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The geomorphology of Ireland's continental shelf

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ABSTRACT

The Irish Shelf Seabed Geomorphological Map (ISSGM) (v2023) presented here, is the first high-resolution geomorphological map of the entire Irish continental shelf. This large-scale mapping exercise took advantage of the vast INFOMAR multibeam echosounder dataset, and used a protocol of semi-automated mapping techniques to accurately and rapidly extract seabed features. All previous mapping efforts and existing literature on the Irish shallow shelf geomorphology have also been collated and integrated in the map, critically evaluating the previous interpretations. An internationally standardised classification scheme was adopted, aligning the ISSGM (v2023) to other international geomorphological work. At a national level, this detailed geomorphological digital map is intended primarily as a resource to better inform multiple offshore activities and management of the marine environment. The map also acts as a baseline for future studies in marine geomorphology, as it identifies gaps in the knowledge and highlights areas of contentious interpretation that require further work. The map is available online on the Irish Marine Atlas (https://atlas.marine.ie – Geology Theme).

Policy Highlights

- We present the Irish Shelf Seabed Geomorphological Map (v2023), which represents the first high-resolution geomorphology map of the Irish continental shelf.
- The map was produced using a protocol of modern machine-assisted mapping techniques to streamline the results.
- All previous mapping efforts and existing literature on Irish shelf geomorphology have been collated and integrated in the map, critically evaluating the previous interpretations.
- An internationally standardised geomorphological classification scheme has been adopted, aligning the map to international work.
- The map is intended firstly as a resource to better inform multiple offshore activities and management of the marine environment on the Irish continental shelf.

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1. Introduction

Over the past twenty years, extensive seabed mapping has been carried out as part of Irish government-funded initiatives to map Ireland's Exclusive Economic Zone, beginning with the Irish National Seabed Survey (INSS, 1999–2005) and continuing as the Integrated Mapping for the Sustainable Development of Ireland's Marine Resource (INFOMAR) programme (INFOMAR, 2006–2026). To date, marine geophysical data, particularly open source multibeam echo-sounder (MBES) bathymetry and backscatter, have been collected in a large portion of Ireland's territorial waters. Surveying is ongoing, with only some coastal and shelf areas, generally < 200 mbsl (metres below sea level), primarily in the south and west, still to be surveyed. The 'Real Map of Ireland' (INFOMAR, 2019) shows the ~880,000 km^2 that make up Ireland's seabed territory. This is one of the largest in Europe, covering between 58°00′N and 46°45′N in the North Atlantic and from 5°16′W in the Irish Sea to 24°46′W in the Atlantic Ocean. The INFOMAR datasets have been used for specific applications, like safe navigation (SOLAS), ship-wreck investigations and marine spatial planning, to name a few (Guinan et al., 2021; Peters et al., 2020). To successfully manage such a large seabed territory and its resources, a holistic,

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accurate and detailed seabed mapping exercise is necessary for the entire area. The deeper areas (>200 metres below sea level (mbsl)) of Ireland's seabed territory have been mapped and described in detail in a deep-water atlas (Dorschel et al., 2010), using a single morphological classification system. This was done by creating digital surface models (DSMs) of the seabed and performing geo-statistical analyses as well as significant expert interpretation to identify various seabed features (Dorschel et al., 2010). However, while there have been numerous independent studies that involved geomorphological mapping on the Irish seabed <200 mbsl (e.g. Benetti et al. (2010) and Evans et al. (2015) (Northwest shelf); Cooper et al. (2002) (offshore Tramore); McCullagh et al. (2020) (Galway Bay), etc.), these have not been collated at a national scale into a single body of work in a consistent, standardised system. This leaves a gap in our understanding of the processes shaping and occurring on the Irish continental shelf, and how they can impact our attempts to manage the available resources. To close this gap, a large-scale and accurate geomorphological map is needed.

To meet this challenge, the following tasks were carried out: (1) a compilation and critical review of all current scientific knowledge of the geomorphology of the Irish continental shelf; (2) the development of an effective and accurate mapping protocol to delineate and characterise landforms for a very large-scale dataset, filling the uninterpreted areas as well as integrating and harmonising existing mapping efforts; (3) the adoption of a standardised terminology and classification system that can be easily compared to other seabed mapping programmes; (4) the production of an interactive GIS database to disseminate the map and scientific knowledge to stakeholders and the general public. In addressing these tasks, we thus produced the first complete, standardised seabed geomorphology map of the Irish continental shelf.

2. Datasets and methods

The information provided in the Irish Shelf Seabed Geomorphological Map (ISSGM) version 2023 has been compiled via a routine of data processing, contextualisation, geomorphological and geological interpretation, numerical extrapolation of seabed bathymetric features, harmonisation, classification and expert judgement. In the following sections, the datasets, the mapping methods and the classification system adopted are presented and described.

2.1. The INSS-INFOMAR datasets

The Irish National Seabed Survey and INFOMAR programmes took advantage of a variety of modern marine survey techniques, including multibeam echosounder (MBES), sediment ground-truthing and sub-bottom profiling, to map Ireland's seabed territory. The surveys have produced high resolution, bathymetric and backscatter datasets, encompassing much of the Irish territorial waters, allowing insight into shelf geomorphology at an unprecedented scale. A concise outline on data types preparation and consultation is given below, although further information on acquisition and pre-processing can be found at the INFOMAR website (https://www.infomar.ie).

2.1.1. Multibeam echosounder (MBES) data

The INSS-INFOMAR hydrographic dataset represents the primary source of information on which this map is based (Figure 1). The data on the continental shelf were acquired during c.270 separate surveys on different vessels in a timeframe spanning from 2002 to 2022. All INFOMAR surveys are conducted following International IHO S-44 survey standards (International Hydrographic Organization, 2020). Rigorous checks for position, depth accuracy, data density, feature detection and bathymetric coverage are implemented routinely during data acquisition and processing and all bathymetric data achieve a minimum of S-44 Order 1A in water depths less than 100 metres and S-44 Order 2 in water depths greater than 100 metres. The multibeam echosounder utilised include mostly Kongsberg and Teledyne systems but R2Sonic and interferometric systems were also used on specific surveys. Depending on water depth, these instruments were operated at frequencies between 100 and 300 kHz, achieving centimetric to decametric spatial and vertical resolutions.

Gridded bathymetric data was obtained from the INFOMAR website and loaded on ESRI ArcGIS Pro v2.8.8 for display and analysis. While INFOMAR bathymetry data can achieve a spatial resolution of less than a metre, for the purpose of the large-scale ISSGM (v2023), bathymetric data were re-gridded at 20 and 10 m resolution. Starting from the 5 m bathymetry grid, fine holes in the dataset were filled with the mean of the surrounding 5×5 pixel neighbours (i.e. ArcGIS Raster Calculator – *(Con(IsNull(DSM), FocalStatistics(DSM, NbrRectangle(5,5, 'CELL'), 'MEAN'), DSM))*. A general median filter (5×5 rectangle) was applied to remove imperfections and fine artefacts before re-gridding using a nearest neighbour algorithm. Although these lower resolutions permitted the removal of artefacts and other issues related to relatively poor data quality in some surveys, further filtering on the 10 m bathymetry ('feature-preserve' smoothing (Lindsay et al., 2019)) – a good compromise between preservation and outlier removal compared to more aggressive median or low pass filters) was necessary to facilitate a semi-automatic extraction of seabed features.

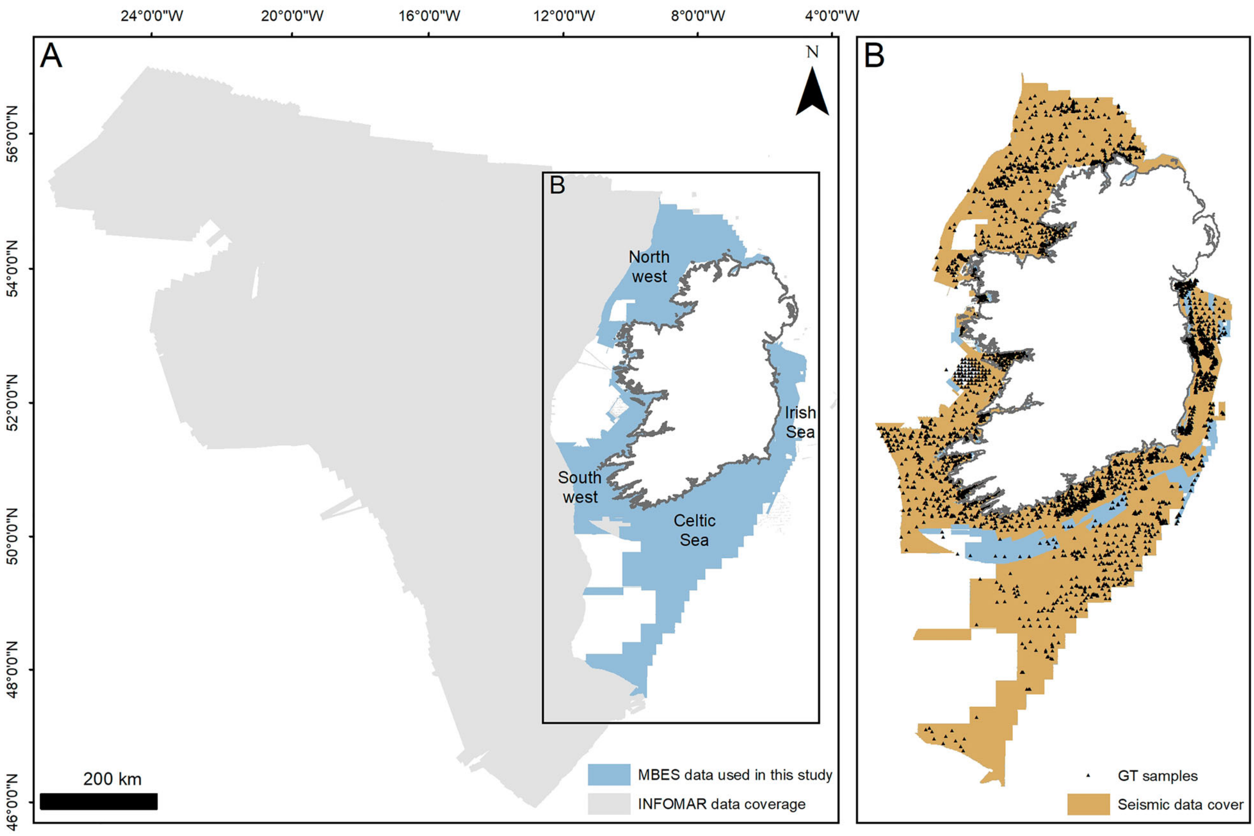

Figure 1. Overview of the INSS-INFOMAR data available at the time of mapping. (A) Extent of the entire INSS-INFOMAR MBES bathymetric data (grey) and the continental shelf data utilised in this study. (B) Location of Ground-truthing samples and surveys where seismic data was collected.

