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1 **Early deglaciation of the British-Irish Ice Sheet on the Atlantic shelf northwest of Ireland**  
2 **driven by glacioisostatic depression and high relative sea level**

3 Colm Ó Cofaigh<sup>1</sup>, Kasper Weilbach<sup>1</sup>, Jerry M. Lloyd<sup>1</sup>, Sara Benetti<sup>2</sup>, S. Louise Callard<sup>1</sup>, Catriona  
4 Purcell<sup>3</sup>, Richard C. Chiverrell<sup>4</sup>, Paul Dunlop<sup>2</sup>, Margot Saher<sup>3</sup>, Stephen J. Livingstone<sup>5</sup>, Katrien J.J.  
5 Van Landeghem<sup>3</sup>, Steven G. Moreton<sup>6</sup>, Chris D. Clark<sup>5</sup> and Derek Fabel<sup>7</sup>

6 <sup>1</sup> *Department of Geography, Durham University, Durham, DH1 3LE, UK*

7 <sup>2</sup> *School of Geography and Environmental Sciences, Ulster University, Coleraine, BT52 1SA,*  
8 *Northern Ireland*

9 <sup>3</sup> *School of Ocean Sciences, Bangor University, Menai Bridge, UK*

10 <sup>4</sup> *Department of Geography, University of Liverpool, Liverpool, UK*

11 <sup>5</sup> *Department of Geography, University of Sheffield, Sheffield, S10 2TN, UK*

12 <sup>6</sup> *Natural Environment Research Council, Radiocarbon Facility, East Kilbride, Scotland, G75 0QF,*  
13 *UK*

14 <sup>7</sup> *Scottish Universities Environmental Research Centre, East Kilbride, Scotland, G75 0QF, UK*  
15

16 **ABSTRACT**

17 Understanding the triggers and pace of marine-based ice sheet decay is critical for constraining the  
18 future mass loss and dynamic behaviour of marine-based sectors of the large polar ice sheets in  
19 Greenland and Antarctica. Numerical models which seek to predict this behaviour need to be  
20 calibrated against data from both contemporary and palaeo-ice sheets, and the latter requires  
21 accurate reconstruction of former ice sheet extent, dynamics and timing. Marine geophysics,  
22 sediment cores, benthic foraminiferal assemblages and radiocarbon dating are used to reconstruct  
23 the extent of the last British-Irish Ice Sheet (BIIS), and the timing and style of its retreat on the  
24 Atlantic shelf northwest of Ireland. Shelf edge moraines and subglacial till recovered in cores from  
25 the outer continental shelf are dated to younger than 26.3 ka cal BP and indicate an extensive ice  
26 sheet at the Last Glacial Maximum (LGM) that was grounded to the shelf edge. Nested arcuate  
27 moraines record the subsequent episodic retreat of the ice sheet across the shelf. Lithofacies and  
28 associated foraminiferal assemblages demonstrate that this retreat occurred in a glacial marine  
29 environment as a grounded tidewater margin and that high relative sea level and cold waters  
30 prevailed during retreat. Radiocarbon dates indicate that the timing of initial ice sheet retreat from  
31 the shelf edge occurred in the interval between 26.3 and 24.8 ka cal BP, during the period of  
32 minimum global eustatic sea level, and that the ice sheet had retreated to the mid-shelf by 24.8 ka  
33 cal BP. The ‘Donegal Bay Moraine’, a large moraine at the mouth of Donegal Bay, records a major  
34 stillstand and readvance of the ice sheet during deglaciation between 20.2 and 17.9 ka cal BP.  
35 Estimated retreat rates of 5.5–35 m a<sup>-1</sup> across the shelf demonstrate that retreat was slow. It is  
36 noteworthy that retreat was initiated in the absence of ocean warming and when eustatic sea level  
37 was at a minimum. The sea-level rise that initiated deglaciation from the shelf edge therefore, is  
38 inferred to have been a product of local glacio-isostatic crustal depression rather than external  
39 forcing. This demonstrates that marine-based sectors of ice sheets can trigger their own demise  
40 internally through glacio-isostatic adjustment and it provides an explanation for the early retreat of  
41 the BIIS on the Atlantic shelf during the global LGM (gLGM).

42

43 **KEYWORDS:** British-Irish Ice Sheet; Ireland; continental shelf; last glacial maximum; ice sheet  
44 retreat; radiocarbon dating; moraines; glacimarine.

45

## 46 1. INTRODUCTION

47 Understanding the dynamic behaviour of marine-based sectors of large ice sheets is of considerable  
48 importance due to the potential inherent instability of these ice masses and their impact on sea level  
49 (Bamber et al., 2007; Rignot et al., 2014; Joughin et al., 2014). Numerical ice sheet models that  
50 seek to predict the future dynamic behaviour of marine-based ice sheets and, in particular, how they  
51 will deglacialate in response to a warming climate are often limited by the short time period over  
52 which modern observations extend. Such models are strengthened when tested against  
53 chronologically, geomorphologically and stratigraphically well-constrained retreat histories  
54 extending over centuries to millennia for individual ice sheets and ice sheet sectors (e.g., Lecavalier  
55 et al., 2011; Bentley et al., 2014; Stroeven et al., 2016).

56 The British-Irish Ice Sheet (BIIS) reached its maximum about 27 ka when it was estimated to have  
57 been ca. 840,000 km<sup>2</sup> in area, of which ca. 300,000 km<sup>2</sup> was marine-based (Clark et al., 2012), and  
58 it was drained by several fast-flowing ice streams (Eyles and McCabe 1989; Ó Cofaigh and Evans,  
59 2001; Bradwell et al., 2007; Livingstone et al., 2010; C. Clark et al., 2012; Chiverrell et al., 2013).  
60 Although the BIIS was relatively small, its proportionately large marine-based area, combined with  
61 its location bordering the North Atlantic, an area known to have experienced large-scale climatic  
62 and oceanographic changes during the last cold stage, would have meant that it was sensitive to  
63 external forcing(s) and thus make it a useful analogue for how marine-influenced ice sheets  
64 deglacialate (C. Clark et al., 2012). While there has been well over a century of research on the last  
65 BIIS, the majority of this work, with some exceptions (Scourse et al. 1991, 2000; Stoker, 1995), has  
66 focused on its terrestrial geological and geomorphological record. In the last decade, however, the  
67 application of improved marine geophysical techniques such as multibeam swath bathymetry (e.g.,  
68 Van Landeghem et al., 2009; Dunlop et al., 2011; Ó Cofaigh et al., 2012) and the compilation of  
69 single beam datasets such as OLEX (Bradwell et al., 2008;; C. Clark et al., 2012; Sejrup et al.,  
70 2016) has accelerated this research on the continental shelves adjoining Ireland and Britain

71 In this paper we refer to the global Last Glacial Maximum (gLGM) and local Last Glacial  
72 Maximum (lLGM). The term gLGM is used to refer to the period of 26.5-19 ka when eustatic sea  
73 level was at a minimum and sheets were at their maximum extent (P. Clark et al., 2009). However,  
74 it is accepted that the timing of the maximum extension of individual ice sheets and different sectors

of individual ice sheets was variable (e.g., Patton et al., 2016). Hence the term ILGM refers to the period when a specific ice sheet, such as the last British-Irish Ice Sheet (BIIS), reached its maximum extent. The ILGM for the BIIS was attained slightly earlier than the gLGM at 27 ka (C. Clark et al., 2012).

On the continental shelf northwest and west of Ireland several studies have reconstructed ice sheet extent and flow patterns from marine geophysical and geological investigations (Benetti et al., 2010; Dunlop et al., 2010; Ó Cofaigh et al., 2012, 2016a; C. Clark et al., 2012; Peters et al., 2015, 2016; Callard et al., 2018). These studies have provided evidence for shelf-edge terminating, grounded ice. Although presumed to be of ILGM age, direct dating control on the age of the ice sheet advance and timing and rate of retreat across the shelf is limited to two studies: Peters et al. (2016) from offshore western Ireland, to the south of our study area, and Callard et al. (2018) from further to the north in the Malin Sea.. On the Atlantic shelf offshore of northwest Ireland Ó Cofaigh et al. (2012) documented a set of well-developed, nested arcuate moraines which extend inshore from the shelf edge to the mouth of Donegal Bay (Fig. 1). These moraines provide compelling evidence for a grounded ice sheet retreating across the shelf but the timing of advance and retreat, the associated drivers and the nature of the depositional environment(s) are unknown. The present paper addresses this through sedimentological and micropalaeontological investigations of a suite of new sediment cores from the shelf (Fig. 1) dated using twenty two AMS radiocarbon dates and constrained by new sub-bottom profiler records. These cores provide potentially the best dated record for any offshore sector of the last BIIS. Together with the sedimentological, micropalaeontological, and seismostratigraphic analyses, they allow us to constrain the timing of ice sheet advance to the Atlantic shelf edge offshore of northwest Ireland and its subsequent retreat, describe the depositional environments during deglaciation, and finally, to characterize the drivers forcing retreat across the shelf and in particular to determine the role, if any, of ocean warming in this.

## 2. METHODS

The study area is located between 55° 40' and 54° 18' N, and 7° 50' and 11° 4' W and is about 30,000 km<sup>2</sup> in size (Fig. 1). The shelf edge is located at about 125 m water depth and the low gradient shelf extends for over 100 km to the mouth of Donegal Bay where water depths shallow to less than 80 m.

The multibeam swath bathymetric data included in this paper were collected by the Irish Marine Institute and the Geological Survey of Ireland since 1999 as part of the Irish National Seabed

109 Survey (INSS) and Integrated Mapping for the Sustainable Development of Ireland's Marine  
110 Resource (INFOMAR) programmes. These data have already been discussed and published in  
111 Benetti et al. (2010) and Ó Cofaigh et al. (2012, 2016a) and no new geomorphological mapping is  
112 provided here. However, these data are included to provide a geomorphological context for the  
113 seismic records, sediment cores and dating. The swath bathymetry data were acquired during  
114 surveys of the continental shelf by the *RV Celtic Explorer* and *RV Celtic Voyager* in the period  
115 2002-2008. The multibeam systems used were a hull-mounted Simrad EM1002S and EM3002 on  
116 the Celtic Voyager and an EM1002 on the Celtic Explorer with decimetric vertical and horizontal  
117 accuracy that varies from 10-50 cm according to water depth. The data are gridded at a cell size of  
118 10, 15 or 20 m on the continental shelf according to depth and data quality.

119

120 The sub-bottom profiler data and sediment cores presented in this paper were collected during  
121 research cruises to the continental shelf in 2008 and 2014. Cruise CE08 of the *RV Celtic Explorer* in  
122 2008 used the Geological Survey of Ireland 6 m long vibrocorer to collect a suite of ten vibrocores  
123 along an east-west transect across the shelf (Table 1 and Fig. 1). A further east-west transect of  
124 seventeen cores were collected further to the south in 2014 using the British Geological Survey  
125 vibrocorer (also with a 6 m barrel) during cruise JC106 of the *RRS James Cook* (Table 1 and Fig.  
126 1). Core sites targeted the series of arcuate moraines imaged in the multibeam data from the shelf  
127 (Fig. 2) and individual sites were picked using data from a hull-mounted Kongsberg SBP120 sub-  
128 bottom profiler. The system operates a sweep frequency between 2500 to 6500 kHz, with a depth  
129 resolution of 0.3 ms and a maximum penetration depth of about 50 m (depending on the nature of  
130 the sediments). The profiles were interpreted using the IHS Kingdom™ software. To convert the  
131 two-way travel time to depth estimates an average p-wave velocity of 1620 ms<sup>-1</sup>, measured from  
132 sediment cores using a Multi-Sensor Core Logger (MSCL) was used.

133 Following recovery the sediment cores were cut into 1 m long sections. They were then split and  
134 information was recorded on grain size, sedimentary and deformation structures, colour, sorting,  
135 bed contacts, clast abundance, clastshape and macrofaunal content. Measurement of sediment shear  
136 strength in kPa was recorded using a Torvane. The cores were stored on ship and subsequently in  
137 Durham University at +4°C. Additional information on sedimentary structures was obtained from  
138 the post-cruise examination of x-radiographs of the sediment cores. The x-radiographs were created  
139 using a GEOTEK MSCL-XCT scanner.

140 Samples of marine carbonate (typically single or broken valves) and benthic foraminifera were  
141 picked from the cores for radiocarbon dating. A total of 22 radiocarbon dates were acquired during  
142 the course of this study. Sampling typically targeted lithofacies boundaries or, where the cores

143 actually bottomed out in deglacial sediment, the base of the core in order to obtain a minimum age  
144 constraint on the timing of ice sheet retreat. Samples were dated at the Natural Environment  
145 Research Council (NERC) Radiocarbon Facility (NRCF-East Kilbride). The radiocarbon dates were  
146 corrected for isotopic fractionation and a BRITICE-CHRONO specific full process background of  
147  $0.30 \pm 0.01$  pMC (percent modern carbon). They were calibrated with OxCal 4.2 (Bronk Ramsey,  
148 2009) using the Marine13  $^{14}\text{C}$  calibration curve (Reimer et al., 2013), which has an in-built marine  
149 reservoir correction of 400 years. Additionally,  $\Delta R$  values of 0, 300, and 700 years were used  
150 (Table 2.) to simulate the possible range of the marine radiocarbon reservoir effect that may have  
151 prevailed in the North Atlantic during the demise of the British-Irish Ice Sheet and which is poorly  
152 constrained (e.g. Wanamaker et al., 2012). For clarity, only the calibrated ages with  $\Delta R = 0$  ( $\pm 2$   
153 sigma) are used in the text.

