

A Plio-Pleistocene sediment wedge on the continental shelf west of central Ireland: The Connemara Fan

Stephen McCarron^{a,*}, Daniel Praeg^{b,1}, Colm Ó Cofaigh^c, Xavier Monteys^d, Benjamin Thébaudeau^{a,d}, Kieran Craven^{a,d}, Muhammad Mudasar Saqab^e, Andrea Cova^b

^a Maynooth University Department of Geography, Maynooth, Co. Kildare, Ireland

^b OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), Trieste, Italy.

^c Department of Geography, Durham University, Durham, UK.

^d Geological Survey of Ireland, Beggar's Bush, Dublin 4, Ireland.

^e CRAG, School of Earth Sciences, UCD, Dublin, Ireland.

ARTICLE INFO

Keywords:

Glacigenic fan
Plio-Pleistocene
British Irish Ice Sheet (BIIS)
Irish Continental Shelf

ABSTRACT

Glacigenic sediment fans recording shelf edge deposition from marine-terminating ice sheets have previously been recognised along the NW European continental margin from Svalbard to as far south as Donegal, off north-west Ireland. Here we present evidence of a previously unrecognised partially glacially-fed Plio-Pleistocene sediment wedge on the continental shelf west of central Ireland using 2D and 3D seismic reflection data correlated to a commercial borehole. The ‘Connemara Fan’ covers a shelf area of approximately 9000 km² in water depths of 125–310 m, extending westwards into the Porcupine Seabight from the Irish Mainland Shelf. The wedge comprises up to 160 m of sediment that culminates in a prominent morainic ridge at seabed and contains two discordant reflection surfaces (R1 and 2) that subdivide it into three seismic units (SU1–3). Stratigraphic boreholes 27/24-2 and 2A located on the inner shelf show that the lower unit (SU1) is composed of Pliocene marine sediments, while SU2 and 3 comprise glacially influenced facies of Quaternary age. Extracts from a 3D seismic data volume within the central part of the fan show channels within the Pliocene succession, while iceberg scours are observed on the R1 and R2 reflectors. The Connemara Fan is inferred to record sediment supply from central western Ireland, with Quaternary units probably recording at least two glacial advance-retreat cycles with ice sheets repeatedly grounding across the inner (Irish Mainland) shelf. Our findings extend the range of glacially-influenced grounding line depocentres southwards along the NW European continental margin.

1. Introduction

The NW European Atlantic continental margin is characterised by a series of large-scale Pliocene to Quaternary (Plio-Quaternary) sediment wedges that have prograded the shelf and slope (Dahlgren et al., 2005; Sejrup et al., 2005) (Fig. 1A). Such fans have been identified from the Arctic margins of the Barents Sea to as far south as the Barra-Donegal Fan (BDF) off NW Ireland (e.g. Armishaw et al., 2000; Dahlgren et al., 2005; Sejrup et al., 2005; Stoker et al., 2002; Stoker et al., 2005). The fans have a common stratigraphic architecture, in which prograding strata as old as late Pliocene are separated by an intra-Pleistocene unconformity from a prograding-aggrading wedge formed from direct glacial sediment supply in front of and beneath an ice sheet margin (Stoker et al., 1994; Stoker et al., 2002; Stoker et al., 2005). Sediments

recovered from above an intra-Pleistocene unconformity on the Norwegian and northern UK margin are < 0.44 Ma old (marine isotopic stage 12 - MIS 12), suggesting that this unconformity correlates to a mid-Pleistocene aged onset of shelf-wide glacial expansions in NW Europe during cold periods (Stoker et al., 2005; Sejrup et al., 2005). This is consistent with cores from the Rockall Trough which record peaks in ice rafted sediment supply from the British Ice Sheet to the BDF during MIS 6 and 4–2 (Hibbert et al., 2010; Knutz et al., 2001).

The British-Irish Ice Sheet (BIIS) is inferred to have reached the northwest Irish shelf edge at the last glacial maximum (LGM), where arcuate moraines are interpreted to record the advance of ice streams from Scotland (Dunlop et al., 2010) and north central Ireland (Benetti et al., 2010; Ó Cofaigh et al., 2012a, 2012b) (Fig. 1B). Southwards, much of the continental slope is incised by deep canyons (Elliott et al.,

* Corresponding author.

E-mail address: Stephen.mccarron@mu.ie (S. McCarron).

¹ Present address: Géozur, UMR7329 CNRS, 250 rue Albert Einstein, 06560 Valbonne, France.

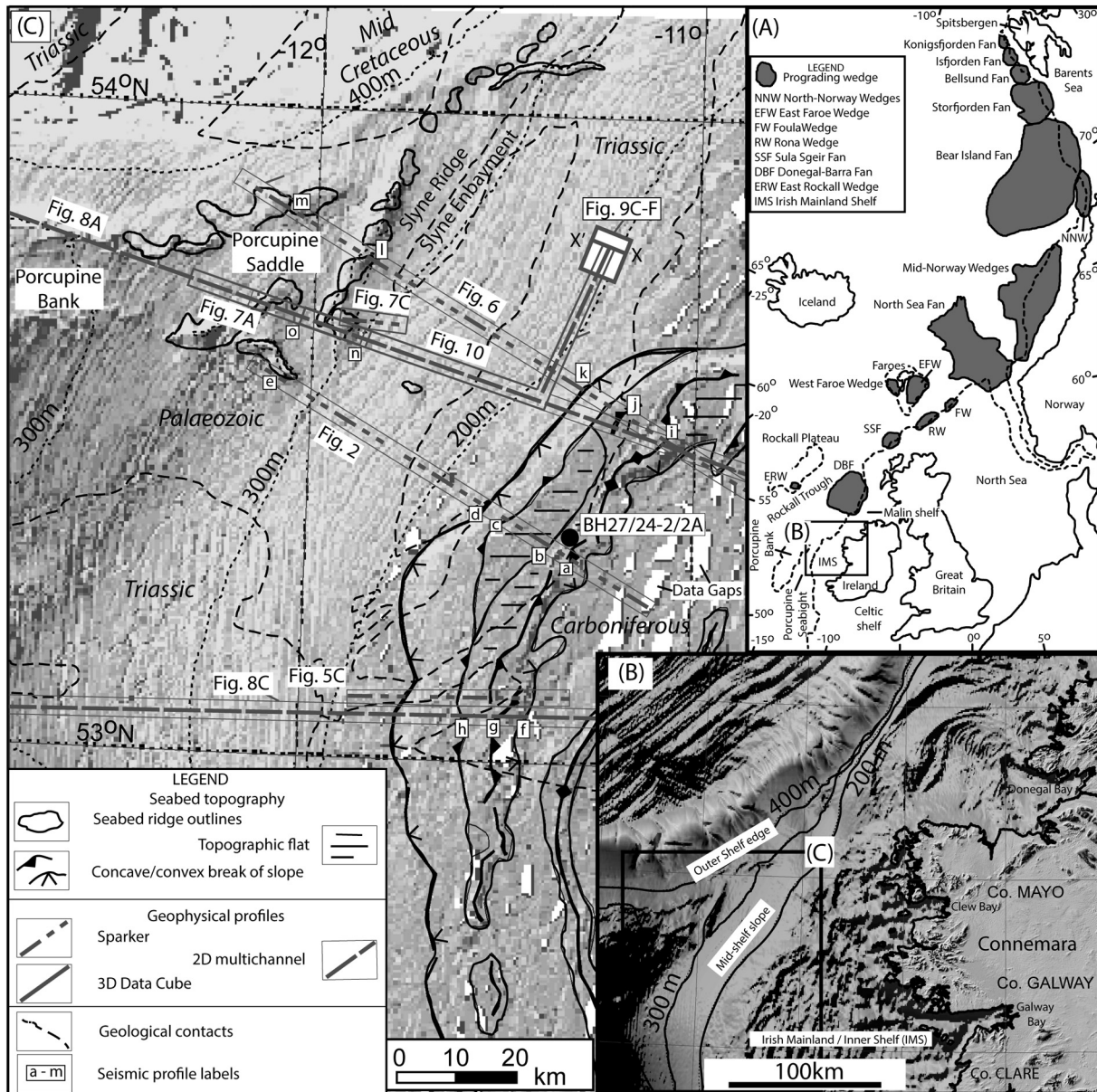


Fig. 1. Location of the study area on the continental shelf west of Connemara, central Ireland.

(A) The distribution of Plio-Pleistocene sediment wedges on the NW European Atlantic margin (after Dahlgren et al., 2005).

(B) The bathymetry of the western Irish Shelf. Data sources: Irish National Seabed Survey (INSS) multibeam echosounder (MBES) data for water depths > 200 m and in Donegal Bay, and GEBCO 2008 0.5 arc sec in < 200 m water depth.

Note (i) the widening Irish Mainland Shelf (< ~150 m water depth) west of Counties Galway and Clare; (ii) prominent, nested arcuate seabed ridges west of Donegal Bay and a prominent large arcuate moraine ridge at the outer shelf edge, in ~200 m water depth (c.f. Ó Cofaigh et al., 2012a, 2012b); (iii) prominent, arcuate, concave-inshore and obliquely intersecting sub-parallel northwest-southeast seabed ridges on the Porcupine Saddle between 300 and 400 m;

(C) A hillshaded relief image of the study area rendered from INSS MBES data showing: lines of examined seismic reflection datasets; summary bedrock geology (after Naylor et al., 1999); the location of BH27/24-2,2A; prominent seabed topography mapped from seismic profiles, INSS MBES data and OLEX bathymetric databases (Thébaudeau et al., 2015).

2006). These canyons initiate at the shelf edge (Weaver et al., 2000) and likely acted as conduits for glacial and glaciofluvial sediment (Sacchetti et al., 2012).

West of central Ireland (~53°N), moraine-like ridges have also been mapped across the inner shelf in water depths shallower than 200 m (Clark et al., 2012). Smaller features on the Porcupine Saddle, in water depths of 300–400 m (Fig. 1), have also been argued to represent moraine ridges, recording LGM grounded ice extension from central Ireland during the Last Glacial Maximum (LGM), and subsequent retreat of marine-terminating ice lobes (Peters et al., 2015; Peters et al., 2016). Radiocarbon dates on reworked marine macrofossils within overconsolidated diamict interpreted as till from the proposed grounding zone indicate the presence of grounded ice on the north flank

of the Porcupine Bank after 24 ka B.P. (Peters et al., 2015; Peters et al., 2016). Reconstructions of LGM BIIS extents on the continental shelf generally fall into one of two groups: (1) inner to mid-shelf (~200 m water depth) limits (e.g. Bowen et al., 2002; Stoker et al., 2005), or (2) outer shelf (> 300 m water depth) limits (e.g. Chiverrell and Thomas, 2010; Clark et al., 2012; Peters et al., 2015; Peters et al., 2016; Sejrup et al., 2005). The difference between the two models in terms of grounded ice sheet extent is significant in terms of the reconstructed volume of the last BIIS.

The purpose of this paper is to present new information on the Plio-Pleistocene stratigraphy of the shelf west of central Ireland. We use seismic reflection datasets, acquired during research campaigns and commercial activities, together with results from a nearby commercial

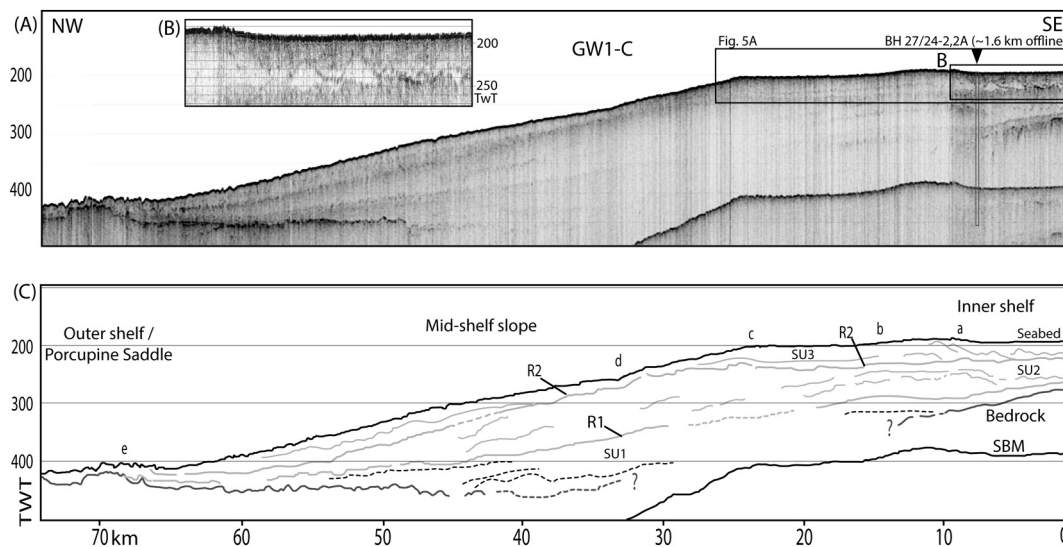


Fig. 2. GATEWAYS1–Line C (GW1-C) sparker seismic reflection profile.