The creation of consistent full-coverage grid from INFOMAR backscatter data was more challenging due to the use of different MBES instruments and system configurations, the absence of internationally accepted calibration methods, the mix of weather conditions and varying water depths impacting the strength of the backscatter acoustic signal. The difficulty in removing the numerous geometric biases and artefacts in the backscatter mosaics has impeded the inclusion of the dataset in any large-scale semi-automated extraction protocol. However, considering the importance and usefulness of backscatter intensity when taking into account the physical properties (e.g. hardness and roughness) of the seafloor, the dataset was consulted at the bed feature interpretation stage, to correct the semi-automated results, and to create the map of the superficial fine-grained sediment cover.

2.1.2. Ground-truthing and sub-bottom profile data

INFOMAR's ground-truthing dataset consists of a record of particle size analyses from sediment grab samples collected during the surveys using different types of sampling systems (i.e. van Veen, Day, Shipek and Hamon Grabs and Box corer) (INFOMAR Ground Truthing and Sampling Strategy, 2007). In some locations, especially in the northwest, vibrocores have also been collected and analysed. A total of about 3700 samples are present on the shelf above 200 mbsl. Shallow sub-bottom profiles from Pinger and Chirp seismic sources have also been routinely collected during the INFOMAR surveys and are readily available on the online database (https://www.infomar.ie/data); together with ground-truthing data they were consulted at the seabed feature interpretation stage when necessary. Further ground-truthing sub-bottom profiles collected by other researchers and available as peer-reviewed publications were also consulted and integrated in the interpretations.

2.2. Mapping techniques

The task of mapping the shelf-wide geomorphology around the island of Ireland made the employment of semi-automated techniques indispensable, as that allows a relatively rapid extraction of seabed features and consistent delineations with minimal manual intervention. Several past studies, focusing especially on drumlin fields (see e.g. Smith & Clark, 2005; Smith & Wise, 2007) have shown how manual delineation relying on hillshaded DSMs introduce azimuthal bias and may lead to erroneous definition of feature boundaries, leading in turn to incorrect interpretations. The use of DSM derivatives (e.g. slope, aspect or bathymetry position index) can mitigate this effect and assist in manual tracing. In this study, one-size-fits-all approaches that aimed to capture all possible features with one single method proved unsatisfactory, or at best produced results that required a great amount of manual intervention and corrections. Therefore, a number of different semi-automated methodologies were adopted and applied *ad hoc* on single landform types or landform groups. Overall, the analysis was conducted on the ESRI ArcGIS Pro v2.8.8 environment and using Python 3.6; in a few cases (as for method 3, see below) QGIS 3.14 was utilised. The procedure utilised in the creation of the ISSGM (v2023), is the following:

(1) Firstly, we performed a detailed visual exploration of the available data, identifying different landform domains and typologies and cataloguing the features to be mapped using a standardised glossary and classification scheme. Specifics on the classification system are given in section 2.3.
(2) Semi-automated and manual methods are applied to extract the landforms in the most accurate and rapid way. For all the methods the final product is a vector file of delineated features. Details on the methods are given in the following subsections (2.2.1 to 2.2.4). After delineation the results were visually checked and manually edited where necessary in the form of polygon deletion, cutting or vertex editing.
(3) Finally, landforms were classified manually labelling the fields in the attribute table of the vector files following the classification system. Details on the information contained within the attribute tables are given in section 2.3. The interpretations were guided by context, morphology and backscatter intensity, by existing ground-truthing and sub-bottom profile data and previous studies in the area.

2.2.1. Method 1: residual-relief separation

This methodology covers the bulk of the mapping undertaken and it is based on the residual-relief separation technique developed by Hillier and Smith (2008). Firstly, regional relief is approximated by a median or modified median filter (e.g. Adam et al., 2005; Kim & Wessel, 2008) using a circular focal neighbourhood tailored to the wavelength of the features of interest. The filtered surface is then subtracted to leave the features of interest in a 'residual' topography. Secondly, the residual relief raster is normalised (e.g. with relative deviation from mean value or DEV (De Reu et al., 2013; Lecours, 2017)) to allow for amplitude variations in the features across the area. The result is explored visually by modifying the symbology by moment statistics (standard deviations or quantiles) to define the best thresholds to extract the features (similarly to Micallef et al., 2007). The features are then extracted by reclassifying the raster to a binary raster and converting it to a vector file. Spurious features in the vector files were removed manually or with the help of the 'description' tool in 2.2.2. The algorithms utilised for this work are contained within the CoMMa Toolbox (Arosio & Gafeira, 2023).

2.2.2. Method 2: footprint casting

This method is based on an operational sequence developed by Gafeira et al. (2012) for the semi-automated extraction of pockmarks from DSMs. For the purpose of the ISSGM (v2023), Gafeira et al.'s algorithm was modified and improved for applicability on any relief. Essentially, this method takes either the bathymetry raster dataset and applies a 'Fill' algorithm followed by a subtraction of the original unfilled layer to extract salient features. Various thresholds can be applied to retain only features of certain size, elongation ratio and prominence. The method can be applied to map both negative and positive features (for the positive features the input raster dataset is inverted). Further, geomorphometry values are extracted using a second 'description' tool, which includes various shape indexes (e.g. Polsby-Popper score, Convex Hull index, dissection index etc.) and morphometric values (e.g. min, max and mean slope, curvature etc.), and are used to remove spurious delineations (i.e. features with morphological characteristics not corresponding to the landform of interest). The algorithms utilised for this work are contained within the CoMMa Toolbox (Arosio & Gafeira, 2023).

2.2.3. Method 3: geomorphons

Geomorphons is an algorithm that isolates ten landform elements from a bathymetry surface based on the principle of pattern recognition, where the z position of every cell in the raster is compared to that of its 8 neighbours using a procedure that self-adapts to identify the most suitable spatial scale at each location (Jasiewicz & Stepinski, 2013). An integer raster is created that assigns a number (1–10) to each raster cell. Useful landform elements included are 'ridge' and 'summit', which identify positive relief, or 'pit' and 'valley'. These can be grouped, filtered and reclassified to extract features of interest. With this method, we applied the *r.geomorphons* algorithm (GRASS GIS) followed by reclassification of negatives vs positives.

2.2.4. Method 4: manual delineation

In many places the seabed is too complex for any of the above methodologies to provide a satisfactory result. The widespread presence of artefact, palimpsest and heavily altered features hinders the identification of thresholds that can separate the 'good' from 'bad', and in other cases the relevant features are so subtle or fragmented that it is impossible to separate them using mathematical filters. As a result, manual delineation or correction was, in many occasions, unavoidable. When adopted, manual mapping was performed generally at a 1:40,000 scale following the findings of Smith and Clark (2005) and Smith and Wise (2007). This reduced azimuth bias using curvature or normal vector derivatives (or residual reliefs from Method 1) to ascertain the geometry of a target, or using derived isobaths together with terrain profiles to determine feature shape and relief, before tracing limits on multidirectional hillshade.

2.3. Classification system and attributes

The classification system adopted for the ISSGM (v2023), corresponds to the MIM-GA (Mareano-INFOMAR-Maremap – Geoscience Australia) two-part marine geomorphology scheme, developed by an ongoing collaboration between geoscience agencies in the United Kingdom, Norway, Ireland and Australia (the MIM-GA group). This mapping scheme was conceived to address a global need in standardised seabed mapping, particularly to enable more consistent classifications (Dove et al., 2016). The novel aspect of the framework was the effort to independently describe seabed features according to their observed physical structure (Part 1-Morphology), and the more subjective interpretation of their origin and evolution (Part 2-Geomorphology). A full description of Part 1 (Morphology) is given in Dove et al. (2020). Part 2 (Geomorphology), which assembles and organises existing geomorphic classification schemes to classify Part 1 shapes with their process origin is presented in Nanson et al. (2023).

At the highest level of the classification, 'Settings' and 'Processes' group geomorphic units that are formed in specific environments or by similar processes. In the case of the ISSGM (v2023), 5 Settings and 2 Processes from the total 11 presented in the MIM-GA scheme have been mapped. They include: Settings – Marine, Solid Earth, Glacial, Fluvial and Coastal; and Processes – Fluid Flow, Current-Induced. The most generic landform classification label is the 'basic geomorphic unit' (BGU), which gives the most elementary geomorphological definition for a landform. Increasing specificity of the interpretation of units are defined within BGU 'Type' (BGU-T) and BGU 'Sub-type' (BGU-sT) levels. Further traits, as relative age, lithology and burial state can be added to further characterise the landform. The reader is directed to Dove et al. (2020) and Nanson et al. (2023) for a full explanation and description of the terminology utilised in the ISSGM (v2023). Classification and attributes for each feature are contained within the attribute table accompanying each vector

Table 1. Attributes that are used to describe geomorphic units in the ISSGM (v2023).

