoid features from glaciated terrestrial and marine environments (e.g. Fader et al., 1997; Greenwood and Clark, 2009). Statistical data from a very large sample (58,983) of drumlins has been recently presented by C. Clark et al. (2009). These authors found mean drumlin length to be 629 m, mean width to be 209 m and mean elongation ratio to be 2.9 which is consistent with the measurements presented here. Based on their morphological and morphometric properties we also interpret the mounds located on this part of the Irish shelf as drumlins which record northwesterly ice flow across the shelf towards the nested moraine complex.

3.2 Furrowed seafloor

Beyond the outermost moraine ridge the seafloor of the outer shelf and upper slope (down to 500 m water depth in places) is characterised by numerous furrows, of two different types. Between 55° 17´ N, 9° 44´ W and 54° 38´ N, 10° 38´ W, the shelf break and upper slope in 110 to 270 m water depth are incised by numerous sub-parallel furrows, mostly oriented east to west (Fig. 7a) but locally sinuous or cross-cutting. These furrows range in length from 0.5-1 km (a few are up to 3 km long), are up to 0.5 km in width and up to 3 m deep. They initiate just offshore of the outermost moraine where the slope gradient changes from <0.5 deg to 0.5 to 1.5 degrees, and they become less pronounced further downslope where the gradient increases to >1.5-2 degrees, although we note that the resolution of the data may not be enough to resolve them as water depths increase. Furrows also occur to the north and south of this area, but they are irregular in plan form, tend to be more sinuous and they display a noticeable cross-cutting pattern. However, in the southern part of the study area they exhibit an overall northeast to southwest orientation. These ‘irregular furrows’ range from a few hundred metres to ~15 km in length, are up to 0.3 km in width and are up to 3-4 m deep (Figs. 3 and 5d). They are present down to 500 m water depth. Profiles drawn across individual furrows show that they are bounded by lateral berms, either single or double (Fig. 7b).

On the basis of their dimensions, form (grooves flanked by lateral berms) and cross-cutting pattern the furrows in the northern and southern parts of the study area are interpreted as iceberg scours in which the movement of icebergs grounded on the seafloor resulted in the erosion of a groove or furrow with displacement of sediment to either side forming the berms (Beldersen et al., 1973; Dowdeswell et al., 1993; Long and Praeg, 1997; Ó Cofaigh et al., 2002). The overall trend of the furrows in the southern part of the study area is interpreted to reflect the predominant palaeo-current direction during iceberg calving events.

The sub-parallel furrows in the central part of the study area do not resemble classical iceberg scours, but could be related to sediment erosion at the shelf break, either by meltwater-generated flows during glaciation or modern shelf currents. The resolution of the data in deeper water is too low to assess if these features are related in any way to the gully and canyon systems on the continental slope.

3.3 Upper slope: gullies and canyons, sediment wedges and scarps

The shelf edge in this region is located in about 200-250 m of water, and the continental slope beyond is dissected by a series of gullies and canyons, both slope-confined and shelf-edge breaching (Figs. 3 and 8)(Cronin et al., 2005; Elliott et al., 2006). In dimensions the U-shaped gullies are typically 1-20 km in length, 1-3 km in width and up to 200 m in depth. They merge downslope into larger and deeper V-shaped canyons up to 6 km wide and up to 40 m deep. These canyons extend for 10-35 km downslope opening out in about 2700 m water depth. Gradients down the gullies on the upper slope range from 3-7 degrees, with side walls reaching angles of 28 degrees. Further downslope, the gradient along the canyon axes decreases to 1.5-3 degrees in water depths of 1600-2300 m. Three major sets of gully-canyon systems are observed on the multibeam records along the margin in this location. The continental slope between the major gully-canyon systems is characterised by occasional gullies but these are better developed at the base of the slope (up to 40-50 m deep and 4 km wide) (Fig. 8). Slope gradient in these inter gully-canyon areas of the slope is between 1.5 and 7 degrees (Fig. 9).

