Glacial and glacially-related features on the continental margin of northwest Ireland mapped from marine geophysical data

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Abstract

Despite over a century of research, reconstructions of the western margin of the last British-Irish Ice Sheet remain controversial. This is mainly because the ice sheet extended offshore onto the continental shelf and therefore significant portions of the glacial record are below present sea level. The availability of high resolution multibeam swath bathymetric and geophysical sub-bottom data for over ∼30,000 km^2 of the northwest Irish continental margin (between 55°40′ and 54°18′ N, and 7°50′ and 11°4′ W) has made it possible to map glacial features on the continental shelf and glacially-related features on the continental slope and rise. The resulting map, presented here at a scale of 1:260,000, shows that the major glacial features consist of subglacial bedforms and nested arcuate moraines of different orientations across the width of the shelf. Distal to these moraines, the outermost shelf and upper slope are crossed by sub-parallel and cross-cutting furrows created by iceberg scouring and meltwater discharge at the ice margin. A well-developed system of gullies and canyons and frequent escarpments incise the continental slope. Several large depositional lobes, likely related to the delivery of vast amount of sediment at the ice margin are found in inter-canyon areas and at the base of the slope. Collectively these data show an extensive ice sheet margin across the entire shelf and sedimentation on the continental margin was greatly affected by the presence of the ice margin at the shelf edge.

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1. Introduction

Despite more than a century of research, there is still no consensus on the western extent of the last British-Irish Ice Sheet (BIIS) (*cf*. Bowen et al., 1986; Hall and Bent, 1990; Stoker and Holmes, 1991; King et al., 1998; Bowen et al., 2002; McCabe and Clark, 2003; Sejrup et al., 2005). Recent studies of the onshore record in Ireland indicate that the Irish portion of the former BIIS extended offshore in the south, west and northwest, in some places up to 20 km (McCabe and Ó Cofaigh, 1996; Ó Cofaigh and Evans, 2001; Bowen et al., 2002; Ballantyne et al., 2008). Other work conducted to the north of the study site on the Scottish continental shelf also has confirmed that the former British Ice Sheet extended westwards as far as the shelf break (Bradwell et al., 2008). However, limited investigations on the western margin of the Irish shelf meant that former ice sheet limits are poorly constrained. This is partly because until recently no images or data of the seafloor around Ireland existed, except for outdated bathymetric charts based on Victorian era sounding lines.

Since 1999, the Irish Government has been collecting high-resolution marine geophysical data as part of the Irish National Seabed Survey (INSS, 1999-2005) and the Integrated Mapping for the Sustainable Development of Ireland's Marine Resource project (INFOMAR, 2006-ongoing) (Figure 1). The aim of the INSS and INFOMAR projects is to fully map Ireland's Exclusive Economic Zone (EEZ) through the collection of multibeam swath bathymetry, backscatter, sub-bottom, gravity, magnetic and ground-truthing data. The data are acquired and managed jointly by the Marine Institute (Galway) and the Geological Survey of Ireland and are made freely available to the scientific community from the web portal https://jetstream.gsi.ie/iwdds/index.html.

These data provide the first real opportunity to investigate the submerged landscape around mainland Ireland. The map presented here is a geomorphological interpretation of features interpreted as glacial and glacially-related on the northwest Irish continental margin based on the INSS and INFOMAR multibeam swath bathymetric data and on some key track-lines of seismic (sub-bottom) data (e.g. Figure 2). The map provides the first detailed view of the interpreted glacial geomorphology of the northwest Irish margin and for the first time shows the western limits of the former BIIS in this region.

2. Methods

The continental shelf, in waters deeper than 10 m, was surveyed in the period 2002-2008 by the RV Celtic Explorer and RV Celtic Voyager. Multibeam data were acquired using hull-mounted Simrad EM1002S and EM3002 on the Celtic Voyager and an EM1002 on