Attribute category	List of possible attributes
(I) Morphology	Morphological classification (see Dove et al., 2020)
(II) BGU	Basic geomorphic units
(III) BGU-T	Basic geomorphic unit types
(IV) BGU-sT	Basic geomorphic unit sub-types
(V) Group (of units)	Field, chain
(VI) Age (relative)	Relict, palimpsest, modern
(VII) Depth (relative)	Surface, buried or partially buried
(VIII) Lithology (relative)	Hard, soft sediment (siliciclastic or carbonate), consolidated sediment.
(IX) Ground-truthing	Metadata on existence of ground-truthing
(X) Confidence	Low, medium or high
(XI) References	Relevant previous studies on the mapped landform or landform group

Notes: A complete description and explanation for these attributes is given in Dove et al. (2020) (attribute I) and Nanson et al. (2023) (attributes II to VIII). Attributes IX to XI are explained in sections 2.3.1 to 2.3.3.

file of the map (Table 1). The ISSGM (v2023) includes three additional attributes not existing in the MIM-GA scheme, which applied to further describe geomorphic units (IX to XII in Table 1). An explanation of the last three fields is given in the subsections below.

2.3.1. Ground-truthing

If relevant ground-truthing for a feature is present it is stated in this field. For example, if a vibrocore has penetrated in a moraine or drumlin ridge and reported till, the information is relevant to the interpretation of the landform and the correspondent metadata are provided. Grab samples, on the contrary, are not considered sufficient proof for the interpretation of glacial landforms, but can be used to support the interpretation of, e.g. superficial current-induced bedforms or barforms.

2.3.2. Confidence

While confidence in geomorphology mapping remains a subjective value, we have nonetheless provided a simple indicator of the degree of certainty in the interpretation proposed. The scores, which are 'low', 'medium' and 'high', are defined as follows: (1) low, a feature possesses only faint and ambiguous morphological attributes that permit tentative identification, and no ground-truthing or previous studies exist; (2) medium, a feature possesses distinct morphological attributes that permit a somewhat confident identification, ground-truthing is absent but previous studies consistently support the interpretation; (3) high, a feature possesses typical morphological attributes that permit a very confident interpretation, ground-truthing and previous studies consistently support the interpretation. If previous studies have conflicting interpretations the confidence is lowered by one point.

2.3.3. References

The ‘references’ field cites the most relevant previous published works that have described, studied and interpreted the feature(s), if existing, in order of publication. Other relevant references are provided in the text of this article.

3. Results and discussion

The ISSGM (v2023) includes 35 different landform units (Table 2) and 4 substrate types generally mapped at 20 m/pixel resolution with a few exceptions (specified below) where a higher resolution (10 or 5 m) was utilised if geological interest counterbalanced time, effort and hindrance caused by artefacts. While the authors do not assume to have represented exhaustively any and all features on the Irish continental shelf seabed, the map is nonetheless the most complete depiction of the shallow marine geomorphology of the highest resolution created to date. The following results section presents each mapped unit giving a general description of morphology, distribution and mapping methodology, and discussing the geomorphological interpretation with the support of all available peer-reviewed literature. If our interpretation is conflicting with previous studies, a discussion on the reasoning behind the new interpretation is given.

3.1. Hard rock setting

3.1.1. Bedrock outcrops

Mapping of bedrock outcrops was carried out at a resolution of 20 m/pixel using a combination of Methods 1 and 2. The results were further cleaned with the aid of backscatter data, removing positive relief with very low backscatter values and therefore not composed of hard rock (although some expert supervision was required as some exceptions are present). Existing seismic data were also consulted on occasion to confirm the presence of bedrock at seabed. Further cleaning was carried out visually, with the assistance of higher resolution MBES data (10 to 5 m/pixel). Bedrock areas usually show very high rugosity, and when forming positive relief present steep slopes or structural signatures (e.g. bedding, faulting etc.). Where bedrock relief is more subdued the identification proved more difficult. As a generalisation, closely spaced bedrock outcrops were aggregated based on distance to create a second layer – bedrock zone – which included flat bedrock areas and bedrock covered by sediment in between prominent outcrops. A final visual check assisted by backscatter data was carried out to ensure that no areas of sediment (especially, also rough, glacial till) had been included in the map. The bedrock outcrop and bedrock zone layers were applied as a mask when semi-automatedly separating and classifying the remaining positive relief.

Bedrock outcrops are mostly distributed in shallow coastal areas, as far as but rarely beyond 45 km offshore, on the southern and western side of the island of Ireland. Bedrock outcrops offshore the southern coastline and West Cork are mainly conglomerate and sandstones of the Devonian Old Red Sandstone (ORS) (EMODnet, 2022; GSI, 2018), and tend to show a characteristic ‘knoll-and-crevice’ and hummocky appearance (Figure 2), although well-stratified outcrops are observed around the Waterford estuary. They produce prominent submarine headlands that constitute a natural extension of the land peninsulas, in contrast to the softer Carboniferous shallow marine mudstones, sandstones and limestones of the Cork Group, which tend to associate to embayments (and be covered by soft sediment, especially in West Cork, (EMODnet, 2022)). Cork Group outcrops are often characterised by regular bedding (observable at and below 5 m/pixel resolution, Figure 2), and occupy an extensive area up to 16 km offshore between Cork Harbour and the River Bandon estuary. To the east, the Cork Group facies are substituted by other Mississippian shallow marine successions, such as Waulsortian massive limestones. An extensive Waulsortian mudbank platform occupies a great portion of the seabed northwest of Kerry, gently sloping (~0.13°) north-westward and extending for several kilometres offshore. The platform is crossed by different fault systems but also cut by sinuous, anastomosing palaeochannels and, offshore the Dingle peninsula, characterised by partially infilled circular steep hollows (approx. 100–200 m wide and a few metres deep) and other larger curvilinear semi-enclosed depressions (Figure 2). These landforms are reminiscent of other similar features observed elsewhere on submerged carbonate pavements (e.g. Kan et al., 2015) and might indicate palaeo karstic action, which is observed onshore on the co-respective Lower-Middle Carboniferous formations (e.g. in the Burren: Drew, 2008). A stark textural contrast is provided by the second most common bedrock outcrop in the west, which is made up of younger (Pennsylvanian) deltaic and turbiditic sediments forming regular and fine bedding distorted by very complex folding and faulting. Pennsylvanian successions outcrop around Loop Head but also in a long south-west trending corridor up to 15 km wide between Waulsortian platform fragments offshore south County Clare and County Kerry. Apart from other regularly bedded Mississippian limestones and calcareous shales cropping out around the Aran Isles, the northwestern outcrops are mainly metamorphic or magmatic in origin, with a hummocky and fractured aspect similar to that presented by ORS rocks. They include mainly competent metasediments (schists, pelites and psammites) of the Dalradian Supergroup or intrusions of Caledonian age (Silurian-Devonian) of granites and granodiorites (GSI, 2018).

Table 2. List of the geomorphological units and substrate types mapped in this study.

Morphology classification		Geomorphology classification					
Relative position	Feature (ideal)	Setting/ Process	BGU	BGU-T	BGU-sT	Mapping style	Definition (for BGU-sT)
High	Bank	Glacial	grounding zone wedge			*crestline*	
High	Bank	Marine	marine barform	*sediment bank*		*polygon*	
High	Hill	Glacial	streamlined landform	*crag-and-tail*		*polygon, crestline*	
High	Hill	Glacial	streamlined landform	*drumlin*	*sediment drumlin or sediment drumlin with rock core*	*polygon, crestline*	.A DRUMLIN (BGU-T) composed of till or stratified drift, and sometimes having a bedrock core (Bell et al., 2016)
High	Hill	Glacial	streamlined landform	*drumlin*	*rock drumlin*	*polygon*	.Bedrock hills (or knolls) completely streamlined, usually with steep stoss sides and gently sloping lee sides, like in a sediment drumlin (Bell et al., 2016).
High	Hill	Glacial/ Marine (Current-induced)	barform	*tidal bar*	*megaridge**	*polygon*	The world's largest continental shelf sediment ridges. Stratigraphically and sedimentologically, the megaridges could represent preserved glacifluvial features, but a recent study shows that they comprise post-glacial tidal deposits (see TIDAL BAR in Nanson et al. (2023)) mantling a partially eroded glacial topography (Lockhart et al., 2018)
High	Mound	Fluid Flow	outcropping methane-derived authigenic carbonate (MDAC)	*MDAC mound*		*polygon*	
High	Various	Solid Earth	bedrock outcrop (undefined)			*polygon*	
High	Ridge	Glacial	esker			*polygon*	
High	Ridge	Glacial	moraine	*terminal moraine*		*crestline*	
High	Ridge	Glacial	moraine	*lateral moraine*		*crestline*	
High	Ridge	Glacial	moraine	*recessional moraine*		*crestline*	
High	Ridge	Glacial	moraine	*push moraine*		*crestline*	
High	Ridge	Glacial	Rogen (ribbed) moraine			*polygon*	
High	Ridge	Marine (Current-induced)	bedform	*Dune*	*transverse*	*crestline, field*	Flow-transverse bedforms with lengths of hundreds of metres and heights commonly between 1 and 15 m, with gentle slopes of mostly 2–5 degrees. They vary from symmetrical to asymmetrical shapes, with their steeper slope in the direction of the residual current (Van Dijk et al., 2021).
High	Ridge	Marine (Current-induced)	bedform	*dune*	*trochoidal*	*crestline, field*	Straight and symmetrical dunes that can attain very large dimensions (Van Landeghem, Wheeler, et al., 2009)
High	Ridge	Marine (Current-induced)	bedform	*dune*	*barchan*	*crestline, field*	Ellipsoidal dunes with a convex stoss slope, a concave slip face (lee), and horns extending down current (Van Dijk et al., 2021).
High	Ridge	Marine (Current-induced)	bedform	*dune*	*parabolic*	*crestline, field*	Relatively stable, U-shaped dunes with lateral lobes anchored and the crest migrating down current (Van Dijk et al., 2021).
High	Ridge	Marine (Current-induced)	bedform	*dune*	*linear*	*crestline, field*	Straight or slightly sinuous dunes, usually ridges typically much longer than they are wide (Van Dijk et al., 2021).
High	Ridge	Marine (Current-induced)	bedform	*sediment ribbon*		*crestline*	
High	Ridge		bedform	*crag-and-tail*		*polygon*	

(*Continued*)

Table 2. Continued.