(A) Sparker seismic reflection profile GW1-C. Labeled locations: (a–b) a prominent (circa 20 m high) seabed ridge cresting at 195 ms/146 m water depth; (c) inner shelf break at ~200 ms/~150 m water depth; (d) a notch/inflexion point on the mid-shelf slope (e) a seabed ridge on the bathymetric plateau of the Porcupine Saddle; (c–e) mid-shelf slope.

(B) Detail of the inner shelf seismic architecture showing prominent, mounded, eastward offlapping subsidiary reflectors within SU3.

(C) Interpretative sketch of Panel A. Note (i) an uneven bedrock surface on the inner shelf, two prominent cross-shelf intra-fan reflectors (R1 & R2), three seismic stratigraphic units (SU1–3).

stratigraphic borehole. Our findings show for the first time that previously identified seabed moraines are underlain by more extensive and thick glaciogenic sediments, the geometries of which provide new insights into the timing and extent of Pleistocene glaciations in the region.

2. Regional setting

2.1. Shelf physiography

The study area lies offshore of Connemara (Counties Mayo, Galway and Clare), central western Ireland (Fig. 1B). Much of the area is shallower than ~200 m water depth comprising the Irish Mainland Shelf (IMS) (Naylor and Shannon, 1982), which extends up to 150 km west of the coastline, narrowing to the north where it meets the Rockall Trough shelf break < 100 km west of the Co. Mayo coast (Fig. 1B). The IMS can be subdivided into the inner shelf (< 140 m water depth) extending seaward to an area of gentle (< 0.5°) slopes up to 70 km wide, referred to as the mid-shelf slope. The mid-shelf slope descends smoothly to the Slyne Ridge (Naylor and Shannon, 1982), which contains the Porcupine Saddle, a bathymetric platform at water depths of ~305–350 m (Fig. 1). The Slyne Ridge links the IMS to the Porcupine Bank, which rises to its shallowest depth of c. 145 m 200 km due west off the Co. Clare coast. The Slyne Ridge and Porcupine Bank are bounded to the north and west by the outer shelf break at ~400 m water depth.

2.2. Bedrock geology

Seismic reflection profiles correlated to existing exploration wells and boreholes show that the inner shelf is underlain by offshore extensions of the Precambrian metasedimentary rocks of Connemara, and Carboniferous limestones of the Clare Basin (Naylor et al., 1999) (Fig. 1C). These units form an acoustic basement that is overlain by Permian to Jurassic strata within the north-south oriented Slyne Basin, which underlies part of the Porcupine Saddle. Basement rocks rise to seabed beneath the Porcupine Bank, and also under the generally north-south oriented Slyne Ridge which crosscuts the Slyne Basin. The Slyne Ridge bifurcates along the line of the Porcupine Saddle, forming a fault-bounded re-entrant of the Permo-Jurassic Slyne Basin, referred to as the

Slyne Embayment (Naylor and Shannon, 2009) (Fig. 1C). A thin late Cretaceous to Tertiary cover is suggested to be present along the western margin of the Carboniferous Clare Basin which underlies the inner shelf IMS (Croker, 1995).

2.3. Pliocene to Quaternary geology

Pliocene to Pleistocene sediment sequences on the continental shelf west of Ireland are thought to comprise a < 150 m thick drape (Naylor and Shannon, 2009) over a pre-Pliocene surface (Miocene and older). Further north, on the inner Hebrides shelf, a variably thick Plio-Pleistocene slope-apron up to 200 m thick (Sula Sgeir Fan) unconformably overlies a pre-Pliocene surface comprising Upper Oligocene/Miocene strata (Stoker, 1995; Stoker et al., 1994). The Plio-Pleistocene sediments there can be subdivided into two main depositional sequences: (1) essentially pre-glacial (conformable Pliocene to early mid-Pleistocene) slope front to basin plain sediments (Lower MacLeod sequence, LLOD); and (2) slope-front (mid- to late Pleistocene) glaciogenic sediments (Upper MacLeod sequence, ULOD) (Stoker, 1995). The ULOD is flooded and bisected by prominent, furrowed, erosion surfaces. The intra-sequence surface subdivides the sequence into a lower and upper seismostratigraphic unit correlated with Anglian and Devensian cold periods respectively (Stoker et al., 1994). Devensian age moraines occur on the inner shelf (MacDonald sequence) and interfinger with the Upper MacLeod sequence, the seismic facies extending seaward as a stratified unit constrained by boreholes (88/7, 7A) to be a normally consolidated glaciomarine drape (MacAuley sequence) (Stoker et al., 1994).

2.3.1. Pliocene sediments on the Irish Shelf

The Porcupine Saddle was a region of relatively low sediment input over the Cenozoic, with the Porcupine Seabight to landward forming a sediment depocentre (Elliott et al., 2006). Pliocene sediment sequences are thus thought to thicken in the Porcupine Seabight and in the northeast Rockall Trough, associated with the BDF, where total sediment thicknesses reach up to 600 ms two-way travel time (TWT) (Stoker et al., 2005). No borehole data have been published to constrain the sedimentology of Pliocene sequences in the Porcupine Seabight.

2.3.2. Quaternary sediments on the Irish Shelf

The presence of shelf-edge parallel Quaternary sediment ridges on the IMS were first recognised by King et al. (1998) using a broadly spaced (10–60 km) array of mainly west-east oriented seismic reflection and echosounder profiles. These were interpreted as end moraines, recording grounded ice margin retreat from water depths of at least 350 m (see distribution in Sejrup et al. (2005), Fig. 2). More accurate information on shelf bathymetry from a combination of sources including Irish National Seabed Survey and fisheries multi- and single beam echosounders has revealed more lobate, mutually discrete seabed ridges on the inner shelf west of Connemara (Fig. 1). These large moraines (up to 200 km long by 18 km wide) are variously interpreted as LGM limits and/or retreat stillstands (Clark et al., 2012) and post-LGM readvance limits (Peters et al., 2016) associated with ice emanating from Galway Bay. Borehole samples in cold water coral mound provinces in deeper waters of the Porcupine Seabight indicated there are 155 m of Pleistocene sediments overlying a seismic surface correlated with the regional intra-Pliocene C10 reflector (Williams et al., 2006). Holocene sediments across the IMS comprise a thick (3 m+) veneer of coarse shelly sand and gravel.

3. Data and methods

3.1. Seismic reflection data

Two main types of seismic reflection data are available for this study: single channel sparker profiles acquired during research campaigns, and multichannel 2D and 3D seismic data. Seismic stratigraphic units were defined within the Neogene succession using regionally correlative reflections inferred on the basis of discordant relations to represent unconformity surfaces (Vail et al., 1977). Throughout, sediment thicknesses are given in ms TWT. Assuming an acoustic velocity range of ~1600–2000 m/s in unconsolidated sediments, sediment thicknesses in metres range between 80 and 100% of these values, and may tend towards the lower end of this range. Unexpectedly low, but unstated, acoustic velocities in the mid-shelf Pleistocene succession were found during commercial hydrocarbon exploration in the region (Fugro, 1994).

3.1.1. Single channel sparker profiles

Sarker profiles were acquired across the shelf during the 2009 Italian GLAMAR cruise (RV OGS Explora) and the 2012 Irish GATEWAYS1 cruise (RV Celtic Voyager) (see Fig. 1 for locations). Both campaigns used a Geo-Resources single-channel sparker system with peak frequencies of 10^2 Hz, resulting in seabed vertical resolution of 1–2 m and penetration of up to 160 ms through sediments to underlying bedrock units. Data quality was poorer in 2009 due to adverse weather conditions and system problems. The data also provide detailed profiles of seabed topography across the inner shelf, previously lacking due to a scarcity of multibeam data in water depths shallower than 200 m.

3.1.2. Multichannel 2D and 3D seismic data

Multichannel seismic data acquired for offshore hydrocarbon exploration were processed using standard sequences of stack, deconvolution and 2D migration. Peak frequency contents of 10^1 Hz correspond to a seabed vertical resolution of 5–10 m in the water depths of interest. Two profiles across the shelf are used to illustrate aspects of sediment geometries in relation to bedrock units (see Fig. 1 for locations).

The 3D seismic volume available for this study (2000/08) covers a total area of ~990 km² on the mid-shelf slope (Fig. 1). It comprises 25 × 12.5 m bins with a vertical sample interval of 4 milliseconds (ms). A dominant frequency of 45 Hz and an average velocity of 1750 m/s for the Neogene interval correspond to a vertical resolution of about 10 m. Seismic attributes were computed on selected horizons over a narrow time window of a maximum ± 7 ms TWT to highlight depositional geometries and discontinuities (see Fig. 9C–F). Results presented in this

study use RGB blending of spectral decomposition attributes (false colour images of seismic signal constituent frequencies). Seismic processing was carried out using PaleoScanTM software.

3.2. Borehole data

Two boreholes (27/24-2 & 2A) were drilled at approximately the same location (UTM30N [054608, 5942163] and [054609, 5942159] respectively) on the inner shelf west of Galway Bay in water depths of 143.8 m and 142.8 m respectively. The sites are located approximately 1.6 km north-northeast offshore from the GW1-C sparker profile track. The holes were drilled for stratigraphic constraint during commercial hydrocarbon exploration activity over the Triassic Slyne Trough (Fugro, 1994), and thus detailed stratigraphic information for the Neogene succession is absent. Lower Jurassic limestones were penetrated at 220 m bsf and drilling was terminated at depths of 211.53 and 273.7 m below sea floor (bsf) respectively.

Drilling of unconsolidated sediment units overlying bedrock was by percussion drilling, with samples (up to 50 cm long when available) extracted by hammer at selected depths. Samples were used to provide basic bio-chronostratigraphic constraint by micropalaeontological analysis of foraminifera and ostracod fauna, and sediment consistency assessments (Table 1). Well-side observations of unexpectedly high penetration resistance during drilling of Pleistocene sediments (e.g. obstruction by frequent cobbles), high drill-bit wear rates and sediment recovery during bit recovery (e.g. of metamorphosed fine sandstone gravel clasts) were also noted. Summary results from Fugro (1994) include lithological unit descriptions (Fig. 3, Table 1), graphic logs, dominant and indicative microfaunal species lists, biostratigraphic age determinations and torvane (TV) and handheld penetrometer (PP) assessments of undrained shear strength (uSS) where recovery allowed sufficient sample volumes.

4. Results

We first present seismic reflection data from across the shelf west of central Ireland showing bedrock units to be unconformably overlain by a sedimentary wedge up to 160 ms thick and over 70 km wide (Fig. 2). This sediment wedge is referred to here as the ‘Connemara Fan’. We then describe available stratigraphic information from BH27/24-2, 2A located 1.6 km offshore from sparker profile GW1-C shown in Fig. 2 (Table 1, Figs. 3–4). We then present evidence for the regional extent of seismostratigraphic units identified within the sediment sequence (Figs. 5–8), including evidence from a 3D seismic volume within the fan’s extent (Fig. 9).

4.1. Borehole lithological units

4.1.1. Miocene and Pliocene

Boreholes 27/24-2 & 2A penetrated heavily fractured Jurassic limestones at ~210 m bsf. These were overlain between 105 and 210 m bsf by a sequence of 10 m thick units of ‘very hard’ shelly reddish clays and clayey glauconitic sand assigned a Miocene to Upper Miocene age based on sample biostratigraphy (Fig. 3; see Table 1 for description of upper 142 m bsf). A conformable contact between Upper Miocene and Lower Pliocene equally ‘stiff to hard’ clay units was placed at 105 m bsf (Table 1). Lower Pliocene sediments (105–88 m bsf) comprise ‘stiff to very hard’ shelly (fragments up to 5 mm in diameter) olive grey sandy clay, which slightly coarsen upwards overall to shelly clays containing sandy interbeds. ‘Upper Pliocene becoming Pleistocene’ sediments (52–88 m bsf) are reported as ‘stiff, very stiff and hard’ shelly, sandy gravel bearing greyish brown clays (diamicts). The sequence coarsens upwards above 75 m bsf from sandy laminated clays to diamicts containing coarse subrounded gravel clasts. A 5 m thick gravel layer occurs at 61–66 m bsf. No erosional unconformities are reported from the borehole logs, but a colour change downhole to a darker greyish brown,

Table 1
Lithostratigraphic and geophysical data extracted from logs of Boreholes 27/24 2 and 2A.