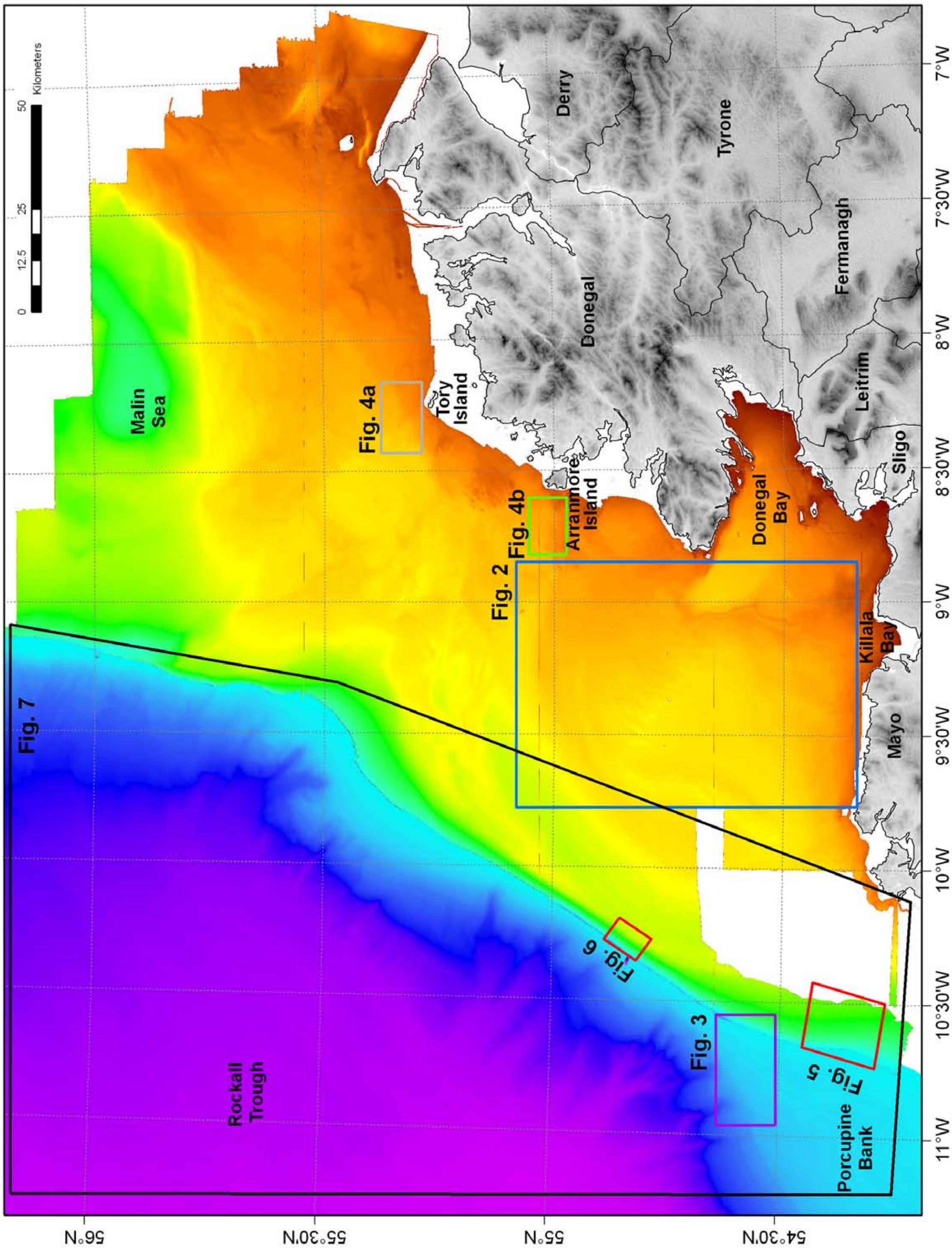

Figure 1. Overview of the INSS and INFOMAR multibeam swath bathymetric data on the north-west Irish margin with figure locations.