Morphology classification		Geomorphology classification					
Relative position	Feature (ideal)	Setting/ Process	BGU	BGU-T	BGU-sT	Mapping style	Definition (for BGU-sT)
		Marine (Current-induced)					
Low	Channel	Coastal	channel	*tidal channel*		*polygon*	
Low	Channel	Fluvial	subaerial channel	*(palaeo) river*		*polygon, thalweg*	
Low	Channel	Glacial	tunnel valley			*polygon*	
Low	Channel	Glacial	meltwater channel			*thalweg*	
Low	Depression	Marine (Current-induced)	bedform	*scour*		*polygon*	
Low	Depression	Marine (Current-induced)	bedform	*scour*	*sorted bedform*	*field*	.Linear or crescent-shaped very shallow depressions characterised by coarse-grained sediments which alternated with elongated or lobated patches composed of finer sand (Cacchione et al., 1984; Murray & Thieler, 2004)
Low	Canyon	Marine	submarine tributary canyon			*polygon*	
Low	Groove	Glacial	iceberg ploughmark			*thalweg, field*	
Low	Groove	Marine (Current-induced)	bedform	*furrow*		*crestline*	
Low	Groove	Marine (Current-induced)	bedform	*obstacle and comet scour*		*polygon*	
Low	Hole	Fluid Flow	pockmark	*unit*		*polygon*	
Low	Hole	Fluid Flow	pockmark	*complex*		*polygon*	
Low	Hole	Fluid Flow	pockmark	*string of pockmarks*		*polygon*	
Low	Hole	Glacial	iceberg grounding pit			*polygon*	
Substrates							
bedrock		bedrock-dominated areas where rock is sub-cropping and/or out-cropping at seabed					
consolidated (glacial)		surfacing or sub-surfacing coarse-grained glacial deposits and tills, confirmed by the presence of surfacing glacial landforms (e.g. moraines), backscatter data and literature.					
fine-grained		accumulations of glacial to postglacial fine-grained (sand to mud) sediment					
undifferentiated		undifferentiated, generally coarse-grained sediment					

Notes: The definitions (down to BGU-T) are provided in Nanson et al. (2023). Definitions for BGU-sTs are provided here.
*Megaridges are not included in the MIM-GA classification and are unique features in the Celtic Sea.

3.2. Fluvial, fluvioglacial and coastal setting

When not specified otherwise, mapping fluvial, fluvioglacial and coastal channel features was achieved using Method 1 at a resolution of 10 m/pixel.

3.2.1. Tidal and estuarine channels

This class includes channels that are active in modern times and are predominantly concentrated close to the coastline. Fluvio–tidal channels are observed mainly on the west coast, in small sediment-rich embayments and associated with tidal flats, swatchways, point bars and sandbars.

3.2.2. Palaeo-rivers

Large (kilometres-wide), partially infilled and often bedrock-incised channels, with the axis perpendicular to modern coastline and, in most cases, a correspondence with modern riverine system outfalls have been classified as palaeo river valleys, active during the Pleistocene at low sea levels. The features mapped include the palaeo Bandon, the palaeo Lee, the palaeo Blackwater, the palaeo Womanagh, the palaeo Suir (also in Gallagher, 2002; Tóth et al., 2020) and the palaeo Castletown (Michel et al., 2023) rivers. An additional set of channels perpendicular to the coastline that seem to be aligned, but not necessarily clearly connected, with onshore river systems across the inner shelf was identified by Giglio et al. (2021) and added to this map. While we adopt Giglio et al.'s original tentative interpretation as palaeo-fluvial systems, the nature of these channels is open to debate, as their orientation and palaeoflow direction is not clear, and they seem to be partly associated with western drainage interpreted as glacial meltwater channels (Giglio et al., 2021).

3.2.2.1. Minor bedrock channels. Highly sinuous, dendritic or anastomosing minor channels, partly infilled and on average 200 m wide and a few kilometres long have been mapped in areas of outcropping bedrock on the shallow seabed around Ireland. The channels are mostly found offshore the southern coast, however

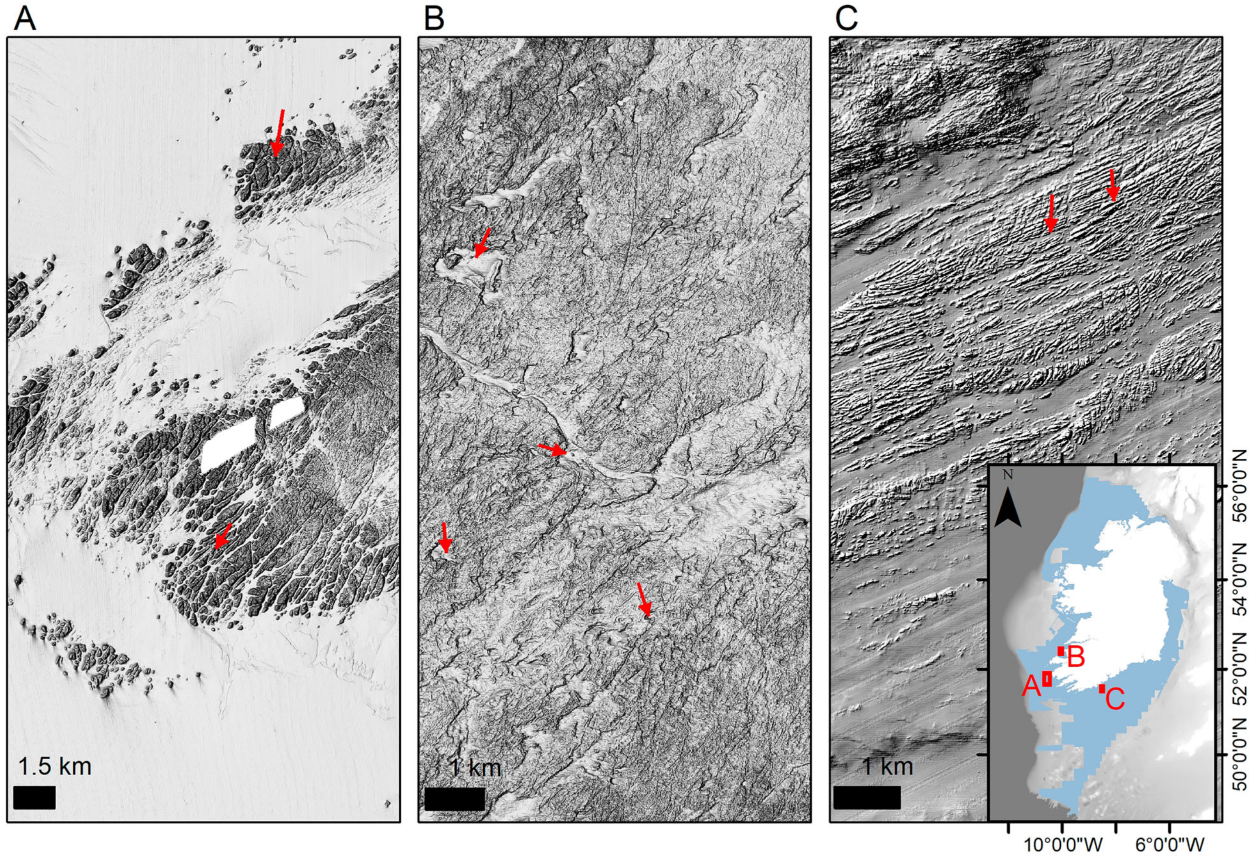

Figure 2. (A) Hillshade (multidirectional, exaggeration ×10) 5 m/pixel bathymetry of bedrock platforms offshore West Cork, showing a hummocky and fractures texture, typical of ORS outcrops. (B) Eroded Waulsortian mudbank platform offshore the Dingle peninsula, where sinuous or circular depressions, potential karstic features (red arrows) are present. (C) Hillshade (light source from the NW (315N), altitude 45 degrees and exaggeration ×10) 5 m/pixel bathymetry of well-bedded Cork Group lithologies.

a few have been identified on the large and flat Carboniferous limestones offshore the Dingle peninsula and on fragmented bedrock a few kilometres from the County Mayo coastline. These bedrock channels show an overall direction perpendicular to the modern coastline, and in some cases they are tributary to larger drainage conduits interpreted as relict extensions at sea level low stand of modern riverine systems (e.g. palaeo river Lee and palaeo river Blackwater). Therefore, they are interpreted as relict minor subaerial drainage features carved into bedrock during past glacial low stands, however re-activation as subglacial meltwater channels during ice occupation is also likely. Mapping of bedrock channels was achieved using Method 4 at a resolution of 10 m/pixel, and 5 m/pixel bathymetry was consulted to improve the quality. The channel thalwegs were automatically extracted.

3.3. Glacial setting

The general extent of exposed or sub-seabed till or glacimarine sediment is provided as a 'substrate' layer (substrate-glacial), and it was created by aggregating areas of high density superficial landforms (e.g. moraines or drumlins), controlled by visual checking and backscatter values. To do this, zones of low backscatter response and smooth sediment patches overlying the glacial morphology were removed. Areas of inferred glacial till or diamict exposure denoted by a rough or hummocky texture were manually added when supported by existing literature (e.g. in the southern Irish Sea, cf. Holmes and Tappin (2005), Robinson et al. (2012), Van Landeghem, Uehara, et al. (2009)).

