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SCIENCE

Seabed geomorphology of the Porcupine Bank, West of Ireland

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ABSTRACT
A new map of the seabed geomorphology on the Porcupine Bank, located at the western edge of the north-eastern Atlantic shelf west of Ireland, uses high-resolution multibeam bathymetric and backscatter data as well as numerous shallow seismic profiles to identify individual landforms. They are described based on their acoustic signature on the various datasets. The landforms comprise sharp-crested ridges, mounds and outcrops often associated with and expressing underlying bedrock topography; sand waves highlighting modern currents directions; and iceberg scours with strongly preferred orientations. The map is intended as baseline evidence to test models of the palaeoceanographic and palaeoglaciological history of the Porcupine Bank.

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Porcupine Bank; multibeam; backscatter; INFOMAR; glaciation

1. Introduction

1.1. *Geographical and topographical setting*

The Porcupine Bank comprises the seabed expression of the bedrock Porcupine High. It lies west of Ireland between 51–54°N and 11–15°W, located approximately between 150 and 250 km from the Irish western coastline and covering an area of more than 40,700 km^2 (Main Map and Figure 1(a)). It is a S–N trending plateau forming the north-western margin of the Porcupine Seabight Basin (Naylor & Shannon, 2009; Naylor, Shannon, & Murphy, 2002). The Slyne Ridge is a NE–SW extension of the north-western Irish Shelf linking to the Porcupine High in water depths of 250–300 m (Naylor et al., 2002). A W–E topographic bench, the 'Porcupine Saddle', is partially underlain by the Slyne Ridge and links the Bank to the Irish shelf. It is characterised by water depths between 300 and 400 m and an approximate width of 100 km. To the north and to the west the Porcupine Bank displays a shelf break at c. 500 m water depth; the slope is steep and narrow towards the Rockall Trough (Sacchetti, Benetti, Georgiopoulou, Dunlop, & Quinn, 2011). To the south and southeast, the bank opens with a gentle slope to the deep embayment of the Porcupine Seabight. The SW–NE oriented Porcupine Ridge (Naylor et al., 2002) is normally taken to be the northern, shallowest section of the Porcupine Bank, where water depths are typically less than 200 m. The shallowest point of the bank is ∼145 m (around 53.40°N–13.80°W) and is situated approximately 200 km west of Ireland. The majority of the bank occurs between 200 and 400 m isobaths (Figure 1(a)).

Overall, gradients on the bank are low (less than 0.5°; see Figure 1(b)). To the north and northwest gradients over 3° are common between the 400 and 500 m isobaths on the outer part of the bank and locally on escarpments. Steep slopes greater than 5° are present on significant seabed features described in Section 3.

1.2. *Sedimentology of the Porcupine Bank*

The bank was first surveyed in 1981 on *MV Challenger* expedition 11/81 using seabed samples, underwater video and shallow seismic profiling (Scoffin & Bowes, 1988), and multiple surveys have been carried out since (Cullen, 2003; Dorschel, Wheeler, Monteys, & Verbruggen, 2010; McDonnell & Shannon, 2001; Naylor & Shannon, 2009). Scoffin and Bowes (1988) subdivided the bank into two broad regions, with a clear depth zonation: (1) an area centred on and surrounding the Porcupine Ridge, dominated by up to boulder-sized clasts in a matrix of coarse sand-sized fragments of benthic organisms, with some quartz sand; and (2) an area between 200 and 500 m water depth dominated by foraminifera-rich (benthic and pelagic) glauconitic quartz sand.

1.3. *Objective of the present study*

This paper describes the Porcupine Bank's geomorphology and near-seabed geology, from the Porcupine Ridge (∼150 m water depth) down to the shelf break at 500 m water depth, covering an area of approximately 65,000 km^2 (Main Map).

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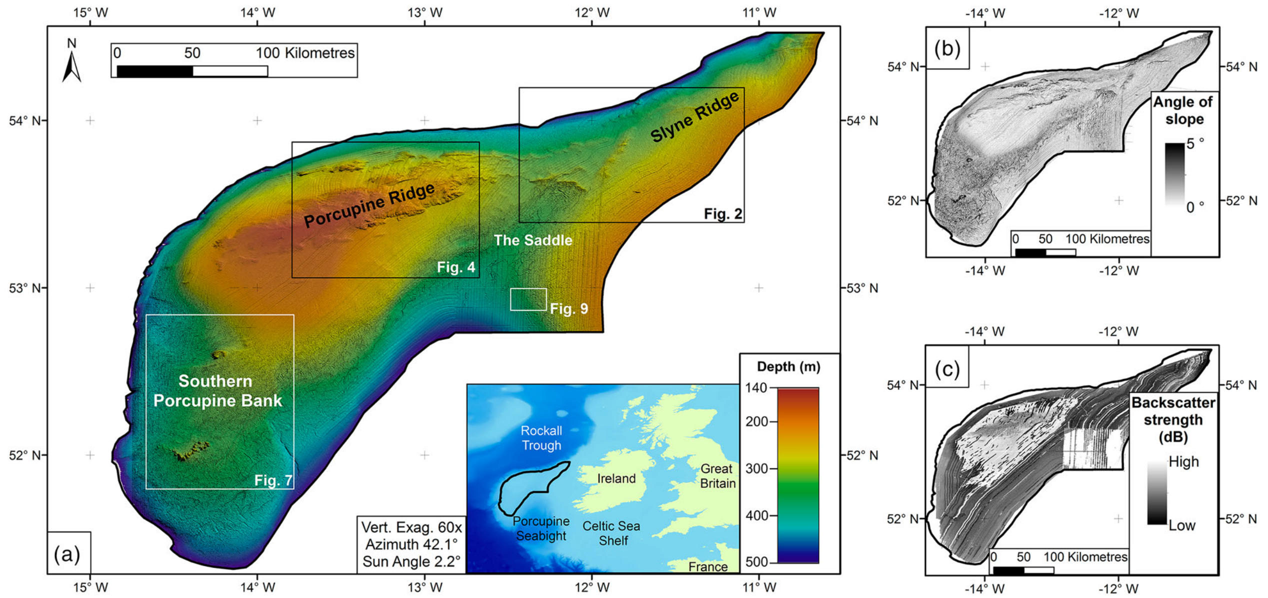

Figure 1. (a) Overview of the multibeam bathymetric dataset for the study area with highlighted locations of Figures 2, 4, 7 and 9. (b) Overview of the bathymetric derivative slope gradient for the study area. (c) Overview of the backscatter data for the study area.