Inter-canyon areas are characterised by three large sediment wedges and frequent escarpments (Fig. 3). Scarps are up to 15 km long, either parallel or perpendicular to the bathymetric contours, and are characterised by a sudden and sharp increase in the slope angle (Fig. 9). Scarps are also often present around gully and canyon heads. Three sediment depocentres are observed within the study area. These depocentres occur as ‘wedges’, off-lapping the lower slope and their offshore sides are characterised by steep angles (up to 13 degrees; Fig. 9). The depocentre to the north is the southern portion of the Donegal Fan

Previous research on the canyon systems along the eastern margin of the Rockall Trough has demonstrated that the canyons in this region have been existence since mid-Cenozoic times, and, in the case of those canyons described here from NE Rockall, were likely active as recently as the Pleistocene (Elliott et al., 2006). The presence of an ice sheet positioned on the outermost shelf (as inferred from the arcuate moraines described above) would have allowed the delivery of sediment-laden, dense meltwater and associated sediment gravity flows into the gully/canyons systems (cf. Hesse et al., 1999; Lowe and Anderson, 2002; Dowdeswell et al., 2006; Noormets et al., 2009). The implication of this is that significant quantities of meltwater and sediment were delivered from the ice sheet margin onto the upper slope and thence downslope via the gullies and canyons.

The distribution of scarps is also indicative of the occurrence of gravity flows on the slope and the association between scarps and the location of canyon and gully heads indicate that headward erosion contributed to the evolution of these systems. The two sediment wedges in the central part of the study area are interpreted as glaciomarine debris that in places prograded or failed onto the slope without evolving into long run-out sediment gravity flows.

Discussion

Ice sheet extent and configuration on the continental shelf offshore NW Ireland

The morainic and subglacial bedform systems that we document here provide direct evidence for a grounded ice sheet on the continental shelf off NW Ireland. Streamlined subglacial bedforms, both on the shelf and on land (Knight et al., 1997; McCabe, 2008) record north-westerly ice flow onto the continental shelf from an ice centre situated around the Donegal highlands. That the ice sheet extended to the shelf edge is indicated by the presence of the large moraine systems, whose configuration indicates different phases of lobate ice sheet activity on the shelf. The sequence of northeast-southwest moraines offshore of Donegal Bay records the former presence of a large ice lobe, which extended over 80 km from the mouth of Donegal Bay to the shelf edge and was about 120 km across at its widest point. This lobe would have been fed by ice from dispersal centres in the Donegal mountains and the Omagh Basin (McCabe, 2008). The pattern of continuous, closely-spaced nested arcuate moraines implies episodic, possibly slow, ice-marginal recession across much of the shelf, punctuated by occasional minor readvances or oscillations (cf. Shipp et al., 2002; Nygård et al., 2004; Ó Cofaigh et al., 2008). Such oscillations are consistent with evidence for localised bifurcation of moraine ridges.

Well developed zones of iceberg ploughmarks occur immediately offshore of the outermost moraines (Figs. 3 and 7b). Significantly, moraines further inshore are *not* overprinted by ploughmarks. This suggests that initial retreat from the shelf edge was associated with an episode of ice sheet break-up and calving, perhaps triggered by rising sea level, which resulted in ice sheet reorganisation and development of a large grounded ice lobe on the shelf. Such an interpretation is consistent with recent reconstructions of the marine-based northern sector of the British-Irish Ice Sheet (Bradwell et al., 2008). These authors have suggested that ice sheet break-up in that sector was closely associated with Heinrich Event 2 (~24 cal ka BP) and that lobate moraines on the outer continental shelf record a dynamically-unstable ice sheet margin which underwent a series of internally-forced, short-lived readvances during deglaciation.

It is difficult to explain the northwest-southeast aligned moraines in the Malin Sea region (Fig. 3) as the product of an ice lobe from northwest Donegal. Such a flow trajectory would be more likely to produce northeast-southwest aligned moraines. We therefore suggest that the most probable explanation for the large Malin Sea moraines is that they were formed by an incursion of an ice sheet sourced from Scotland (Fig. 3). The temporal relationship of the Porcupine Bank moraines to the larger moraines of the Donegal Bay lobe is difficult to assess. They may be related to a separate, but temporally correlative, ice lobe situated to the south of Donegal Bay during deglaciation or they may represent an earlier ice sheet advance.