3.3.1. Moraines (terminal, recessional, lateral) and grounding zone wedges (GZW)

Arcuate banks or ridges on the continental shelf of varying dimensions, orientation and overall shape have been interpreted as moraines or GZWs by previous authors (see below), indicating ice marginal extent and retreat pattern after the Last Glacial Maximum. In this study moraine/GZW mapping was limited to the approximate delineation of their crests using Method 4 at a resolution of 20 m/pixel due to their often fragmentary nature and the abundance of palimpsest modern features hindering a clean automated extraction. Moraines and large shelf-edge GZW dominate the seabed in the northwest, were they either clearly crop out at seabed or are partially or completely buried by modern sediment sheets and ribbons. Previous authors identified different sets of recessional, readvance and lateral moraines in Donegal Bay and on the Malin shelf, subdividing them into three main sets: Donegal, Killala Bay and Scottish /Malin moraines (Benetti et al., 2010; Callard et al., 2018; Craven et al., 2021; Dunlop et al., 2010, 2011; Ó Cofaigh, Benetti, et al., 2016; Ó Cofaigh et al., 2012). Killala and Donegal moraines have also been recently partially ground-truthed using vibrocores (Ó Cofaigh et al., 2019). Our mapping confirms the previous features and adds a few subtler ridges that according to their similar morphology and location are interpreted as potential moraines.

Moraines or GZWs are scarce in the Celtic and Irish Sea (Irish sector), the exception being a series of terminal and recessional ridges described and partly ground-truthed with vibrocores by Giglio et al. (2022) and associated with the retreat of the Irish Sea Ice Stream (ISIS), as well as moraines identified by Michel et al. (2023) offshore Dundalk. In this study an additional set of very subtle, partially buried, broad and curvilinear ridges forming an arc ~102 km long extending from ~18 km south of Cape Clear Island to approximately −8.1807°W. 51.1838°N has been tentatively classified as moraine/GZW, and could represent an older ice margin position.

Moraines are expected also on the central portion of the western Irish shelf edge, however INFOMAR bathymetry is still largely absent in this region. Using European Marine Observation and Data Network (EMODnet) bathymetry Peters et al. (2016) and Roberts et al. (2020) show the existence of very large arcuate ridges in the area, the Galway Lobe Grounding Zone Wedge (GLGZW), the Galway Lobe Readvance Moraine (GLRM), the Galway Lobe Moraine (GLM), the Connemara Lobe Moraine (CLM) and the Mayo Lobe Moraine (MLM). Ground-truthing with vibrocores of GLGZW, CLM and MLM was presented in Ó Cofaigh et al. (2021) and Peters et al. (2016). This study partially maps the GLGZW, GLRM, GLM and MLM, and reveals smaller recessional moraine ridges associated with the larger features (see in particular the Mayo Lobe terminal moraine).

3.3.2. Drumlins (sediment)

Drumlins are the archetypal Irish glacial landform, forming in subglacial conditions and representing general ice flow direction (Menzies, 1979; Stokes et al., 2013), but while they are extremely widespread onshore their occurrence offshore is quite limited. Drumlins have been predominantly mapped within 15 km from the coastline and mostly on the west coast, especially offshore Donegal (Benetti et al., 2010; Dunlop et al., 2011; Ó Cofaigh, Dunlop, et al., 2016), in Clew Bay (Knight, 2016) and Galway Bay (McCullagh et al., 2020). Recently, drumlins were described for the first time offshore the south west of Ireland (Giglio et al., 2022). The mapping of these features was carried out manually and in the case of the Donegal drumlins only the main axis of the landform was drawn. Morphometrically speaking drumlins are multi-convex landforms that have an elliptic and elongated planar shape (Menzies, 2004). These properties were modelled using Method 1 and 2 at a resolution of 10 m/pixel, filtering the results removing features too subdued or not elongated enough to be considered drumlins. The results showed a good correspondence with previous mapping and highlighted several other features (especially in the south west) that, based on their morphology and location, are interpreted here to be drumlins. In the absence of ground-truthing the confidence remains medium to low. Drumlins were mapped for the first time offshore Carlingford Lough (County Louth), in association to the Mayo Lobe moraine, in Broad Water (County Donegal) and east of Rathlin island (UK). In the southwest, Galway Bay, Clew Bay, and in Donegal Bay a significant number of additional drumlins were incorporated to the previous mappings. A total of 1225 drumlins are now included in the offshore Irish list. The features offshore Carlingford Lough – broad, flat-topped asymmetric and elongated platforms, have been classified as drumlins due to their similarities to wave and tidally eroded drumlins observed in Clew Bay (Carter et al., 1989) and Donegal Bay (see Figure 4). The drumlin map proposed by Dunlop et al. (2010) that includes numerous features on the Malin shelf could not be replicated via semi-automated methods as features resembling drumlins could not be extrapolated. This could be due to the high degree of current reworking that have heavily degraded the landforms (Paul Dunlop pers. comm. 2023) or at times to an incorrect original manual mapping caused by hillshade bias. We suggest that several of the drumlins mapped in the paper by Dunlop et al. (2010) are most likely iceberg scour berms. Either way, while a general directional pattern is observable and drumlin-like features are likely present, the features have not been included in this anthology due to their morphological ambiguity.

Craven et al. (2021) mapped a pattern, observed through bathymetric position index (BPI), of broad and low ridges, up to 1 km wide and extending for tens of kilometres south of the Malin Deep, as mega-scale glacial lineation, based on the acoustic characteristics on sub-bottom profiles. We found these features difficult to extract and confirm automatically, especially as they are superimposed by abundant modern current-induced bedforms (i.e. sediment ribbons and furrows) (Dunlop et al., 2010; Evans et al., 2015). Therefore they are acknowledged here but have not been included in the map.

3.3.3. Crag-and-tails and rock drumlins

Drumlins mapped as described in the previous section that corresponded fully or partially to bedrock

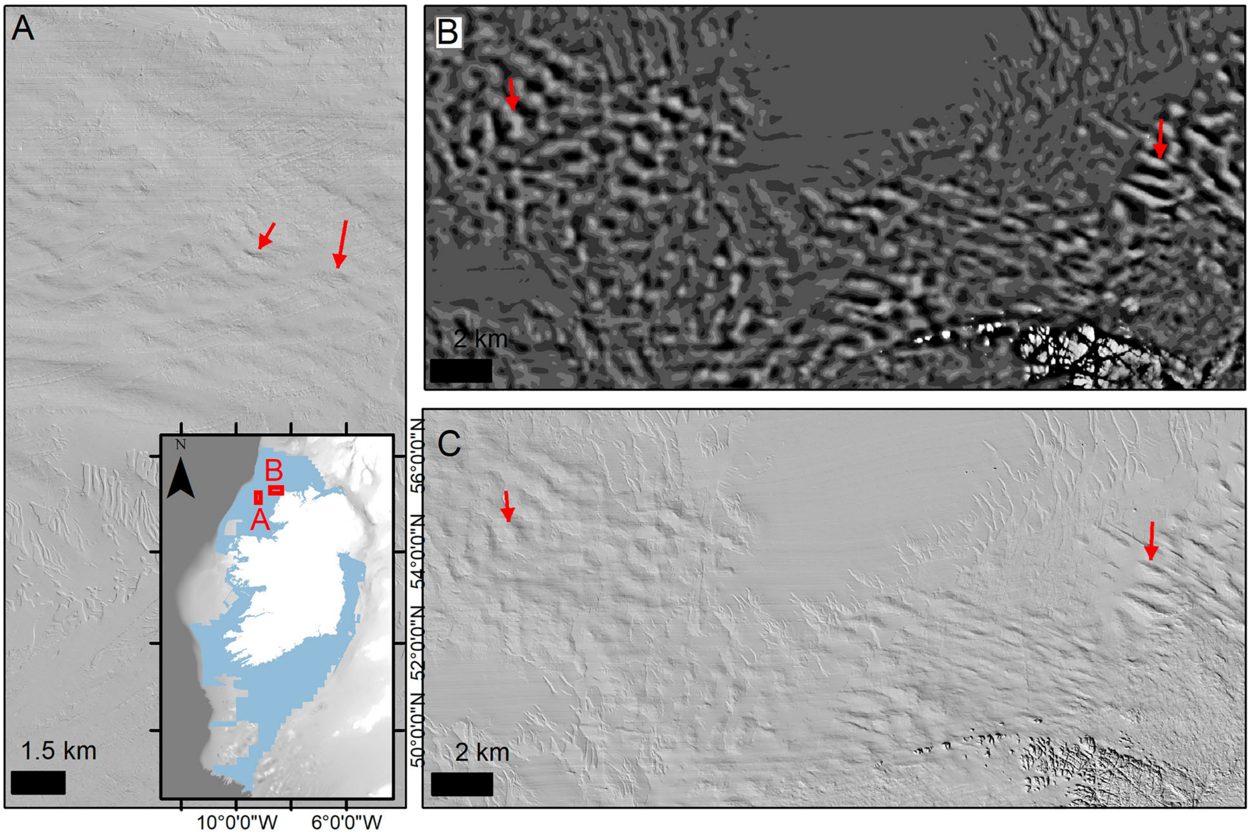

Figure 3. (A) Elongated and subdued ridges in between moraines on the shelf, similar to those found in (B)/(C). (B) and (C) Hummocky ridges, potentially Rogen moraines (on the left) compared to drumlins (right), note the different morphology, more arcuated, broader and anastomosing, especially evident on the median filtered bathymetry (B). Hillshade in (C) is from the SW (225 N), with altitude of 45 degrees and exaggeration ×10.

outcrops (see Section 3.1.1) were further reclassified as either rock drumlins or crag-and-tails.