154 Micropalaeontological analysis on foraminifera was conducted on a total of 63 samples from six  
155 sediment cores. Two cores were sampled at 16 cm increments through the entire core length, and  
156 another four cores were sampled at varying increments across key changes in lithofacies. For each  
157 sample 5 to 7 ml of sediment was wet sieved through 500 microns and 63 microns sieves.  
158 Foraminifera were then dry picked from the 63 to 500 micron fraction of sediment using a Leica  
159 MZ75 binocular microscope. Large bulk samples were split to obtain samples with 300 foraminifera  
160 tests. Individuals were counted and identified to species level and species counts were then  
161 converted to percentages.

## 162 **3. GEOPHYSICAL DATA**

### 163 **3.1 Seafloor geomorphology**

#### 164 *3.1.1 Description*

165 Multibeam-swath bathymetric data extending from the mouth of Donegal Bay to the continental  
166 shelf edge show a series of prominent NE to SW aligned and nested sediment ridges on the shelf  
167 (Fig. 2) (Ó Cofaigh et al., 2012, 2016a). Most of the ridges are arcuate in planform although some  
168 of the longer ridges have relatively straight sections. The most prominent ridge occurs at the mouth  
169 of Donegal Bay (Fig. 2). This large ridge (termed hereafter the ‘Donegal Bay Moraine’) is 35 km  
170 long, up to 2.5 km wide and 15 m high. The ridge is generally sharp-crested but towards its  
171 northern end it has a broader, flatter profile. Further offshore and extending across the mid-shelf is a  
172 suite of closely-spaced, arcuate ridges. The outer ridges in this sequence are 0.2 to 3.5 km wide, 1 to  
173 4 m high, and are lobate and nested. Morphologically the ridges tend to be asymmetric with a  
174 gentler seaward (NW) side and a steeper landward (SE) side.

175 A further set of ridges extends northwards from the mouth of Killala Bay off the north Mayo coast.  
176 They are predominantly aligned east–west, are straight to arcuate in planform, 0.7–3 km long, 0.1–  
177 0.7 km wide and 2.5–5 m high. Termed the ‘Killala Moraines’ (Fig.1) (Benetti et al., 2010; Ó  
178 Cofaigh et al., 2012). They are superimposed on top of the Donegal Bay Moraine, and are therefore  
179 younger.

180

### 181 3.1.2 Interpretation

182 The arcuate sediment ridges on the shelf have been interpreted as moraines formed at the margin of  
183 a grounded Irish Ice Sheet (see Ó Cofaigh et al. 2012, 2016a). The largest moraines are positioned  
184 along the shelf edge and record the outermost extent of shelf glaciation. Further inshore the  
185 moraines are smaller, closely spaced, nested and often arcuate in planform and are asymmetric with  
186 steeper ice-contact faces. They record episodic, ice-marginal recession, punctuated by minor  
187 readvances or oscillations (Ó Cofaigh et al. 2012, 2016a). Such oscillations are consistent with  
188 localised bifurcation of the ridges. The arcuate outer moraines record the former presence of a large  
189 ice lobe which extended over 80 km from the mouth of Donegal Bay to the shelf edge and was up to  
190 approximately 120 km wide. The moraines indicate that at the glacial maximum the BIIS margin  
191 was grounded at the shelf break (Ó Cofaigh et al. 2012). The prominent Donegal Bay Moraine (Fig.  
192 2) has been interpreted variously as a readvance limit formed during the Killard Point Stadial (J.  
193 Clark *et al.* 2009) or a recessional moraine formed during deglaciation (Ó Cofaigh *et al.* 2012). The  
194 age of this moraine is discussed further below. Based on their superimposition on top of the  
195 Donegal Bay Moraine, the smaller east-west ridges are interpreted as a series of moraines that  
196 record a late-stage, lobate, readvance of ice into Donegal Bay from the south (Benetti et al., 2010; Ó  
197 Cofaigh *et al.* 2012).

198

## 199 3.2 Acoustic Facies

### 200 3.2.1 Description

201 Figure 3 shows a sub-bottom profile line that extends eastwards from the shelf edge to Donegal  
202 Bay. The profile can be divided into four sections: (1) Outer shelf and shelf break; (2) Mid-shelf;  
203 (3) Donegal Bay Moraine; and (4) Inner shelf (Fig. 3). The outer shelf contains a prominent  
204 moraine that is visible on both the multibeam (see above) and sub-bottom profiler data (Figs. 2 and  
205 3). The mid-shelf extends ca. 35–40 km to the Donegal Bay Moraine with a water depth of about  
206 100 m. The Donegal Bay Moraine consists of two parts: a 2.5 km wide "eastern ridge" with a steep

207 inner slope and a western, outer ridge that has an irregular surface. The inner shelf extends  
208 eastwards from the Donegal Bay Moraine for approximately 25 km to the shallow coastal area. .  
209 Three acoustic facies are recognised along this sub-bottom profile (Figs. 3 and 4).

#### 210 Facies A

211 Facies A is acoustically structureless and constitutes the lowermost acoustic facies imaged in this  
212 study. It occurs across the shelf but is best seen in records from the mid- and inner shelf. It has a  
213 pronounced sub-seafloor topography within the mid-shelf basin where it comprises a series of what  
214 appear to be buried ridges 20-25 m high and 0.5-1 km wide (Figs. 3 and 4). The buried ridges can  
215 be seen across the mid-shelf and become larger with increasing distance to the west. Inter-ridge  
216 areas are commonly infilled by acoustic Facies B (Fig. 4). On the west side of the Donegal Bay  
217 Moraine, Facies A is interbedded with the acoustically laminated sediments of Facies B the west  
218 (Fig. 4). Cores from Facies A (CE08-008, JC106-108, JC106-110, JC106-111, JC106-112)  
219 recovered stiff, massive, matrix-supported diamicton (Lithofacies 1 – see below).

#### 220 Facies B

221 Facies B overlies unconformably Facies A and is characterised by well-developed, acoustic  
222 stratification with frequent parallel and sub-parallel, moderate amplitude reflectors (Figs. 3 and 4).  
223 It is particularly prominent on the inner-shelf where it onlaps Facies A and reaches a thickness of at  
224 least 40 m (Fig. 3). On the mid-shelf Facies B attains a thickness of ca. 25 m and infills the  
225 depressions between the topographic highs of Facies A, in some cases on-lapping the basin sides.  
226 (Fig 3). Figure 5 shows the acoustic characteristics of the Donegal Bay Moraine. On the eastern  
227 side of the moraine, Facies B is markedly contorted and in places has a chaotic appearance with  
228 only traces of the original reflectors visible (Fig. 5A, B).

229 Within the Donegal Bay Moraine itself acoustic penetration is reduced but traces of Facies B are  
230 imaged beneath the eastern ridge and also between the eastern and western ridges (Fig. 5). In the  
231 latter location Facies B appears locally contorted (Fig. 5A). Facies B thickens westwards from the  
232 Donegal Bay Moraine and appears to terminate on the outer shelf moraine, although the base of the  
233 facies is not always visible due to acoustic attenuation. Sediment cores from Facies B recovered  
234 laminated and massive muds (CE08-003, JC106-95, JC106-99, JC106-100, JC106-101, JC106-102,  
235 JC106-105) (Lithofacies 2 and 3 – see below).

#### 236 Facies C



237 Facies C is acoustically transparent to structureless (Figs. 3 and 4). Stratigraphically it is the  
238 uppermost acoustic facies and typically immediately underlies the seafloor reflector. It is prominent  
239 on the mid- and inner-shelf, both inshore and offshore of the Donegal Bay Moraine and also occurs  
240 on the outer shelf but disappears close to the shelf break (Fig. 3). On the mid-shelf the thickness of  
241 Facies C ranges from ca. 4.5-7 m and is up to 8 m thick on the inner-shelf. Sediment cores from  
242 Facies C recovered massive and horizontally bedded gravels (clast- and matrix-supported) and  
243 sands often containing a 'shell hash' of broken and whole bivalves (Lithofacies 5-8 – see below).

### 244 3.2.2 Interpretation

#### 245 Facies A

246 Facies A is stratigraphically the lowermost acoustic facies in this study and it forms a series of  
247 buried bathymetric highs across the shelf. These include the Donegal Bay Moraine and outer shelf  
248 moraine but on the mid-shelf most of the moraines are lower in amplitude and are buried by Facies  
249 B; hence they have no seafloor expression and are only visible in the sub-bottom profile (Fig. 3).  
250 Cores from this facies recovered stiff, matrix-supported massive diamicton (see below). Based on  
251 its lack of internal structure, its unconformable upper surface, its composition as a stiff diamicton  
252 and its geomorphological expression as a series of topographic highs, either buried or visible above  
253 the seafloor, we infer that Facies A is a diamicton of either subglacial and/or ice-marginal origin  
254 which forms a series of shelf moraines (cf. Forwick and Vorren, 2011; Hogan et al., 2016; Graham  
255 and Hodgson, 2016). In this interpretation the infills of acoustically stratified Facies B between the  
256 moraine ridges were deposited time-transgressively as the ice sheet retreated across the shelf.

257 Interbedding of facies A and B on the western (ice distal) side of the Donegal Bay Moraine is  
258 inferred to reflect glacial sedimentation sourced from an ice margin grounded at the moraine.  
259 The interbedding of transparent and laminated acoustic facies suggest subaqueous depositional  
260 processes, with Facies A produced by sediment failure and downslope resedimentation of unstable  
261 glacial sediment from the moraine (cf. Whittington and Niessen, 1997; Forwick and Vorren,  
262 2011; Dowdeswell et al., 2016). Resedimentation of glacial sediment is common in ice-proximal  
263 glacial marine settings where depositional oversteepening due to high sedimentation rates, combined  
264 with disturbance from grounding icebergs and ice-front oscillations, act to trigger mass flows  
265 (Lønne, 1995; Powell, 2003).

266 The prominent seafloor morphology and large size of the Donegal Bay Moraine indicate that it  
267 represents a major stillstand and/or ice-marginal oscillation. The latter is suggested by the  
268 composite form of the moraine that actually comprises two ridges with the western (outermost)

ridge being the older of the two. It is also supported by the presence of heavily contorted Facies B sediments in the eastern side of the moraine which we suggest were glactectonised following their initial subaqueous (see below) deposition (Fig. 9). Undeformed, acoustically stratified, conformable sediments of Facies B to the east of the Donegal Bay Moraine were deposited after the ice margin had receded from the moraine into the inner part of Donegal Bay.

#### 274 Facies B

The well-developed stratification and on-lapping geometry of Facies B, combined with sediment core evidence which shows it is composed of laminated and massive muds are consistent with fine-grained sediment input in a subaqueous setting. Such facies have been commonly described from glacimarine environments where they are formed by rain-out from turbid meltwater plumes and iceberg rafting, likely combined with localised deposition from dilute sediment gravity flows (Gilbert et al., 1985; Powell and Domack, 1995; Hogan et al., 2012; Ó Cofaigh et al., 2016b). Facies B tends to infill the depressions between the topographic highs of Facies A rather than drape them and this suggests that emplacement of Facies B was likely time-transgressive and associated with sediment being sourced from the vicinity of the topographic highs.

#### 284 Facies C

Stratigraphically this is the uppermost acoustic facies in the study area and is therefore the youngest. It is acoustically transparent or structureless and occurs beneath the seafloor reflector. Cores from Facies C show that it variably comprises sand and poorly-sorted clast- and matrix-supported gravel, in some cases rich in single and broken bivalve shells. Facies C is interpreted to post-date ice sheet retreat in the bay. The sedimentological evidence for clast-supported gravels and shell hash points to bottom-current winnowing (cf. Howe et al., 2011; Howe 2006) and Facies C is therefore interpreted largely as a product of post-glacial sedimentation and bottom-current activity (Viana et al., 1998).

## 293 4. SEDIMENT CORES

### 294 4.1 Radiocarbon Dates

Twenty two radiocarbon dates were obtained on samples of shells and foraminifera from cores across the shelf (Tables 1 and 2). The dates are shown at their stratigraphic depths on the core logs in Fig. 6. Samples for dating were selected predominantly to constrain the timing of retreat across the shelf but two samples of reworked shell fragments were dated to constrain the maximum age of till formation and thus ice sheet advance on the outer shelf. The conventional radiocarbon and calibrated ages are shown in Table 2.

301

## 302 **4.2 Sedimentology**

303 Twenty seven vibrocores from outer Donegal Bay and the adjoining shelf were investigated in this  
304 study. Core sites were selected from analysis of the seafloor geomorphological and acoustic  
305 stratigraphic data and targeted acoustically stratified sediments (Facies B) in between moraine  
306 ridges where possible. Lithofacies were identified and are described stratigraphically from oldest  
307 (bottom) to youngest (top). Lithofacies codes are based on Eyles et al. (1983) and outlined in Table  
308 3.

309

### 310 **4.2.1 Lithofacies: Description**

#### 311 **Lithofacies 1 – Massive, matrix-supported diamicton (Dmm)**

312 This lithofacies corresponds to acoustic Facies A. Massive, matrix-supported diamicton was  
313 recovered in cores from the mid- and outer-shelf: cores CE08-008, CE08-010, CE08-011, JC106-  
314 108VC, JC106-111VC and JC106-112VC. The diamicton is brownish grey in colour and it  
315 comprises the basal unit in all of the cores where it is present (Figs. 6 and 7). Recovery of this  
316 lithofacies ranged from 0.6-2 m. Two sub-facies can be recognised.

317 Lithofacies 1a comprises stiff, massive, matrix-supported diamicton which in some cores (e.g.,  
318 112VC from the outer shelf) contains shell fragments (Figs. 6, 7a and 7b). Shear strengths range  
319 from 50-220 kPa. The matrix consists of silt and clay with dispersed clasts, mostly up to 2 cm in  
320 diameter although occasional clasts up to 5 cm in diameter are also observed. Clasts display no  
321 preferred orientation on the x-radiographs and are predominantly sub-angular with subsidiary sub-  
322 rounded and angular clasts.