Unit Top (m bsf)	Unit Base (m bsf)	Approx. Thick. (m)	Facies Description.	Sample	Sample depth (m bsf)	Foraminifera taxa recovered	Comments (Fugro, 1994)	Biostrat. Age / Environment	TV (kPa)	PP (kPa)
0	0.2	0.2	Olive brown medium to coarse SAND with numerous fine to medium gravel and shell fragments	H1	0.2				160	113
0.2	29	29	STIFF to VERY STIFF very dark grey calcareous CLAY with occasional fine to medium gravel and shell fragments (< 1mm).	H2	15	No Recovery				
29.0	43.0	14	STIFF to VERY STIFF very dark grey calcareous CLAY with occasional fine to medium gravel, cobbles and shell fragments (< 1mm).	H3	35	No Recovery				
43.0	48.0	5	GRAVEL							
48.0	52.0	3	STIFF to VERY STIFF very dark grey calcareous CLAY with occasional fine to medium gravel, cobbles and shell fragments (< 1mm).							
52.0	61.3	9	VERY STIFF to HARD very dark greyish brown sandy calcareous CLAY with fine to coarse sub rounded gravel	H4	55.4	<i>Ephidium</i> ex gr. <i>exlanatum</i> , <i>Cassidulina laevigata</i> , <i>Islandiella islandica</i> , <i>Globorotalia inflata</i> .	Low diversity assemblage with no evidence of Pliocene sediments.	Pleistocene / Inner shelf, 50-150 m water depth	197	123 220
61.3	66.3	5	GRAVEL							
66.3	75	11	VERY STIFF to HARD very dark greyish brown slightly sandy calcareous CLAY with fine to coarse sub rounded gravel							
75.0	88.0	13	STIFF to VERY STIFF dark grey/dark greyish brown slightly sandy laminated CLAY with pockets and partings of grey silty fine sand and occasional black staining.	H5	75.4	<i>Cibicides</i> <i>pseudoungertianus</i> , <i>Bulimina marginata</i> , <i>Dentalina</i> spp., <i>Melonis affine</i> , <i>Pullenia bullioides</i> , <i>Cassidulina laevigata</i> , <i>Ephidium</i> ex gr. <i>Excavatium</i> , <i>Neogloboquadrina</i> <i>atlantica</i> , <i>Neogloboquadrina</i> <i>pachyderma</i> .	The presence of <i>Melonis affine</i> , <i>Pullenia bullioides</i> and <i>Neogloboquadrina atlantica</i> confirm penetration of Pliocene sediments.	Upr. Pliocene / Inner- mid shelf, 100 – 200 m water depth.	135 175	85 103
88.0	100	12	STIFF to VERY HARD olive grey structureless sandy CLAY with numerous shell fragments (< 1 mm), fine grains of glauconite, with pockets and partings of olive grey medium to coarse sand and occasional shells (< 5 mm)	H6	95.3	<i>Sigmoilina schlumbergeri</i> , <i>Pullenia bullioides</i> , <i>Cibicides grossus</i> , <i>Melonis affine</i> , <i>Brazilina catamensis</i> , <i>Neogloboquadrina</i> <i>atlantica</i> , <i>Neogloboquadrina</i> <i>pachyderma</i> , <i>Globorotalia inflata</i> .	Very rich assemblage with possible evidence of Miocene reworking.	Lwr. Pliocene / Middle shelf, 150 – 250 m water depth.		900 900
100	100.2	0.2	SAND							
100	105	5	STIFF to VERY HARD olive grey structureless sandy CLAY with numerous shell fragments (< 1 mm), fine grains of glauconite, with pockets and							

(continued on next page)

Table 1 (continued)

Unit Top (m bsf)	Unit Base (m bsf)	Approx. Thick. (m)	Facies Description.	Sample	Sample depth (m bsf)	Foraminifera taxa recovered	Comments (Fugro, 1994)	Biostrat. Age / Environment	TV (kPa)	PP (kPa)
105	139	34	partings of olive grey medium to coarse sand and occasional shells (< 5 mm) STIFF to HARD grey calcareous foliated and fissured CLAY with occasional shell fragments (< 1 mm), pockets of black staining and fine rounded high sphericity grains of glauconite.	H7	105.5	<i>Globigerina ?parabulloidides</i> <i>Globigerina bulloides</i> <i>Globorotalia inflata</i> , <i>Neogloboquadrina atlantica</i> , <i>Neogloboquadrina pachyderma</i> , <i>Spiroplectammina carinata</i> <i>Cibicides grossus</i> , <i>Cassidulina laevigata</i> <i>Canosphaera</i> spp. <i>Melonis affine</i> , <i>Monspeliansina pseudorepida</i> , <i>Nodosaria</i> spp., <i>Sphaeroidina bulloides</i> , <i>Uvigerina ?acuminata</i> (?reworked), & abundant sponge spicules.	Sample dominated by sponge spicules and broken shell/mollusc debris, suggesting high energy depositional environment. Miocene evidence is sparse, and possibly reworked.	Lwr Pliocene / Middle shelf, 150 – 250 m water depth.	128	113 162 333 358
				BH2A_S1	110.45			Lwr Plioc. / Inner - ?Middle shelf, 100 – 200m water depth.		
				H8	125.3	<i>Siphonina reticulata</i> , <i>Globigerina woodi</i> , <i>Neogloboquadrina acostensis</i> , <i>Neogloboquadrina atlantica</i> , <i>Uvigerina hosiusi</i> , <i>Melonis affine</i> , <i>Pullenia bulloides</i> , <i>Trifarina fluens</i> , <i>Bulimina marginata</i> , <i>Cibicides grossus</i> , <i>Cibicides pseudoungertanus</i> , <i>Bolboforma clodiusi</i> , <i>Sphaeroidinellopsis disjuncta</i> , <i>Aspergerina staeschei</i> , <i>Globigerina ciproensis</i> 'atypica', <i>Sphaeroidina bulloides</i> , <i>Siphonina reticulata</i> , <i>Uvigerina</i> spp., <i>Globigerina woodi</i> , <i>Cibicides pseudoungertanus</i> .	Extremely rich assemblage containing Upper Miocene indices <i>Bolboforma</i> spp., <i>Uvigerina hosiusi</i> , <i>Siphonina reticulata</i> .	Upr. Miocene / Middle-?outer shelf, 200 – 300 m water depth.	153 138 108	150
139	142	3	Olive grey silty, clayey fine to coarse subrounded to rounded glauconitic SAND with shell fragments and occasional fine rounded gravel and occasional pockets of olive clayey fine sand.	BH2A_S2	140.4		Residues dominated by glauconite. It is probable that many of the Lower Miocene forms recorded here (<i>sic</i>) are reworked.	Miocene / Inner- middle shelf, 100 – 200 m water depth.		

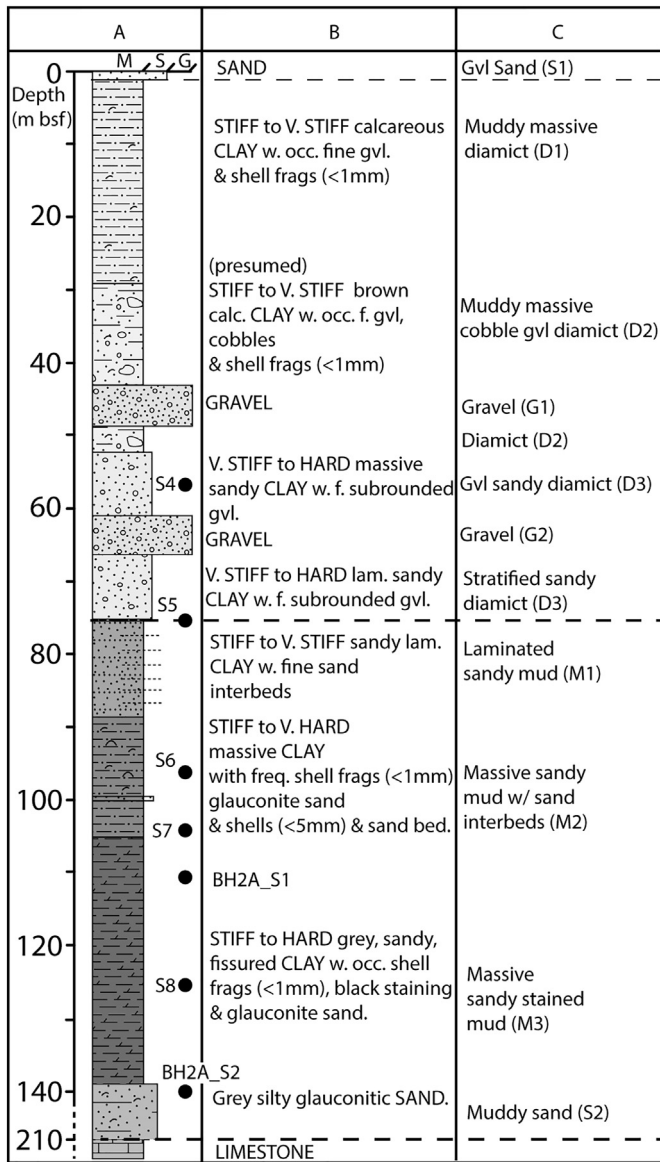


Fig. 3. Lithological log of stratigraphic boreholes 27/24-2 and 2A.

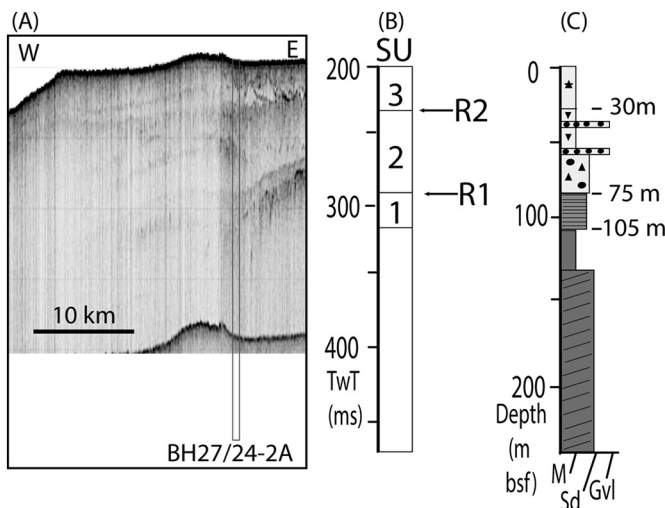


Fig. 4. Correlation of GW1-C seismic stratigraphy on the inner shelf with chronostratigraphic interpretations of boreholes 27/24-2 and 2A (Fugro, 1994).

and texturally to laminated clay is noted at 75 m. A sample containing an Upper Pliocene foraminiferal fauna was recovered at 75.5 m bsf. Sediments become very sandy from 105 m bsf, and the same stiff to hard, grey, foliated and fissured clays containing rounded glauconite sand grains are logged as occurring down to 139 m bsf and biostratigraphically assigned to ‘Lower Pliocene/Upper Miocene’ in age. No erosional unconformity is observed within the sequence. Miocene and Pliocene sediments were reported as generally ‘stiff’ (uSS values ranging from 75 to 150 kPa) to ‘hard’ (200–400 kPa uSS) in consistency (Table 1), with uSS values generally in excess of 130 and with outlier values up to 900 kPa (at 95.6 m bsf) within Lower Pliocene sediments.

4.1.2. Quaternary

Below 0.2 m of Holocene seabed sand and gravel, the Pleistocene sediment sequence in BH27/24-2A is comprised of up to 75 m of variably consolidated calcareous clays (ranging from ‘stiff’ to ‘hard’ in consistency) containing fine to medium and cobble gravel clasts and comminuted (< 1 mm) shell fragments where sampled (Table 1) (Fig. 3). The foraminiferal palynology of a sample (S4) from 55.5 m bsf is identified as containing a distinctly Pleistocene age assemblage including *Elphidium ex gr. exclavatum*, *Cassidulina laevigata*, *Islandiella islandica* and *Globorotalia inflata* (Table 1). A sample from 75.5 m downhole (S5) within relatively well-sorted muds with sandy interbeds indicative of an open water non-glacial marine environment contains distinctive upper Pliocene shallow marine foraminifera species including *Melonis affine*, *Pullenia bulloides* and *Neogloboquadrina atlantica*.

A gradational contact between diamict at base Quaternary and sandy muds of Pliocene age was placed at 75 m in BH27/24-2A (Fugro, 1994). This stratigraphic marker is correlated to the well-defined reflection R1 on GW1-C, which lies at ~285 ms at a distance of 7 km along profile (Fig. 2). This yields a sediment column seismic transmission velocity of 1680 m/s which is consistent with estimates of local seismic transmission velocities (Fugro, 1994). This value is used to convert other prominent reflection features in the GW1-C profile into approximate depths below sea floor (Table 2). The proposed correlation also matches other prominent reflectors in profile GW1-C (R2) to stratigraphic markers in BH27/24-2,2A.

4.2. Seismic stratigraphy

Above the bedrock surface unconformity, two regionally extensive reflectors (R1 & 2) are recognised within the Neogene to Quaternary succession on several sparker profiles (Figs. 2, 4, 5, 6) and on a number of coincident or near-coincident multichannel seismic (including 3D) lines (Figs. 8–10). Two less extensive reflectors are also recognised above R2. R1 and R2 define three regional seismic stratigraphic units, referred to as SU1–3.