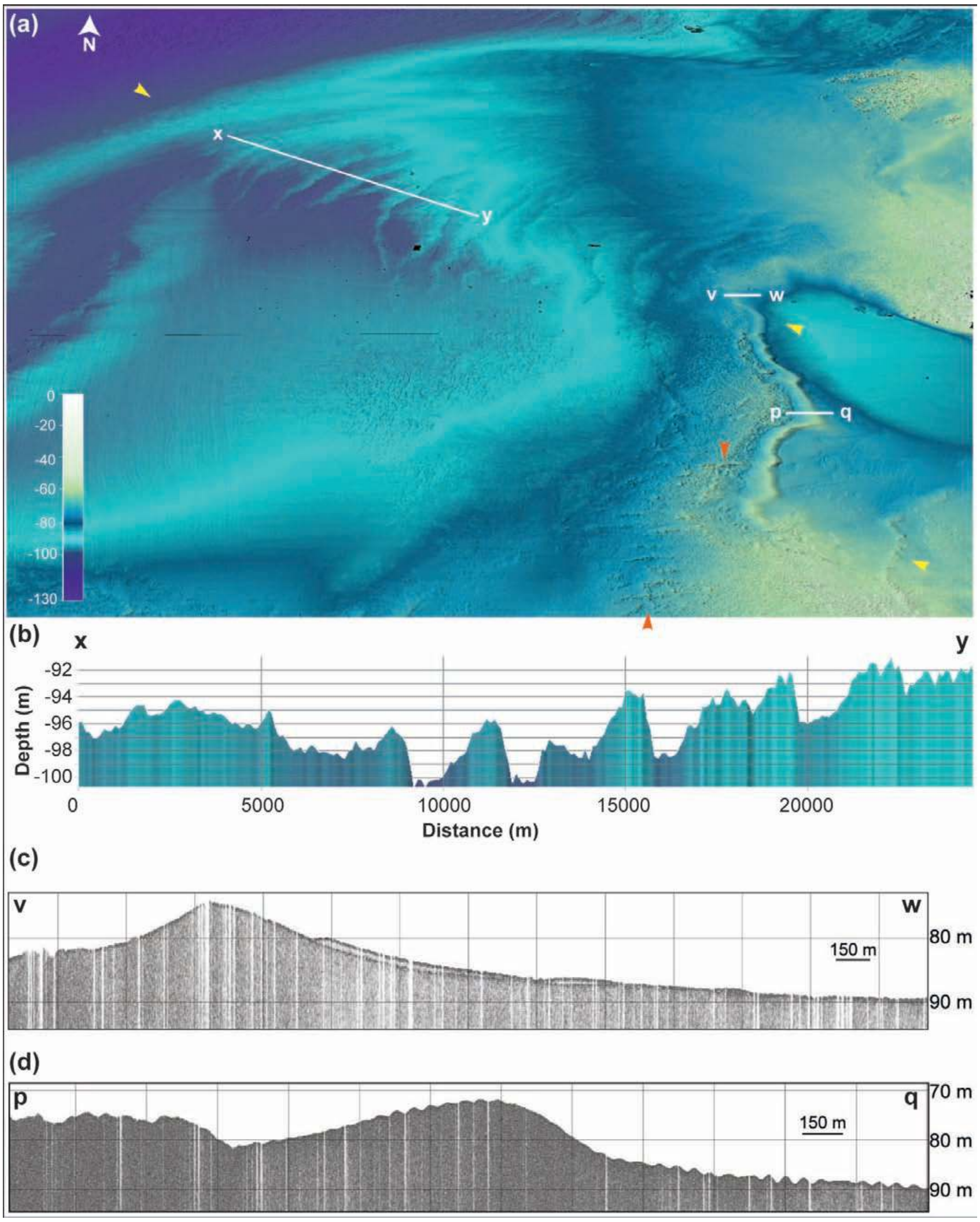

Figure 2. (a) Oblique view of multibeam swath bathymetry shaded relief showing the main set of nested NE-SW shelf moraines extending from the mouth of Donegal Bay (within yellow arrows). The outermost shelf moraine is not displayed. The set of east-west aligned moraines out of Killala Bay are also visible (within the orange arrows). See Figure 1 for image location. Image vertical exaggeration ×6. Note that the colour scale is not linear but has been modified in order to better display the moraine features. The topographic profile in (b) provides an indication of the horizontal distance at the profile location and the horizontal distance shown at the base of this figure is 55 km. (b) Topographic profile across a series of mid-shelf moraines (vertical exaggeration ×400). (c,d) Two examples of sub-bottom (pinger) profiles across the main moraine at the mouth of Donegal Bay at two different locations. (c) Shows stratified sediments draping the ridge and acoustically transparent sediment lenses (interpreted as debris flows by (Ó Cofaigh et al., in press) offlapping the ridge. The "corrugations" on the seafloor in (d) are artefacts due to weather conditions during acquisition.

the Celtic Explorer with decimetre vertical and horizontal accuracy that varies from 10 to 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 Bligh with an EM120 multibeam system. All survey positioning was done by differential GPS, which has a decimetre to metre horizontal accuracy. Additional information on data handling, processing and resolution for each of the surveys that cover the study area can be found in the cruise reports available online at https://jetstream.gsi.ie/iwdds/index.html.

The multibeam bathymetric data were gridded at a cell size of 5, 10, or 20 m on the continental shelf (between 10 and 230 m water depth) and at 25, 50 or 100 m on the continental slope and rise (below 200 m water depth), according to data quality, using the hydrographic package CARIS HIPS and SIPS 6.0. The gridded datasets were directly imported in ESRI ArcGIS 9.2, with shaded relief images also created in ERDAS Imagine 9.2 and IVS3D Fledermaus 6.7. At this stage the size of some of the datasets was such that the software could not handle them and the resolution was thus reduced to 15 or 20 m (see map for final resolution of gridded data).

The different visualizations (shaded reliefs in 2D in ArcGIS and 3D views in Fledermaus with vertical exaggeration $\times 6$) and the topographic profiles generated in Fledermaus were used to identify glacial and glacially-related features. To avoid the problem of azimuth biasing (*cf.* 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 within ESRI ArcGIS 9.2/9.3 or in IVS3D Fledermaus and then imported in to ESRI ArcGIS 9.2/9.3. Where single features are overlapping and they are evenly spread over a very large area (e.g. iceberg scours, Figure 6), then the overall distribution was delimited in place of mapping each singular feature.

The detailed interpretation of the glacial and glacially-related features included in this map and their significance for the glacial history of the British-Irish Ice Sheet are discussed in Ó Cofaigh et al. (in press).

3. Results

3.1 Moraines

Nested arcuate to straight moraines are the most common glacial landform observed on the continental shelf. The main series of moraines have a general northeast-southwest crest line orientation and extend over 90 km from the shelf break at 120 m water depth to the entrance of Donegal Bay at ∼60 m water depth (Figure 2). The crest line orientation of the main set of nested moraines suggests that they were formed at the margin of an ice lobe that extended offshore from Counties Donegal, Leitrim and Sligo (these moraines are referred to as 'Donegal moraines' in Ó Cofaigh et al., in press). The Donegal moraines are interpreted as ice marginal and recessional in origin (Ó Cofaigh et al., in press).

In the northernmost part of the study area, the moraines on the shelf display northwest to southeast crest lines and have been interpreted as being deposited by an ice advance from western Scotland . In the south, the moraines north of Killala Bay are smaller and their east-west alignment (Figure 2) suggests they were formed by an ice lobe centred south of Killala Bay in County Mayo. These moraines are superimposed on the Donegal moraines and are therefore younger, likely representing a readvance in the southern part of Donegal Bay after the deglaciation represented by the Donegal moraines (Ó Cofaigh et al., in press).

Additionally, a series of moraines with crest lines aligned in a east-northeast direction are found on the upper continental slope of the Porcupine Bank (in water depths of 300 to 400 m), in the south-western portion of the study area. Unlike the other moraines found on the shelf, they are overprinted by iceberg scours (Figure 3).

Dimensions of the moraines vary greatly: from the 14 m height, 11 km width, and 125 km length of the outermost moraine at the shelf edge to the 2.5–5 m height, 100–700 m width, and 0.7–3 km length of the east-west aligned moraines out of Killala Bay (some examples of topographic profiles across the shelf moraines are in Figure 2). More details on the dimensions of these moraines are given in Ó Cofaigh et al. (in press).