323 Lithofacies 1b was only observed in core CE08-010 where it is the lowermost facies in the core at  
324 578-484 cm (Figs. 6 and 7). Like Lithofacies 1a it comprises a matrix-supported diamicton.  
325 However, it differs from Lithofacies 1a in that in places it is locally transitional to a diffusely  
326 laminated diamicton (Dml) (567-555 cm depth) with dropstones (Fig. 7b). It also contains marked  
327 variations in clast content resulting in subtle transitions from clast-poor to clast-rich diamicton.  
328 Clasts within Lithofacies 1b are sub-angular to sub-rounded and are up to pebble size. The upper  
329 contact is gradational into massive clast-free sand (Sm). Shear strength in the diamict ranges from  
330 76-48 kPa from 572 to 534 cm, whereas above 534 cm depth, the diamicton is softer with shear  
331 strength values ranging from 48-31 kPa.

#### 332 **Lithofacies 2 – Laminated mud (Fl; minor Fld)**

333 This lithofacies corresponds to acoustic Facies B. It comprises laminated muds with occasional  
334 clasts, usually sub-cm in diameter. It is thickest in cores from the mid-shelf (e.g., JC106-99VC,  
335 JC106-100VC, JC106-101VC and JC106-101VC) but also occurs in the lower parts of cores from  
336 the inner shelf (JC106-95VC, CE08-04 and CE08-03) (Figs. 6, 7e and 7f). It reaches a maximum  
337 thickness of 4.5 m in core JC106-99VC. The muds are soft with typical shear strengths ranging  
338 from 10-15 kPa. Lamination is imparted by alternating bands of silt or fine sand and grey clay  
339 which appear on x-radiographs as alternating light (coarser and less dense) and dark (finer and  
340 denser) sediment (Fig. 7e). Lamination is typically horizontal or sub-horizontal and undeformed,  
341 apart from occasional contortion and normal faults. Down-warping at core edges is attributed to the  
342 coring process. Rare, small, pebble-sized clasts occur within the laminated muds. In several cores  
343 (e.g., JC106-100VC and JC106-101VC) the lamination appears rhythmic and the laminae form  
344 couplets with a sharp-based, coarser lower lamina (lighter on x-radiographs) grading upwards into  
345 the finer (darker) lamina. However, this relationship is not consistent and some finer laminae also  
346 have sharp bases. In places the lamination is more stratified with interbedded sands and silty clays  
347 (e.g., the lower 1 m of core JC106-105VC). Bounding contacts for this lithofacies are typically  
348 abrupt (Fig. 7f).

349 Lithofacies 3 – Massive mud and massive diamictic mud (Fm, Fmd)

350 This lithofacies corresponds to acoustic Facies B. It consists of grey and olive-grey massive mud  
351 with (Fmd) or without (Fm) clasts that is occasionally bioturbated. As in the case of Lithofacies 2  
352 (laminated mud) it is particularly common in cores from the mid-shelf (e.g., cores CE08-010,  
353 JC106-100VC, JC106-101VC and JC106-105VC) although it also occurs in cores from the Donegal  
354 Bay Moraine (JC106-95VC) and the inner shelf (CE08-003) (Fig. 6). In thickness Lithofacies 3  
355 ranges from a few cm to almost 2 m. In some cores (e.g., CE08-010 352-372 cm depth; JC106-  
356 100VC 310-494 cm depth) the massive mud contains sufficient numbers of small clasts to be  
357 transitional to massive diamicton although shear strength values are much lower (25 kPa) than is the  
358 case with Lithofacies 1a (see above). In core JC106-100VC the massive mud is separated from the  
359 overlying laminated mud of Lithofacies 2 by a sharp contact, although thin horizons of massive  
360 mud with clasts are interbedded with clast-poor laminated mud for about 10 cm above this contact  
361 (Fig. 7f). Although predominantly massive, Lithofacies 3 occasionally shows localised zones of  
362 very diffuse lamination/stratification up to a few cm thick.

363  
364 Lithofacies 4 – Laminated or stratified sand (Sh)

365 Laminated or stratified sand (Lithofacies 4) was observed in a few cores, primarily from the mid-  
366 shelf (Fig. 6 and 7g). Beds of this lithofacies tend to be relatively thin ( $\leq 0.2$  m). The sediment is  
367 clast-poor, and individual laminae range from weak and diffuse to well-developed with sharp  
368 boundaries. In some cores laminae may be disturbed or contorted. Lithofacies 4 is relatively thin  
369 ( $\leq 0.2$  m) and either corresponds to acoustic Facies C or B. A correspondence with Facies B is more  
370 consistent with the age of this lithofacies which we discuss below.

371 Lithofacies 5 – Normally graded sand (Suf)

372 Lithofacies 5-8 correspond to acoustic Facies C. Fining upwards sands were occasionally observed.  
373 The sands tend to have sharp bases and range from poorly sorted granular sand that fines upwards  
374 into well sorted fine sand, to finer sands that grade upwards to diffusely laminated silty sand (e.g.,  
375 CE08-03, 430-410 cm depth). Typically normally graded sands have concentrations of broken and  
376 fragmented shells and occasional pebbles along their lower boundary or within the lowermost few  
377 centimetres.

378 Lithofacies 6 – Massive sand (Sm)

379 Massive sand occurs in most of the cores and ranges in thickness from 0.1 m to several metres (Fig.  
380 6). Texturally it ranges from silty to coarse but is usually well sorted. Clast content is variable from  
381 granules and pebbles to, occasionally, cobbles. Bounding contacts are usually sharp although in  
382 some cores massive sand beds may have sharp lower and upper gradational contacts and are  
383 overlain by either laminated or massive muds (e.g., CE08-003, 443-374 cm). In many cores  
384 massive sand forms the uppermost lithofacies and caps the stratigraphic sequence (e.g., CE08- 003,  
385 CE08-004, CE08-005, CE08-010, CE08-011, JC106-100VC, JC106-106VC) (Fig. 6) and is  
386 equivalent to Acoustic Facies C. These capping massive sands contain broken and fragmented  
387 shells which are often abundant, and contain clasts from granule to pebble size, either dispersed or  
388 arranged in layers 1-3 clasts thick. The massive sand in the top of the cores may display diffuse  
389 textural variation. They commonly overlie gravelly facies (Gm and Gms).

390 Lithofacies 7 – Clast-supported, massive gravel (Gm)

391 This facies comprises clast-supported gravel which is usually well sorted, massive and contains sub-  
392 rounded to rounded clasts (Figs. 6 and 7d). Occasionally it can exhibit a subtle normal grading.  
393 Together, lithofacies 6 and 7 often form part of a sequence of sand and gravel facies that are  
394 separated by gradational contacts and cap many of the sediment cores from across the shelf. Clast  
395 sizes range from granules to pebbles and in some case cobbles. Beds of this facies generally range  
396 from 0.1-1.2 m in thickness. Lower bed contacts are typically sharp and, in some cases, clearly

erosive. A common feature of this lithofacies is that it often contains abundant whole or broken shells, and, in cores from the outer shelf, shell fragments constitute a coarse matrix forming a type of 'shell hash'.

#### Lithofacies 8 – Matrix-supported, massive gravel (Gms)

This facies comprises matrix-supported granule and pebble gravel which is usually massive (e.g., CE08-004, 199-134 cm). The matrix ranges from silty mud to, more commonly, sand, usually coarse. The gravels are often rich in broken and sometimes whole shells forming a 'shell hash'. Individual beds are up to a few tens of centimetres in thickness. Clasts are typically sub-angular to rounded. Lower contacts are sharp and upper contacts range from sharp to gradational.

#### 4.2.2 *Lithofacies interpretation and age*

The diamicton of Lithofacies 1a is the lowermost stratigraphic unit in cores from the mid- and outer-shelf and is characterised by a massive structure with dispersed clasts in an over-consolidated muddy matrix with fragmented shells. Stratification and grading within the diamicton that might be indicative of subaqueous mass-flow or iceberg-rafting were not observed. Rather its characteristics are more consistent with an origin as a subglacial till with the high shear strengths reflecting loading and compaction by grounded glacier ice (Ó Cofaigh et al., 2007, 2013; J. Evans et al., 2005; D. Evans et al. 2006; Hogan et al., 2016).

The presence of occasional shell fragments within the diamicton indicates that it is formed, at least in part, from the overriding and reworking of pre-existing marine sediment over which the ice sheet advanced (cf. Ó Cofaigh and Evans, 2001; England et al., 2009; Ó Cofaigh et al., 2013). Two AMS radiocarbon dates on individual shell fragments from the diamicton in core JC106-112VC dated  $26382 \pm 257$  cal BP (SUERC-63584) and  $26372 \pm 259$  cal BP (SUERC-63585) (Fig. 6 and Table 2) and provide a maximum age for emplacement of the till and the associated ice sheet advance. They indicate till formation and a grounded ice sheet on the outer shelf after 26.3 ka cal BP.

Although Lithofacies 1b also comprises a stiff, matrix-supported diamicton it differs from Lithofacies 1a in that it is locally transitional to a diffusely laminated diamicton, contains marked variations in clast abundance, dropstones, and it also contains a well preserved glacimarine microfauna (see above and section 5 below). These observations are more consistent with formation of Lithofacies 1b in a glacimarine depositional environment during deglaciation rather than subglacially. The coarse-grained nature of the facies and the high consolidation suggest formation by a combination of the rain-out of iceberg rafted debris and intermittent scouring of the seafloor by grounded iceberg keels (consolidating the sediment)(cf. Dowdeswell et al., 1994; Sacchetti et al.,

2012). Radiocarbon dates on two samples of mixed benthic foraminifera from the base of Lithofacies 1b in core CE08-010 and from 6 cm above its upper contact bracket the age of the diamicton and thus glacimarine sedimentation at this core site (mid-shelf). The sample from the core base dated  $18063 \pm 167$  cal BP (SUERC-58324) and the sample from above the diamicton dated  $15250 \pm 145$  cal BP (UCIAMS-133551) (Fig. 6 and Table 2).

Lithofacies 2 comprises fine-grained, soft laminated mud and is common in cores from the mid- and inner-shelf. It corresponds to acoustic Facies B. Lamination is typically horizontal or sub-horizontal and clasts within the muds are small and relatively infrequent. The presence of grading, rhythmicity, sharp laminae bases, and horizontal or sub-horizontal lamination with relatively minor and localised deformation indicates that the laminated muds are a product of meltwater deposition, most likely from the settling of suspended sediment from turbid meltwater plumes issuing from the retreating ice-margin during deglaciation although it is possible that at least some of the lamination is a product of deposition from turbidity currents (Makiewicz et al., 1984; Hesse et al., 1997; Ashley and Smith, 2000; Ó Cofaigh and Dowdeswell et al., 2001). Clasts within the muds are relatively rare and small implying that iceberg rafting was low and was subsidiary to meltwater deposition (Cowan et al., 1997; Lloyd et al., 2005). Benthic foraminifera indicative of cold, Arctic glacimarine conditions (*E. excavatum* f. *clavata*; *Cassidulina reniforme*) are common in Lithofacies 2 and 3 (see section 5 below) indicating that subaqueous sedimentation and ice-sheet retreat occurred in a glacimarine depositional environment (cf. Hald and Korsun, 1997; Lloyd et al., 2005; Jennings et al., 2006).

Lithofacies 3, massive mud (Fm) is interpreted as a product of rapid meltwater sedimentation in which high sedimentation rates of fine-grained material settling from suspension suppressed the formation of laminations. A similar origin is proposed for the formation of the massive mud with clasts (Fmd) but one in which the rain-out of iceberg-rafted debris played a significant role (Elverhøi et al., 1983; Domack, 1984; McCabe, 1986; Dowdeswell et al., 1994).

Radiocarbon dates from the laminated and massive glacimarine mud facies (lithofacies 2 and 3) provide age constraints on the timing of glacimarine sedimentation on the mid-shelf and thus ice sheet retreat. Five dates were obtained from samples of mixed benthic foraminifera from the bases of cores JC106-099VC, JC106-101VC, JC106-102VC, JC106-105VC and JC106-106VC. The oldest date is  $24804 \pm 388$  cal BP (UCIAMS-164437) with the other dates ranging from 23.7-20.2 ka cal BP (UCIAMS-164431, UCIAMS-164438, UCIAMS-164435, UCIAMS-164429) (Fig. 6 and Table 2). Further inshore two samples of mixed benthic foraminifera from laminated glacimarine muds close to the base of core JC106-095VC from the Donegal Bay Moraine and from core CE08-

004 from immediately inshore of the moraine dated  $17,493 \pm 176$  cal BP (SUERC-63557) and  $17,918 \pm 161$  cal BP (SUERC-47522) respectively (Fig. 6 and Table 2).

Both lithofacies 2 and 3 infill basins between moraines across the shelf (acoustic Facies B) and, on the mid-shelf, blanket the moraines themselves (Fig. 3). This implies they initially formed time-transgressively in association with successive stillstands of the grounded ice-sheet margin at the moraines. Sedimentation was by a range of glacial-marine processes including suspension settling from meltwater plumes, rain out of iceberg-rafted debris (IRD) and dilute sediment gravity flows.

Lithofacies 4 - Laminated or stratified sand facies (Sh) are relatively thin, are characterised by blurred or sharp boundaries, are clast poor and sometimes disturbed. The sands are interpreted as a product of emplacement by discrete sandy gravity flows, probably sandy turbidites. The contorted, disrupted appearance to some beds suggests that they may have undergone slumping and disturbance either pene-contemporaneous with deposition or subsequently (Eyles and Eyles, 2000). The oldest date from this lithofacies is from a sample of mixed benthic foraminifera from the core catcher of core CE08-018 from the outer shelf which dated  $23796 \pm 267$  cal BP (UCIAMS-133552) (Fig. 6 and Table 2).