4.2.1. Bedrock unconformity

The bedrock surface beneath the Connemara Fan is clearly discernable on the GW1-C & B profiles to ~300 ms (250 m) depth as a gently westward dipping (< 0.5°), strong, diffuse reflector (Figs. 2, 5). The surface is irregular to ‘craggy’, with topographic highs interspersed by common v-shaped incisions forming substantial depressions up to ~25 ms deep (Fig. 5E). At the approximate offline location of BH 27/24-2,2A, 7.5 km along GW1-C, the reflector is at 125 ms bsf (Fig. 2). It is correlated with the top Miocene/Pliocene contact at the borehole locations at 105 m bsf (Fig. 4) (Fugro, 1994). 2D seismic profiles across the mid- to outer shelf show that the bedrock surface continues to be irregular and cuts down into older strata (up to Precambrian in age) on the outer shelf where bedrock highs rise to within 20–30 ms of seabed (Figs. 6–7).

4.2.2. R1

Reflector R1 can be traced from the inner shelf onto the Porcupine Saddle, as a well-defined discordant reflector that truncates underlying

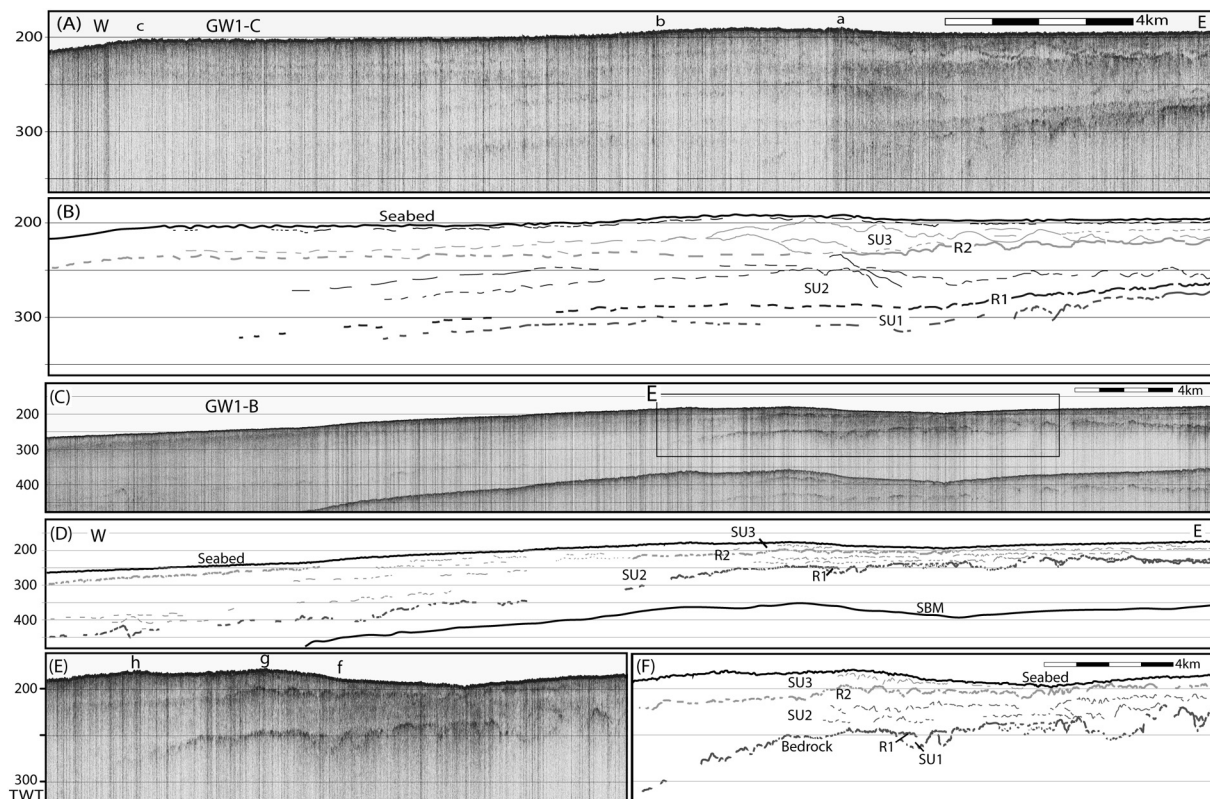


Fig. 5. Detail of sparker profile GW1-C and profile GW1-B.

(A) Detail of sparker seismic reflection profile GW1-C across the inner to mid-shelf.

(B) Interpretative sketch of Panel (A) Note: (i) stacking of relatively steeply inclined units within SU2 and SU3 directly under the prominent seabed ridge (locations a–b); (ii) generally low angle seaward extending and thinning packages within SU2 & 3.

(C) East-west sparker seismic reflection profile GW1-B across the inner- to mid-shelf transition (~25 km south of GW1-C) (See Fig. 1 for location).

(D) Interpretation of seismic profile GW1-B on Panel C.

(E) A detail of the GW1-B sparker reflection profile across the area under and immediately landward of the inner shelf seabed ridge (locations f–h). Note: (i) the prominent double-crest (g–h) on the seabed ridge at this location; (ii) the decreasing reflection strength of R2 with distance west of location (g); (iii) the asymmetric, more steeply landward dipping geometry of subsidiary reflectors within SU3 immediately underlying the inner shelf seabed ridge.

(F) Interpretation of seismic profile GW1-B on Panel E. Note: (i) the confinement of SU1 to within undulations on the irregular bedrock surface.

horizons, and is onlapped or offlapped by sediment packages above (Figs. 2, 8). On sparker profiles it appears as a strong, continuous reflector where reached by sparker profiles (Fig. 2), and dips smoothly seaward across the fan on multichannel data (Fig. 8). R1 is interrupted by bedrock highs both on the inner shelf along the line of sparker profile GW1-B (Fig. 5E), and on the outer shelf across the Porcupine Saddle (Fig. 7).

4.2.3. R2

Reflector R2 is recognised within the Connemara Fan on both sparker and multichannel profiles as a well-defined, sharp (inner shelf) to diffuse (mid-shelf) reflection that is observed to locally truncate underlying reflections and, on sparker profiles, is onlapped by overlying reflections (Figs. 2, 5, 6). On the inner shelf, R2 is a strong sub-horizontal reflection at ~50 m bsf which extends seaward of the modern mid-shelf slope break on GW1-C and GLAMAR profiles (Fig. 2, loc. c and Fig. 6B loc. J, respectively). Beneath the mid-shelf slope, R2 becomes more diffuse and dips seaward at approximately 25 ms bsf (Figs. 2, 6, 8). R2 extends to the base of the mid-shelf slope where sparker data (CV16011_PBB3-2) show it to rise towards seabed (Fig. 7C).

Two relatively prominent, localised reflectors also occur within sediments above R2. On the inner shelf a set of well-defined, undulating, westward onlapping, discontinuous reflectors occur within SU3 at 20–50 ms, ~17–42 m bsf (Fig. 2 inset). The reflectors shallow westward as a set of mounds cresting 1.5–2.0 km apart, to within 10–15 ms

(~10 m) of the seafloor. The largest and westernmost of the mounds underlies and gives rise to the prominent seafloor ridge on the inner shelf edge (Fig. 2 loc a). A thinner, sharper reflector can also be traced seaward of the seafloor ridge for approximately 15–20 km as a gently westward dipping surface, increasing from ~25 ms bsf at the outer edge of the inner shelf ridge (Fig. 2 loc b) to 30 ms bsf at the inner shelf edge (Fig. 2 loc c). The reflector appears to cross the inner- to mid-shelf slope transition, terminating 3–4 km downslope.

An approximately 20 km long, shallow (max 15 ms), gently curvilinear concave-upwards internal reflector occurs within SU3 under the lower mid-shelf slope (Fig. 2 loc d–e). The reflector has an irregular crenulated relief at its seaward end where it terminates abruptly along the base of the mid-shelf slope, landward of the Porcupine Saddle (Fig. 7C).

4.2.4. Unit SU1

Bedrock across the Irish Mainland Shelf is overlain by seismic unit 1 (SU1), which is truncated by the R1 horizon (Figs. 2, 8). On profile GW1-C across the inner shelf, SU1 forms an up to 30 ms thick, continuous, seaward-thickening, acoustically semi-opaque unit (Fig. 2). On the inner shelf the top surface of the unit mirrors the topography of the bedrock reflector below, sloping seaward and then levelling out at ~10 km along GW1-C before dipping seaward again at ~15 km.

Beneath the mid-shelf slope, sparker and multichannel seismic profiles show SU1 to thicken to ~70–80 ms in total (~70 m) (Figs. 2, 8), forming a wedge of stratified sediments that includes elongate,

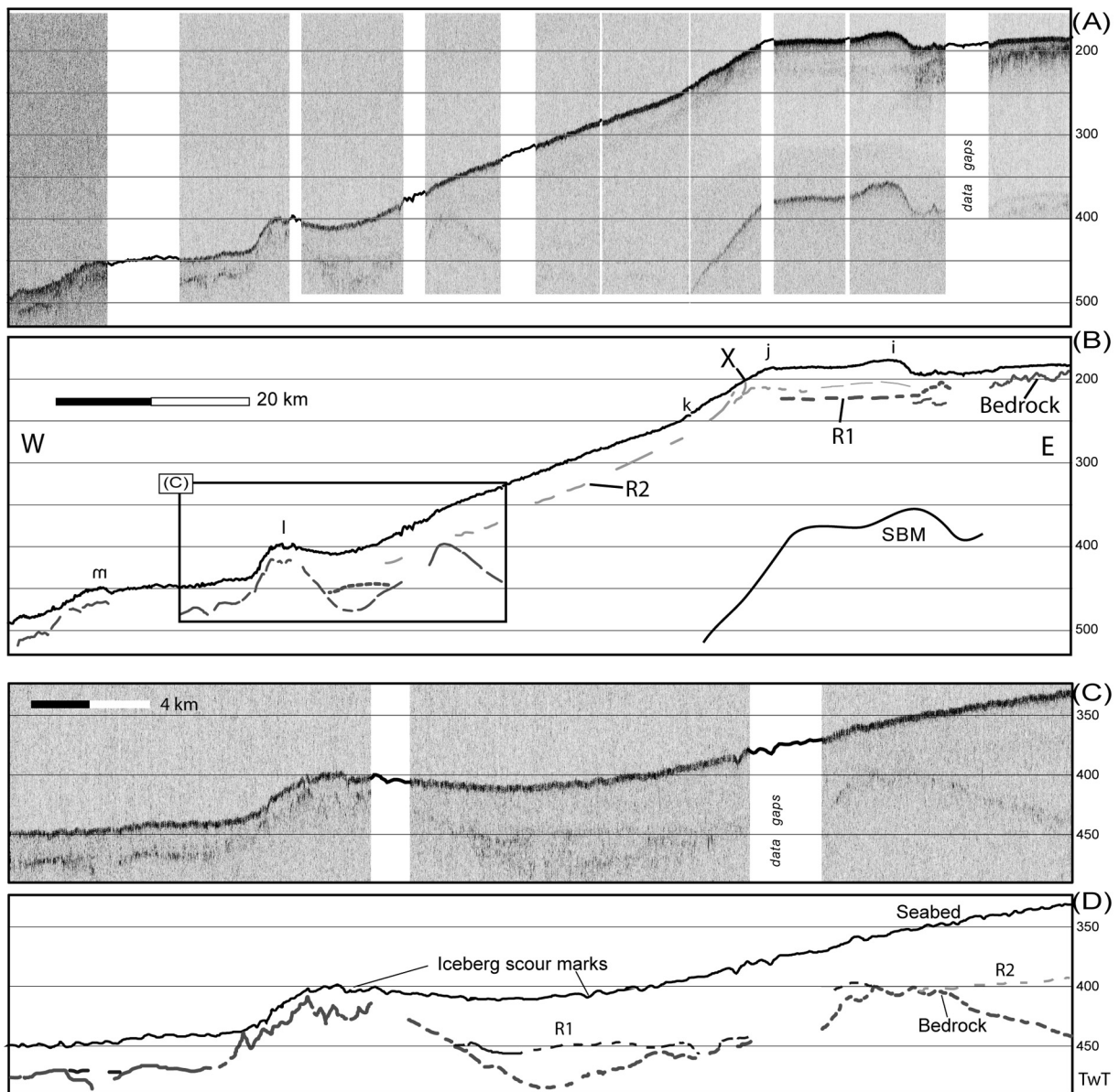


Fig. 6. 'GLAMAR' sparker seismic reflection profile.

(A) An arbitrary line of GLAMAR campaign sparker seismic reflection profiles across (R-L) the inner shelf, prominent inner shelf ridge, mid-shelf break and mid-shelf slope westwards onto the Porcupine Saddle;

(B) Interpretations of prominent reflectors in Panel A. Note (i) an approx. 60 ms thick sediment ridge on the inner-shelf at ~180 ms/~113 m water depth (locations i-j); (ii) a bulge in the mid-shelf slope profile; (iii) sediment thinning over and infilling the undulating surface of the bedrock high forming seabed ridges on the Porcupine Saddle (l-m);

(C) A detail from the seismic profile in Panel A, profiling the scoured seabed topography of the mid- to outer shelf and the seabed ridge on the Porcupine Saddle (Fig. 1 location l);

(D) Interpretation of reflectors visible in Panel C. Note: (i) the onlap of R1 at depth onto a bedrock high underlying the seabed to within 20 ms (Fig. 6 location l); (ii) the lateral thinning of an extensively iceberg scoured, acoustically transparent, unstratified sediment cover over the bedrock high underlying an asymmetric (steeper face to seaward) seabed ridge (Fig. 1 location l) on the inner margin of the Porcupine Saddle.

interconnected, meandering channel features 10's of km long by < 200 m wide (Fig. 9C). The unit thins again further seaward, tapering out westwards against the bedrock high of the Porcupine Ridge (Figs. 2, 7). It appears restricted to discontinuous pockets within bedrock depressions across the Porcupine Saddle (Figs. 7, 8). SU1 also appears to thin laterally southwards across the inner shelf, and it is observed on sparker profile GW1-B only as discontinuous pockets < 20 ms thick within depressions on the bedrock surface (Fig. 5E).