The two outermost ridges are narrower and more fragmented in their southern portion, while they spread out in the northern parts to reach the aforementioned dimensions. Conversely, the moraines in the mid- and inner shelf appear to be sharper and narrower. Modern bottom currents are known to be quite intense in the area and especially near the shelf edge, but quickly become less intense when moving onto the mid-shelf (Xing and Davies, 2001). Thus post-glacial reworking of seafloor sediments by bottom

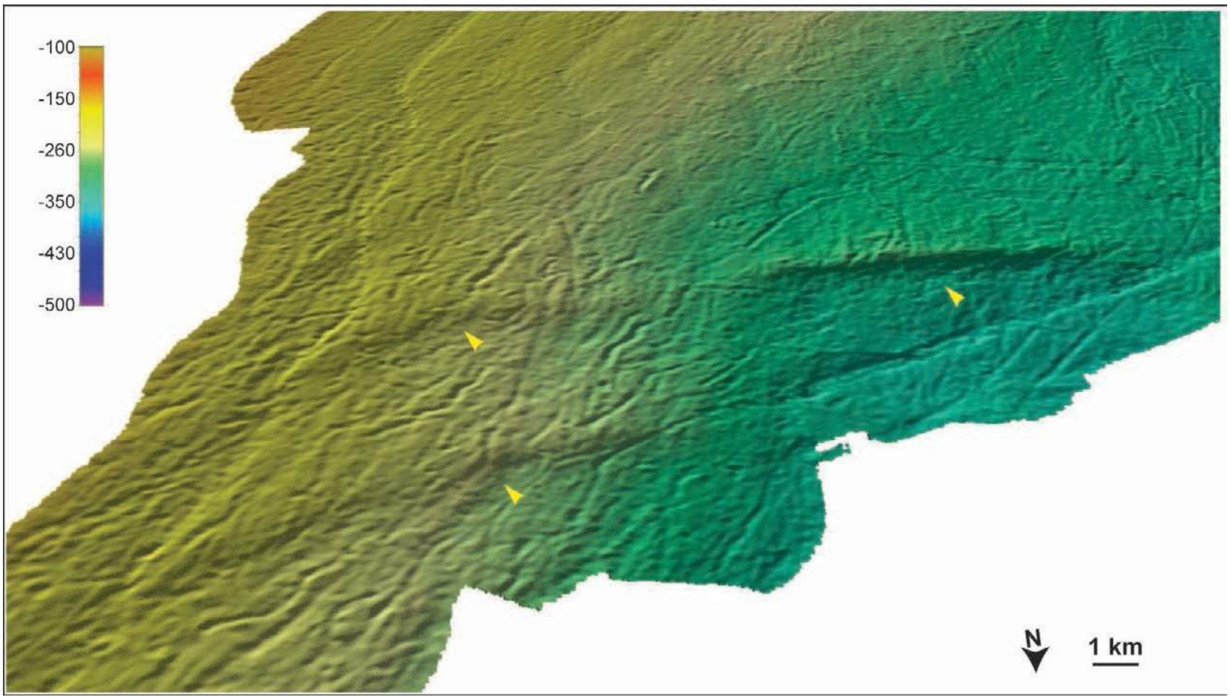

Figure 3. Vertical view on some of the slope moraines (yellow arrows) crossed by iceberg scours. The resolution of this dataset is 25 m. See Figure 1 for image location. Image vertical exaggeration ×6. Note that the colour scale is not linear but has been modified in order to better display the features.

currents may partially explain the large dimensions and fragmentation of the outermost moraines.

3.2 Drumlins and drumlinoid landforms

In the northeastern sector of the study area, 5 km northwest of Tory Island, a field of well defined elongate mounds are clearly visible on the multibeam data (Figure 4a; 55°18′N 8°21′W). The mounds range in height from 1 to 5.5 m (e.g. Figure 4b), 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 (Figure 4c; 55°1′N 8°39′W). Although smaller in scale, they have a similar elongate morphology and all have the same northwest-southeast alignment (∼290°–310°). 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. The majority of them tend to be between 100 and 1200 m in length, 100 and 600 m in width and 1.5 to 5 times longer than they are wide. 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; Ó Cofaigh et al., 2002; McCabe and Dunlop, 2006; Smith et al., 2006; Greenwood and Clark, 2009). Statistics from a large sample of drumlins (58,983) has been recently presented by Clark et al. (2009) who report mean drumlin length to be 629 m, mean width to be 209 m and mean elongation ratio to be 2.9. Therefore based on their morphological and morphometric properties, the mounds located on the NW Irish shelf have been interpreted as being drumlins which record northwesterly ice flow across the shelf (Ó Cofaigh et al., in press).

3.3 Iceberg scours and sub-parallel erosional features

Beyond the outermost shelf moraine, the seafloor of the outer shelf and upper portion of the continental slope is extensively furrowed, in places down to 500 m water depth. Two different types of furrows can be observed.

The first are iceberg scours, which are evident north of 55°17′N and south of 54°38′N. These furrows are generally sinuous and form a cross-cutting pattern on the seafloor. They are up to 3–4 m deep, up to 300 m wide, range from a few hundred metres to ∼15 km in length (Figure 5a,b) and they are bounded by either single or double lateral berms (Figure 5b). In the northern part they have an overall east to west orientation and in the southern part a northeast to southwest orientation (Figure 5a), which is interpreted to reflect the predominant palaeo-current direction during iceberg calving events.