The normally graded sand of Lithofacies 5 is characterised by sharp lower contacts, concentrations of clasts or shell fragments at the base of beds, and a fining upwards sequence in which sands grade upwards into silts. These features are consistent with an origin as the product of deposition from sandy turbidity currents (Lowe, 1982; Walker, 1992).

Massive sands (Lithofacies 6) with sharp lower contacts and gradational upper contacts with muds are most likely a product of the freezing of dilute sediment gravity flows with the finer grained material settling out of suspension. However, massive sands are also common in the top sections of cores across the shelf (Fig. 6), where they are typically associated with the gravels of Lithofacies 7 (Gm) and 8 (Gms). contain abundant single and broken shells, often in the form of a 'shell hash' and coarser horizons or bands of pebbles or granules. Lithofacies 6, 7 and 8 therefore comprise an association of variably-sorted, sandy and gravelly facies that are predominantly massive and are the uppermost stratigraphic units in sediment cores from across the shelf. We interpret these sediments as postglacial formed predominantly by the activity of bottom currents on the shelf (cf. Anderson et al., 1984; Howe et al., 2001). Zones of upwards fining sand record either reworking by gradually weakening bottom currents or a marine transgression (Viana et al., 1998). Shell hash, granule and pebbly horizons within massive sands, and clast-supported gravel are likely to be lag deposits.

#### 4.3. Foraminiferal analysis



494 The aim of the foraminiferal analysis was to provide additional information on the depositional  
495 environment(s) across the continental shelf through time to combine with the lithofacies and  
496 acoustic facies analysis. To achieve this six cores were selected from the outer to inner shelf: CE08-  
497 018 from the outer shelf; CE08-010, JC106-100 and JC106-102 from the mid-shelf; and JC106-095  
498 and CE08-003 from the Donegal Bay Moraine and inner shelf respectively . Sample selection was  
499 concentrated in particular on the lower sections of the cores with the aim of understanding  
500 depositional environments during deglaciation. Other sections of the cores were also sampled to aid  
501 in the interpretation of depositional environments. Acoustically, most of the sediments sampled  
502 were from acoustic Facies B.

503 Foraminifera were counted from a total of 63 samples and a total of 48 benthic foraminiferal species  
504 were identified (45 calcareous and 3 agglutinated species). Planktonic foraminifera were also  
505 counted, but were not identified to species level and have not been included in the percentage  
506 calculation. The following sections provide a brief description and interpretation of the  
507 foraminiferal assemblage data (see SOI for a full species list and detailed count data).

#### 508 5.1 CE08-018 (Outer-shelf)

509 Foraminifera were counted from four samples from the base of the core (100 cm) up to 62 cm (Fig.  
510 8). The samples were from Lithofacies 4 (Sh). The assemblage is dominated by *Cibicides lobatulus*  
511 (24 – 53%) and *Elphidium excavatum f. clavata* (16 – 40%) with *Cassidulina reniforme* (4 – 22%)  
512 also common (Fig. 8). There are minor occurrences of *Cassidulina laevigata* (up to 5%) and  
513 *Quinqueloculina seminulum* (increasing to 12%).

514 Interpretation: The dominance of *C. lobatulus* indicates relatively coarse sediment grain size  
515 associated with strong bottom water currents (Jennings and Helgadottir, 1994; Hald and Korsun,  
516 1997) while the co-dominance of *E. excavatum f. clavata* and with *C. reniforme* also common  
517 indicates a glacial marine environment. These latter two species are typically found in modern Arctic  
518 fjord and shelf environments with *E. excavatum f. clavata* in particular being common in proximal  
519 glacial marine environments while *C. reniforme* tends to dominate in more distal glacial marine and cold  
520 polar water dominated environments (e.g. Hald and Korsun, 1997; Korsun and Hald, 2000). Indeed  
521 *C. lobatulus*, while not typically a glacial marine species, is common in Arctic fjord and shallow shelf  
522 environments associated with strong meltwater fluxes from tidewater glacier margins (e.g. Jennings  
523 and Helgadottir, 1994). A mixed benthic foraminifera sample from the core catcher dated  
524  $23,796 \pm 237$  cal BP (UCIAMS-133552) (Fig. 6, Table 2).

#### 525 5.2 CE08-010 (Mid-shelf)

Foraminifera were counted at 16 cm intervals from the base of the core (578 cm) up to a depth of 144 cm, and thus from a range of lithofacies (lithofacies 1, 2, 3, 5, 6 and 7) (Fig. 8). The assemblage through this core is dominated by three species, *Elphidium excavatum f. clavata*, *Cassidulina reniforme* and *Cibicides lobatulus* (Fig. 8). The core can be divided into 5 foraminiferal assemblage zones, FAZ 1 to FAZ 5. The lower zone, FAZ 1 (samples from 578 to 528 cm), is dominated by *E. excavatum f. clavata* (35 – 70%) with *C. reniforme* also abundant (20 – 33%). Absolute abundance in this section is rather low, with total foraminifera counted generally below 100 specimens, the abundance of planktic foraminifera is also low. FAZ 2 (samples from 512 to 352 cm) is dominated by *C. reniforme* (16 – 75%) with *E. excavatum f. clavata* still abundant (20 – 40%) and *Cibicides lobatulus* becoming more common (5 – 15%). Absolute abundance and the number of planktic foraminifera increase in this zone. There is a significant change with the transition to FAZ 3 (samples from 336 to 256 cm) with *C. lobatulus* becoming dominant (17 – 28%) and a decrease in abundance of *C. reniforme* (12 – 23%) and *E. excavatum f. clavata* (5 – 13%). FAZ 4 (samples from 240 to 176 cm) is characterised by a gradual decrease in abundance of *C. lobatulus* (17% decreasing to 0%) as *C. reniforme* (26 – 63%) and *E. excavatum f. clavata* (5 – 45%) both increase to co-dominate. This trend is reversed in FAZ 5 as *C. lobatulus* increases to dominate the assemblage again while *C. reniforme* and *E. excavatum f. clavata* both decrease.

Interpretation: The benthic foraminiferal assemblage in FAZ 1, dominated by *E. excavatum f. clavata* and *C. reniforme*, is indicative of a glacimarine environment. This is also supported by the relatively low absolute abundance indicative of the relatively harsh conditions in a glacimarine setting. FAZ 1 is characterised by a matrix-supported diamicton that ranges from massive to diffusely laminated at the base of the core (see section 4 above) and a radiocarbon date on benthic foraminifera from the base returned an age of 18,063±167 cal BP (SUERC-58324) (Fig. 6 and Table 2). The increase in abundance of *C. reniforme*, but still with a relatively high proportion of *E. excavatum f. clavata* through FAZ 2 indicates more distal glacimarine conditions (allowing a greater absolute abundance of foraminifera to develop). Sedimentologically this change in environments is associated initially with the upper part of Lithofacies 1b (diamicton) which fines upwards through massive sands (Sm) into laminated and massive mud (Fld, Fm, Fmd). A sample of mixed benthic foraminifera from massive sand 6 cm above the contact with the diamicton dated 15,250±145 cal BP (UCIAMS-133551) (Fig. 6 and Table 2). The major shift into FAZ 3 indicates increasing distance from a glacimarine environment, but still relatively cold polar waters, with an increase in species other than glacimarine indicators, principally *C. lobatulus* and also the appearance of *C. laevigata*. The dominance of *C. lobatulus* is associated with an increase in sediment grain size indicative of stronger bottom water currents. Supporting this interpretation, the

560 lithofacies within this zone are dominated by matrix-supported gravels (Gms) which may, at least in  
561 part, represent a lag deposit. Lower energy conditions then return during the deposition of FAZ 4  
562 with continuing distal glacimarine / cold polar water conditions (*C. reniforme* dominant). This  
563 transition is also marked by a return to finer grained sediments, predominantly massive silts and  
564 clays (Fm), and massive sand (Sm) often associated with higher abundance of *C. lobatulus*. Higher  
565 energy conditions then return during the deposition of FAZ 5 (a mixture of massive sands and  
566 gravels, (lithofacies Sm and Gms) with an assemblage dominated by *C. lobatulus*.

### 567 5.3 JC106-102 (Mid-shelf)

568 Foraminifera were counted at 16 cm intervals from 248 cm (near the base of the core) up to 56 cm  
569 (Fig. 8). The samples were from the laminated and massive mud of Lithofacies 2 and 3. The  
570 assemblage shows limited variability, but can be divided into two zones (Fig. 8). FAZ 1 from 248  
571 to 88 cm is associated with a thick sequence of Lithofacies 2 (laminated mud) and is dominated by  
572 *E. excavatum f. clavata* (30 – 54%) and *C. reniforme* (24 – 46%), with *Elphidium excavatum f.*  
573 *selseyensis* also common. The transition to FAZ 2 is characterised by a slight increase in other  
574 species such as *C. lobatulus*, *C. laevigata* and *Elphidium excavatum*, though while there is a  
575 reduction in *Elphidium excavatum f. clavata* in particular and also in *C. reniforme*, these two  
576 species still dominate the assemblage. FAZ 2 is associated with Lithofacies 3 (massive mud; Fm,  
577 Fmd).

578 Interpretation: The dominance of *E. excavatum f. clavata* and *C. reniforme* through this core  
579 indicates a glacimarine environment, becoming progressively more distal through FAZ 1 and into  
580 FAZ 2 in particular as the abundance of *E. excavatum f. clavata* gradually decreases and other  
581 species, such as *E. excavatum f. selseyensis* (a cold water rather than glacimarine indicator; Murray  
582 1991) and *C. laevigata*, increase slightly. This interpretation is consistent with the lithofacies  
583 through this section which comprise laminated muds overlain by massive muds and with a slight  
584 increase in silt content through FAZ 2. A sample of mixed benthic foraminifera from the base of the  
585 core dated  $24,804 \pm 388$  cal BP (UCIAMS-164437) (Fig. 6 and Table 2).

### 586 5.4 JC106-100 (Mid-shelf)

587 Foraminifera were counted from four samples taken from the lower section of this core, 336 to 284  
588 cm (Fig. 8). The samples extend across a lithofacies transition from massive diamictic mud  
589 (Lithofacies 3) to laminated mud (Lithofacies 2) at 310 cm depth. The assemblage is dominated by  
590 *E. excavatum f. clavata* (50 – 80%) with *C. reniforme* also abundant (10 – 20%) and *E. excavatum f.*  
591 *selseyensis* and *Quinquelocaulina seminulum* also common (5 – 10%).

592 Interpretation: The dominance of *E. excavatum f. clavata* with *C. reniforme* also common indicates  
593 a glacial marine environment through this section of massive diamictic mud and then laminated silts  
594 and clays (lithofacies Fmd to Fl).

#### 595 5.5 JC106-095 (Donegal Bay Moraine)

596 Foraminifera were analysed from the lower section of this core, six samples from 218 to 138 cm  
597 (Fig. 8). The samples were collected from Lithofacies 3 (laminated mud). The assemblage is  
598 dominated by *E. excavatum f. clavata* (40 – 80%) with other species of *Elphidium* also dominant  
599 and *C. reniforme* common (15 – 20%) (Fig. 8).

600 Interpretation: The abundance of *E. excavatum f. clavata* indicates a glacial marine environment,  
601 likely to be relatively proximal due to the dominance of this species. *C. reniforme*, more of a distal  
602 glacial marine to cold polar water indicator and *E. excavatum f. selseyensis*, associated with cold  
603 waters, are also common. The sedimentology of this section of the core is dominated by laminated  
604 silts and clays (Lithofacies 2, Fl). A sample of mixed benthic foraminifera from laminated muds at  
605 209 cm and a shell fragment from 175.5 cm depth dated 17,493±176 cal BP (SUERC-63557) and  
606 15,740±192 cal BP (SUERC-58403) respectively (Fig. 6 and Table 2).

#### 607 5.6 CE08-003 (Inner-shelf)

608 Foraminifera were counted from two sections in this core, a lower set of six samples from 510 to  
609 425 cm, primarily from laminated mud (Lithofacies 2) with minor upwards fining sand (Lithofacies  
610 5), and then an additional two samples from a shallower section, 180 to 162 cm from massive sand  
611 (Lithofacies 6) (Fig. 8). The core can be split into three foraminiferal assemblage zones, FAZ 1 to  
612 FAZ 3 (Fig 8). FAZ 1 from 510 to 459 cm is dominated by *C. reniforme* (50 – 60%) with *E.*  
613 *excavatum f. clavata* also common (15 – 20%) and other species of *Elphidium* also present. There is  
614 a subtle change in assemblage from 442 to 425 cm (FAZ 2). There is a slight decrease in abundance  
615 of *C. reniforme*, though this species still dominates (40%), there is also a slight decrease in  
616 abundance of *E. excavatum f. clavata* (<10%) and several other species become more common,  
617 such as *Pygo williamsoni* and *Rosalina spp.* The upper section of the core (FAZ 3 from 180 to 162  
618 cm) has a significantly different assemblage with a wider range of species abundant and no clear  
619 dominant species. *Cibicides lobatulus* and *Quinqueloculina spp.* are most abundant (20 – 30%) and  
620 *Glabratella milleti*, *C. laevigata*, *Nonionella turgida* and *Miliolinella* also present in low  
621 abundances. Radiocarbon dates on four samples from the laminated muds provide a core  
622 chronology. A mixed benthic foraminifera sample from 493-499 cm dated 12,800±118 cal BP  
623 (UCIAMS-133550); two single valves of *Macoma calcarea* from 477 cm and 466 cm dated

12,702 $\pm$ 112 cal BP (SUERC-47516) and 12,622 $\pm$ 80 cal BP (SUERC-47515); and a shell fragment from 387 cm depth dated 12,284 $\pm$ 218 cal BP (SUERC-47514) (Fig. 6 and Table 2).