2. Datasets and methodologies

In 2000 and 2001, the Irish Government mapped the Porcupine Bank using Multibeam Echosounder (MBES) bathymetry surveying on the *SV Bligh* and the *SV Siren* with contemporaneous collection of shallow seismic profiles as part of the Irish National Seabed Survey (INSS) programme. High-resolution seabed imagery derived from the data has facilitated the delineation of submarine geomorphology to an unprecedented level of detail; preliminary mapping of these features has been presented in Dorschel et al. (2010). MBES also provides co-located multibeam backscatter information from which sea floor sediment acoustic properties can be inferred.

2.1. *Multibeam sonar data collection and processing*

Bathymetry and backscatter data were collected using a Simrad EM1002 multibeam echosounder, with an operational frequency of 93–98 kHz and pulse lengths of 0.5 ms (150–250 m) and 0.7 ms (250–500 m). The Simrad EM1002 system operates from a semicircular transducer mounted on the ship hull, which emits 111 beams with a spacing of 2° by 2° over an angular sector of 150°. Vertical resolution exceeds 0.2% of water depth, excluding position, attitude and refraction uncertainties. The spatial sampling density in the study area varied from 10 by 10 m in the shallowest areas, to 20 by 20 m in the deepest parts.

Bathymetry Digital Terrain Models (DTMs) were gridded from hydrographically and tidally corrected soundings using weighted average (12 nearest neighbours) algorithms. Two spatial resolutions were produced: 50 by 50 m for small-scale mapping (i.e. large areas) and 20 by 20 m grid spacing (large scale mapping) to characterise individual features. The 20 by 20 m grid was used to display bathymetry in the figures of this paper (Figures 1–4 and 6–9). In addition, a set of bathymetry derivatives were generated from these DTMs: shaded relief images in orthogonal orientations (Figures 1–4 and 6–9) and slope indices (Figure 1(b)) using Jenness tools in Esri ArcGIS (Wright et al., 2012). Linear data artefacts located at the overlapping edges of the survey lines are visible over the whole study area and a range of shaded relief illuminations angle were used to limit their visual impact.

Backscatter data were acquired coincident with the bathymetry data. Post-processing of the backscatter data was performed using QPS FMGT Geocoder tools as detailed by Fonseca and Calder (2005). The acquisition parameters for the data varied based on the water depth, the vessel used and the year of the survey. This situation created an issue where a mosaic for the whole study area could not be harmonised and so will always show contrast between various lines of the survey (Figure 1(c)). However the data are of very high quality and were used with mosaics created for specific regions.

2.2. *Sub-bottom data collection and processing*

The sub-bottom data were acquired using a pinger system during the main operations of the INSS programme. The source was a heave-corrected 3.5 kHz transceiver in conjunction with an Oretech 3010S hull-mounted 4° by 4° transducer array. The raw signal was processed by an Octopus 360 sub-bottom processor, where the signal was corrected by applying time varying gain and filtered for heave and swell.

Over 40,000 line km were collected coincident with the main INSS survey lines.

2.3. *Morphometric analysis*

2.3.1. *Geomorphology*

The geomorphology of the bank and surrounding area was mapped using high-resolution MBES data. The band pass filtering techniques of Hiller and Smith (2008) were applied to de-trend (remove regional slope) and remove azimuthally biased interpretation from landform morphology and pattern analysis. Morphometric analysis was performed predominantly through visual interpretation of raster grids in QPS Fledermaus v 7.4.0 and Esri ArcGIS^{TM} v10.1 (similar to the procedures adopted by Dolan, Grehan, Guinan, & Brown, 2008; Sacchetti et al., 2011; Sacchetti, Benetti, Ó Cofaigh, & Georgiopoulou, 2012). This initial interpretation was completed using bathymetry, shaded relief (false illumination at right angles) and slope gradient (in degrees). In some cases, cross-sectional profiles were created as validation of the identified features (Figure 3(b)), which were digitised manually in ArcGIS.

2.3.2. *Backscatter*

A range of backscatter mosaics with a spatial resolution of 20 × 20 m^2 were produced and interpreted in a geographic information system (GIS) for further characterisation of geomorphological features (Figures 1(c) and 5). The backscatter strength displayed in this paper is the logarithmic form of the backscatter coefficient in decibels (dB). This coefficient is defined as the characterising quantity for seafloor reflectivity and, at a given frequency, is an inherent property of the seafloor that varies with the angle of incidence (Hammerstad, 2000).

2.3.3. *Shallow seismic profiles*

A number of sub-bottom profiles were investigated when appropriately crossing the geomorphological features recognised from the MBES data (Figures 2, 7, 8 and 9). The aim was to characterise the acoustic signature of the material forming or cut by the feature and infer its potential nature and/or internal structure (Bradwell & Stoker, 2015; Mitchum, Vail, & Sangree, 1977). An average estimated acoustic velocity of 1650 m/s was used to calculate the thickness of the sedimentary units as calculated in the nearby vicinity of the Porcupine Bank western slopes (Haughton et al., 2005; Øvrebø, Haughton, & Shannon, 2006). Maximum acoustic penetration was about 60 m below seabed with approximately 0.4 m vertical resolution. Acquisition parameters, data logging and interpretation were carried out using the CodaOctopus Seismic suite.

3. Results

A large number and wide range of distinctive seabed features and lineaments have been identified. These will be described according to their assigned classes, beginning with positive linear features (ridges and bedform lineations), followed by positive polygonal features (rock outcrops and mounds), and finally negative linear features (iceberg scours and gullies and channels).