A number of workers have discussed ice sheet extent offshore NW Ireland during the last cold stage. Bowen et al. (2002) suggested that the ice sheet reached its maximum extent in this region ca. 37 ^{36}Cl ka BP and that the LGM advance was actually more restricted. On the basis of onshore radiocarbon-dated stratigraphic sequences from the southern shore of Donegal Bay McCabe et al. (2007) argued for a rapid fluctuation of the margin of the Irish Ice Sheet onto the continental shelf at about 28 cal ka BP. Similar to Bowen et al. (2002), these authors also proposed that the subsequent ice sheet margin during the LGM was less extensive. Clark et al., (2009) interpreted the prominent ridge at the mouth of Donegal Bay (between 54° 44´ and 54° 27´ N, and along 9° 2´ W), herein referred to as the Donegal Bay Moraine, as being the offshore extension of the Tawnywaddyduff moraine which extends from Clew Bay to Carrowtrasna on the north Mayo coast and as marking the limit of a post–LGM readvance of the Irish Ice Sheet during the Killard Point Stadial (ca. 15.6 ka BP) (McCabe et al., 1998). Collectively these reconstructions imply a dynamic ice sheet which was characterized by major ice-margin fluctuations commencing in Marine Isotope Stage 3 and extending to 15.6 ka BP. Crucially, in these reconstructions the LGM advance is more limited and is considered as essentially a deglacial event in the development of the ice sheet in this sector. In contrast, reconstruction of the Donegal Ice Dome at the LGM based on cosmogenic surface exposure dating and trimline mapping suggests an extensive ice sheet that advanced at least 20 km onto the adjacent continental shelf (Ballantyne et al., 2007). Most recently, on the basis of terrestrial glacial geomorphological evidence, Greenwood and Clark (2009) have proposed that a major ice stream converged through Donegal Bay and flowed onto the shelf during the LGM.

The new data that we present here provide unequivocal evidence for past extension of the Irish Ice Sheet far across the continental shelf offshore NW Ireland, reconfiguration of the ice sheet into a series of lobes during deglaciation and subsequent episodic retreat of grounded ice across the shelf. One interpretation of the age of the moraines is that they pre-date the LGM (either wholly or in part) and record a long period of ice occupancy of the continental shelf which encompassed the LGM and during which the ice sheet occupied a position between the Donegal Bay Moraine and the outermost shelf - i.e., a restricted LGM ice sheet extent (cf. Bowen et al., 2002; McCabe et al., 2007). It is, however, difficult to see any reason to chronologically subdivide the large moraines on the shelf offshore of the mouth of Donegal Bay on morphological grounds (see section 3.1.1 above). However, the moraines are presently undated and it is therefore important to consider relevant dated sediment records from elsewhere on the margin in this region.

Scourse et al. (2009) have recently reviewed IRD records from sediment cores along the western margin of the British-Irish Ice Sheet including core MD95-2006 from the Barra Fan (Fig. 1). These records indicate major growth of the ice sheet in the north after 29 cal ka BP, with the Barra Ice Steam reaching the shelf edge and generating turbidity currents on the Barra Fan at about 27 cal ka BP (cf. Wilson and Austin, 2002). Dated IRD flux records from further south along the margin, notably from core MD01-2461 from the Porcupine Bank (Fig. 1), show that ice sheet growth in the south occurred slightly later, after 27 cal ka BP, but all the core records show maximum ice sheet growth was attained by 24 cal ka BP and deglaciation occurred at 23 cal ka BP (Scourse et al., 2009). Early advance of the Irish Ice Sheet in the NW is consistent with recent terrestrial glacial geomorphological research utilising flowset mapping of the landform record (Greenwood and Clark, 2009) and with onshore radiocarbon dated chronologies (McCabe et al., 2007). However, as noted above, McCabe et al. (2007) have also argued for major early deglaciation of this sector of the ice sheet about 28 cal ka BP. Greenwood and Clark (2009) point out that such early deglaciation is glaciologically problematic in the context of the ice sheet as a whole, as it would require an extremely steep ice surface profile in order to prevent extension of ice onto the shelf during the LGM. Taking the above points into consideration, we suggest therefore that at present, the simplest interpretation is that the Irish Ice Sheet last attained a shelf edge position offshore of Donegal Bay about 29-27 cal ka BP. Subsequent retreat as a lobate grounded ice sheet margin across the shelf from this maximum position took place sometime after 24 cal ka BP, was episodic, and was punctuated by occasional minor readvances.