Between the two areas of iceberg scours, the second type of furrows, sub-parallel furrows, are observed in 110 to 270 m water depth, although the resolution of the data in deeper water is too low to assess to which depth these features continue. They are mostly oriented east to west, and measure up to 3 m deep and 50 m wide, and are on average between 500 and 1000 m long (Figure 6). They do not resemble classical iceberg scours (*cf.* Belderson et al., 1973; Praeg et al., 1987; Ó Cofaigh et al., 2002), being sub-parallel, generally shorter and not presenting any berms. Their position distal to the outermost moraine and beyond the shelf break, where there is a marked increase in slope angle, indicates they are not ice contact features but are more likely related to erosion due to either meltwater discharge during glaciation or shelf edge spill over of modern shelf currents (Ó Cofaigh et al., in press).

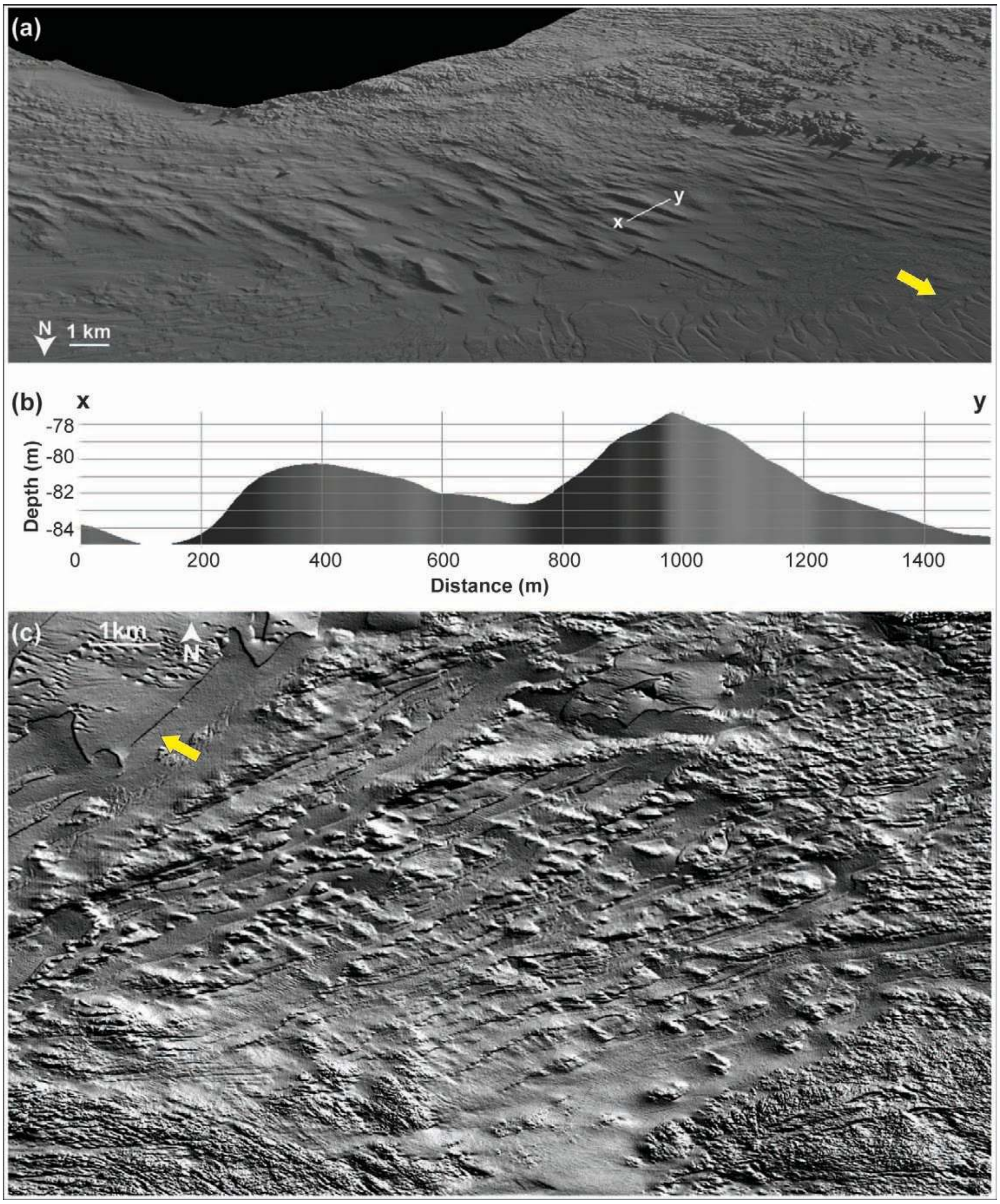

Figure 4. (a) Vertical view of the shaded relief of a swarm of drumlins, 5 km northwest of Tory Island, recording the north-westerly ice flow across the NW Irish shelf (indicated by the yellow arrow) (Image vertical exaggeration ×6). (b) Topographic profile across two of the drumlins. (c) A swarm of 59 smaller drumlinoid landforms 5 km northwest of Arranmore Island also recording of north-westerly ice flow across the shelf in this region. The location of both drumlin fields is highlighted in Figure 1.