3.1. *Ridges and plateau*

A number of seabed ridges, up to 30 m high have been identified to exist at water depths between 150 and 400 m in the northern portion of the study area. These features have a positive relief (i.e. the two sides have positive slopes) with a range of dimensions, plan outlines and orientations. The ridges have been mapped with a line for their crest and a polygon to mark their footprint, or the recognised extent of their slopes. They have been grouped according to

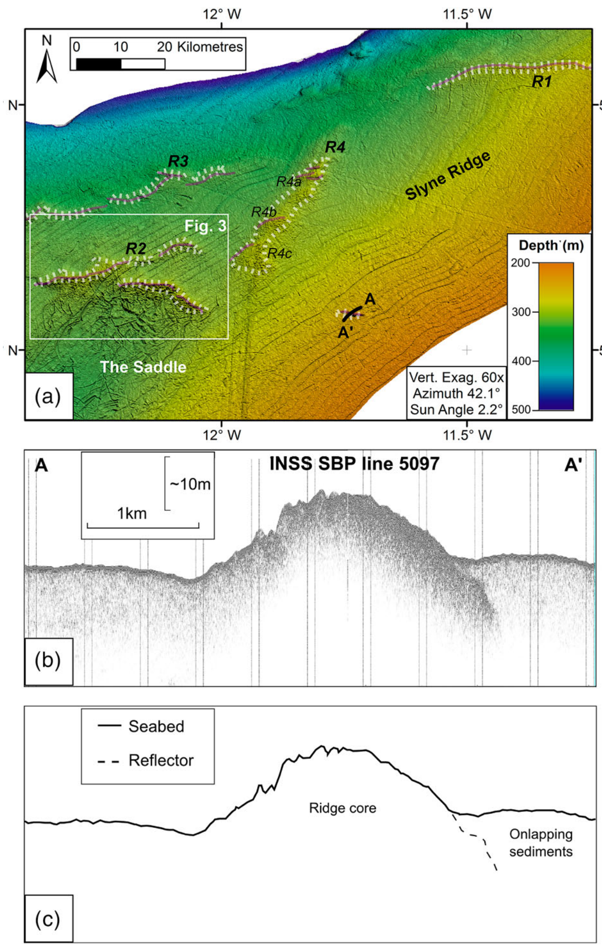

Figure 2. (a) Bathymetry of the saddle and Slyne ridge sector with highlighted ridge crests and footprints and the location of Figure 3. (b) Section of the INSS sub-bottom line 5097 over a West-East oriented ridge of the Saddle sector. (c) Interpretative diagram for the seismic profile of (b) with indication of onlapping sediments on the ridge material.

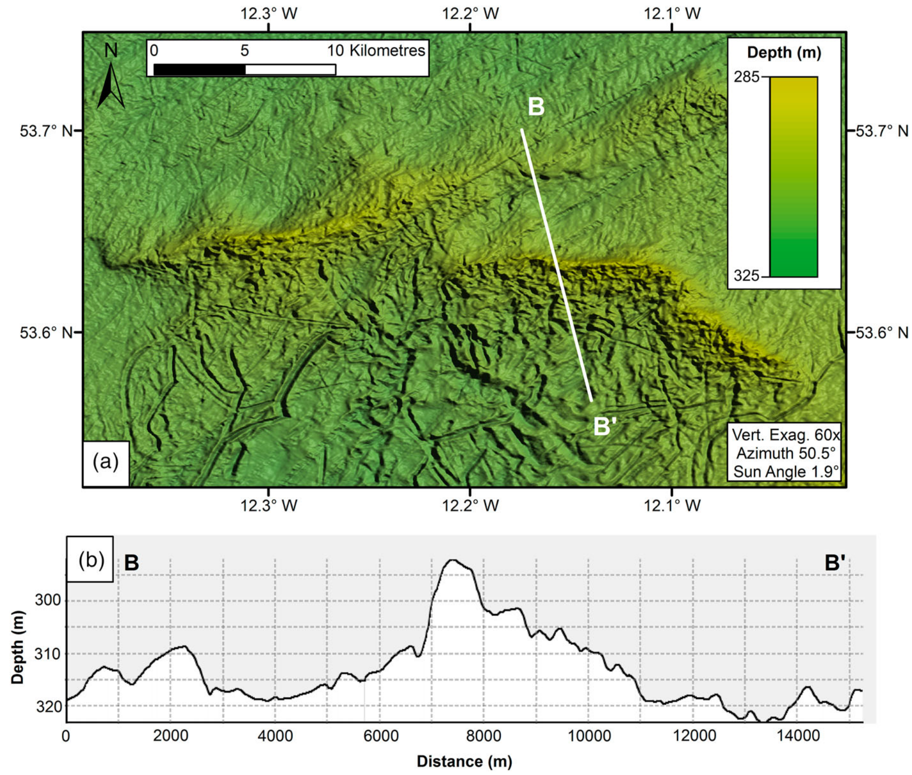

Figure 3. (a) Bathymetry of the large west-east oriented ridge complex R2 of the Saddle sector. (b) Associated bathymetric profile B–B′.

their specific region and morphologies and described in the next sections following a westward direction, from the Slyne Ridge to the northwest of the Porcupine Bank.

3.1.1. *The Porcupine Saddle area*

Several prominent, large sharp crested ridges occur across the Porcupine Saddle on the outer shelf (Figure 2(a)). They are up to 30 m high, 20 km long and up to 1 km wide with slopes typically of 1.5° but some are up to 3° (Figure 3). The majority of these features are curvilinear and their orientation is approximately E–W (Figure 2(a): ridges R1, R2 and R3). The footprint of an apparent NNE–SSW-oriented ridge (Figure 2(a): ridge R4) appears to separate the area into two, but closer examination reveals four more subtle ridge crests