Interpretation: The abundance of *C. reniforme* in FAZ 1 indicates cold polar water conditions, potentially distal glacimarine, particularly with the presence of *E. excavatum f. clavata*. The abundance of glacimarine species decreases in FAZ 2 as abundances of other typical North Atlantic boreal species increase (for example *P. williamsoni* and *Rosalina spp.*). The upper section of the core, FAZ 3, is characterised by a further reduction in glacimarine species (<10%) as a more diverse range of typical North Atlantic boreal species dominate the assemblage. The relatively high abundance of *C. lobatulus* (20%) suggests higher bottom water current speeds with an associated increase in sand content.

## 5. DISCUSSION

### 5.1 Ice sheet extent on the continental shelf northwest of Ireland at the LGM

On the basis of six terrestrial  $^{36}\text{Cl}$  surface exposure dates of  $36.5 \pm 3.6$  ka to  $25.1 \pm 1.1$  ka obtained from ice-moulded bedrock or erratic boulders at widely separated sites Bowen et al. (2002) proposed that the last ice sheet in Ireland reached its maximum extent before  $\sim 37.5$  ka (during Marine Isotope Stage 3), and was more restricted during the subsequent ILGM. This view was supported by McCabe et al. (2007) on the basis of a set of fifteen radiocarbon dates from stratigraphic sequences at Glenulra on the south side of Donegal Bay. Eleven dates were on reworked single *Arctica islandica* shells from either till or deglacial outwash and ranged from  $\sim 43.3$  to  $\sim 26.1$  ka cal BP. The final four dates were from 27.8-25.3 ka cal BP obtained from *Elphidium clavatum* tests interpreted as in-situ by McCabe et al. from raised marine muds. They inferred that high relative sea levels, implying marked isostatic depression and thus the proximity of a thick ice sheet, had persisted over a period of  $\sim 20$  ka prior to the gLGM and that the ice sheet underwent a rapid advance-retreat on the continental shelf about 28 ka cal BP and thus immediately prior to the ILGM, although offshore evidence from the shelf was not presented (see Ballantyne and Ó Cofaigh 2016).

By contrast, Greenwood and Clark (2009) and Clark et al. (2012) argued on the basis of glacial geomorphological mapping that a major ice stream flowed onto the shelf through Donegal Bay at the ILGM. This supported the results of an earlier study by Ballantyne et al. (2007) based on cosmogenic surface exposure dating and trimline mapping which proposed a ILGM ice sheet that extended at least 20 km across the shelf from the present coastline. Ó Cofaigh et al. (2012) mapped streamlined subglacial bedforms on the inner continental shelf and arcuate moraines that extend across the shelf from the mouth of Donegal Bay to the shelf edge. They interpreted the moraines as

657 recording the former presence of a grounded, shelf-edge terminating ice sheet that then underwent  
 658 lobate, episodic retreat back across the shelf and into Donegal Bay. This is consistent with glacial  
 659 geomorphological mapping by Dunlop et al. (2010) from the Malin Sea immediately to the north,  
 660 which indicated extensive shelf edge glaciation with convergent ice flows from western Scotland  
 661 and northwest Ireland reaching the shelf edge at the ILGM. Ó Cofaigh et al. (2012) suggested an  
 662 ILGM age for the shelf-edge advance offshore Donegal Bay based on comparison to the timing of  
 663 BIIS IRD fluxes onto the Barra Fan which implied that maximum ice sheet growth was attained by  
 664 24 cal ka BP and deglaciation occurred at 23 cal ka BP (Scourse et al., 2009). However, the  
 665 moraines were not dated directly and thus the timing of ice sheet advance and retreat across the  
 666 Atlantic shelf northwest of Ireland remained poorly constrained until the present study.

667 Working further to the south, offshore of Galway Bay, Peters et al. (2015, 2016) presented marine  
 668 geophysical and geological evidence supported by radiocarbon dating which indicated that the last  
 669 BIIS extended across the shelf west of Ireland and onto the Porcupine Bank, with retreat underway  
 670 by 21.8 cal ka BP. Extensive grounded ice on the shelf is also supported by the recent study of  
 671 Callard et al. (2018) from the Malin Sea. These authors propose advance of the Barra Fan Ice  
 672 Stream to the shelf edge west of Scotland at the ILGM with retreat underway by 25.9 cal ka BP and  
 673 the majority of the shelf ice free by 23.2 cal ka BP.

674 Cores JC106-108VC, JC106-111VC and JC106-112VC from the outer shelf offshore Donegal Bay  
 675 recovered stiff, matrix-supported diamictos (see above). The characteristics of these diamictos  
 676 are consistent with their formation as subglacial tills associated with a grounded ice sheet. Two  
 677 AMS radiocarbon dates on reworked shells from JC106-112VC provide a maximum age for till  
 678 formation and thus the advance of ice onto the outer shelf (see above). They indicate this occurred  
 679 after 26.3 ka cal BP (Fig. 9). This was a little later than previous interpretations of the timing of the  
 680 ILGM at 27 ka (C. Clark et al., 2012), but is consistent with IRD records from the Barra Fan which  
 681 indicate shelf-edge glaciation occurred after 27 ka (Scourse et al., 2009).

682 Retreat of the ice sheet from the outer shelf is constrained by several dates from laminated sand and  
 683 mud facies that record glacimarine conditions during deglaciation in cores from the outer and mid-  
 684 shelf. A date of  $23,796 \pm 267$  cal BP (UCIAMS-133552) from mixed benthic foraminifera in core  
 685 CE08-018 dates retreat from the outer shelf but older dates from the mid-shelf of  $24,804 \pm 388$  cal  
 686 BP (UCIAMS-164437) from glacimarine muds in JC106-102VC and  $26,319 \pm 247$  cal BP (SUERC-  
 687 63558) from massive sands at the base of JC106-103VC indicates that the ice sheet retreat from the  
 688 outer shelf was actually underway before this time. The date of  $26,319 \pm 247$  cal BP (SUERC-  
 689 63558) is within the 2 sigma error range of the dates from till in core JC106-112VC. This either

690 implies a very short-lived rapid advance/retreat on the outer shelf or, perhaps more likely, that the  
691 date of  $26,319 \pm 247$  cal BP is actually a maximum constraint on retreat. Either way the dates on  
692 reworked shells from tills and on benthic foraminifera from glacialmarine deposits constrain the most  
693 recent episode of ice occupancy on the outer shelf to between 26.3 and 24.8 cal ka BP and thus  
694 during the gLGM when eustatic sea level was at a minimum (P. Clark et al., 2009; Lambeck et al.,  
695 2014). This implies the existence of ice free conditions and crustal depression immediately prior to  
696 that advance, at least on the outer shelf

697 The new radiocarbon dates from till and deglacial sediments that we present in this study provide  
698 directly dated evidence for an extensive grounded ice sheet offshore of northwest Ireland at the  
699 gLGM. It is consistent with earlier work which proposed a similar reconstruction on  
700 geomorphological grounds (Dunlop et al., 2010; Ó Cofaigh et al., 2012), and a recent study from  
701 the Malin Sea Shelf which inferred a shelf edge advance of the Barra Fan Ice Stream after 26.7 cal  
702 ka BP (Callard et al., 2018). Collectively we suggest that this implies a shelf-edge terminating BIIS  
703 along the continental margin offshore of northwest Ireland and western Scotland at the ILGM.. This  
704 refutes earlier proposals (Bowen et al., 2002; McCabe et al., 2007), which argued for a restricted  
705 LGM advance onto the shelf in this region. Given the weight of geomorphological,  
706 sedimentological and chronological evidence for a grounded ice sheet emanating from Donegal Bay  
707 and extending to the shelf edge at the LGM the four Glenulra dates on benthic foraminifera  
708 (McCabe et al., 2007) are inferred to be anomalous (Ballantyne and Ó Cofaigh, 2016). As proposed  
709 by Ballantyne and Ó Cofaigh (2016) they could be explained by preservation beneath LGM ice,  
710 possibly in permafrost, due to their protected position in a valley orthogonal to the direction of ice  
711 sheet flow, or alternatively they are reworked and thus provide only maximum ages for the timing  
712 of ice sheet retreat.

## 713 **5.2 Glacimarine conditions during deglaciation**

714 Our sedimentological and foraminiferal data demonstrate that retreat of the last ice sheet across the  
715 Atlantic shelf northwest of Ireland took place in a glacimarine environment (Fig. 9). This  
716 interpretation is supported by laminated and massive muds with dropstones (lithofacies 2 and 3  
717 above) that contain a foraminiferal assemblage with abundant *E. excavatum f. clavata* and *C.*  
718 *reniforme*. These species are common in modern glacier-influenced, Arctic fjord and shelf  
719 environments which are characterised by low salinity and cold temperatures (Hald and Korsun,  
720 1997; Korsun and Hald, 2000; Lloyd 2006). Present day water depths in the study area are deepest  
721 at the shelf edge (125 m) but then decrease to less than 80 m at the mouth of Donegal Bay, where  
722 the Donegal Bay Moraine is located. The cores containing glacimarine sediments generally were

723 recovered in water depths of ca. 75-105 m. Given a global eustatic lowstand of -134 m at the gLGM  
724 (Lambeck et al., 2014) this indicates isostatic depression of at least 25-55 m on the shelf. However,  
725 the presence of marine muds up to 10 m asl with in-situ glacimarine macro- and microfauna dated  
726 to the last deglaciation from the south side of Donegal Bay at Belderg and Fiddauntawnanoneen  
727 imply that crustal depression was probably at least 145 m (McCabe et al., 1986; McCabe et al.,  
728 2005, 2007). It is possible that this GIA-induced sea-level rise was augmented by any rise  
729 associated with the H2 event (24 ka; Hemming, 2004; Scourse et al., 2009). However, estimates of  
730 sea-level rise associated with the Heinrich events are 3-15 m (Hemming, 2004), and the H2 event is  
731 not visible in the eustatic sea-level curve of Lambeck et al. (2014). Thus the relative sea level rise  
732 recorded by the glacimarine sediments across the shelf and onshore in southern Donegal Bay must  
733 have been predominantly a consequence of local glacioisostatic depression. This was likely a  
734 cumulative effect involving crustal depression during both ice sheet build-up and glacial  
735 maximum.

736 The seafloor bathymetric data on the sediment ridges across the shelf shows they are sharp-crested,  
737 nested and lobate. They differ in morphology from grounding-zone wedges, often described from  
738 polar continental margins, which tend to be asymmetric with a gentler stoss- and steeper lee-slopes,  
739 have a distinct wedge-like geometry, may have internal bedding or 'foresets' and may be over-  
740 printed by subglacial lineations and/or iceberg scours (e.g., Ó Cofaigh et al., 2005; Evans et al.,  
741 2005; Dowdeswell and Fugelli, 2013; Batchelor and Dowdeswell, 2015; Livingstone et al., 2016).  
742 This suggests that the BIIS retreated across the northwest shelf as a grounded tidewater margin  
743 rather than as an ice-shelf (Fig. 9). Further indirect support for this interpretation is provided by the  
744 thick sequences of laminated and massive muds with dropstones and abundant foraminifera in the  
745 sediment cores. These record deposition by suspension-settling from meltwater plumes combined  
746 with rain out of ice-rafted debris as well as sandy mass flows (cf. Mackiewicz et al, 1984; Pfirman  
747 and Solheim, 1989; Powell and Domack, 1995). Ice-shelf facies in contrast tend to be characterised  
748 by coarse-grained, sometimes rubbly, diamictons, pelletised mud facies and massive clast-free muds  
749 overlain by diatomaceous open marine muds with IRD (cf. Domack and Harris, 1988; Powell et al.,  
750 1996; Domack et al., 1999; Evans et al., 2005; Kilfeather et al., 2011).

### 751 **5.3 Timing and drivers of ice sheet retreat**

752 Initial retreat from the outer shelf was complete at or before 24.8 cal ka BP by which time the ice  
753 sheet was depositing deglacial glacimarine facies on the mid-shelf (Fig. 9). Dates from cores that  
754 bottomed out in glacimarine sediments on the mid-shelf gave ages of 23.7-22.3 ka cal BP (Fig. 5).  
755 Although these are interpreted as minimum ages on retreat across the mid-shelf (i.e., retreat  
756 occurred earlier than these dates), in conjunction with the earlier dates of 26.3-24.8 ka cal BP they



757 provide a consistent chronology that indicates ice sheet recession across the shelf occurred early  
758 during the last deglaciation. This is consistent with work from further north in the Malin Sea where  
759 Callard et al. (2018) demonstrate that retreat from the shelf edge was underway by 25.9 cal ka BP.  
760 However, it is ca. 3-4 ka earlier than previous estimates of retreat further to the south on the  
761 western shelf (Peters et al., 2016) and is also earlier than the date of 23 ka for deglaciation inferred  
762 from deep sea IRD records of the BIIS (Scourse et al., 2009).

763 The Donegal Bay Moraine marks a major ice-marginal position on the inner shelf (Figs. 2 and 9).  
764 Acoustic profiles from across the moraine show that it is comprised of two ridges (Fig. 5). The  
765 acoustic profiles also imaged deformed acoustic Facies B (stratified glacimarine deposits) both  
766 behind and within the moraine (Fig. 5). This suggests that formation of the moraine may relate to a  
767 readvance or oscillation of the ice sheet margin during deglaciation. The age of the moraine is  
768 constrained by radiocarbon dates on glacimarine muds in three cores from either side and from the  
769 top of the moraine. Glacimarine sediments from the base of core JC106-99VC from west of the  
770 moraine dated  $20,239 \pm 239$  cal BP (UCIAMS-164429) and in core CE08-004 east of the moraine  
771 dated  $17,918 \pm 161$  cal BP (SUERC-47522). A further sample from core JC106-095VC collected  
772 from between the two moraine crests dated  $17,493 \pm 176$  cal BP (SUERC-63557) (Fig. 6 and Table  
773 2). The age of the moraine is thus bracketed to between 20.2 and 17.9 cal ka BP. Thus, contrary to  
774 some previous interpretations (J. Clark et al., 2009), the moraine pre-dates the Killard Stadial  
775 readvance ( $\sim 17.3$ - $16.5$  ka; McCabe et al., 2007b; J. Clark et al., 2009) and was formed earlier,  
776 during deglaciation of the shelf at ca. 20-19 ka cal BP. The position of the moraine is consistent  
777 with an interpretation of the ice sheet margin slowing as it retreated from the wide continental shelf  
778 back into the narrower confines of Donegal Bay (cf. Jamieson et al., 2012).