At the approximate offshore location of BH27/24-2,2A (7.5 km along GW1-C) SU1 occurs between approximately 285–320 ms TWT (0.09–0.125 ms bsf). This depth (~75–105 m bsf) corresponds to a sequence of 'stiff, laminated sandy clays and sands' assigned a Pliocene age based on foraminiferal analyses (Fugro, 1994) (Fig. 4, Table 1).

4.2.5. Unit SU2

Unit SU2 is approximately ~70 ms (60 m) thick across the inner shelf on GW1-C, thickening to ~90 ms (75 m) under the mid-shelf slope, where it conformably overlies R1/SU1 (Fig. 8). SU2 thins towards the base of the mid-shelf slope before coming to seabed (Fig. 7). The unit directly underlies seabed sands across the Porcupine Saddle as a < 30 ms (< 25 m) thick acoustically homogeneous unit (Fig. 7, 8E). The unit infills local bedrock undulations and forms a broad bathymetric high (Fig. 1) with an irregular, scoured surface mirroring a subjacent broad (~6 km wide) bedrock high (Figs. 2, 6, 7).

On the inner shelf, SU2 contains a lower wedge-shaped mound defined by a diffuse landward-dipping reflector, observed on GW1-C at 8–10 km along line (Fig. 2). The reflector forming the wedge top

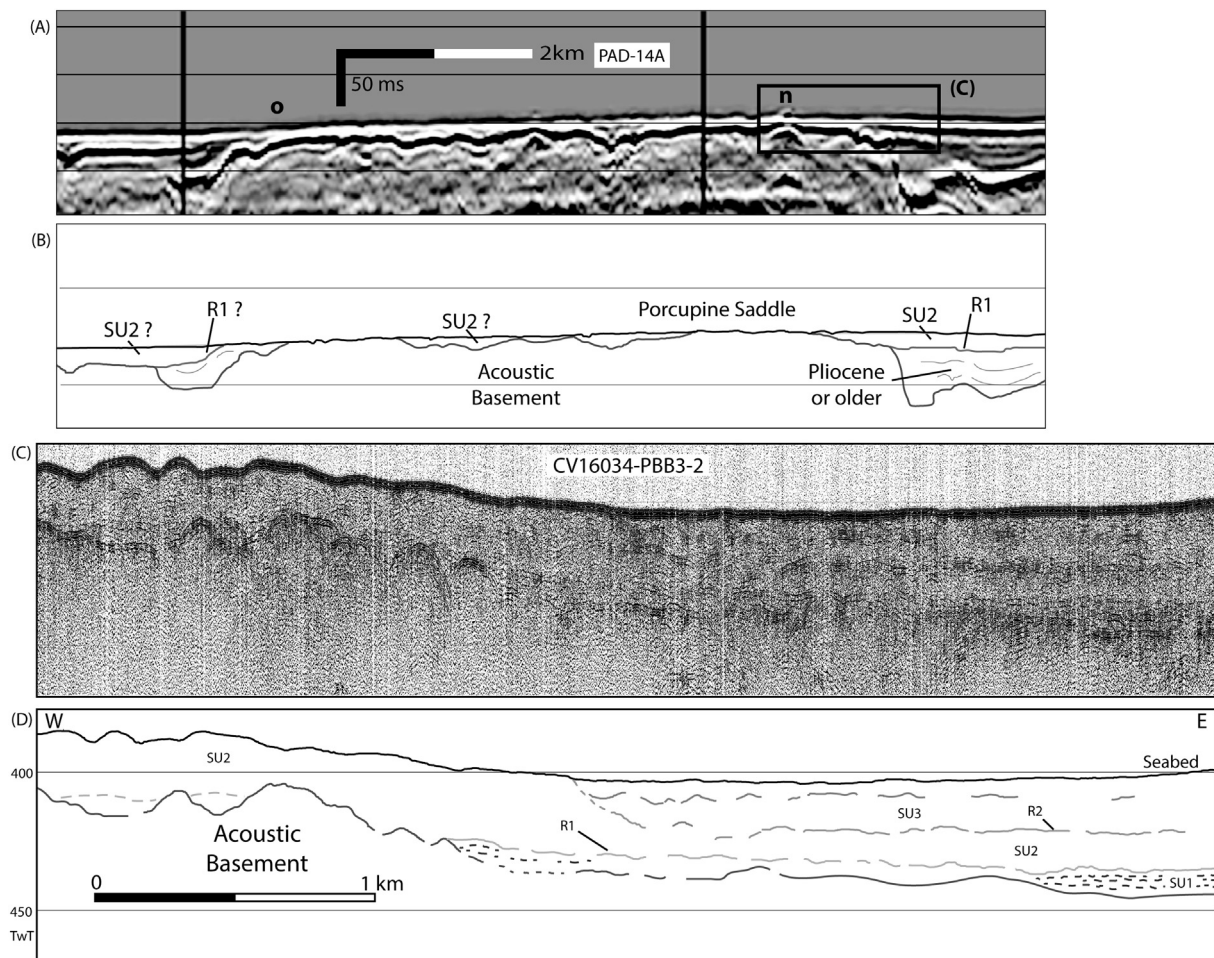


Fig. 7. CV16034-PBB3-2 sparker profile crossing the landward (eastern) margin of the Porcupine Saddle.

(A) A detail of seismic reflection profile PAD-14A where it crosses the Porcupine Saddle;
 (B) An interpretative sketch of seismic reflections in Panel A. Note: (i) the onlap of a prominent reflector (R1) to within the ~20 ms thick seabed reflector at Fig. 8n–o; (ii) the stratified, nested, arcuate, asymmetric reflectors within SU1, interpreted to profile strike sections across fluvial channels; (iii) the thinning of sediment cover between Fig. 8n–o coincident with the ~6 km wide N–S oriented 27 km long seabed ridge at this location on the Porcupine Saddle (Thébaudeau et al., 2015).
 (C) Sparker seismic reflection profile CV16034-PBB3-2 crossing the landward margin of the Porcupine Saddle (for location see Fig. 1).
 (D) Interpreted sketch of Panel C. Note (i) onlap of SU1 below R1 onto rising bedrock underlying the Porcupine Saddle and possible occurrence as discontinuous pockets within relatively steep-sided bedrock undulations; (ii) the continuation of SU2 over the Porcupine Saddle, forming ridges at seabed; (iii) the relatively steep, erosive (outer) margin of SU3 along R2 at this location, and its termination east of the Porcupine Saddle high; (iv) the relatively chaotic, disrupted internal seismic character of SU3 and regular concertina-like folding of a prominent reflector.

descends seaward over a tabular unit draping the R1 reflector beneath. A thin (< 10 ms, < 8 m) flat-topped wedge ~5 ms below the top of the unit extends and thickens seaward over and beyond the lower mound for at least 10 km before increasing in slope at approximately 15 km along line (Figs. 2b, 5). Landward of the wedge, relatively acoustically transparent sediments underlie subhorizontal, undulating, discontinuous reflectors at 260 ms (218 m bsf) (Figs. 2, 5). To seaward, beneath the mid-shelf slope, SU2 contains tabular, seaward-dipping units defined by relatively diffuse reflectors on sparker profiles (Figs. 2, 5) but are well-defined on multichannel seismic profiles (Fig. 8).

On the inner shelf, SU2 lies at depths of ~230–285 ms (~30–75 m bsf) on sparker profile GW1-C, which in nearby 27/24-2A corresponds to a sequence of shell-bearing gravelly clay and gravel layers containing Pleistocene-age microfauna (Table 2, Fig. 3). Two multi-metre thick gravel units occur within the sediment sequence, at 43–48 (G1) and 62–66 m bsf (G2), intervals which correlate well with strong, diffuse, internal SU2 reflectors defining a steep sided mound and flat-topped wedge respectively (Fig. 4). Each gravel unit is enclosed within poorly sorted, clay-dominated units (D2 & D3), with D3 described as a ‘very stiff to hard’ sandy calcareous clay containing fine pebbles (52–62 & 66–75 m bsf). D3 has a recorded uSS of ~220 kPa at 55.5 m bsf

(Table 1) (Fugro, 1994).

4.2.6. Unit SU3

Unit SU3 conformably overlies R2 and displays a similar transparent acoustic character to SU2. On the inner shelf it thickens westwards across along the line of GW1-C to nearly 50 ms thick beneath a prominent seafloor ridge, before thinning seaward to form a terrace-like seafloor feature extending to the inner shelf edge (Fig. 2 loc c). Across the mid-shelf slope (Fig. 2 loc c–e), SU3 thickens again to 40 ms thick below a seafloor notch at 250 m water depth (Fig. 2 loc d) which defines the upslope margin of a slight topographic bulge in the seafloor. The unit pinches out landward of the Porcupine Saddle (Figs. 2, 5, 6, 7, 8). Its architecture is characterised by subhorizontal stratification on the inner shelf defined by mounded subsidiary reflectors, and seaward dipping units beneath the mid-shelf slope (Figs. 2, 8). On the inner shelf these mounds offlap progressively landwards, with the largest and outermost forming a prominent seafloor ridge on the inner shelf (Fig. 2 loc a–b).

On the inner shelf, SU3 lies at depths of 195–230 ms (~0–30 m) on sparker profile GW1-C, corresponding in BH27/24-2,2A to seabed sands underlain by 30 m of ‘stiff’ clay containing gravel (Fig. 3, Table 1).

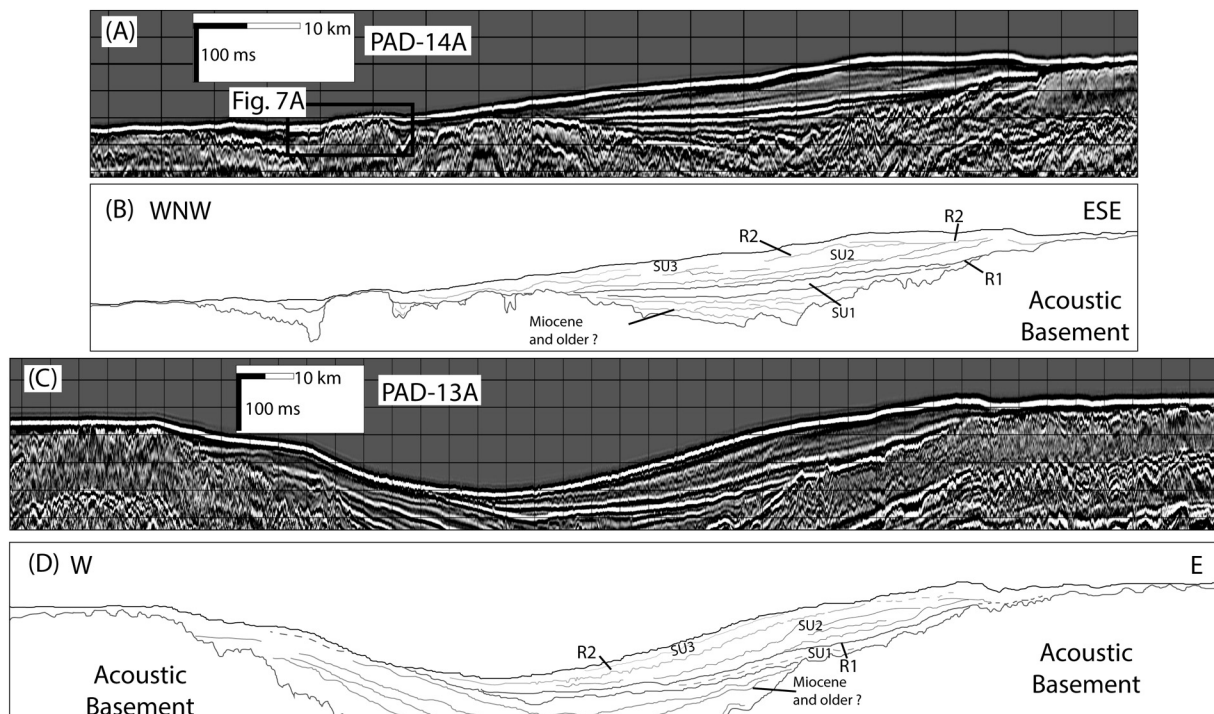


Fig. 8. Regional commercial 2D multichannel seismic profiles traversing the shelf and Porcupine Seabight west of central Ireland.