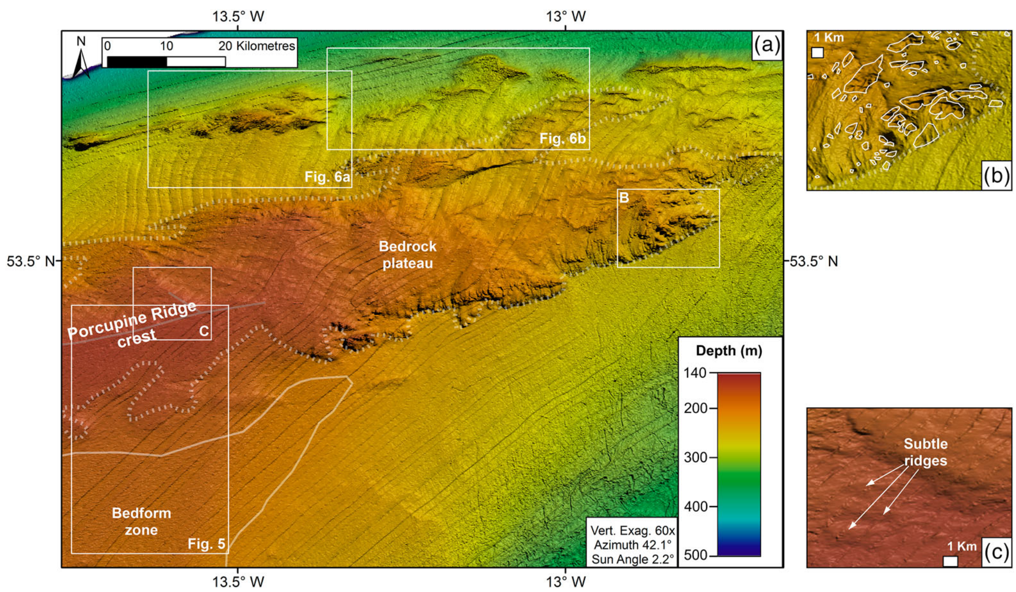

Figure 4. (a) Bathymetry of the Porcupine ridge sector with highlighted outlines of the bedrock plateau and the bedform zone as well as the Porcupine ridge crest. The locations of Figures 5 and 6 are also presented. (b) Focus on the bathymetry of a part of the largest cluster of bedrock outcrops (with highlighted outlines) in the study area at the southeastern edge of the bedrock plateau. (c) Focus on the central area of the bedrock plateau to display the more subtle ridges there.

with a more regular E–W orientation across it and reaching local heights of up to 15 m (Figure 2(a): ridges R4a to c). The uniformly chaotic acoustic signature with poor signal penetration in the sub-bottom profiles of the ridges in the area suggests a hard substrate core (Figure 2(b)). Additionally, some profiles indicate onlapping sedimentary layers onto a reflective ridge core (Figure 2(c)).

3.1.2. *The Porcupine Ridge area*

The Porcupine Ridge lies at the centre of the Porcupine Bank bedrock plateau (Figure 4(a)). The bedrock plateau is 100 km long and 25 km wide with sharply defined escarpments to the east and north and blocky mounds interpreted as outcropping bedrock (see below and Figure 4(b)) in places along its eastern and far western edges. It lies at shallow depth with a minimum at 145 m over a surrounding seabed at 250 m water depth. The terrain to the south is smooth with slope angles under 0.1°. The southern edge of the plateau is determined by the break of slope at the edge of the Porcupine Ridge where slopes up to 0.5° occur.

The Porcupine Ridge itself is 40 km long and up to 10 km wide. Its crest bifurcates twice to the north and to the south (Figure 4(a)). A number of smaller ridges of subtle morphology occur over the Porcupine Ridge. They are usually less than 5 km long, a few hundred meters wide and appear to be also stepped towards the Porcupine Ridge edges reaching local heights of about 4–5 m and slope angles of 0.5° (Figure 4(c)).

The Porcupine Ridge surface is characterised by a generally high backscatter background strength (Figure 1(c)) with large N–S oriented bands (over 1 km wide) of low backscatter which are themselves striated by SW–NE oriented thin bands (around 200 m wide) of high backscatter (see the northern half of Figure 5). The high backscatter signal background for this area suggests a hard substrate, which is confirmed by the absence of penetration in the local sub-bottom data.

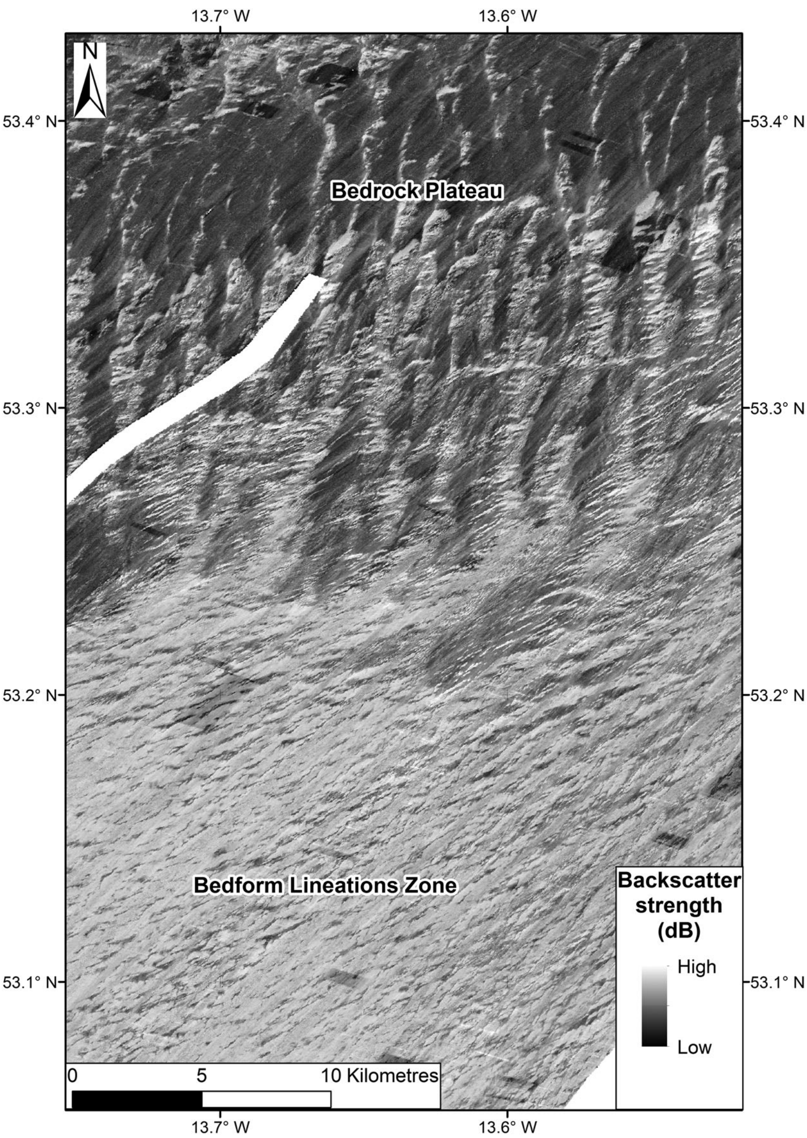

Figure 5. Backscatter response of the Porcupine Ridge plateau to the north and a part of the field of bedform lineations to the south.