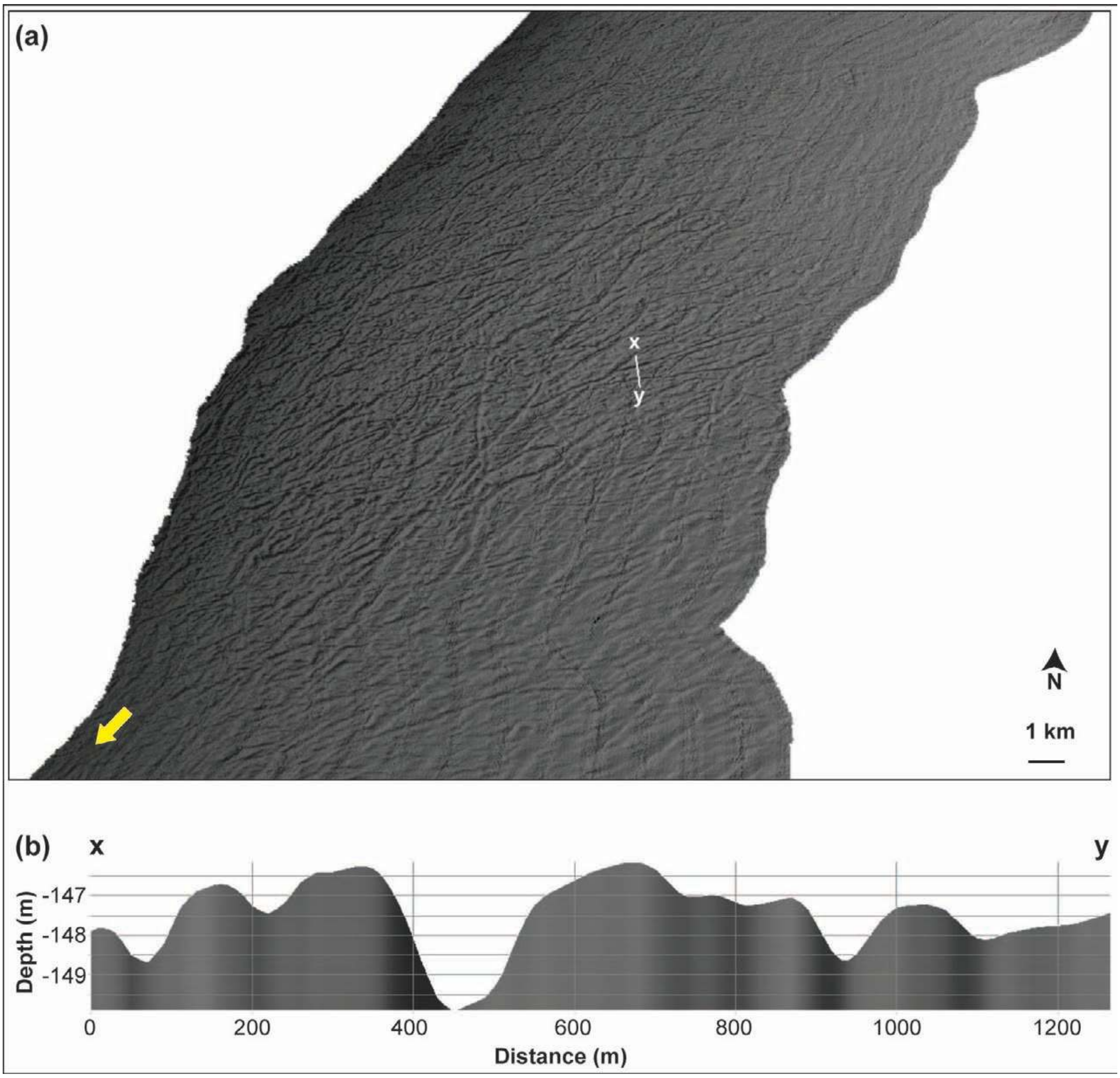

Figure 5. (a) Vertical view of iceberg scours in water depths of 140 to 200 m from the southern outermost continental shelf. The yellow arrow indicates the overall NE-SW orientation of the furrows. (b) Cross-section across several scours showing depths of furrows and pronounced lateral berms.

3.4 Deep water: gullies and canyons, scarps and depositional lobes

The upper continental slope below 400 m water depth is dissected by gullies that are up to 20 km long, 3 km wide and 200 m deep. They merge downslope into larger (up to 6 km wide) and deeper canyons (up to 350 m deep) that extend to about 2700 m water depth, where they open onto the abyssal plain of the Rockall Trough. Four vast gully