779 Our interpretation of episodic ice sheet retreat across the Atlantic shelf northwest of Ireland is  
780 supported regionally by several studies from offshore western Ireland and Scotland. Peters et al.  
781 (2016) document a large, arcuate, glacigenic depocentre on the mid-shelf offshore Galway Bay that  
782 they interpret as a grounding-zone wedge marking a major stillstand during deglaciation. They term  
783 this feature the 'Galway Lobe Grounding Zone Wedge' (GLGZW). As with the Donegal Bay  
784 Moraine (see above), Peters et al. (2016) infer that the GLGZW record periods of local ice re-  
785 coupling or readvance based on the presence of glacitected glacimarine sediments on its flanks.  
786 However, it differs from the Donegal Bay Moraine in an apparent absence of topographic control on  
787 its formation. Further to the north, in the Malin Sea, Callard et al., (2018) have presented marine  
788 geophysical evidence for grounding zone wedges, and thus episodic retreat, dating to the last  
789 deglaciation of the outer- to mid-shelf. Topography appears to have exerted a strong control on

790 retreat dynamics once the ice sheet reached the fjords and islands of western Scotland which acted  
791 as pinning points (Small et al., 2017).

792 The ice sheet underwent ~81 km of retreat from the shelf edge to the Donegal Bay Moraine which  
793 formed ca. 20-19 ka BP. Dates of 26.3 ka from reworked shells in till from the outer shelf provide a  
794 maximum age for the timing of retreat and a date of 24.8 ka from glacial marine sediments on the  
795 mid-shelf provides a minimum age for retreat from the outer shelf. These dates allow an envelope  
796 of retreat rates to be estimated. If these are averaged across the outer shelf to the Donegal Bay  
797 Moraine they range from 11.25 m/yr to 14 m/yr. It is, however, perhaps more instructive to break  
798 this down further into retreat from the shelf edge to the mid-shelf (core JC106-102VC with retreat  
799 dated at 24.8 ka BP) and then retreat from JC106-102VC to the Donegal Bay Moraine over  
800 distances of 50 km and 32 km respectively. This gives a minimum retreat rate of 35.7 m/yr from the  
801 shelf edge to the mid-shelf with the caveat that this retreat must actually have been faster as the 26.3  
802 ka date constraining pull-back from the shelf edge is a maximum date for retreat. Ice sheet retreat  
803 then slowed to 5.5 m/yr from core site JC106-102VC to the Donegal Bay Moraine. While retreat  
804 across the outer shelf was faster when compared to that from the mid-shelf to the Donegal Bay  
805 Moraine, overall these retreat rates are slow and consistent with the geomorphological evidence  
806 which points to episodic retreat characterised by numerous still-stands. By way of comparison they  
807 are an order of magnitude less than retreat rates recorded for contemporary ice streams in West  
808 Antarctica (e.g., 120-450 m/yr; Conway et al., 1999; Thomas et al., 2011) and the largest ice stream  
809 of the BIIS the Irish Sea Ice Stream (100-550 m/yr; Chiverrell et al., 2013). These relatively slow  
810 retreat rates offshore NW Ireland are consistent with the predominantly normal bed slope across the  
811 shelf and lack of major overdeepenings (cf. Briner et al., 2009; Stokes et al., 2014).

812 Our radiocarbon chronology indicates that the timing of initial BIIS retreat from the Atlantic shelf  
813 offshore of NW Ireland occurred relatively early during the gLGM (Clark et al., 2009), thereby  
814 implying that atmospheric warming is unlikely to have been the main driver of initial retreat.  
815 Furthermore, the foraminiferal assemblages within the cores show no evidence for the advection of  
816 warm ocean waters during initial deglaciation across the shelf. Rather they are dominated by  
817 glacial marine and cold-water indicator species. This, and the presence of glacial marine sediments along  
818 the adjoining coastline of north Mayo (see above), argues against ocean warming as a trigger for ice  
819 sheet retreat from the shelf and indicates high relative sea level during deglaciation. It is notable  
820 that extensive zones of well-developed iceberg ploughmarks occur immediately offshore of the  
821 outermost moraines on the shelf (Benetti et al., 2010; Ó Cofaigh et al., 2012). Initial retreat from  
822 the shelf edge therefore appears to have been linked to a major episode of ice-sheet break-up and  
823 iceberg calving (cf. Bradwell et al., 2008; Small et al., 2017). It is likely that retreat was triggered

824 by relative sea-level rise causing a buoyancy threshold to be crossed and destabilisation of grounded  
825 ice at the shelf edge. The early timing of initial retreat (<26.3->24.8 cal ka BP) coincides with the  
826 gLGM eustatic sea level lowstand (Lambeck et al. (2014). Hence the high relative sea level must  
827 have been predominantly a function of glacioisostatic depression related to the presence of the BIIS.

828 The concept of high relative sea level due to glacioisostatic depression has long been known (e.g.,  
829 Walcott, 1970; Andrews, 1970), as has the importance of this for triggering the retreat of marine-  
830 based ice sheet sectors (e.g., Andrews, 1987; Hughes, 1987). More recently, modelling has also  
831 drawn attention to the important effects of glacioisostatic adjustment in modulating ice age cycles  
832 (Abe-Ouchi et al., 2013) and possibly Heinrich events (Bassis et al., 2017). In the case of the BIIS,  
833 deglaciation of the Irish Sea Basin was inferred by some workers (Eyes and McCabe, 1989) to have  
834 been triggered by rising relative sea level as the basin underwent glacioisostatic subsidence  
835 (although aspects of this interpretation have proved controversial; cf. McCarroll 2001). In their  
836 assessment of the timing of the gLGM and the associated controls on ice sheet growth and decay,  
837 Clark et al. (2009) argued that many of the northern hemisphere ice sheets, including the BIIS,  
838 began to retreat from their maxima at 19-20 ka and that this was triggered by northern insolation.  
839 The much earlier deglaciation of the BIIS from the continental shelf offshore of NW Ireland that we  
840 document here (cf. Callard et al., 2018) occurred in the absence of external forcing such as  
841 atmospheric or ocean warming and was likely driven by glacioisostatic depression and high relative  
842 sea level. This demonstrates that marine-based sectors and margins of large ice sheets can trigger  
843 their own demise internally through glacioisostatic adjustment and it underscores the importance of  
844 including glacioisostasy and relative sea level changes at a high enough spatial and temporal  
845 resolution in numerical ice sheet models to ensure that they capture the full range of processes of  
846 marine-ice sheet dynamics.

## 847 6. CONCLUSIONS

- 848 • On the Atlantic shelf northwest of Ireland, arcuate moraines imaged in multibeam swath  
849 bathymetric and sub-bottom profiler data on the outer shelf and subglacial tills in sediment  
850 cores record the former extension of a grounded BIIS to the shelf edge. Radiocarbon dates  
851 on reworked shells indicate till formation and ice sheet advance occurred after 26.3 ka cal  
852 BP and thus during the gLGM.
- 853 • Nested moraines record the subsequent episodic retreat of the ice sheet across the shelf.  
854 Acoustically stratified facies formed during deglaciation and cores from these facies  
855 recovered laminated and massive muds containing glacimarine foraminiferal assemblages.

These landforms and sediments were deposited by a retreating grounded (tidewater) ice sheet margin.

- Radiocarbon dates indicate that the ice sheet had retreated to the mid-shelf by >24.8 cal ka BP and so initial pull-back from the shelf edge occurred in the interval <26.3->24.8 cal ka BP. A prominent moraine at the mouth of Donegal Bay the ‘Donegal Bay Moraine’, records a major stillstand and/or readvance during deglaciation, and formed at c. 20-19 cal ka BP. Ice had retreated eastwards of this moraine by 17.9 cal ka BP. Hence formation of the moraine pre-dated the Killard Point Stadial readvance.
- The foraminiferal and sedimentological data indicate that glacimarine conditions, high relative sea level and cold waters prevailed during ice sheet retreat across the shelf. Evidence for retreat being driven by the advection of warm ocean water onto the shelf was not observed. Extensive zones of iceberg ploughmarks across the outer shelf imply that retreat was associated by a major phase of iceberg calving as the ice sheet stepped back from the shelf edge with glacimarine conditions, and thus high relative sea level, accompanying ice sheet retreat across the shelf.
- The data presented in this paper provide directly dated geomorphological and sedimentological evidence for a shelf-edge terminating, grounded BIIS at the LGM on the Atlantic shelf northwest of Ireland. Early retreat of the ice sheet in this sector during the gLGM eustatic lowstand was triggered by glacioisostasy and high relative sea level. This provides an explanation for the early retreat of the BIIS on the Atlantic shelf offshore Ireland and emphasises the importance of local relative sea-level rise driven by glacioisostatic crustal depression to initiate marine-based, ice sheet retreat.

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## 1190 **Figures and Tables**

1191 Fig. 1. Continental shelf offshore of northwest Ireland showing numbered core locations and the  
1192 location of seismic profiles (shown in Figures 3 and 5). JC106 (RRS James Cook) cores shown in  
1193 red (cores 093VC-113VC; 'southern transect') and CE008 (RV Celtic Explorer) cores shown in  
1194 blue (cores 3-18; 'northern transect'). Geomorphological interpretation of glacial features on the  
1195 continental margin (modified from Benetti et al., 2010 and Ó Cofaigh et al., 2012) is also shown.  
1196 The location of the 'Donegal Bay Moraine' is arrowed ("X"). Inset map shows locaton of study area  
1197 offshore northwest Ireland. Labels on inset map: CS = Celtic Sea, MS = Malin Sea, RT = Rockall  
1198 Trough.

1200 Fig. 2. Shaded relief image of arcuate moraines in Donegal Bay and the adjoining shelf. The  
1201 Donegal Bay Moraine (see text) is labelled 'X'.

1203 Fig. 3. Seismic profile (and associated interpretation) extending eastwards from the continental  
1204 shelf edge to Donegal Bay showing the location of sediment cores. The location of the seismic  
1205 profile is shown in Figure 1. The profile is split into two parts. Part A covers the shelf edge to mid-  
1206 shelf, and the eastwards continuation of the profile is shown underneath in part B which covers the  
1207 mid- to inner-shelf.

1209 Fig. 4. Acoustic facies observed in sub-bottom profiles from the study area.

1211 Fig. 5. Examples of internal structure of the Donegal Moraine. Note the contorted stratified acoustic  
1212 sediments on southeast side of eastern ridge in both profiles. The location of the upper profile (A)  
1213 is shown in Figure 3, and that of the lower profile (B) is shown in Figure 1.

1215 Fig. 6. Core logs presented as a west to east transect from outer shelf to inner shelf. The lithofacies  
1216 are colour coded. Radiocarbon dates are shown alongside the logs at their stratigraphic depth. Dates  
1217 in green are from shells, dates in black are from benthic foraminifera. (a) Northern core transect  
1218 (Celtic Explorer cruise CE08 cores; see Fig. 1). (b) Southern core transect (James Cook cruise  
1219 JC106 cores; see Fig. 1). Shear strength profiles (in kPa) are also shown in b.

1220  
1221 Fig. 7. X-radiographs showing details of lithofacies from the study area. See Figure 1 for core  
1222 locations. (a) Facies Dmm. Massive, matrix-supported diamicton from the lower part of core  
1223 JC106-112 (40-70 cm depth). (b) Facies Dmm-Dml. Massive to diffusely laminated matrix-  
1224 supported diamicton from the lower part of core CE08-010 (48-78 cm depth). (c) Facies Fmd.  
1225 Poorly sorted, massive diamictic mud with dispersed clasts. Core JC106-100 (414-445 cm depth).  
1226 (d) Facies Gm. Clast supported massive gravel. Core JC106-095 (5-35 cm depth). (e) Facies Fl  
1227 (minor Fld towards bottom of image). Laminated silts and clays. The clays are of higher density and  
1228 appear as dark bands on the image while silt appears light. Note occasional small pebbles in the  
1229 lower part of the core. Core JC106-101 (5303-332 cm depth). (f) Facies Fmd-Fl. Massive diamictic  
1230 mud overlain by laminated mud. Note the sharp contact between the two facies and diamictic layers  
1231 within the upper laminated facies. Core JC106-100 (295-325 cm depth). (g) Facies Sh. Laminated  
1232 sand. Core JC106-105 (428-445 cm depth).

1233 Fig. 8. Foraminiferal assemblage data from cores along a transect from outer- to inner-shelf: (a)  
1234 CE08-018 (outer shelf); (b) CE08-010 (mid-shelf); (c) JC106-102VC (mid-shelf); (d) JC106-100  
1235 (mid-shelf); JC106-095VC (Donegal Bay Moraine); and (f) CE08-003 (inner-shelf).