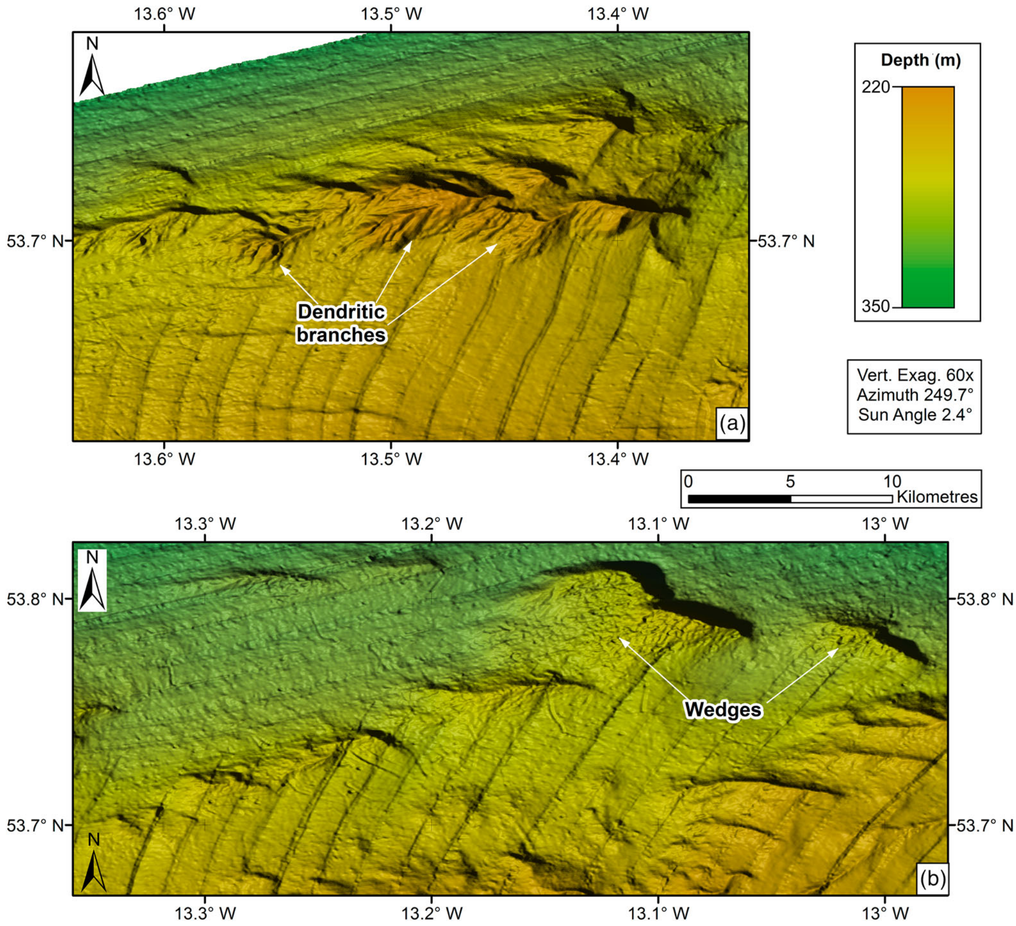

Figure 6. Bathymetry of two large west–east oriented ridge complexes of the Northwest sector; (a) dendritic branches of the ridge crests and (b) wedge on the western side of the ridges.

The origin of the complex seafloor for the region may lie in competing currents influencing the deposition of softer (sandy) sediments over bedrock or gravel (Mohn & Beckmann, 2002).

3.1.3. *The north and northwest area*

The ridges of this area (Figure 4(a)) appear to have similar orientation and morphologies to the ridges on the Saddle (Section 3.1.1 and Figure 2(a)). However, a number of these are distinct and defined as asymmetric in slope gradients with a shape comparable to a step and are described as stepped ridges (Figures 4(a), 6(a) and b). They are generally 1.5° on the step side and 3° on the steeper side. These ridges are up to 20 km long and often have a convex curved crest with respect to the bedrock plateau to the south. Their heights range from 5 to 25 m. Some of these stepped ridges have been associated with extensional faults (Dingle, Megson, & Scrutton, 1982). Additionally, on their southern gently sloping side (1.5°), some of the stepped ridges display branching crests in a dendritic pattern (Figure 6(a)). These branched ridges are only a few metres high and have sloping sides of up to 4° and run down the larger ridge slope over distances of more than 1 km. Furthermore, some of the ridges appear to delineate accumulation wedges on their western sides as illustrated in Figure 6(b). The backscatter and sub-bottom signatures for the ridges in the area (not illustrated here) are similar to the ones on the Porcupine Ridge, suggesting a hard substrate extending to the north and northwest ridges.

3.2. *Bedform lineations*

A 1800 km^2 field of linear bedforms has been identified to the south of the Porcupine Ridge between 180 and 210 m water depths (Figures 4(a) and 5). The bedforms have a relief of ~1 m, an average length of 600 m and an average width of 250 m with slopes between 0.2 and 0.4°. There are two main directions for these lineations: NE–SW and W–E. These characteristics distinguish them from the MBES bathymetrical data artefacts. The backscatter strength from the zone is generally high, including over the bedforms while the depressions formed between them have generally lower backscatter. The size of the bedform lineations prevents them being resolved in the sub-bottom profiles. However, the datasets from the zone where they appear present a signal penetration of more than 15 m and show a continuous reflector at a depth of 5–10 m that runs mostly parallel with the seabed.