Our evidence also suggests that the east-west ridges at the mouth of Killala Bay, herein referred to as the Killala Bay Moraines, are the offshore extension of the Tawnywaddyduff Moraine system (Clark et al., 2009) (Fig. 3). As noted earlier, the Killala Bay Moraines are superimposed on top of the main Donegal Bay Moraine system. Thus, the Killala Bay Moraines are younger than the Donegal Bay Moraine and likely represent a late stage readvance into the southern part of Donegal Bay. The Donegal Bay Moraine has been proposed as the offshore extension of the ice sheet limit during the Killard Point Stadial (Clark et al., 2009). However, it is undated and it is equally plausible that it represents a marginal oscillation and/or longer stillstand of the ice sheet during retreat from its LGM position on the outer shelf. The latter interpretation is consistent with the well developed moraine morphology and its position at the mouth of Donegal Bay which might have acted to buttress and slow the ice sheet once it retreated back off the wide open shelf further offshore.

Continental margin morphology and relationship to palaeo-glaciology

At the shelf edge, and extending for distances of up to 40 km, well developed networks of gullies and canyons incise the continental slope offshore of NW Ireland (Fig. 8)(cf. O'Reilly et al., 2006; Elliott et al., 2006). The overall distribution of gullies and canyons is consistent with a line-sourced delivery of sediment to the continental slope by turbidity current and mass-wasting activity (cf. Hesse et al., 1999; Dowdeswell et al., 2006; Vorren et al., 1998). We note, however, that gullies are not ubiquitous along the slope in this region but rather occur as three major systems (albeit with more weakly developed gullies in between). When combined with the presence of prograding sediment wedges in between the canyon systems, this suggests that whilst sediment delivery to the slope was from a line source overall, there was some concentration of meltwater/sediment flows. Direct evidence for mass wasting is documented by O'Reilly et al. (2006) who present side-scan sonar and sub-bottom profiler data showing a composite submarine fan apron, composed of a series of individual turbidites and debris flows on the slope in this region. Progradation of the continental margin in the form of a trough mouth fan is not apparent from the swath bathymetric records, except for the area of the Donegal Fan to the north of the study area (Dahlgren et al., 2005; O'Reilly et al., 2006). Hence there is a marked change in margin morphology southwards from the Barra-Donegal Fan to the gully/canyon systems immediately to the south.