- (A) 2D multichannel long offset seismic reflection profile PAD-14A spanning (R-L) the inner shelf, mid-shelf break and slope and Porcupine Saddle (for location see Fig. 1);
 (B) Interpretative sketch of prominent seismic reflectors on profile PAD-14A;
 (C) 2D multichannel seismic reflection profile PAD-13A spanning (R-L) the inner shelf, mid-shelf break and slope, the northern reaches of the Porcupine Seabight and onto the Porcupine Bank. The profile occurs at an oblique angle approximately 65 km south of profile PAD-14A and is roughly coincident across the mid-shelf break with sparker profile GW1-B;
 (D) Interpretative sketch of prominent seismic reflectors on profile PAD-13A.

4.2.7. 3D seismic evidence of buried and seabed morphologies

A 3D seismic volume within the extent of the Connemara Fan on the mid-shelf slope was used to examine the seismic reflection characteristics of horizons within the sediment column (Fig. 9). The R1 and R2 reflectors seen on GW1-C can be traced westwards across intersecting multichannel profiles including the 3D data cube to the base of the mid-shelf slope, where they rise to within 20 ms of the seabed (Fig. 10). A broad horizon slice from within SU1 shows multiple, highly convoluted, overlapping, meandering channels (Fig. 9C).

Horizon slices along R1, R2 and the seabed reflector (Fig. 9C–F) reveal convoluted, curvilinear, cross-cutting features up to 5 km long by < 100 m wide. The overall orientation of lines is predominately (> 70%) north-south. Also observed are multiple small-scale (< 50 m diameter) circular features that can be traced into underlying stratified strata, and so are tentatively interpreted as gas escape pockmarks (cf. Games, 2001).

The curvilinear features on R1, R2 and the seabed are typical of iceberg ploughmarks (e.g. Todd et al., 2007). On Irish National Seabed Survey high resolution multibeam bathymetric data (Cullen, 2003), iceberg scours are also observed on the contemporary seabed, occurring throughout the region in water depths of 180–575 m (Sacchetti et al., 2012; Thébaudeau et al., 2015) (Fig. 1). Both pockmarks and iceberg scours have been recognised within the Plio-Pleistocene succession of the Porcupine Seabight (Games, 2001). No other horizons within the 3D seismic volume show evidence of iceberg scouring or any other morphology. Apparent scours at levels between R1 and R2 are spatially coincident with features on R1 and are inferred to have formed from drape-like infilling of depressions on this underlying surface.

4.3. Interpretation of borehole and seismic data

Seismic reflection and borehole data from the continental shelf west of central Ireland show bedrock covered by a sediment wedge up to

160 ms/140 m thick. Sparker reflection profiles e.g. GATEWAYS 1 Line C (GW1-C) contain generally diffuse but laterally persistent fairly well-defined seaward dipping reflectors that allow the definition of three broad seismo-stratigraphic units (SU1–3). The units are separated and capped by well-defined iceberg scoured horizons (R1, R2 and seabed) that can be traced across multiple seismic profiles across the mid- to outer-shelf region subsurface (Fig. 10). The units occur above a regionally correlative reflector within the Neogene succession (possibly the Early Pliocene C10 reflector).

The reflection surfaces within the inner shelf sediment sequence down to ~300 ms are correlated to the nearby (~1.6 km offline) stratigraphic boreholes 27/24-2,2A. Biostratigraphic constraint of SU1 shows it to be of Pliocene age and units SU2 & 3 to be of Quaternary age (Fugro, 1994) (Fig. 11). Units SU1 and SU2 thicken seaward from the inner shelf forming a wedge up to 160 ms thick. SU3 is best developed on the inner shelf, forming a prominent seabed moraine and terrace complex which controls the morphology of the modern inner shelf edge. Sediment cover thins again beyond the wedge across the outer shelf where SU1 and 3 pinch out and SU2 reduces to < 20 ms over structurally controlled bedrock/seabed highs. The sediment apron along the outer margin of the inner shelf is inferred on this evidence to include the previously unrecognised Plio-Quaternary ‘Connemara Fan’.

Here we first consider the depositional and erosional events responsible for the growth of the Connemara Fan. We argue that its Quaternary development involved deposition and erosion during multiple glacial cycles and consider the implications for our understanding of BIIS glacial history west of central Ireland.

4.3.1. Pliocene

On the inner shelf, Pliocene sediments occur as a thin to laterally discontinuous seismic unit (SU1) that in places is limited to infills of depressions on the reflector surface that correlates closely with the down hole depth of Miocene strata in BH27/24-2,2A. Unit SU1 is thus

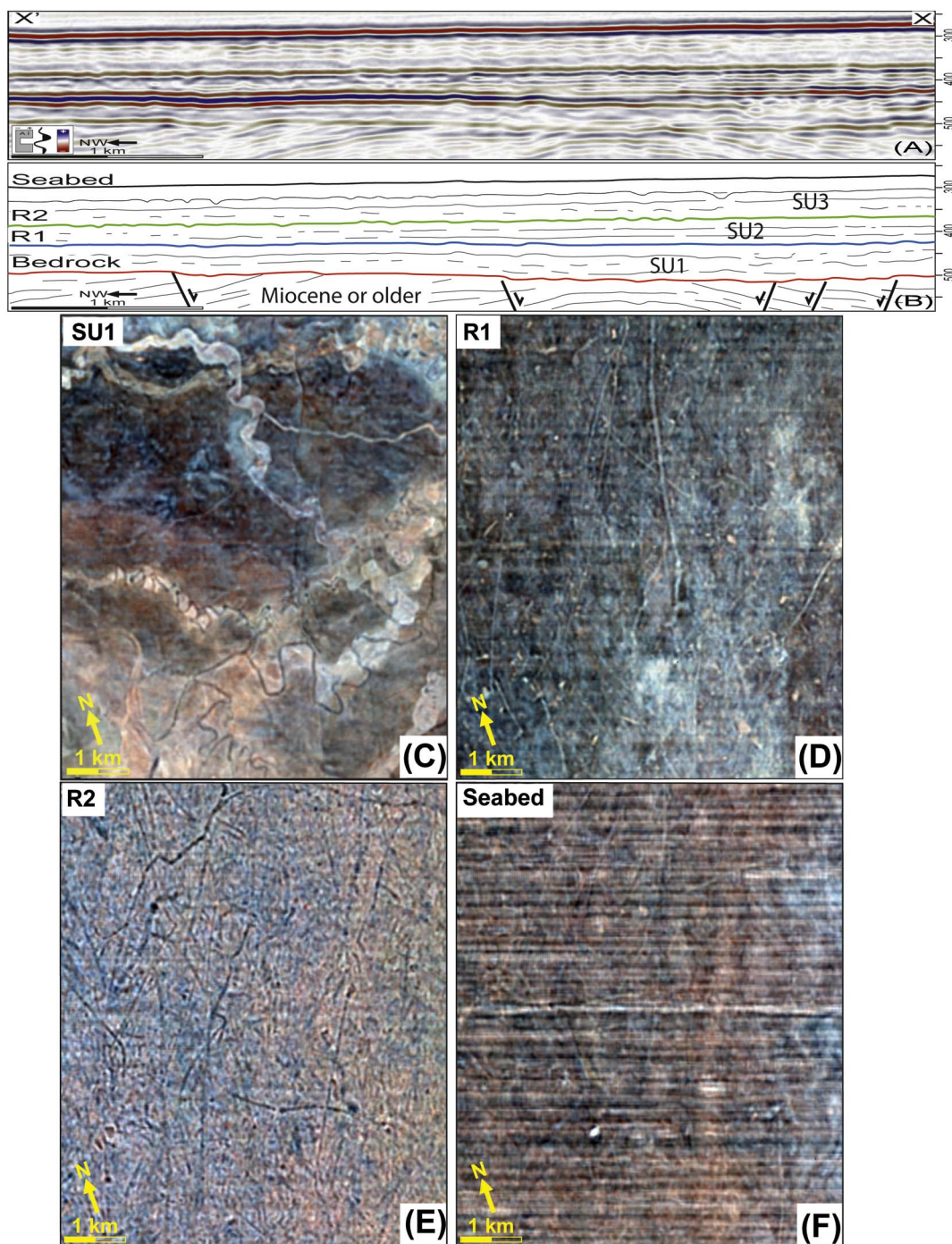


Fig. 9. Seismic reflection data from 3D survey 2000–08 over the mid-shelf slope.

(A) A northwest-southeast 2D seismic profile across the 2000–08 3D data cube (for location see Fig. 1).

(B) Interpretation of Panel A. Note (i) prominent intra-fan reflectors R1 & R2, (ii) faulted Mesozoic Slyne Trough sedimentary bedrock strata;

(C, D, E, F) RGB blends of three frequency components (25, 40 and 55 Hz) within SU1 and along R1 & 2 and modern seabed, respectively. Note: (i) The well-developed meandering channel network within SU1 sediments, (ii) The well preserved iceberg scour marks across R1 & 2 and the seabed; (iv) Circular bright spots on R1(D), thought to be gas release pockmarks from underlying Pliocene sediments (Games, 2001).

inferred to represent upper Pliocene strata overlying an erosional unconformity of intra-Pliocene age. The truncation of upper Pliocene strata elsewhere along the NW European margin has been linked to intra-Pliocene differential uplift to form the regional C10 unconformity (Stoker et al., 2005), and it is inferred that the irregular 'bedrock' reflector seen on the inner shelf is composed of Lower Pliocene to Miocene units and can be correlated with the regional C10 surface.

Overall, the Pliocene strata of SU1 thin laterally towards both the inner and outer shelf, and from a maximum thickness under the mid-

shelf slope, and so appear to form part of the larger depocentre, in a manner analogous to the Plio-Quaternary wedges observed farther north along the NW European margin (Stoker et al., 1994; Stoker et al., 2005). Under the mid-shelf slope the unit is a thickening wedge of generally sub-horizontal strata containing a meandering channel network. The channel geometry seen in 3D data and palynology of samples from BH27/24-2,2A (Fugro, 1994) on the inner shelf from a lateral equivalent of the same unit both indicate a shallow shelf submarine deltaic depositional environment.

Table 2

Conversion of Gateways 1-C profile seismic stratigraphy to depths below seafloor using a sediment seismic velocity of 1680 m/s and proposed correlation to units in BH27/24-2,2A.

GW1-C features	TWT top (ms)	TWT bottom (ms)	Top TwT bsf (s)	Bottom TwT bsf (s)	GW1-C Top (m bsf)	GW1-C Bottom (m bsf)	BH27/24-2,2A units	Top (m bsf)	Bottom (m bsf)
Seabed	195	195	0	0	0	0	Seabed sands	0	0.2
SU3	200	230	0.05	0.035	4.2	29.4	D1	0.2	29
SU2	230	285	0.035	0.09	29.4	75.6	D2, G1, D3, G2	29	75
SU1	285	320	0.09	0.125	75.6	105	M1, M2	75	105
Miocene	320	Not imaged	0.125	?	105	?	M3	105	210

The Pliocene unit is truncated across the inner to mid-shelf area by R1. On the inner shelf, seismic profiles show an irregular unit surface (Fig. 5) that may record channelised erosion. Under the mid-shelf slope 3D seismic data show that R1 is extensively incised by iceberg scour marks. Iceberg scouring is assumed to have taken place following truncation of the Pliocene strata by processes that may have included both marine and glacial erosion. In contrast, boreholes 27/24-2,2A provide evidence of highly consolidated Quaternary glacial diamicts (possibly tills) directly overlying R1, suggesting a correlation to the intra-Pleistocene glacial unconformity observed in other wedges (Stoker et al., 2005). Subglacial erosion along R1 is also supported by the overconsolidated character (uSS of up to 900 kPa) of Pliocene sediments in 27/24-2,2A (Table 1), however no morphological evidence to support cross-shelf subglacial erosion of Pliocene aged substrates is present on the 2008/08 3D data volume.

4.3.2. Quaternary

The base-Quaternary surface is inferred to be defined by the iceberg scoured R1 reflector. The Quaternary sequence is further subdivided by reflector R2 into two seismic units (SU2 & 3).

4.3.2.1. SU2. At approx. 10 km along line on GW1-C, the basal part of SU2 contains a well-defined mound with a steeper-dipping landward face, and a set of over-topping and prograding horizontal reflectors. This composite feature is interpreted as a ‘till delta’, comprised of a moraine ridge and overlying topset units (Alley et al., 1989; Batchelor and Dowdeswell, 2015). Conformably overlying this basal sequence, the upper part of SU2 comprises more seaward dipping, poorly defined packages, which are truncated by the R2 reflector. In both parts of SU2, thin subhorizontal units on the inner shelf thicken into acoustically transparent, tabular, offshore dipping, poorly separated packages under the mid-shelf slope. These packages comprise the bulk of the Connemara Fan, and from their consistently transparent acoustic properties, tabular geometries and sedimentology are inferred to comprise largely homogenous, rapidly emplaced debris flows (King et al., 1996; Laberg and Vorren, 1995). Deposition of thick diamictic mud facies in this manner is associated with high rates of cross-shelf subglacial sediment supply to ice stream margins grounded at shelf-

edge positions (e.g. Armishaw et al., 1998; Dowdeswell et al., 1996; Ó Cofaigh et al., 2013; Ó Cofaigh et al., 2003; Vorren et al., 1998).