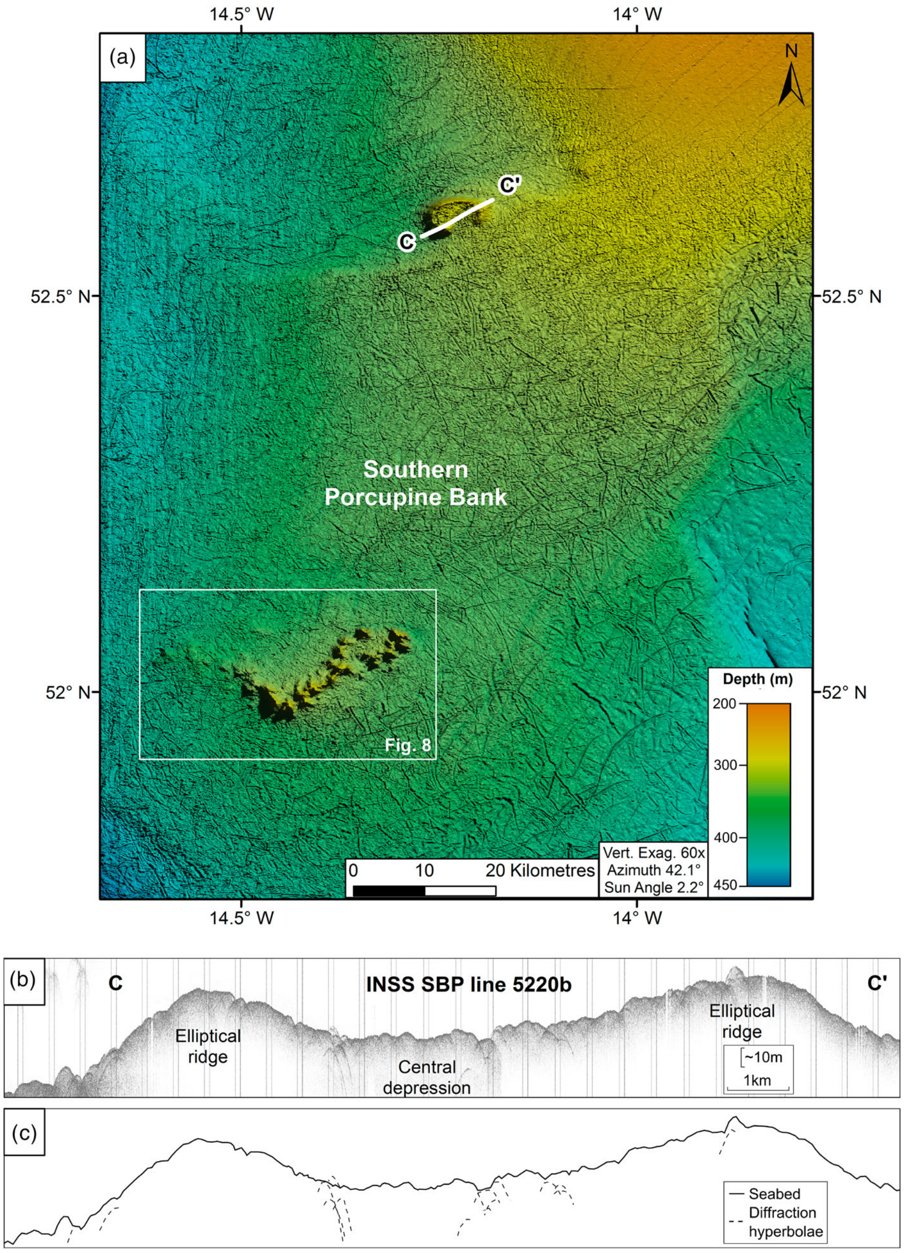

Figure 7. (a) Bathymetry of the southern part of the Porcupine Bank with highlighted locations of Figure 8. (b) Section of the INSS sub-bottom line 5220b over the mound with central depression. (c) Associated interpretative diagram to the seismic profile displayed in (b).

The morphology of these bedform lineations points towards their interpretation as sand waves, comparable though smaller to contourite drifts lineations (Belderson, Johnson, & Kenyon, 1982; Kenyon & Stride, 1970; Stow et al., 2009). Their two differing directions could correspond to either a change in subsurface current and/or sediment supply or two concurrent deposition processes with directions running NW–SE or N–S. The backscatter signature for the area is interpreted as coarse sand to gravel material (as indicated in Scoffin and Bowes (1988)), with the possible deposition of soft sediment in the depression between the bedforms (see the southern half of Figure 5). The deeper pernetration observed on the shallow seismic data suggests a softer substrate than the one on the Porcupine Ridge, while the detected reflector could represent the continuation of the bedrock plateau surface below the coarse sand.

3.3. *Bedrock outcrops*

Patchy clusters of low positive relief, high rugosity features (metre-scale textural patterns) were recognised on the edges of the bedrock plateau surrounding the Porcupine Ridge at depths shallower than 250 m in three separate zones; the main one extending over 75 km with a ENE–WSW orientation at the south-eastern edge of the plateau (Figure 4(a) and (b)), a smaller zone located on the northern edge of the middle of the plateau extending over 20 km with a W–E orientation (Figure 4(a)). The final zone located at the south-western edge of the plateau covering an area less than 25