3.3.4. Minor recessional or Rogen moraines

A series of ridges identified by Benetti et al. (2010) and classified as drumlins, located about 32 km northwest of Bloody Foreland in County Donegal and extending in a radius of about 6 km has been re-interpreted following detailed morphological reassessment with the aid of bathymetry derivatives. The ridges are undulating and possess a sinuous morphology, sometimes with anastomosing to curved crests and intervening troughs (Figure 3). Crests vary from slightly to markedly asymmetrical with some completely rounded. The features are generally 1.5–3.5 km long, ~ 3 m high and ~800 m wide, although their real lengths are masked by the presence of modern sand patches and drift. Based on these observations and the morphological differences with the drumlins (straight, elongated, 1–2 km long, 500 m wide and up to 10 m high ridges) located only a few kilometres to the southeast, we re-interpret the ridges as Rogen moraines (Dunlop & Clark, 2006). Other ridges with similar morphology have been observed on the shelf between the large Donegal moraines and GZWs (Figure 3), and on the Malin shelf, however they are either partially covered by Holocene drift, or are very fragmentary and eroded. These features have been assigned a similar classification, however the confidence is low.

3.3.5. Eskers

Long, narrow, often non-continuous winding ridges with flat tops have been interpreted as eskers: landforms composed of stratified sand and gravel deposited by a subglacial or englacial meltwater stream. Eskers were mapped using Method 1 at a resolution of 10 m/pixel. On the Irish continental shelf eskers are not common, with a total of only eight major units identified between offshore Waterford Harbour, in the northern Celtic Sea, and in the Wicklow Trough, Irish Sea (Coughlan, Tóth, et al., 2020). Offshore Waterford Harbour the four easternmost eskers were originally discovered by Gallagher et al. (2004), who subdivided them into two 'Outer arcs' and two 'Inner arcs', the latter placed in between the two Outer arcs (Figure 4). Gallagher et al. (2004) interpreted them as moraine deposits, but the Outer arcs have since been re-interpreted as eskers (O'Toole et al., 2020; Tóth et al., 2020). In our map, we tentatively classify all arcs as eskers and include additional ridge fragments in the neighbourhood that might be assigned the same origin. In the absence of groundtruthing, the assignment is made with low confidence.

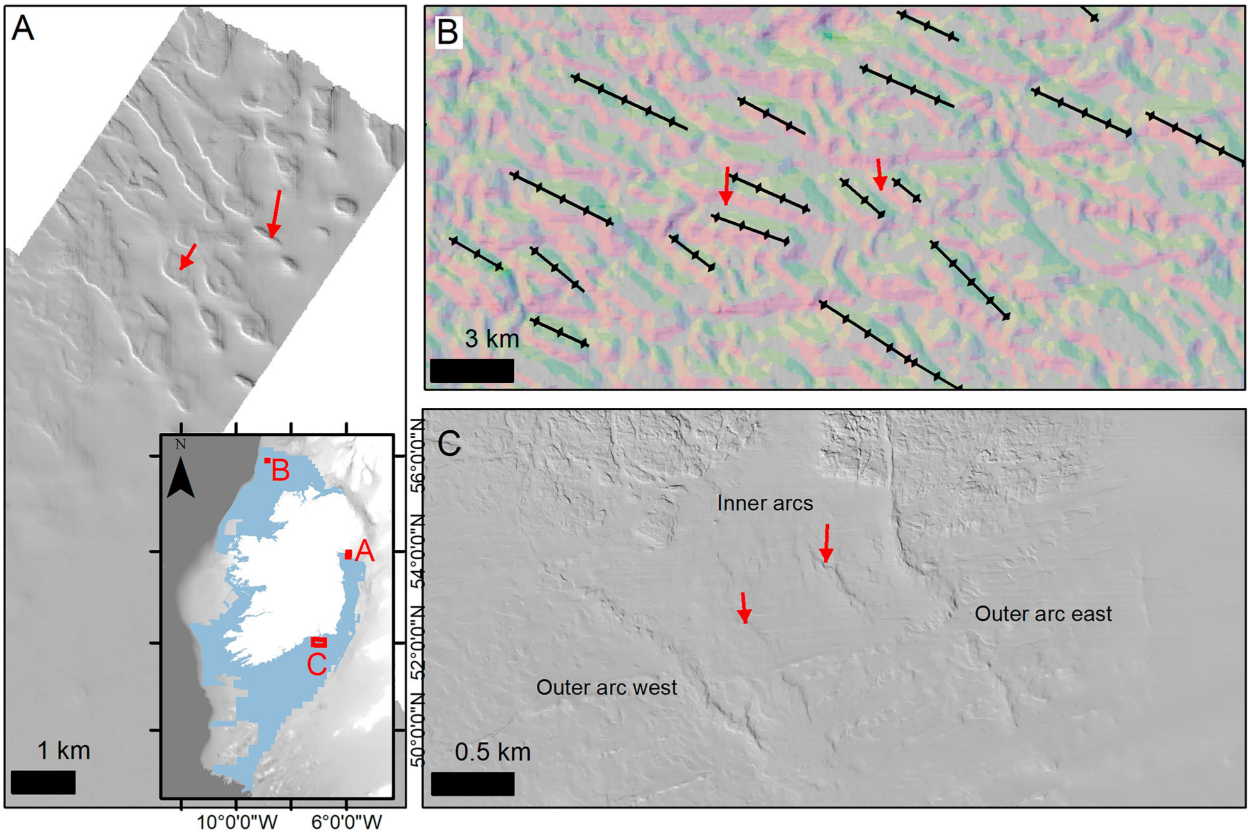

Figure 4. (A) Fragmented topography offshore Carlingford Lough that might represent tidally eroded drumlins. (B) Normal vector and hill shaded (multidirectional, exaggeration ×10) bathymetry of the outer Malin shelf. The seabed is heavily modified by iceberg ploughmarks (red arrows), while the black lines show the mapping of drumlin crestlines by Dunlop et al. (2010). Some of the lines are more likely to be the berms of the scours, while other cannot be fully reconciled with the topography. (C) Eskers offshore Waterford Harbour as classified originally by Gallagher et al. (2004).

The longest eskers offshore Waterford Harbour remain the most morphologically unambiguous, with two of them clearly linked to bedrock palaeo-channels. Other ridges occurring in the Celtic Sea to the south east and interpreted by Giglio et al. (2021) as eskers were re-assessed. These ridges are several km-long, generally regular and straight but fragmented in shorter segments; they are approximately 2 m high and can be a few 100 m wide. They are oriented NE-SW, are somewhat regularly spaced and generally present a marked asymmetry, with steeper slopes to the SE. Given their morphology and the very thin sediment cover in the area, we believe it more likely for them to be bedrock ridges.

3.3.6. Iceberg ploughmarks

A web of criss-crossing furrows and grooves on the sea floor is a common sight on palaeo-glaciated continental margins, and it represents the action of moving iceberg keels on seabed sediment (Belderson et al., 1973). Thousands of iceberg ploughmarks have been mapped on the Porcupine and Rockall Bank (Sacchetti et al., 2012; Thébaudeau et al., 2016) using manual methods, while for the Irish continental shelf edge Benetti et al. (2010) and Dunlop et al. (2010) provide respectively maps of areal distribution and single landform manual mapping (the latter limited to the Malin Sea). Limited areas of iceberg scouring have been identified closer to the coast, just off Bantry Bay by Plets et al. (2015) and in the western Irish Sea by Michel et al. (2023). In this study we mapped the ploughmarks using Method 3 at 10 m/pixel resolution, cleaning manually and extracting the centreline of the features using a skeletonisation algorithm (arcpy Thin). Thousands of features have been identified using this process, although the confidence for a great part is low due to the extensive weathering, reworking by bottom currents and superimposition of modern current-induced bedforms. Particularly ambiguous are the features identified in the central part of the north western shelf edge, which had not been mapped as such previously and were considered as simple 'furrows' by Benetti et al. (2010). A fuller discussion on those features is provided in Section 3.4.3. A polygon representing the extent of the scoured region was also created to provide a simplified layer.

3.3.6.1. Iceberg scour pits. Potential iceberg scour pits were separated from the ploughmarks layer on the basis of their circularity and dimension. Any ploughmark automatically extracted with circularity index (Polsby-Popper score) > 0.7 was assigned to this class. To our knowledge, scour pits have not been previously mapped on the Irish continental shelf.

3.3.7. Tunnel valleys and meltwater channels

In the Irish and Celtic Seas, several large, exposed and over deepened channels carved both in bedrock and glacigenic till have been interpreted as tunnel valleys (Coughlan, Tóth, et al., 2020; Eyles & Mccabe, 1989; Giglio et al., 2021; Wingfield, 1989). The morphology of the channels is strongly supportive of the interpretation: longitudinal profiles show an irregular base containing a series of troughs and sills at varying depths, in many occasions the channels start and terminate abruptly or have tributaries that are left hanging above them (as hanging valleys). This type of morphology suggests that the channels were carved by water driven under pressurised flow rather than by a gravity gradient (Kirkham et al., 2022; van der Vegt et al., 2012). The formation of the tunnel valleys appears to be also linked to underlying lithology and existing structural control, which may have influenced meltwater accumulation and erosion at the ice-bed interface (Coughlan, Tóth, et al., 2020; Giglio et al., 2021). In this study, we tentatively identify a number of additional and almost completely buried tunnel valleys in the Celtic Sea, in the region between the main exposed valleys and the coast-proximal palaeoriverine channels. Identification of the buried valleys was achieved using relief enhancement separation (Method 1), which showed the faint trace of the meandering channels. In some cases the modern sand patches migrating in that region appear to be deviated or 'broken up' by the presence of the underlying features, assisting in their detection. Other completely buried tunnel valleys have been described by Giglio et al. (2021) and Wingfield (1989), but they are not included in this map as they do not possess any surface expression.