SU2 conformably onlaps the iceberg scoured R1 reflector, indicating deposition that postdates one or more periods of large-scale deglaciation. As no evidence of streamlined elongate landforms on R1 that might record subglacial over-riding was recognised on 3D seismic data within the fan, we infer that beneath the mid-shelf slope R1 is not a former subglacial surface but rather records an iceberg-scoured surface incised into Pliocene sediments during the late Pliocene and early Pleistocene, comparable to the present seabed. We therefore argue that the morainic ridge in the lower part of SU2 marks the seaward limit of a grounded ice advance from west central Ireland that postdates the iceberg scouring of R1. Inshore of the moraine, undulating reflectors conform to the pattern, scale and geometry of deglacial morainal bank complexes (e.g. Cai et al., 1997). These are inferred to be associated with the eastward staged retreat of a grounded ice margin, as inferred for nested moraines at seabed on the north-west Irish shelf (Ó Cofaigh et al., 2012a, 2012b). The physical limit to glacial extent may have been formed by increasing water depths and concomitant increases in ice marginal buoyancy and calving (Howe, 1995).

This model of a subglacial and ice-marginal origin for SU2 is supported by the sediment facies in the upper 75 m of BH27/24-2 & 2A, which comprise gravel-rich stiff to hard clays, and 5 m + thick gravel units (Fig. 11). At this location on the inner shelf this sequence is inferred to comprise a typically variable ice marginal signature of interbedded subglacial tills and sub- to proglacial gravels associated with periods of ice marginal oscillation and/or advance-retreat cycles. It is thus inferred from the ice proximal sedimentological character of mounded packages on the inner shelf feeding laterally into offshore thickening acoustically transparent units that direct deposition from advancing grounded ice west of central Ireland deposited the offshore thickening, down- and offlapping sequence of westward dipping strata comprising the main body of SU2 under the mid-shelf slope.

4.3.2.2. R2. The well-defined, sub-horizontal R2 reflector at 230 ms/29.4 m bsf on the inner shelf underlies SU3, and forms a prominent unconformity within the Quaternary sediment sequence. It truncates seaward dipping packages in SU2 and in BH27/24-2,2A can be

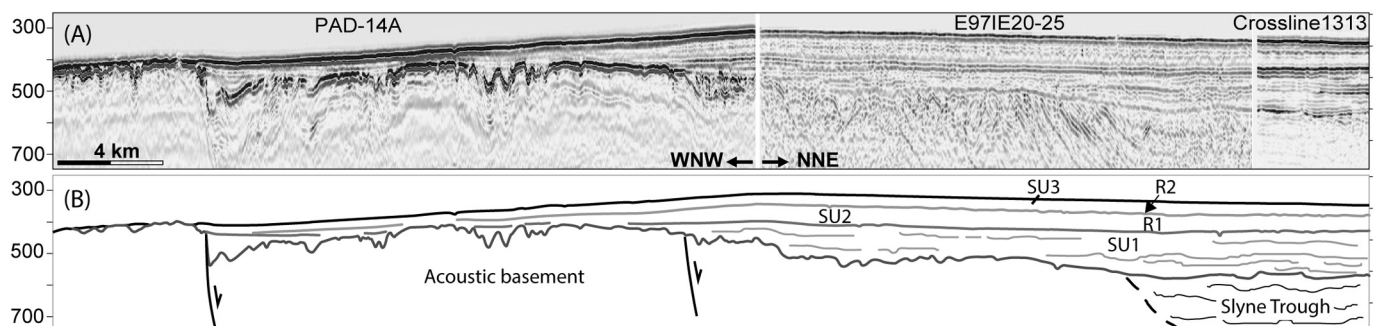


Fig. 10. An arbitrary 2D multichannel seismic profile across the mid- to outer shelf west of central Ireland.

(A) An arbitrary seismic profile across three data sources spanning (L-R) the Porcupine Saddle eastwards over the mid-shelf slope penetrating the Slyne Trough (Crossline-1313). Crossline-1313 is part of the 3D 2000–08 seismic cube. For line locations and orientations see Fig. 1;

(B) Interpretation of principal reflectors on Panel A, showing the lateral continuity of R1 & R2 and their onlap westward onto a fault-controlled basement high.

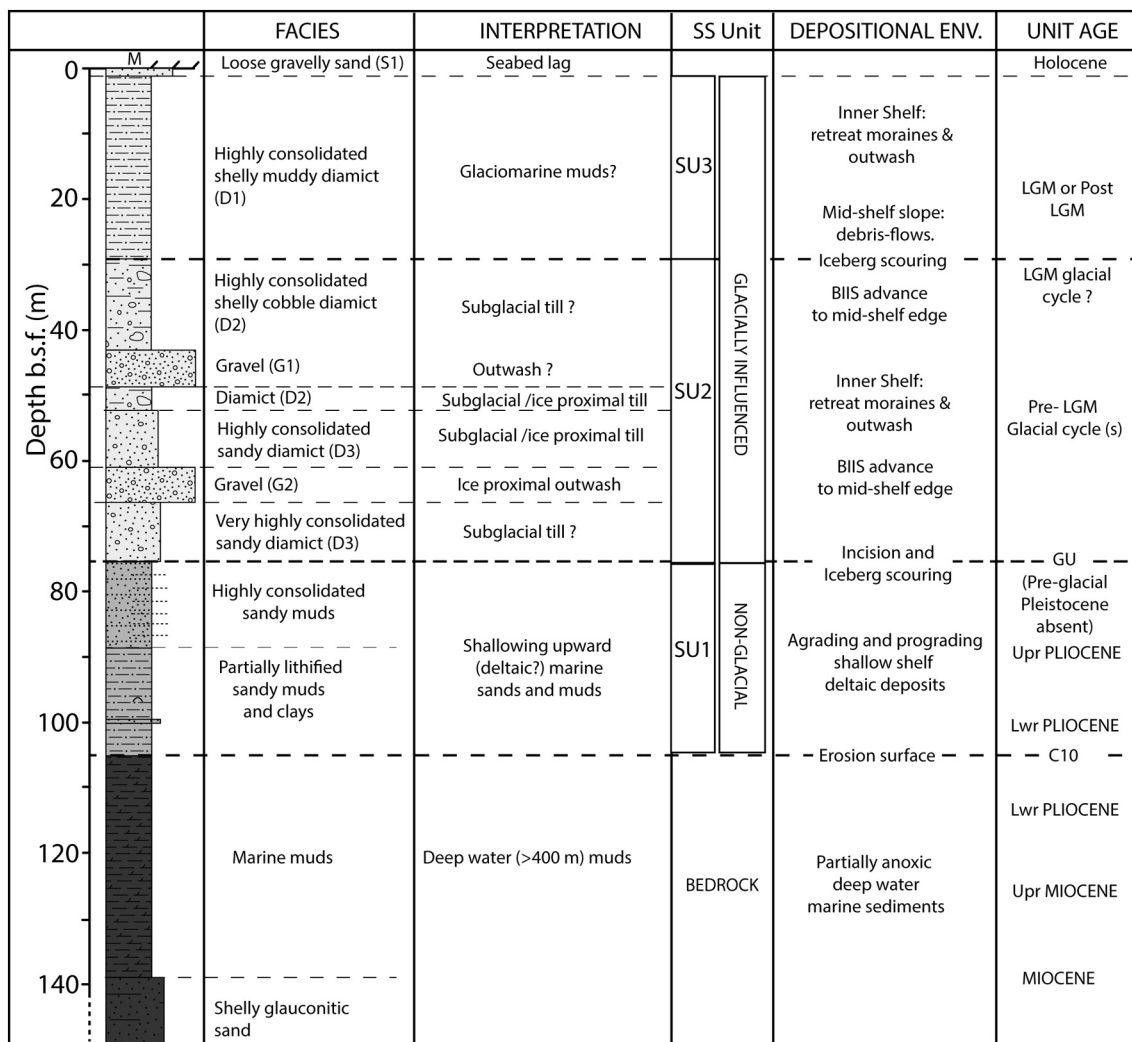


Fig. 11. Interpretation of the sedimentology and chronostratigraphy of boreholes 27/24-2 and 2A, with a proposed correlation to the seismic architecture and features of the Connemara Fan.

correlated with a distinct change in diamict facies at 30 m bsf. R2 is inferred to represent a subglacial surface and regularly spaced, smooth undulations on the surface may thus represent subglacial bedforms, possibly drumlins. The seaward extension of R2 under the mid-shelf slope is extensively iceberg scoured and forms the submarine slope controlling modern seabed geometry. R2 and the iceberg scours are draped by SU3 on the mid-shelf slope. The scouring must presumably postdate or begin with the subglacial erosion associated with R2 on the inner shelf, and thus is associated with the deglacial phase of an ice advance to the modern inner shelf edge.

4.3.2.3. *SU3*. On the inner shelf, SU3 overlies the R2 unconformity and defines the seabed topography. At its thickest point it is interpreted to represent a glacial moraine forming a seabed ridge 20 km inshore of the modern inner shelf edge. Eastward offlapping buried sediment mounds onlap the eastern margin of the moraine and are inferred to represent a set of recessional moraines associated with the staged retreat of a grounded ice margin following deposition of the moraine and associated terrace to seaward. On the mid-shelf slope SU3 is generally thinner and appears to have been subject to downslope remobilisation. Similar slope morphologies are known from elsewhere on the NW European margin on rapidly emplaced, glacial fans (Holmes et al., 1998).

The evidence appears to support a model of SU3 as a deglacial unit, with the large inner shelf seabed ridge formed at either the maximum

extent of ice extension westwards along R2, or during a stillstand from a maximum extension further westwards (represented by the extent of R2 on the inner shelf). The inner shelf seabed ridge has been interpreted as an LGM-aged terminal moraine (Clark et al., 2012) and grounding zone wedge associated with ice retreat from the Porcupine Saddle (Peters et al., 2016).

On the mid-shelf slope, SU3 is associated with sedimentation of ice distal deglacial glaciomarine facies to seaward of the seabed and buried morainic ridges on the inner shelf. This is inferred to have occurred during and possibly following the formation of morainic topography within SU3 on the inner shelf with ice distal, IRD-rich plumites inferred to have draped and buried the scour marks on R2 (c.f. Zecchin et al., 2016). The rapid emplacement of fine-grained facies on the mid-shelf slope possibly contributed to remobilisation of the sediment column downslope along an internal décollement plane, leading to the slope topographic bulge and folding of toe slope strata. Strata of SU3 do not appear to extend onto the outer shelf/Porcupine Saddle.

5. Discussion

5.1. Connemara Fan Quaternary chronostratigraphy

The Connemara Fan appears to have been initially established as a submarine deltaic system during the Pliocene. The first evidence observed of deteriorating climate and glacial influence comprises iceberg

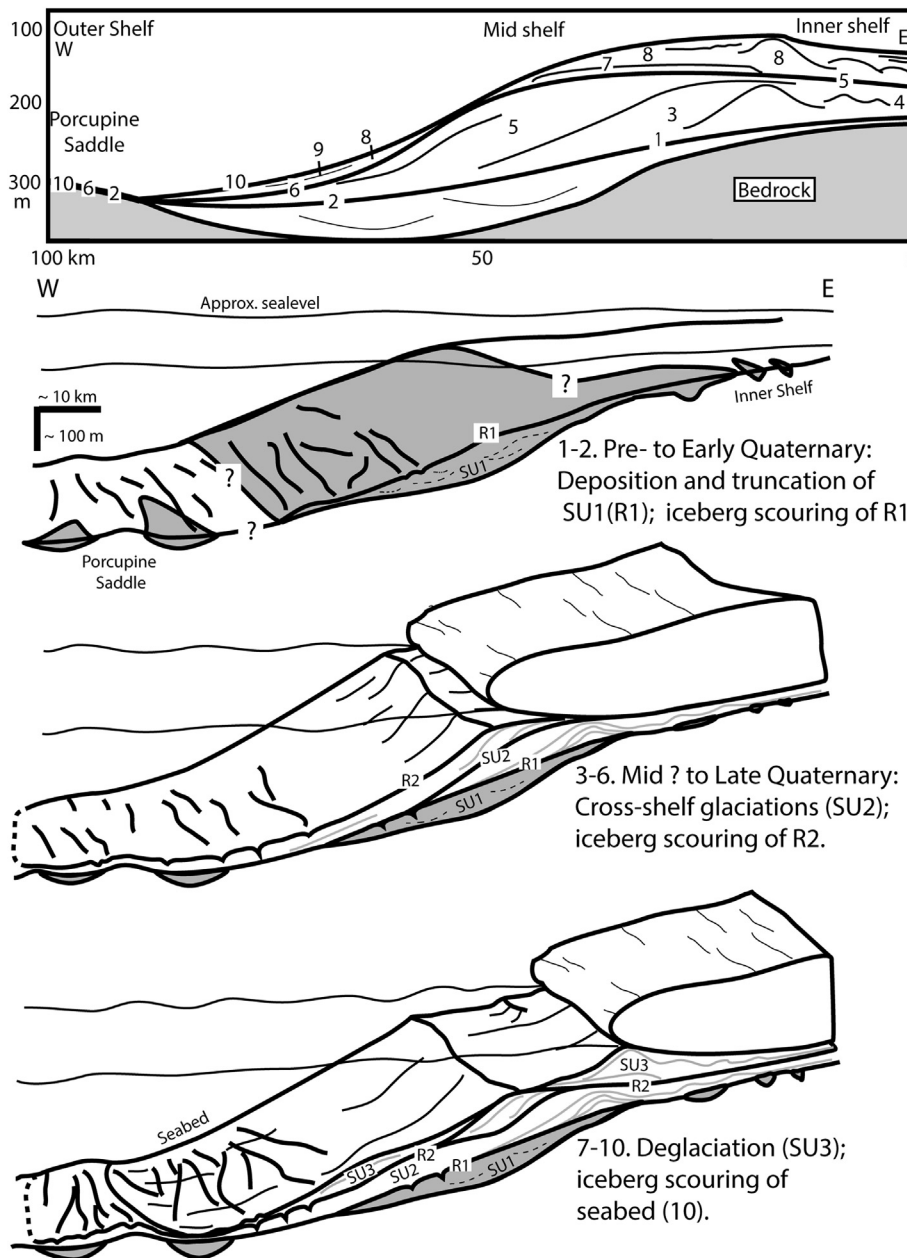


Fig. 12. A proposed cartoon chronology of depositional and erosional events recorded in the Connemara Fan.