1236

1237 Fig. 9. Reconstruction of glacial and deglacial history on the continental shelf northwest of Ireland.  
 1238 (A) Shelf-edge ice sheet at LGM ( $\leq 26.3$  ka BP). (B) Initial ice sheet retreat from shelf edge  
 1239 ( $< 26.3 - > 24.8$  ka BP). (C) Ice sheet retreat across the mid-shelf (24.8-20.2 ka BP). (D) Ice sheet  
 1240 marginal stillstand at the Donegal Bay Moraine ('DBM') ( $< 20.3 - > 17.9$  ka BP). (E) Retreat from the  
 1241 Donegal Bay Moraine ('DBM') ( $\geq 17.9$  ka BP). (F) Present day. Acoustic Facies A-C are also  
 1242 indicated.

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1244

1245 Table 1. Site information on sediment cores from Donegal Bay and the adjoining shelf.

1246

1247 Table 2. Radiocarbon dates from marine sediment cores on the continental shelf offshore of  
 1248 northwest Ireland. In the Notes column, "DBM" = Donegal Bay Moraine. Radiocarbon ages were  
 1249 calibrated using OxCal 4.2, web interface build number 94 (Bronk Ramsey 2009) with the  
 1250 Marine13  $^{14}\text{C}$  - modelled ocean average calibration curve (Reimer et al., 2013).

1251 Table 3: Lithofacies in cores from Donegal Bay and adjoining shelf (after Eyles et al., 1983)

1252

<b>Table 1. Site information on sediment cores from Donegal Bay and the adjoining shelf</b>			
<b>Core name</b>	<b>Location</b>	<b>Water depth (m)</b>	<b>Recovery (m)</b>
CE08-003	54.6415° N, 8.9324° W	88	5.12
CE08-004	54.6601° N, 9.0260° W	82	2.75
CE08-005	54.6679° N, 9.0414° W	67	6.9
CE08-008	54.7869° N, 9.3348° W	90	3.22
CE08-009	54.7891° N, 9.3428° W	90	0.74
CE08-010	54.8316° N, 9.4233° W	97	5.78
CE08-011	54.8370° N, 9.4332° W	95	1.39
CE08-015	54.8403° N, 9.6179° W	99	2.78
CE08-017	54.8926° N, 9.6872° W	122	1.3
CE08-018	54.9822° N, 9.9172° W	122	1.0
JC106-092VC	54° 24.331'N, 9° 10.608'W	75	2.7
JC106-093VC	54° 33.898'N, 8° 59.177'W	81.6	3.55
JC106-094VC	54° 34.009'N, 9° 0.049'W	75.6	0.86
JC106-095VC	54° 34.238'N, 9° 1.832'W	77.6	2.31
JC106-096VC	54° 28.913'N, 9° 10.181'W	75	3.06
JC106-097VC	54° 27.287'N, 9° 10.322'W	75	4.71
JC106-098VC	54° 26.115'N, 9° 10.446'W	75	0
JC106-099VC	54° 36.218'N, 9° 20.139'W	99	4.75
JC106-100VC	54° 36.243'N, 9° 20.496'W	99	4.97
JC106-101VC	54° 36.784'N, 9° 25.241'W	100	5.65
JC106-102VC	54° 37.407'N, 9° 31.134'W	90.5	2.52
JC106-103VC	54° 38.438'N, 9° 35.833'W	100	1.49
JC106-104VC	54° 40.393'N, 9° 41.239'W	102	0.94
JC106-105VC	54° 40.917'N, 9° 42.838'W	108	5.82
JC106-106VC	54° 41.202'N, 9° 43.656'W	105	3.94
JC106-107VC	54° 48.783'N, 10° 4.829'W	117	1.22
JC106-108VC	54° 49.023'N, 10° 5.607'W	119	0.45
JC106-109VC	54° 49.521'N, 10° 7.189'W	120	0
JC106-110VC	54° 49.714'N, 10° 7.808'W	122.7	0.31

JC106-111VC	54° 49.739'N, 10° 7.881'W	123	0.3
JC106-112VC	54° 50.708'N, 10° 10.882'W	125	1
JC106-113VC	54° 50.742'N, 10° 10.98'W	125	0.23

**Table 2. Radiocarbon dates from marine sediment cores on the continental shelf offshore of northwest Ireland. In the Notes column, “DBM” = Donegal Bay Moraine. Radiocarbon ages were calibrated using OxCal 4.2, web interface build number 94 (Bronk Ramsey 2009) with the Marine13 <sup>14</sup>C - modelled ocean average calibration curve (Reimer et al., 2013).**

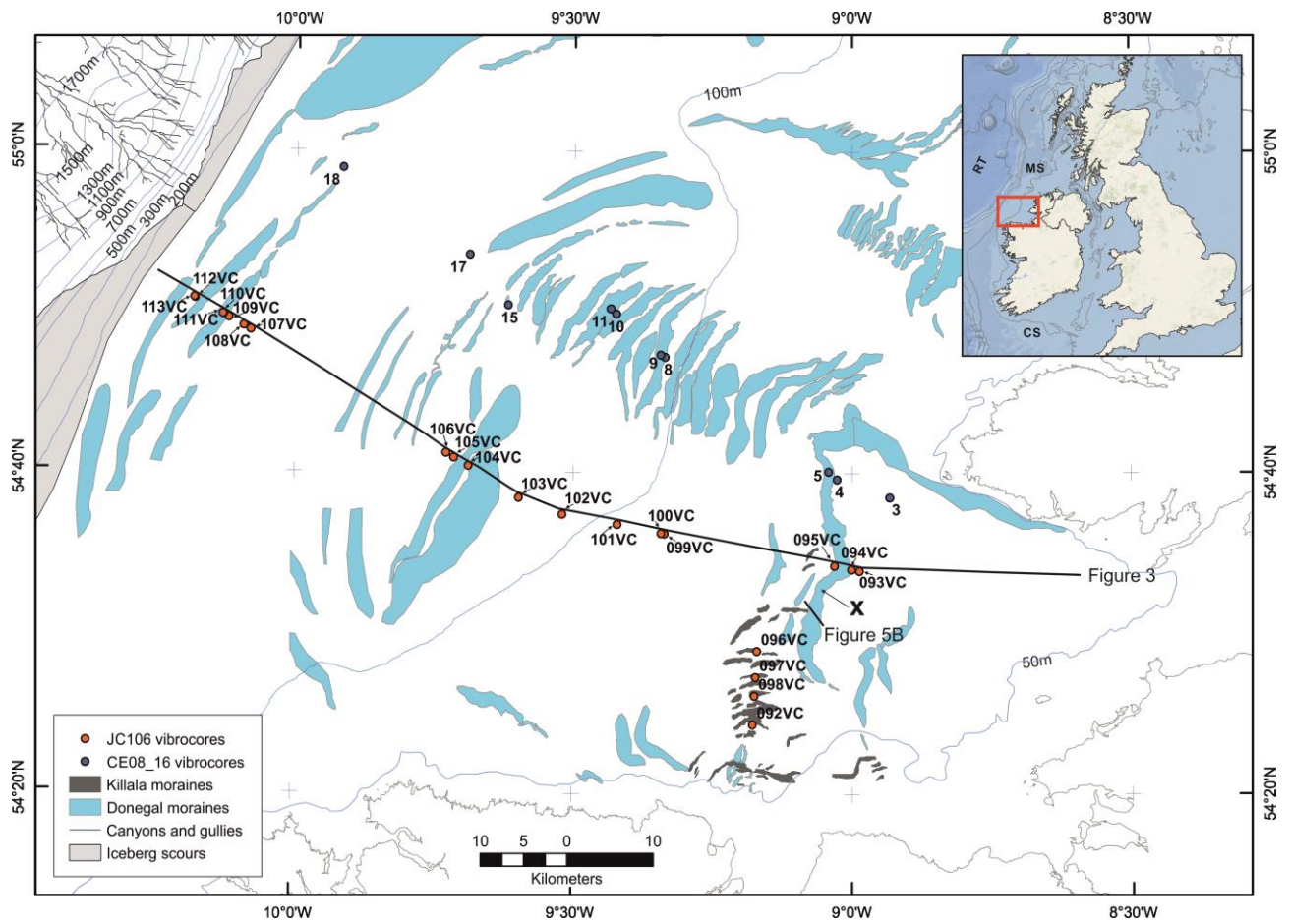
Sample ID	Lab code	Sample depth (cm)	Sample material	Conventional <sup>14</sup> C age (yr BP) ± 1σ	Calibrated age (cal yr BP) ± 1σ. ΔR=0 yr.	Calibrated age (cal yr BP) ± 1σ. ΔR=300 yr.	Calibrated age (cal yr BP) ± 1σ. ΔR=700 yr.	Notes
T6-095VC-128	SUERC-58402	128	Shell fragment	13527±39	15759±190	15283±171	14518±329	From massive glacimarine mud, 95VC, DBM
T6-095VC-175.5	SUERC-58403	175.5	Shell fragment	13516±38	15740±192	15266±161	14493±319	From laminated glacimarine mud, 95VC, DBM
T6-095VC-209	SUERC-63557	209	Mixed benthic foraminifera	14760±45	17493±176	17084±212	16465±220	From laminated glacimarine mud, 95VC, DBM
T6-099VC-474	UCIAMS-164429	474	Mixed benthic foraminifera	17180±80	20239±239	19870±245	19394±233	From interbedded laminated & massive glacimarine mud, 99VC base, mid-shelf
T6-101VC-548-551	UCIAMS-164431	548-551	Mixed benthic foraminifera	20110±120	23733±319	23361±353	22885±353	From laminated glacimarine mud, 101VC base, mid-shelf
T6-102VC-72	SUERC-59510	72	Shell fragment	16692±45	19669±186	19300±190	18835±106	From laminated glacimarine mud 102VC, mid-shelf
T6-102VC-247	UCIAMS-164437	247	Mixed benthic foraminifera	21000±110	24804±388	24387±339	23939±300	From laminated glacimarine mud, 102VC base, mid-shelf
T6-103VC-145	SUERC-63558	145	Mixed benthic foraminifera	22521±70	26319±247	26031±161	25744±163	From massive sand, 103VC base, mid-shelf
T6-105VC-572	UCIAMS-164438	572	Mixed benthic	19290±90	22745±259	22460±194	22052±267	From interstratified sands and muds, 105VC base,

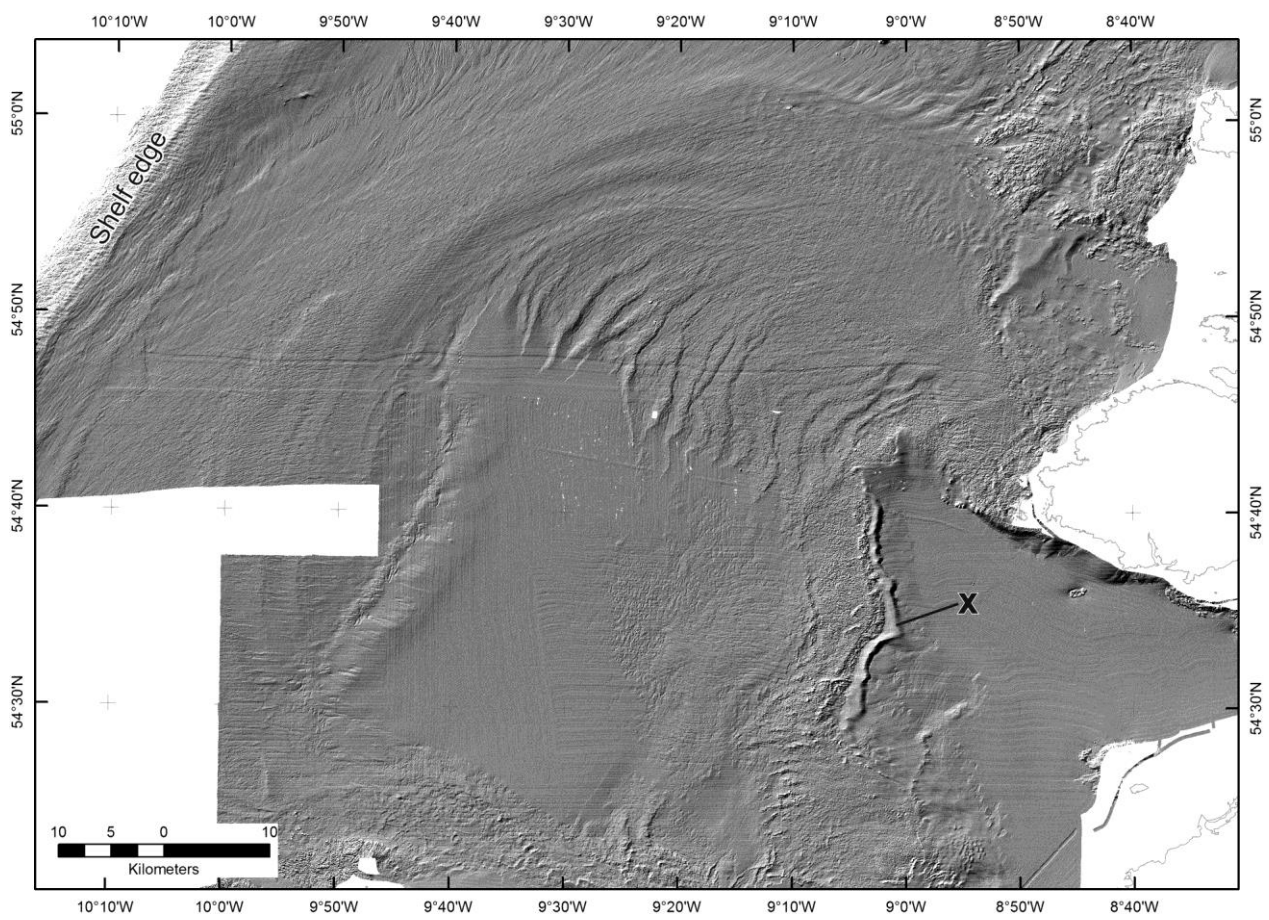


			foraminifera					mid-shelf
T6-106VC-389	UCIAMS-164435	389	Mixed benthic foraminifera	18850±90	22307±237	22007±274	21484±310	From massive glacimarine mud, 106VC base, mid-shelf
T6-112VC-51	SUERC-63584	51	Shell fragment	22582±67	26382±257	26082±178	25791±153	From massive diamicton (till), 112VC, outer shelf
T6-112VC-59.5	SUERC-63585	59.5	Shell fragment	22572±71	26372±259	26074±180	25783±159	From massive diamicton (till), 112VC, outer shelf
T6CE08-018-CC	UCIAMS-133552	core catcher	Mixed benthic foraminifera	20170±90	23796±267	23436±310	22964±308	From laminated sand, base, CE08-018, outer shelf
T6CE08-015-272	SUERC-47518	272	Shell fragment	12495±40	13976±137	13645±151	13272±104	From massive sand, CE08-015, mid- shelf
T6CE08-010-573	SUERC-58324	573-578	Mixed benthic foraminifera	15263±43	18063±167	17743±176	17241±196	From massive glacimarine diamicton CE08-010, mid-shelf
T6CE08-010-471	UCIAMS-133551	471-478	Mixed benthic foraminifera	13205±35	15250±145	14735±339	13987±131	From massive sand, CE08-010, mid- shelf
T6CE08-004-264	SUERC-47522	264-273	Mixed benthic foraminifera	15130±44	17918±161	17584±178	17036±212	From laminated glacimarine mud, CE08-004, inner shelf, inshore of DBM
T6CE08-004-217	SUERC-47517	217	Shell fragment	11555±39	13030±139	12730±110	12371±208	From massive sand, CE08-004, inner shelf, inshore of DBM
T6CE08-003-493	UCIAMS-133550	493-499	Mixed benthic foraminifera	11345±30	12800±118	12595±76	11981±157	From laminated glacimarine mud, CE08-003, inner shelf
T6CE08-003-477	SUERC-47516	477	Single valve, <i>Macoma</i>	11219±39	12702±102	12472±157	11725±270	From laminated glacimarine mud, CE08-003, inner shelf