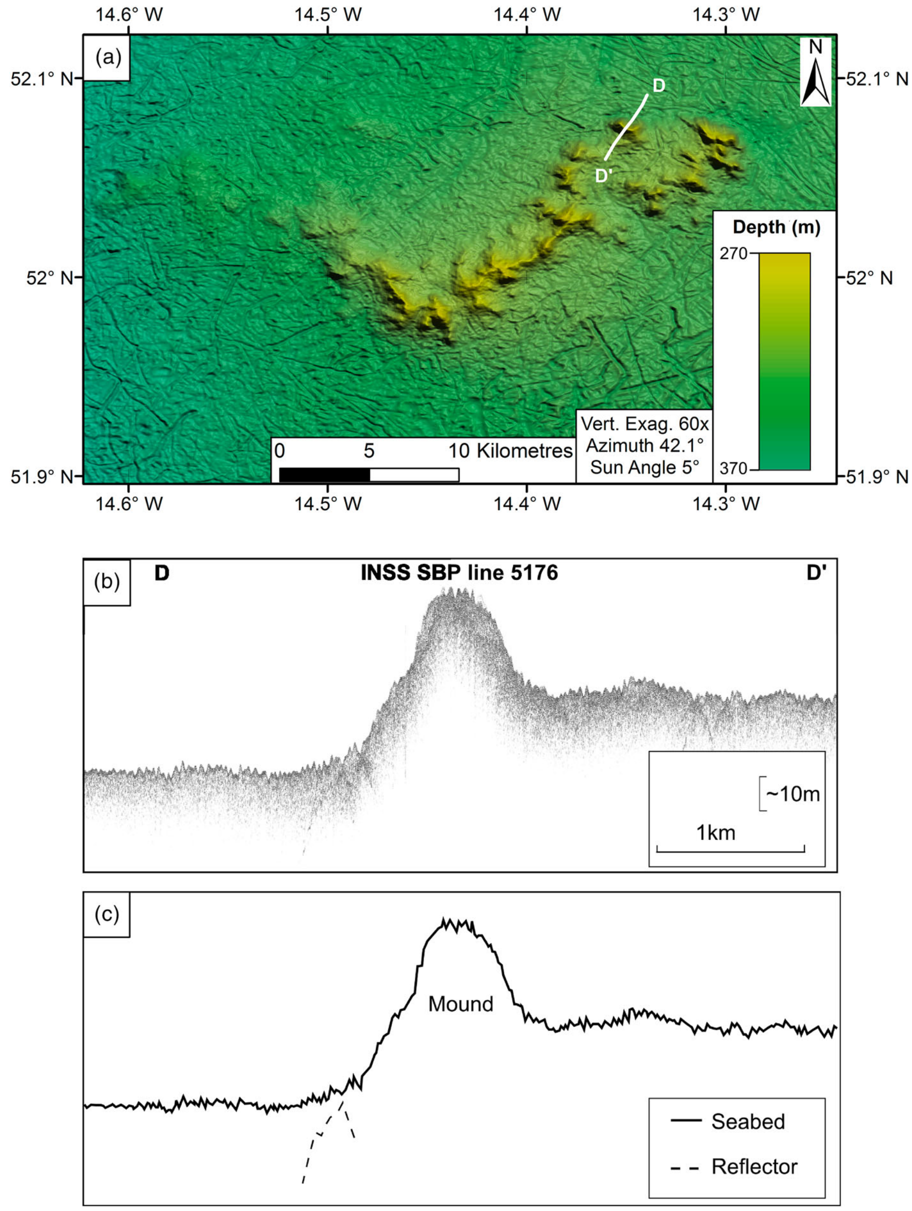

Figure 8. (a) Bathymetry of the cluster of mounds and ridges. (b) Section of the INSS sub-bottom line 5176 over one of the mounds of the cluster. (c) Associated interpretative diagram to the seismic profile displayed in (b).

km^2 (not illustrated here). They are low relief, blocky features of 10–100 s m in diameter with well-defined slopes (up to 4°). They follow a WSW–ENE trend but with very varied heights and widths; the large outcrops from the south-eastern edge of the Porcupine Ridge protrude 20–40 m above the surrounding seafloor (Figure 4(a)). Interpretation of sub-bottom seismic profiles (not illustrated here) and backscatter data over the area indicate a hard substrate for these features and they have been interpreted as bedrock outcrops.

3.4. *Mound with a central depression*

A conical mound with a central depression occurs on the southern part of the bank between 340 and 350 m water depth (Figure 7(a)). This feature has an elliptical ridge with a major axis of 7 km and the minor of 5 km. The average inside height above seafloor is 50 m, with a maximum of 70 m at the crest of the ridge and a total area of 70 km^2. The outer wall of the cone is steep (slopes of 3° in average and over 4.5° in places) and smooth, ending in a sharp elevated crest on the north-eastern side. Higher backscatter response over this feature suggests a hard substrate. Interpretation of the seismic profile with low signal penetration and numerous hyperbolae (Figure 7(b) and (c)) also indicates a hard substrate with probable gravel and/or boulders present at the surface.

3.5. *Clustered mounds and ridges*

A cluster of low mounds and ridges occurs in the southern area, located southwest of the top of the

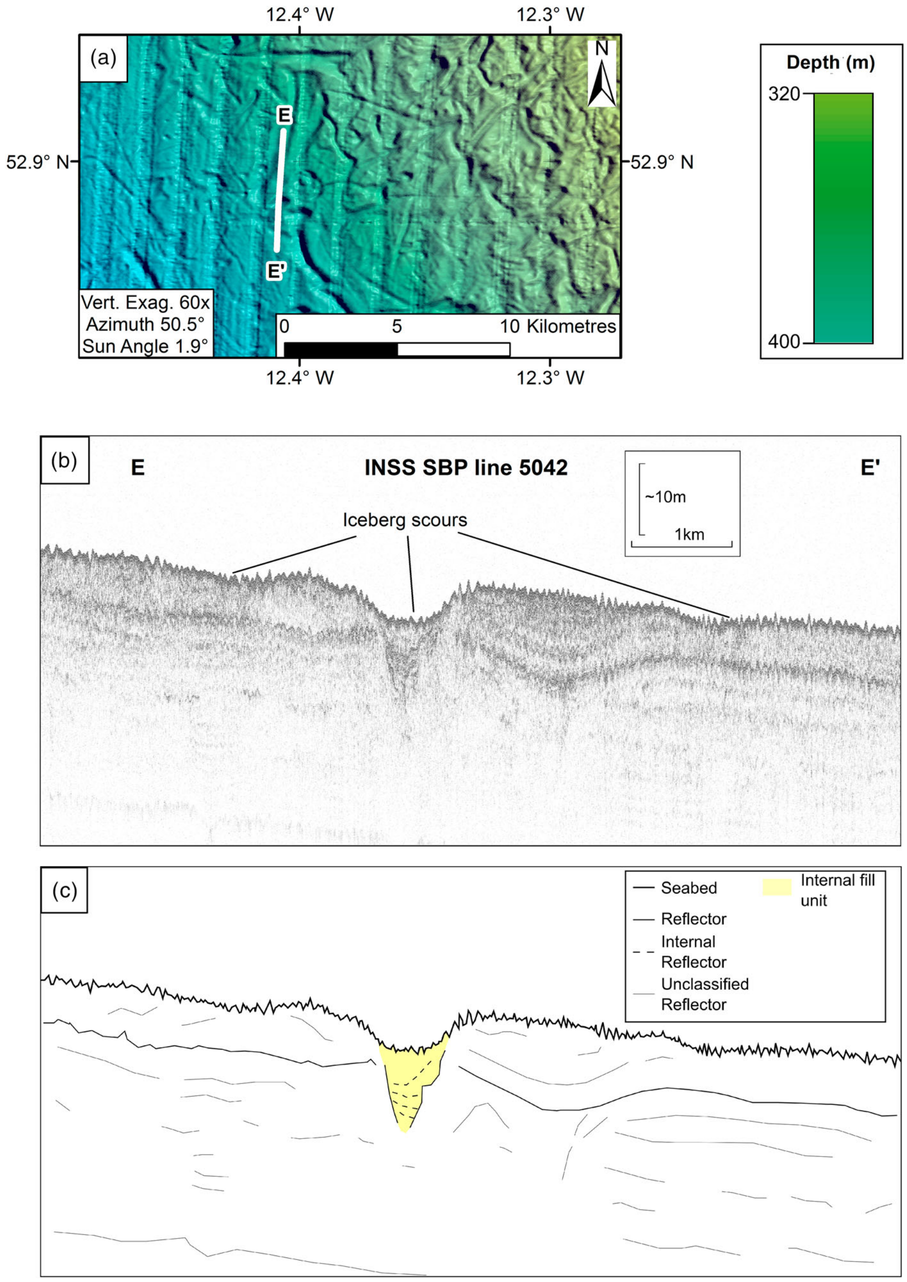

Figure 9. (a) Bathymetry of a region of the eastern slopes of the Saddle displaying numerous iceberg scours. (b) Section E–E′ of the INSS sub-bottom line 5042 over iceberg scours. (c) Associated interpretative diagram of seismic profile displayed in (b) with indication of an infilling seismic unit in the larger iceberg scour.