- 1 Truncation of Pliocene sediments (SU1) along R1.
- 2 Iceberg scouring of R1, pre-dating Pleistocene cross shelf ice extension west of Ireland.
- 3 Initial deposition phases of SU2 during cross shelf glaciation west of Ireland as moraines and a “till delta” on the inner shelf; preservation of underlying iceberg scours on mid-shelf slope.
- 4 Minor morainic ridges within SU2 formed during a period of deglaciation.
- 5 Deposition of upper parts of SU2 during ice sheet extension across the inner shelf and subglacial erosion along R2. MIS 2 and/or older in age.
- 6 Major phase of deglaciation. Iceberg scouring of R2 on the mid-shelf slope. MIS 2 and/or older in age
- 7-8 Moraines and mid-shelf slope drape over R2 formed during either: An ice marginal still-stand during overall deglaciation, OR maximum westward extent of an ice sheet. MIS 2 (ILGM) in age.
- 9 Slide/mass movement of sediment drape on mid-shelf slope. MIS 2 (post-LGM) in age.
- 10 Iceberg scouring of seabed. MIS 2 (post-LGM) in age.

scours imaged on the base Quaternary unconformity (R1) (Fig. 9D). Icebergs inundating the Porcupine Seabight appear to have largely followed regional south to north current vectors. Minor levels of ice-rafted detritus from unknown sources are known in the Porcupine Seabight throughout the span of the Quaternary, predominating in sand-sized populations only after < 1 Ma (Thierens et al., 2010), in association with the mid-Pleistocene transition. Ice rafted debris from BIIS sources has been identified in the Porcupine Seabight during MIS4 to MIS2 (Van Rooij et al., 2006), so the influx of icebergs from wider afield in the circum-North Atlantic may have been a relatively common occurrence over the Pleistocene.

Paired boreholes 27/24-2 & 2A allow a distinction of Pliocene from Pleistocene sediments (Fig. 3), but the precise age of seismic units within the Connemara Fan remains poorly constrained. Without detailed biostratigraphical information, the chronostratigraphy of the Pleistocene succession and intra-fan scoured surfaces can only be tentatively inferred. However, some inferences can be made based on the internal geometry of the two Quaternary units (SU2 & 3) (Fig. 12). We note that the architecture of the fan allows the possibility that the entire

Quaternary wedge was deposited during a single (last) glacial cycle, beneath an ice margin that oscillated between shelf-edge and inner shelf positions. This model is consistent with SU3 recording the last deglaciation, given that it includes seabed moraines interpreted in that sense. The evidence presented here indicates formation of the Connemara Fan across at least two stadials of sufficient magnitude to result in repeated cross shelf glaciation. This is currently not a pattern associated with MIS 2 (Late Midlandian/Late Devensian) glaciation in Ireland, with the ILGM (local Last Glacial Maximum) (Clark et al., 2009) in the west of Ireland thought to have occurred relatively early at about 27–28 ka BP (Clark et al., 2012; McCabe et al., 2007) with a more aerially restricted ice build-up in this region at the gLGM (Global LGM) at 22–24 ks BP.

However, a model of Connemara Fan formation during the last glacial cycle *only* fails to explain other observations, in particular the extensive iceberg scouring at two subsurface levels. Calving of deep-keeled icebergs are associated with the break-up and retreat of ice sheets following advances to shelf edge positions, and thus major episodes of glaciation (Scourse et al., 2009). Extensive iceberg scouring of

R1 & R2 in areas of modern water depths of > 300 m (circa 200 m during at least the LGM glacioeustatic lowstand) (Yokoyama et al., 2000) suggests that the surfaces formed submarine slopes following separate major stadials. As R1 appears to truncate Pliocene sediments, the scouring of R1 on the mid-slope region is tentatively correlated with the regional intra-Pleistocene 'Glacial Unconformity' associated with the onset of cross-shelf glaciation on the NW European shelf during MIS 12 (~0.44 Ma) (Stoker et al., 2005). As R2 is also indicative of the end of a major glacial cycle (i.e. MIS2 or older), the deposition of SU2 and subglacial erosion of R2 on the inner shelf may therefore have occurred during one of, or a combination of, mid- to late Quaternary glaciations. However, as additional iceberg scoured horizons have not been observed within SU2, a model of SU2 deposition during a single glaciation associated with multiple glacial advance-retreat cycles appears the most probable. This model is also broadly comparable to the Quaternary architecture of the Sula Sgeir fan on the Hebridean shelf. This sequence shows a comparable sequence of a Pliocene to Pleistocene succession (Lower MacLeod sequence, possibly equivalent to S1?) and an Upper MacLeod sequence (equivalent to SU2 or SU3?). On the northern Hebridean Shelf, these sequences are subdivided by a scoured cross-fan reflector (possibly equivalent to R1?) and on the inner shelf, they are separated into the MacDonald and MacIver sequences) (Stoker et al., 1994) (possibly equivalent to SU 2 and 3 on the Irish Mainland Shelf?). Additional biostratigraphical age constraint across the sequence in the Connemara Fan is needed to narrow the provisional age estimates proposed here. However we argue that the occurrence within the Fan of two Quaternary-aged seismic units, and the preservation of iceberg-scoured horizons, provides evidence for at least two ice sheet advance and retreat cycles from western Ireland as far as the outer edge of the Irish Mainland Shelf.

In comparison, recent reconstructions of the extent of the BIIS during the LGM west of Ireland (e.g. Peters et al., 2015; Peters et al., 2016) tend towards much larger grounded ice volumes, extending to the Porcupine Saddle and outer shelf. In this model, the Connemara Fan would accumulate during the last deglacial period possibly over the course of one or more ice marginal oscillations across the shelf. Given the internally conformable architecture of the Fan, in such a model a grounded ice extension from the west of Ireland onto the Porcupine Saddle could only be represented by the lowermost sediment packages of SU2. However, our results from 3D seismic data within the mid-shelf sections of the Connemara Fan indicate the preservation of an extensively iceberg scoured surface below this stratigraphic level (at the base Quaternary) and no evidence of subglacial sediment emplacement and/or moulding.

It is argued therefore that the Connemara Fan formed over multiple Pleistocene cold stages and their associated BIIS advance-retreat cycles. During periods of cross shelf ice extension west of central Ireland and progradation of the Fan, grounded ice extension was to the outer limit of the Irish Mainland Shelf with the preservation of deglacial iceberg scoured seabed topographies beneath glaciomarine and subsequently marine settings. This model implies that the morainic topography on the inner shelf at modern seabed (SU3) represents either 1) a retreat stage from a slightly farther seaward LGM limit or 2) the furthest-west extension of grounded ice during the LGM (e.g. Bowen et al., 2002; Clark et al., 2012). Model (1) is preferred given the distinct erosion surface underlying SU3 that extends seaward of the morainic topography, which points to ice sheet advance across the full extent of the Irish Mainland Shelf.

5.2. Implications for models of the BIIS

Our results suggest repeated phases of deposition from ice sheets grounded on the inner shelf west of Ireland forming a significant depocentre during several Pleistocene glacial cycles. Lobate moraines formed at the margins of grounded ice lobes crossing the Irish Mainland Shelf have previously been inferred from bathymetry (Clark et al.,

2012; Peters et al., 2016). On the evidence presented here, the presence of moraines and buried moraines on the inner shelf is confirmed. However in contrast to Peters et al. (2016), ice sheet extents during glacial cycles during which the Fan was deposited appear to have been limited to the inner shelf (cf Clark et al., 2012), prograding it by > 20 km during the Pleistocene. We interpret the architecture of sedimentary packages within the Connemara Fan to indicate that repeated glacial advances across the IMS resulted in ice contact deposition at similar positions, presumably at tidewater ice margins controlled by glacio-eustatic water depths which restrained ice advance further west. This implies a repeated pattern of ice-ocean interaction during successive glaciations, comparable to inferences for other glacial wedges to the north (Stoker et al., 2005).

The transport of large volumes of glacial sediment west from Ireland to the Connemara Fan is consistent with models of subglacial sediment erosion and transport by ice streams flowing across continental shelves during glacial maxima (Alley et al., 1989). Geological evidence from studies of the extensively subglacially eroded and drumlinised Galway Bay/Co. Clare coastal fringe (McCabe and Dardis, 1989a, 1989b, 1994) support models of offshore directed fast ice flow centred on major coastal topographic embayments along the western Irish coastal margin. Ice stream development across the IMS along these paths has previously been inferred from terrestrial ice-flow indicators (e.g. Bigg et al., 2010; Clark et al., 2012). The repeated development of fast flowing ice lobes across the IMS during the last glacial cycles has also been proposed in recent numerical dynamical reconstructions of the BIIS (Hubbard et al., 2009).

6. Conclusions

The Connemara Fan is a 160 m thick, largely glacial Pliocene-Pleistocene sediment wedge on the Irish Mainland Shelf west of central Ireland. Aggradation and progradation of the sediment wedge into the Porcupine Seabight from the inner shelf began with Pliocene deltaic sedimentation (SU1) followed erosion and iceberg scouring of this unit possibly before and into the early Quaternary. The Connemara Fan contains two glacial units (SU2 and 3) which are separated by a second extensively iceberg scoured marine surface under the mid-shelf slope and a subglacial erosion surface on the inner shelf. These two units are inferred to represent pre- and LGM-aged depositional units respectively. Direct glacial deposition onto the Fan may have begun as early as the mid-Pleistocene transition, contemporaneously with the initiation of cross-shelf glaciation elsewhere along the north-east Atlantic fringe, or record deposition at a oscillating margin over the last glacial (Late Midlandian) cycle. The preservation of intra-fan iceberg scoured horizons and the architecture of the Fan, containing buried morainic mounds and till-delta type structures, support the former model. The Fan's preservation implies that grounded glaciation extents west of Galway were limited to the Irish Mainland Shelf, during the LGM at least. The Fan contains a record of BIIS dynamics and extents that requires further study and constraint and is critical to any evaluation of BIIS palaeoglaciological models. More widely, the Connemara Fan is an important discovery that extends the southern range of directly glacially fed fans on the north-east Atlantic margin. It comprises a marine sediment depocentre ideally placed to potentially yield detailed palaeoenvironmental, palaeoclimatic and palaeoceanic data for a critically important region immediately downwind and up-stream of the climatically sensitive Pleistocene mid-North Atlantic ocean.

Acknowledgements

The authors acknowledge the support of the Geological Survey of Ireland and Marine Institute INFOMAR programme for the GLAMAR (2009) campaign, funded by the Irish Government through the Department of Communications, Climate Action and the Environment

(DCENR) as part of the National Development Plan (NDP), 2007 – 2013. We acknowledge the Shiptime Grant Awards under the SeaChange Strategy of the NDP 2006–2012 by the Marine Institute for the GATEWAYS1 (CV12003) and GATEWAYS3 (CV16034) cruises. We thank the Master, crew and onboard and onshore support parties of the RV Celtic Voyager during the campaigns. We thank Ms. Clare Morgan and Mr. Michael Hanrahan of the Petroleum Affairs Division, DCENR, Dublin 4. D. Praeg thanks the Captain and crew of the OGS Explora, Trieste and the GSI for assistance during the GLAMAR 2009 campaign. This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 13/RC/2092 and is co-funded under the European Regional Development Fund and by PIPCO RSG and its member companies. The authors would like to thank Dr. Jasper Knight for reading an early draft of the manuscript. The manuscript was greatly improved by the critical reviews of P. Coxon and an anonymous reviewer.

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