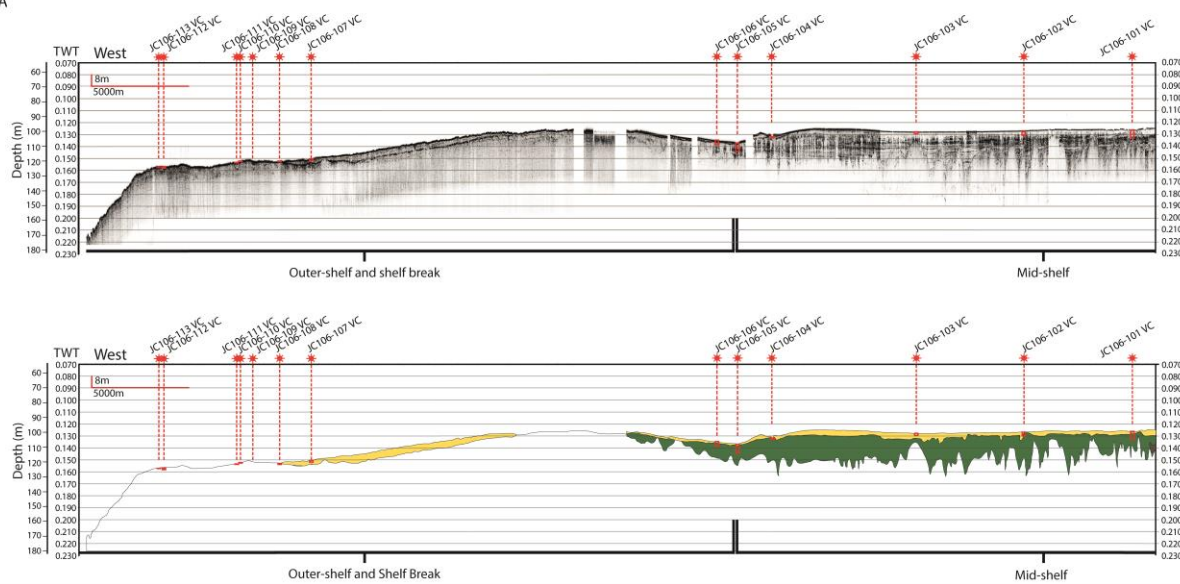
			<i>calcareo</i>					
T6CE08-003-466	SUERC-47515	466	Single valve, <i>Macoma calcarea</i>	11091±38	12622±80	12266±220	11469±247	From laminated glacimarine mud, CE08-003, inner shelf
T6CE08-003-387	SUERC-47514	387	Shell fragment	10802±38	12284±218	11683±274	11107±112	From laminated glacimarine mud, CE08-003, inner shelf

<b>Table 3: Lithofacies in cores from Donegal Bay and adjoining shelf (after Eyles <i>et al.</i>, 1983)</b>	
<b>Lithofacies</b>	<b>Description</b>
Dmm (minor Dml)	Diamict, matrix-supported and massive. Can be divided into two sub-facies. Lithofacies 1a (Dmm) is stiff, massive, contains reworked shells fragments, matrix of silt-clay with dispersed clasts of no apparent preferred orientation. Lithofacies 1b is a massive diamicton (Dmm) that is locally transitional to a diffusely laminated diamicton (Dml) with dropstones. Texturally it ranges from zones of clast-poor to clast-rich diamicton. Well preserved benthic glacial marine foraminiferal assemblage.
Gm	Gravel, clast-supported
Gms	Gravel, matrix-supported
Suf	Sand, normally graded.
Sh	Sand, horizontally-laminated
Sm	Sand, massive
Fl	Mud, laminated.
Fld	Mud, laminated with clasts
Fm	Mud, massive
Fmd	Mud, massive with clasts. Occasionally transitional to Dmm

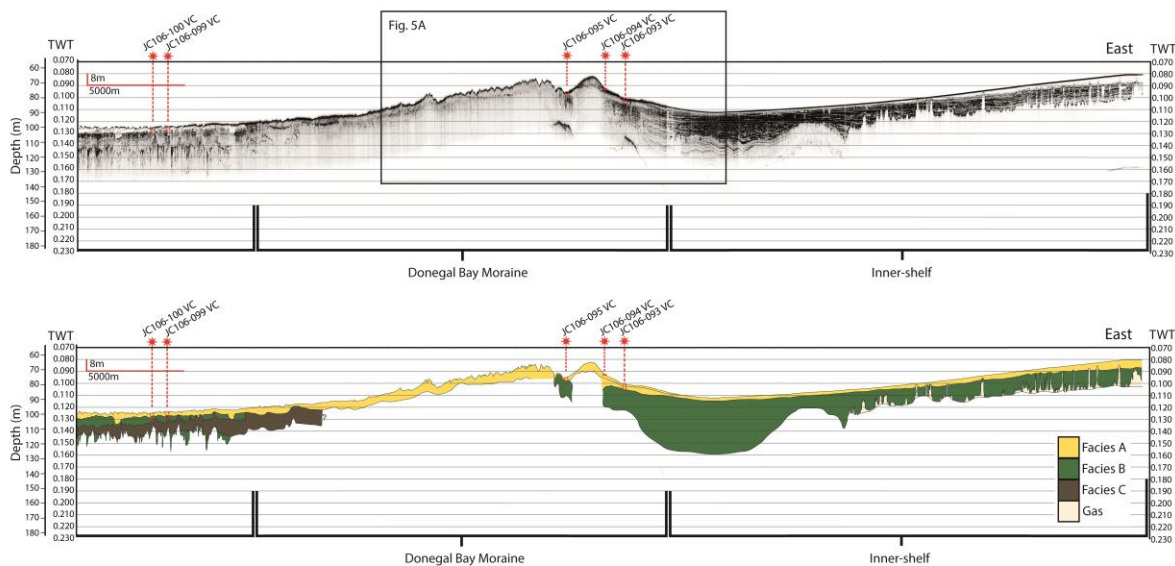


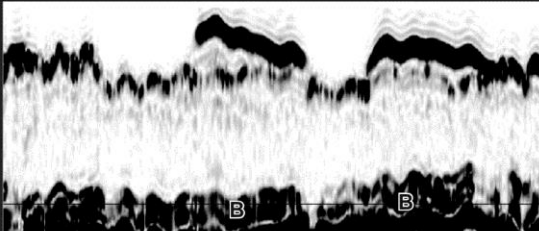
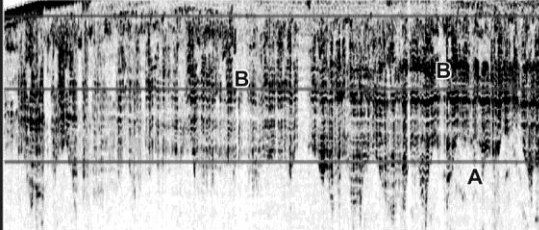
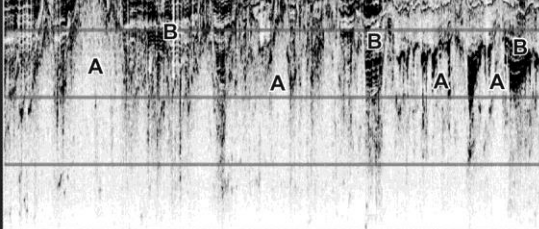


A

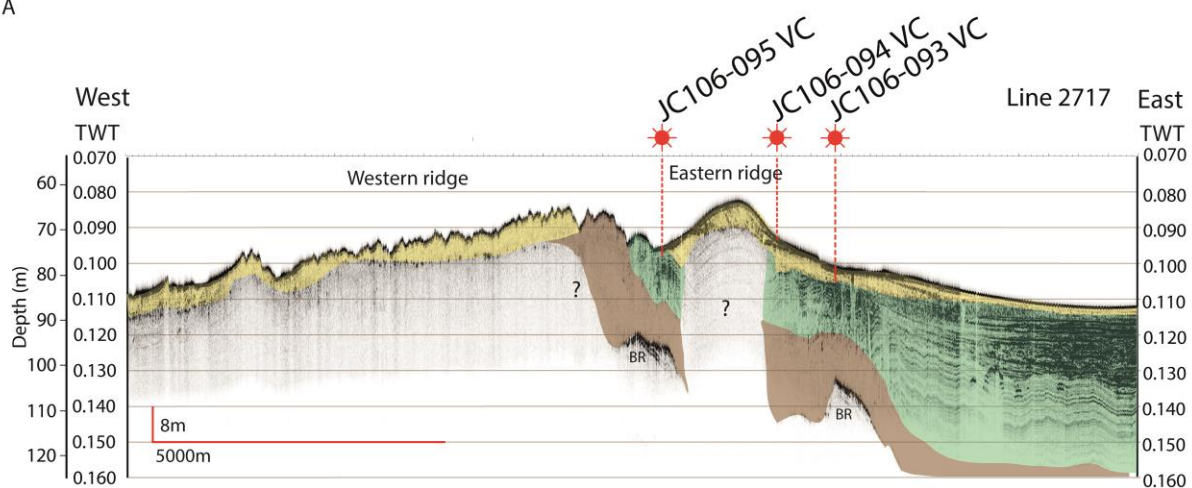


B

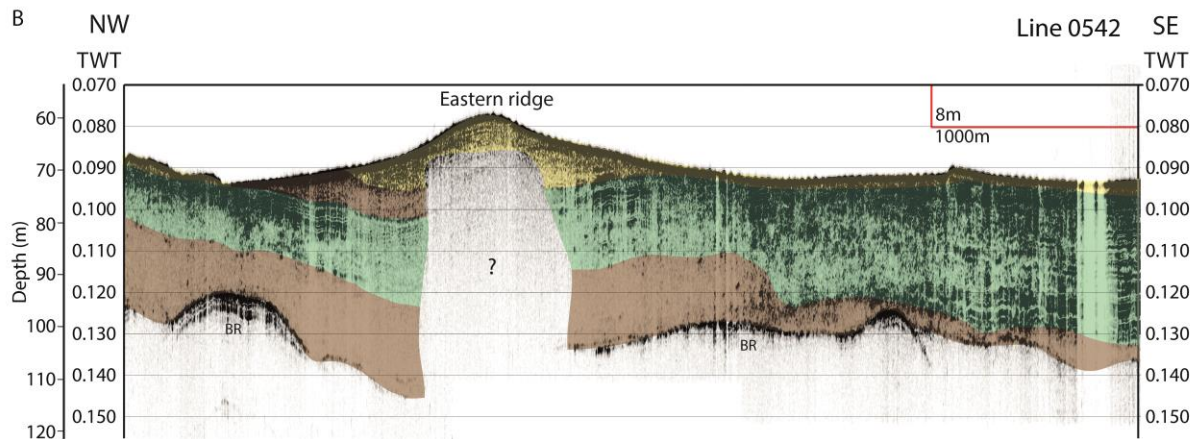


Facies	Acoustic signature	Description
C		<p>Acoustically transparent. Stratigraphically the uppermost acoustic facies in the study area, occurring directly beneath the sea floor. Found across most of the study area but especially on the inner and mid-shelf. It ranges in thickness from 0.8~ 8 m and tends to be thickest on the inner shelf.</p>
B		<p>Facies B is acoustically laminated to well stratified. Prominent on the inner and mid-shelf. Reaches a maximum thickness of ~24 m. Across the mid-shelf it infills topographic depressions between the highs of Facies A. Stratification ranges from horizontal and sub-horizontal to locally contorted (e.g., east side of the Donegal Bay Moraine).</p>
A		<p>Facies A is acoustically homogeneous/ structureless. Stratigraphically it forms the lowermost acoustic facies in the study area. It has a pronounced topography in the form of a series of sharp buried ridges across the shelf. Ridges are typically overlain by the laminated sediments of acoustic Facies B which also infills inter-ridge depressions.</p>

A



B







(b) West