A set of mesoscale channels, with morphologies very similar to the tunnel valleys and running parallel to the coastline ~20 km offshore from Cork Harbour to Grancore North were interpreted as glacial meltwater channels, instead of tunnel valleys by Giglio et al. (2021), due to their smaller dimensions.

3.4. Marine and current-induced setting

3.4.1. Dunes (parabolic, trochoidal, transverse, linear)

Dunes (also referred to as 'sediment waves') are arguably the most ubiquitous of marine bedforms on continental shelves, and form as a result of turbulent shear generated by the interaction of marine currents with the shallow mobile layer of marine sediment. On the Irish shelf, dunes are found predominantly in the Irish and Celtic Seas, where they often occur as large dune fields (Guinan et al., 2021), however more confined fields are present also on the Malin shelf (Evans et al., 2015; O'Toole et al., 2020). Irish Sea modern dune migration has been extensively studied, especially for the purpose of reconstructing the hydrodynamics of the region and the shaping of dune morphology in response to tidal action (Creane et al., 2022; Van Landeghem, Wheeler, et al., 2009; Van Landeghem et al., 2012).

In this study we have applied Method 1 to extract dune crests at a 10 m/pixel resolution; the crests were then aggregated to create dune fields polygons. The automated extraction of all dune crests is hindered by the complexity of dune fields (especially in the Irish Sea) and the presence of palimpsest features, as sediment furrows or older dune patterns. Only prominent dune crests (assumed for this reason to be either active or moribund, i.e. modern or palimpsest) were actively mapped. Large fields of asymmetric and trochoidal dunes extend across the western Irish Sea to the northern Celtic Sea, with wavelengths on the order of 100–600 m. Fields of more subdued and fragmentary ridges are found in the central southern Irish Sea, and are interpreted as palimpsest, moribund to completely relict features. The trochoidal dunes of the Irish Sea are associated with elongated or rounded bathymetric depressions, considered of glacial origin. Van Landeghem, Uehara, et al. (2009) conclude that the dunes have likely been constructed between 7 and 10 ka BP, due to stronger and nearly symmetrical tides, changes over time in the direction of the dominant current-induced bed stress and readily available sediment in the depressions.

The northern/central parts of the Celtic Sea are devoid of major dune fields, exhibiting a roughly flat sediment-starved seafloor, with portions of semi-exposed bedrock or coarse to mixed sediments transiently covered by highly mobile broad sand patches less than a metre thick, often breaking up into isolated crescentic and flat-topped sorted bedforms (these are also found over the megaridges, see Section 3.4.7.1). The central and southern parts instead are characterised by lower frequency dunes (wavelength over 1 km), often associated with the megaridges, into which they seem to partly merge. They form continuous fields with other sets of shorter wavelength, low, symmetrical and rounded dunes found in between the megaridges. Overall, the subdued morphology of the dune field and the fact that they are covered by the active scoured sandy sediment layer (the same found in the northern part) suggests a moribund or relict state. Close to the shelf edge the dunes reacquire a prominent morphology, with higher frequencies and sharp asymmetrical crests indicating a north-eastward migration direction.

3.4.2. Sediment ribbons

Large sediment ribbons have been mapped across the shelf, and they acquire significant dimensions when

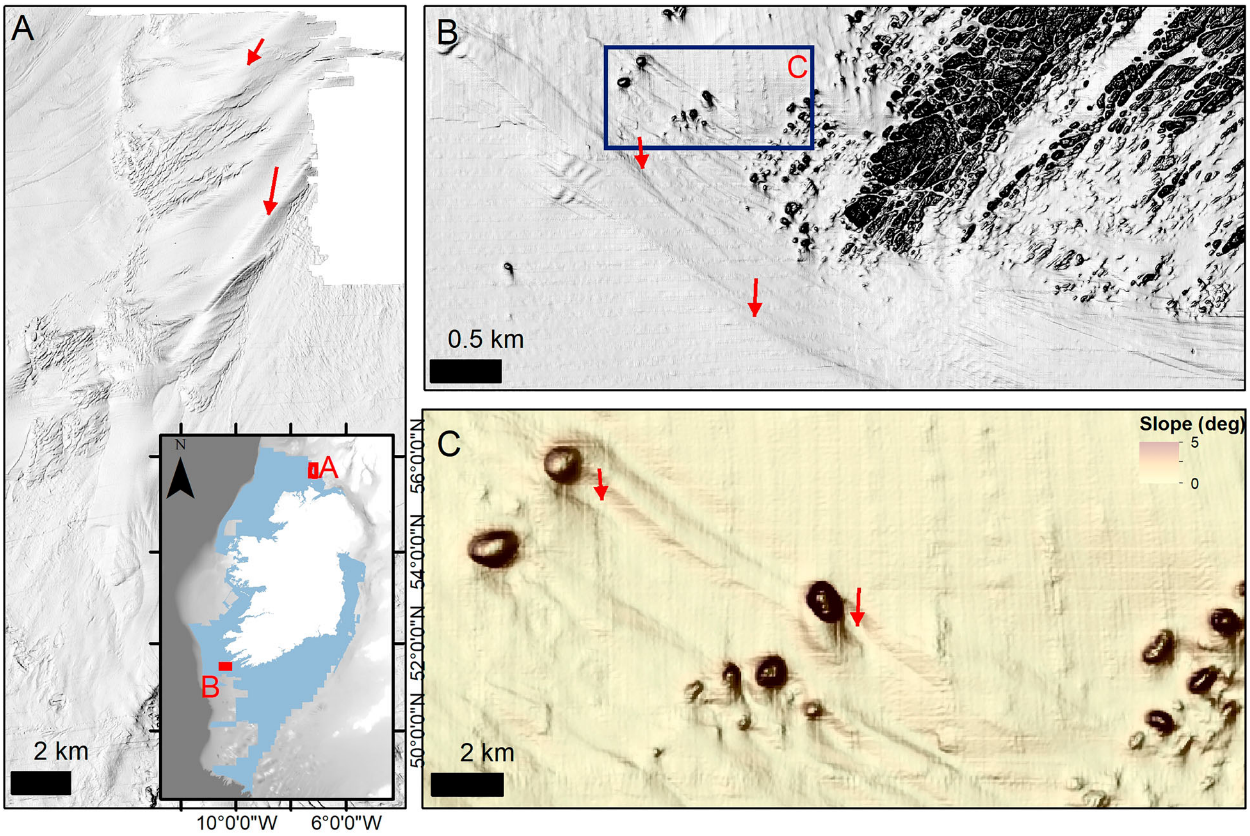

Figure 5. (A) Very large ribbons on the Malin shelf (previously mapped by Dunlop et al. (2010)). (B) Relict ribbons offshore Bantry Bay mentioned in Plets et al. (2015). (C) Zoom in showing the obstacle and comet scours associated with ribbons and indicating a prevalent south-eastward current direction.

mobile sediment is readily available (Malin Sea, Figure 5, northern and southern Celtic Sea).

The third interpretation provided by Plets et al. (2015) for the curvilinear ridges identified offshore Bantry Bay (Figure 5) – relict tidal bedforms (ribbons), is adopted in this map, due to the clear smooth and curved morphology of the ridges, the presence of several similar but smaller curvilinear ridges tapering to the southeast and the evident associated obstacle and comet scouring. In contrast to what is suggested by Plets et al. (2015), the current residual must have been towards the southeast, and not northwest, as indicated by the scouring (Figure 5). The ribbons were mapped at a 20 m/pixel resolution using Methods 1 and 4.

3.4.3. Furrows

Sediment furrows, typically only a few tens of centimetres deep (up to 1 m at times) and 50–100 m wide, are pervasive across the Malin shelf, the west and in the northern Celtic Sea. These low-relief features occur quasi-parallel to each other in large swarms and alter the underlying pre-Holocene landforms. On the north-western shelf the furrows were mapped by Evans et al. (2015) (classified as 'lineations' in the paper). Evans and co-authors interpreted the features as primarily erosive (hence the change of terminology in this study, from 'lineations' to 'furrows') due to the wide range of granulometries (from fine sand to gravel), suggesting reworking and winnowing of any superficial sediment by unidirectional flow sub-parallel paths. Benetti et al. (2010) identified a distinctive type of furrowing close to the shelf edge in the northwest (Figure 6). These features form a sequence of straight, elongated, sub-parallel depressions extending across a broad arc on the top and to the lee side of the shelf-edge GZW. Benetti and co-authors find these features to water depths of 270 m and possibly more, however our morphometric study detected furrows only between 110 and 200 mbsl, and indicate that they stop rather abruptly. Another set of scour-like features beyond and within the same area of the furrows, have slightly distinct connotations, being more sinuous, narrow and showing in places criss-crossing pattern or even berms on the side. We interpret this second set as palimpsest, altered iceberg ploughmarks, similar to those observed elsewhere on the shelf edge. Due to their palimpsest nature – caused most likely by the furrows, as we will explain shortly, they can be mixed up with the furrows themselves, with azimuthal bias leading to confusion.