Sejrup et al (2005) have suggested previously that latitudinal changes in the morphology of the NW European margin may reflect variations in the nature of the sediment supplied by ice sheets and in particular an increase in the importance of meltwater processes at southerly latitudes. Thus they interpret the morphological transition from the Donegal Fan in the north to the gully/canyons systems further south as recording a change from a depositional setting dominated by the delivery of poorly-sorted glacigenic sediments by shelf-edge terminating ice streams to one in which subglacial drainage networks supplied meltwater and sediment directly to the shelf edge further south. We suggest, however, that this transition reflects a combination of factors, which, in addition to the nature of sediments delivered to the margin, is likely to include spatial variations in sediment flux as well as slope gradient; the latter with implications for slopes dominated by turbidity current activity vs. glacigenic debris flows (cf. Ó Cofaigh et al., 2003). We emphasise the link between sediment flux and palaeo-glaciology (ice stream vs. ice sheet flow)(cf. Dowdeswell et al., 1996, 2002; Dowdeswell and Elverhøi, 2002; Vorren et al., 1998) and suggest that one reason for the absence of a sediment fan offshore of Donegal Bay is that this area of the margin was not fed by a major shelf-edge terminating ice stream during glacial maximum. Whilst we have presented clear evidence that this sector of the ice sheet supported a major outlet draining through Donegal Bay to the shelf edge (see above), features diagnostic of streaming flow (e.g., convergent, highly elongate streamlined subglacial bedforms; Stokes and Clark, 1999) were not observed on the multibeam records. Rather the main zone of ice-stream related sediment delivery was focused immediately to the north on the Donegal-Barra Fan. Whilst we do not discount the possibility of ice streams draining the western margin of the Irish Ice Sheet onto the continental shelf, the canyon dominated margin and apparent absence of major trough mouth fans (Fig. 1) suggests, at least in part, that if there were major ice streams present, they did not extend to the shelf edge. In this regard it is noteworthy that the Irish Sea Ice Stream (Scourse et al., 1991; Scourse and Furze, 2001; Ó Cofaigh and Evans 2001, 2007) did not extend to the edge of the Celtic Sea Shelf and it lacks an associated trough mouth fan (Scourse et al., 2009). Thus the ice sheet offshore western Ireland appears to have acted as a line source, delivering meltwater and sediment to the slope via canyon/gully systems rather than prograding large submarine fans composed of glacigenic debris flows.

Conclusions

- Multibeam swath bathymetry data collected as part of the Irish National Seabed Survey and INFOMAR provides direct evidence for extensive glaciation of the continental shelf offshore of NW Ireland. Streamlined subglacial bedforms on the inner shelf from this region record former offshore-directed ice sheet flow. A series of well developed nested arcuate moraines can be traced across the shelf offshore of the mouth of Donegal Bay. These moraines define a former lobate ice margin(s) that extended to the shelf edge. A further lobe of Scottish-sourced ice is indicated by the set of prominent moraines located north of Donegal Bay in the Malin Sea
- Prominent zones of iceberg-ploughmarks are observed on the multibeam records distal to the moraines offshore of Donegal Bay. These give way downslope into a well developed system of gullies and canyons which incise the continental slope and extend to depths of 500 m. The gullies and canyons record a former line-sourced sediment supply related to an ice sheet margin that was positioned at or close the shelf edge (as indicated by the distribution of the arcuate moraines), and would have acted as pathways for the downslope transfer of sediment via turbidity current activity and mass wasting.
- The large-scale nested arcuate moraines offshore of Donegal Bay indicate that ice sheet retreat across the shelf in this region was grounded, episodic and was punctuated by occasional minor readvances. Initial retreat from the shelf edge was associated with an episode of ice sheet break-up and calving as recorded by the extensive zones of iceberg ploughmarks distal to the outermost moraine. It is conceivable that this could have been driven by rising sea level. Irrespective of the precise trigger for initial ice retreat, however, it would appear that the Irish Ice Sheet in this sector underwent a major reorganisation from an initial elongate ice sheet configuration that extended along the shelf edge, to a pronounced lobate form during retreat.
- Whilst the absence of dated sediment cores from the moraines themselves currently precludes a definitive age assessment, consideration of dated marine stratigraphic records from the wider NW margin nonetheless allows a provisional chronological interpretation.

Ice sheet extension to the shelf edge likely occurred about 29-27 cal ka BP, prior to the globally defined LGM, with subsequent retreat from this shelf edge position after 24 cal ka BP.

- Large-scale contrasts in continental margin morphology west of Ireland, from trough mouth fans in the north to gully/canyon systems further to south, reflects a combination of factors including relative dominance of meltwater-related sedimentation and spatial variations in sediment flux related to palaeo-glaciology. The Irish Ice Sheet offshore of western Ireland appears to have acted as a line source, delivering meltwater and sediment to the slope via canyon/gully systems rather than the formation of prograding large submarine fans composed of glacigenic debris flows.