bank between 340 and 360 m water depth, with a total area of 140 km^2 (Figures 7(a) and 8(a)). These mounds, in excess of 20, are spatially distributed along a curving line forming a 'V' pointing to the south and with a rough circular head to the east. Some of these mounds are isolated whereas some are connected by ridges. The features are up to 70 m high (higher in the east) and several hundred meters long for isolated mounds to a few kilometres long for ridges. They have moderate to very steep slopes angles of up to 10° (Figure 8(b)). The backscatter signal for the cluster is of high strength but this is mainly due to the steep slopes of these features. The sub-bottom signature of these mounds is one of little penetration but some potential continuation of their steep morphology below the modern seafloor (Figure 8(c)).

3.6. *Iceberg scours*

Over 30,000 lineaments, consisting of cross-cutting segments of negative relief, have been mapped in this study (Figures 1(a) and 9(a)). They are ubiquitous and surround the Porcupine Bank in water depths between 180 m on the shelf margin to 575 m on the western edges of the bank (Figure 1(a)), sometime appearing over positive features described above such as ridges and the mound with a central depression (Figures 3(a) and 7(a)). Typically, they show two different morphologies: linear to curvilinear furrows up to 10 m deep, up to 300 m wide and up to 20 km long (with occasional side berms of 1–2 m in height and slopes of 1–3°) or crater pits up to 15 m deep and up to 200 m in diameter (a long axis was identified for their representation as lineaments on the map), sometimes forming one end of a furrow. Two main orientations were recorded: S–N and E–W. The multibeam backscatter signature of the area where these features are formed is of lower strength than the bedrock plateau area (Figure 1(c)), while some of the furrows and craters themselves present a lower strength still than the surrounding seabed. Due to their size, these features are generally not resolved in the sub-bottom data but the area where they are found is characterised by relatively high penetration of the acoustic signal showing two clear units with internal sub-parallel discontinuous reflectors (Figure 9(b) and (c)). Some of the seismic profiles display a separate unit inside some of the larger furrows (Figure 9(c)).

These features have been interpreted as relict iceberg scours (Dorschel et al., 2010; Monteys, Praeg, Caloca, & Gardia-Gil, 2008) produced by floating ice grounding on the seabed. Their two main orientations suggest different phases of formation. Both the backscatter and shallow seismic (Figure 9(c)) data suggest that some of the larger furrows are infilled with finer homogenous sediment that show less compaction (Monteys et al., 2008).

3.7. *Gullies and channels*

Further linear depressions have been identified in the study area and were classified as gullies and channels due to their morphology, location and isolation. Two channels were recognised in the southern Porcupine Bank with dimensions up to 50 km long and 10 m deep (with wall slope angles of about 2°) and with a cross slope direction. Shorter gullies (maximum length of 5 km) were identified between outcropping bedrock to the southeast of the bedrock plateau (Figure 4(a)). The backscatter strength of the two identified channels is lower than their surroundings while the acoustic signal of the areas where they formed displays the deepest penetration (over 50 m) with numerous sub-parallel continuous internal reflectors. These data suggest a softer stratified substrate and would indicate a concentrated flow to the outer bank and eventually the slopes.

3.8. *Escarpments*

Sharp breaks of slope were digitised and classified as escarpments. These were recognised mainly on the northern edges of the study area at the top of the steep slopes running to the Rockall Trough (Sacchetti et al., 2011) and to the edge of the cluster of identified bedrock outcrops to the southeast of the bedrock plateau. Another two long escarpments (30 and 40 km long) were identified in the southern Porcupine Bank at 350–370 m water depth.

4. Conclusions

The map associated with this article constitutes the first detailed study of the seabed geomorphology of the Porcupine Bank, a prominent bathymetric feature of the western Irish Shelf. A range of distinctive features have been interpreted based on multibeam and sub-bottom surveys. A number of ridges are present running mainly W–E along the northern edge of the Porcupine Bank. Their sharp-crested, arcuate morphology, scale and acoustic signature would draw comparisons with the subglacial ridges identified elsewhere on the Irish Shelf (Benetti, Dunlop, & Ó Cofaigh, 2010; Dunlop, Shannon, McCabe, Quinn, & Doyle, 2010; Ó Cofaigh, Dunlop, & Benetti, 2012; Sacchetti, Benetti, Georgiopoulou, et al., 2012). However, further work is needed to test this hypothesis. Bedforms interpreted here as sand waves were found clustered to the south of the bedrock plateau and their orientation and size could help us to characterise the local currents. A range of mounds were classified in three categories based on their morphologies and their various origins are at this point unknown. The presence of iceberg scours over the Porcupine Bank was previously recognised, but their widespread density has here been mapped and provides the basis for further research into the age and origin of their formation. Finally, channels, gullies and escarpments were identified and their presence could indicate contrasting seabed stress.

Software

The bathymetric DTMs were created using QPS Fledermaus v7.4 with grids of approximately 50 × 50 m^2 and 20 × 20 m^2 horizontal resolution using a weighted moving average gridding algorithm. These DTMs were then shaded in two orthogonal illumination directions (NW–SE and NE–SW) and a vertical exaggeration of 60X applied. The DTM grids were imported into Esri ArcGIS and analysed using QPS Fledermaus v7.4 to identify the geomorphological features which were then digitised.

The backscatter mosaics were created using QPS Fledermaus FMGT v7.4 with a horizontal resolution of about 20 m. The final backscatter mosaics were imported, balanced and merged into Esri ArcGIS and utilised together with multibeam bathymetry for geomorphological interpretation.

The landforms presented in this paper were visually digitised by the authors using Esri ArcGIS.

Data

The authors will supply the digitised datasets created for the map as a compressed rar archive containing the shapefiles of the various seabed features.

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