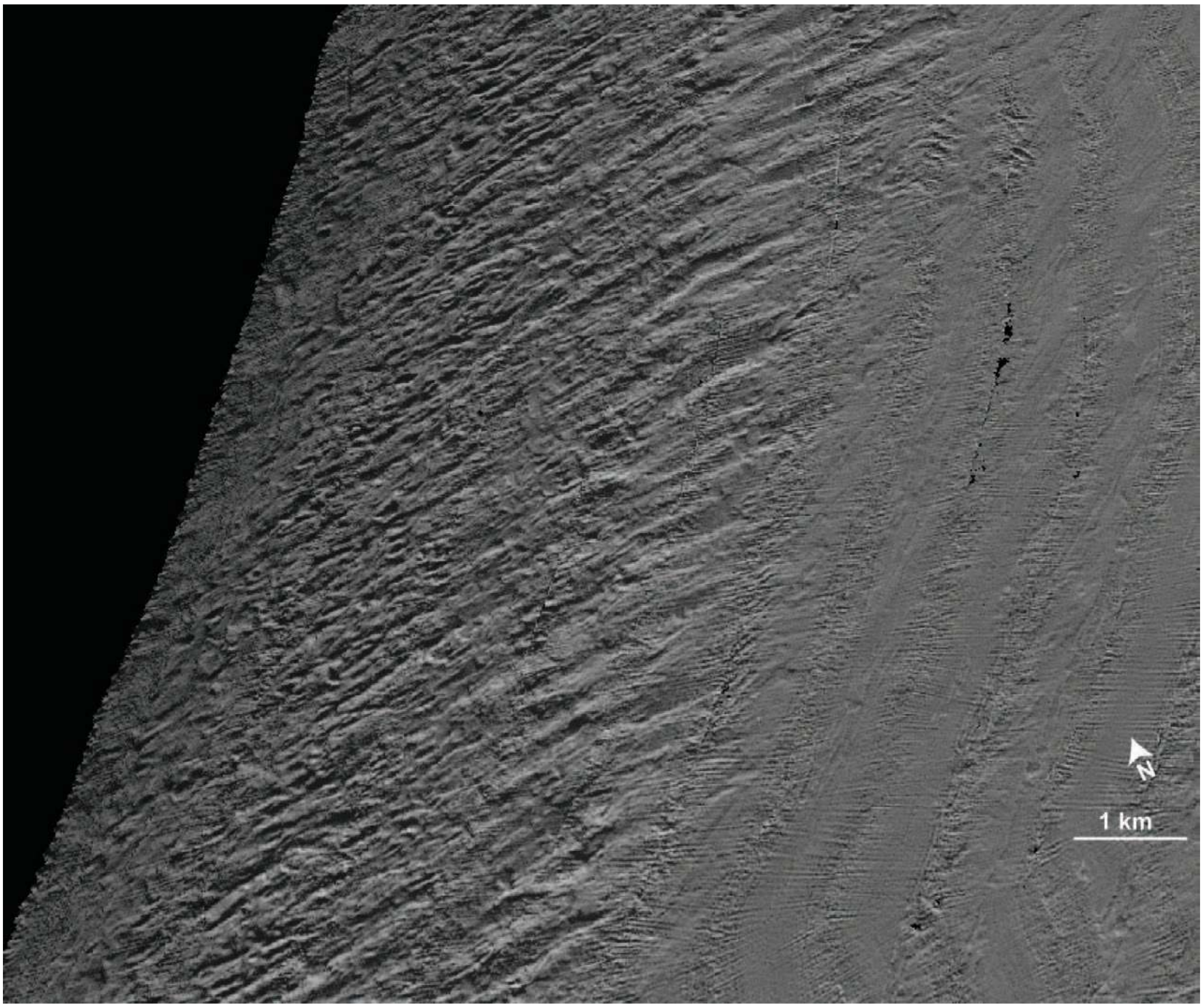

Figure 6. Vertical view over east-west aligned sub-parallel furrows on the outer shelf in the centre of the study area in water depths between 110-210 m. Location show in Figure 1. Image vertical exaggeration ×6.

and canyon systems have been identified along the continental margin within the study area (Figure 7).

Inter-canyon areas are characterised by three large sediment depositional lobes, frequent escarpments (especially around the gully and canyon heads), and shallow gullies (up to 40-50 m deep and 4 km wide) which are better developed below 1500 m water depth.

The northernmost depositional lobe is formed by glacigenic debris flows deposited in the southern portion of the Donegal Fan (Stoker, 1995). Additional depositional lobes, offlapping onto the basin of Rockall Trough, are observed extending from the base of the continental slope to water depths of 2400 to 2600 m (Figure 7).