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Figure Captions

Figure 1.

The northwest Irish continental margin showing published reconstructions of the extent of the former British-Irish Ice Sheet at the Last Glacial Maximum. Note the lack of agreement between the various authors on LGM ice limits in this region. Bathymetric data was gridded to 100 m and both grey depth scale and contours were derived from Irish National Seabed Survey data.

Figure 2.

(a) Multibeam swath bathymetry relief image of the NW Irish shelf showing the large northeast-southwest aligned arcuate recessional moraines. Note the regularly stepped sequence the moraines have across the shelf towards outer Donegal Bay. (b) Cross sectional profile taken across the nested moraines on inner to mid-shelf give an indication of the vertical scale of the nested moraines. (Note all profiles were generated from original depth values measured from the Multibeam swath bathymetry data. Image vertical exaggeration ×6.).

Figure. 3.

Geomorphological interpretation of the NW Irish shelf showing all the glacial and glacially related features identified on the Multibeam swath bathymetry data. Because two different data sets were needed to produce the background elevation image, one for deep water and one for the shelf, two different colour scales were needed.

Figure 4.

Sub-bottom profiler records from transects taken across two ridges in the study area. (a) Shows a profile of the ‘Donegal Bay Moraine’ (b) is taken across a moraine located on the mid-shelf. Note the stratified sediments that drape the ridges and the acoustically transparent sediment lenses interpreted as debris flows that off-lap the ridges. Sub-bottom profiler transect locations are shown in Figure 3. The ‘corrugations’ on the seafloor are artefacts.

Figure 5.

(a) 3D Multibeam bathymetric image gridded at 25 m showing a moraine ridge on the upper continental slope of the Porcupine Bank ~300m below sea level (See Fig. 3). Note how both the ridge and the surrounding seabed have been incised by numerous iceberg keels. (Image vertical exaggeration ×6).

Figure 6.

(a) A swarm of drumlins 5 km northwest of Tory Island provides a record of north-westerly ice flow across the shelf (b) A field of smaller scale drumlinoid landforms 5 km northwest of Arranmore Island give the seabed a streamlined appearance and provide a record of north-westerly ice flow across the shelf in this region. The location of both drumlin fields is highlighted in Figure 3. (c) Histograms of the frequency distribution of drumlin width, length and elongation ratio along with basic statistical measures of each measured parameter (See Fig. 3 for their location. Image vertical exaggeration ×6).

Figure 7.

(a) Numerous east-west aligned sub-parallel furrows incise the outer shelf in the centre of the study area in water depths between 110 to 210 m. They differ morphologically from the ice berg furrows identified on the NW shelf and may be related to erosion at the shelf break by either meltwater discharge and/or modern shelf currents (b) Iceberg ploughmarks in water depths of 140 to 200 m from the southern outermost continental shelf. (c) In cross-section many ice berg furrows have troughs several metres deep and pronounced lateral berms. All locations are shown in Figure 3. (Image vertical exaggeration ×6).

Figure. 8.

(a) Multibeam swath bathymetry 3D image showing gully/channel systems on the continental slope. The outermost moraine on the continental shelf and the sediment bulge of the Donegal Fan are clearly identifiable on the data. South of the Donegal Fan, three gully-canyon systems (1, 2 and 3 discussed in Section 3.3) dissect the continental slope. Between systems 2 and 3, a series of straight shallow gullies crossing the mid and lower slope can be observed. At the right side of the image, the ridges on the slope are also apparent. (b) Shows a topographic profile taken across a gully in the upper reaches of gully-canyon system 3. (c) Topographic profile taken across the lower reaches of gully-canyon system 3. (Image vertical exaggeration ×10).

Figure 9.

Slope analysis of the continental slope showing the steep gully and canyon walls and the off-lap of sediment wedges particularly around the edges of the Donegal Fan (north of 55°30' N). The largest slope angles (i.e. purple and blue) are observed along the canyon walls and at the gully heads.