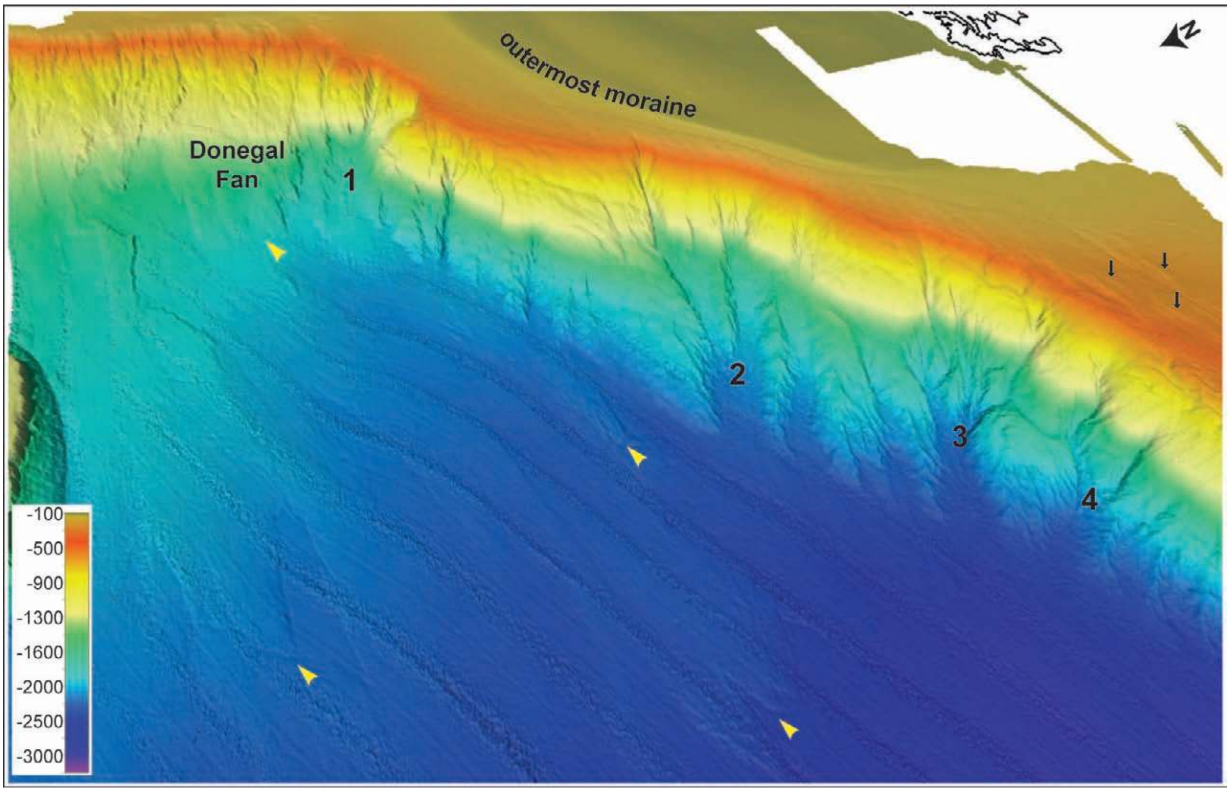

Figure 7. Oblique view of shaded relief of deep water portion of the north-west Irish continental margin from INSS multibeam data. The sediment bulge of the Donegal Fan is evident in the northern part of the margin (right inside). Main gully and canyon systems are numbered. The yellow arrows show the offlapping of mass transport deposits onto the abyssal plain of the Rockall Trough. Black arrows point to some of the slope moraines that are visible in the southern portion of this view (left inside). See Figure 1 for image location. Image vertical exaggeration ×10. Note that the colour scale is not linear but has been modified in order to better display the features. The horizontal distance shown at the base of this figure is 17 km.

It is likely that the dimensions and location of many of these deep-water features are related to the presence of former ice margins on the outermost shelf or at the shelf edge and ensuing delivery of large volumes of sediment and meltwater to the upper slope. In some areas, these sediments have been redistributed downslope by turbidity currents and mass wasting, thus contributing to further incision of the large canyon systems (*cf.* Cronin et al., 2005; O'Reilly et al., 2007). In other places, the glaciomarine debris has prograded or failed onto the slope without evolving into long run-out gravity flows, as for example on the Donegal Fan (*cf.* Stoker, 1995). Ó Cofaigh et al. (in press) argue that the difference in these slope depositional processes is related to variations in sediment flux related to paleo-glaciology, with a main zone of ice-streaming focused in the area of the Donegal Fan.

4. Conclusions

This map provides the first unequivocal evidence for extensive glaciation on the northwest Irish continental shelf.

Drumlins on the inner shelf record former offshore-directed ice sheet flow. The series of well-developed, nested, arcuate moraines across the shelf document a former ice margin(s) that extended to the outermost continental shelf/shelf edge. The extensive zones of iceberg plough marks distal to the outermost moraine indicate that the initial retreat from the shelf edge was associated with large calving events, perhaps triggered by rising sea level. These calving events resulted in ice sheet reorganisation and development of a large grounded ice lobe on the shelf. This is consistent with recent reconstructions of the marine-based northern sector of the British-Irish Ice Sheet (Bradwell et al., 2008). After this, the spatial distribution of shelf moraines indicate slow ice sheet retreat, characterised by numerous still-stands, without the occurrence of major calving events as testified by the lack of iceberg scours overprinting the shelf moraines.

The gullies and canyons on the continental slope record a former line-sourced sediment supply related to an ice sheet margin that was positioned at, or close to, the shelf edge. This arrangement would have provided pathways for the transfer of sediment from the shelf to abyssal depths via turbidity current activity and mass wasting.

The age of all these features is still unknown. Ó Cofaigh et al. (in press) took into consideration dated marine stratigraphic records from the wider NW Irish margin and proposed that the ice sheet extended to the shelf edge at about 29-27 cal ka and subsequently retreated from this shelf edge position after 24 cal ka. Dated sediment cores are required to verify this hypothesis.

Software

The multibeam data were gridded in CARIS HIPS and SIPS hydrographic software package version 6.0 and rendered in ERDAS Imagine 9.2 and IVS3D Fledermaus 6.7. All landforms identified on the data were digitised on-screen directly into ESRI ArcGIS 9.2/9.3 or in IVS3D Fledermaus and then imported in ESRI ArcGIS 9.2/9.3. The final map was created using ESRI ArcMap 9.3. The sub-bottom data were consulted in CODA DA series system.

Data

The author has supplied data (as an ESRI Shapefile) used in the production of the accompanying map. This PDF has a ZIP archive embedded within it (stored as a .ZI file extension) containing the data and can be accessed by right-clicking on the "paperclip" icon at the beginning of this section (you will need to save the file and edit the file extension to .ZIP). Whilst the contents of the ZIP file are the sole responsiblity of the author, the journal has screened them for appropriateness.

Acknowledgements

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