The furrows are mostly oriented east to west, at an angle of 10–30° to the contour lines, they can be up to 3.4 km long (mean 1.1 km) and measure 1–4 m in

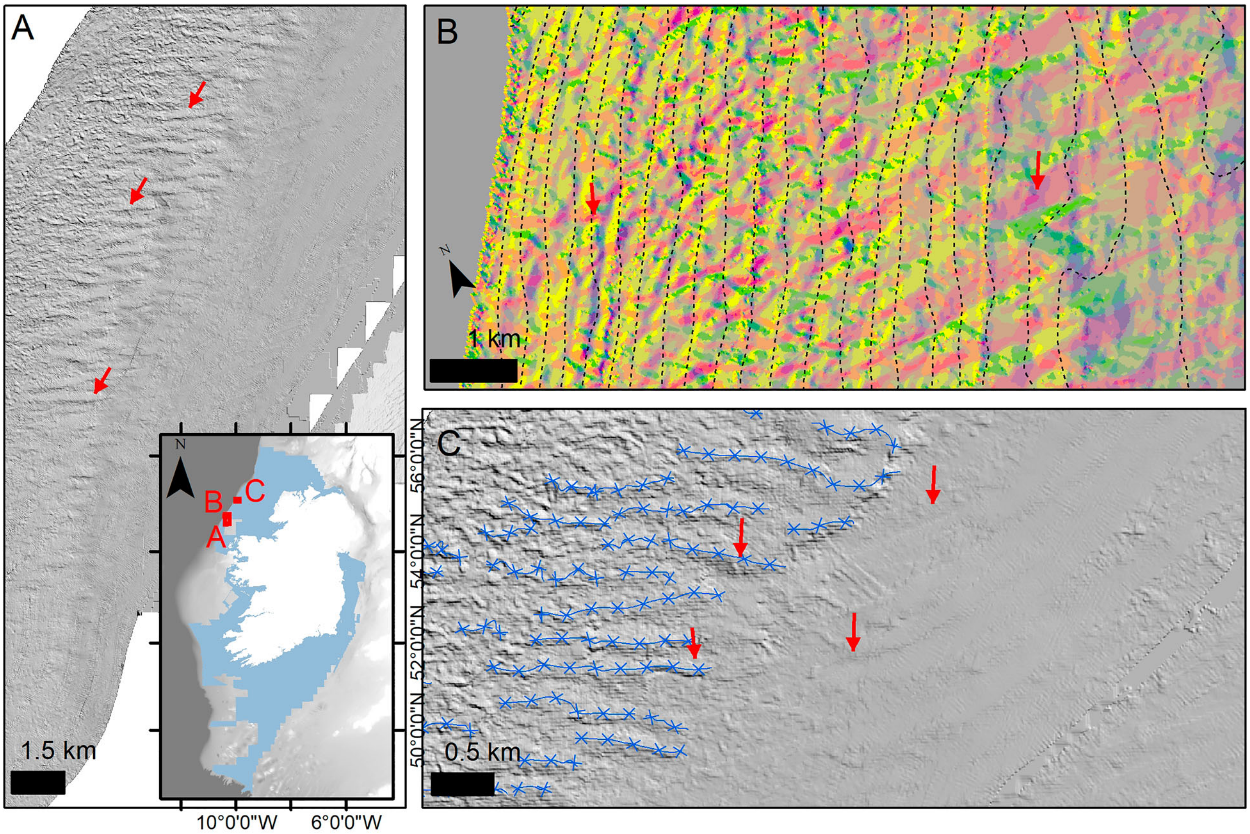

Figure 6. (A) Elongated furrowing described by Benetti et al. (2010) over the large GZW at the western shelf edge (red arrows indicating a few). (B) Normal vector map of a subset of the furrows compared to contour lines (every 4 m), note the difference in morphology between the broad linear furrows proper (right) and the narrow sinuous grooves at deeper levels (right), interpreted to be altered iceberg ploughmarks. (C) Extracted thalwegs of the furrows (blue lines) show correspondence with the direction of the pervasive furrowing on the shelf (red arrows), suggesting a continuation in erosion by shelf currents.

depth and 150–320 m in width. Their abrupt ending and transverse orientation to slope direction does not support a gravity-driven erosional process (e.g. turbiditic or mass wasting), hence a normal shelf-edge gully formation process (Gales et al., 2013). The furrows appear to be aligned (albeit connections are faint and disturbed by artefacts of the MBES data) with overall furrowing orientations mapped on the shelf. Therefore an interpretation as erosional features created by shelf edge spill over of modern shelf currents (also proposed by Benetti et al., 2010) is adopted in this map.

3.4.4. Sediment banks

A number of sediment banks are present on the Irish continental shelf (predominantly in the Irish Sea), and were previously studied by several authors including as potential aggregate targets or sites for wind turbines (Coughlan, Long, et al., 2020; Creane et al., 2023, 2022; Panigrahi et al., 2009; Van Landeghem, Uehara, et al., 2009; Wheeler et al., 2001, 2000). The Irish Sea sandbanks are distributed as a coast-parallel and north–south trending quasi-linear 'sequence', at a distance of approximately 10 km offshore. The sandbanks include from north to south: Dundalk Bank; Bray Bank; Kish Bank; Burford Bank; Fraser Bank; Codling Bank; Seven Fathom Bank; Arklow Bank; Glassgorman Bank; Rusk Bank; Moneyweights, Blackwater Bank, Lucifer Shoals & New Ground, and Long Bank & Holden's Bay (Creane et al., 2022; Roche et al., 2007; Wheeler et al., 2001, 2000). They stand in 20–30 m of water and rise to within a few metres of the water surface, offering wave protection to the coast and having a strong control on tidal flow pathways. The banks are quasi-stable features in dynamic equilibrium with tidal and wave conditions and are an integral part of the coastal system, but still with significant daily average changes of the superficial mobile sediment (Panigrahi et al., 2009; Wheeler et al., 2001, 2000). A study by Hanna and Cooper (2002) on historic morphological changes based on bathymetric charts (1844–1979) of the Wexford sandbanks indicated progressive northward extension and steepening of the landward margin of the sandbanks over the 135 year period. Boomer seismic data by Wheeler et al. (2001, 2000) over the Kish Bank revealed the feature is composed of a single seismic facies: an upper layer of sand (Unit A) with weak internal reflectors overlying a thin unit (Unit B) with a strong acoustic character that is present at a comparable altitude throughout the survey area. Bank formation was inferred to have occurred after the deposition of

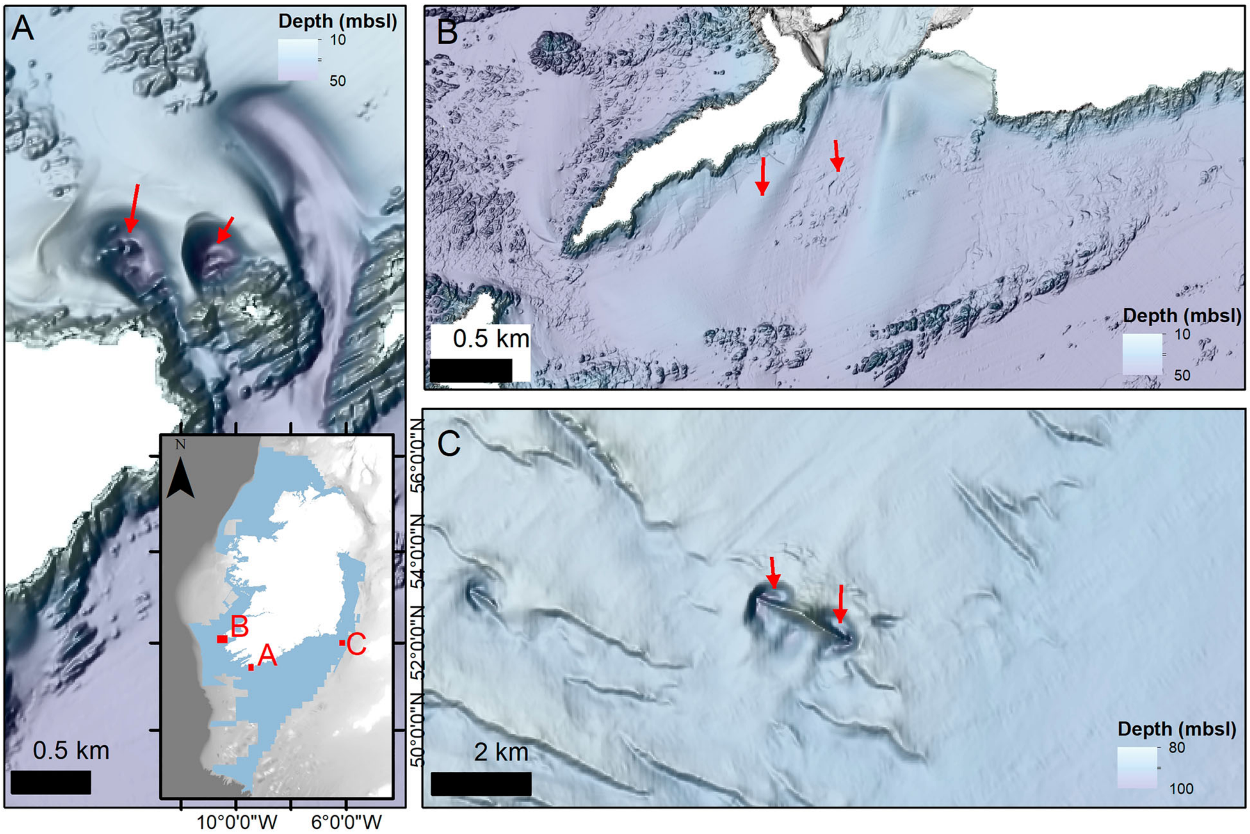

Figure 7. Bathymetry data (10 m/pixel) superimposed on hillshades (A) deep scouring and northward net sediment transport between Sherkin Island and Cape Clear Island. (B) Scouring and associated lateral sediment banks formed southwards of the strait between the mainland and Great Blasket Island. (C) Scouring on the sides of a trochoidal dune. All hillshades are multidirectional with exaggeration ×10.

Unit B with banks composed of poorly stratified sand/gravel.

Sandbanks were mapped using Method 1 at a resolution of 20 m/pixel.

3.4.5. Crag-and-tails (marine bedforms)

Not to be confused with glacial crag-and-tails (Section 3.3.3), these are elongate and smooth mounds or ridges (tail or shadow) deposited immediately downstream of an obstacle in the path of flow are common current-induced marine bedforms observed on the Irish continental shelf. Stow et al. (2009) suggest that they begin to appear on muddy and sandy substrates in association with surface lineation at 0.1–0.3 m s^{-1}, while they become more prominent and widespread, and occur in association with comet scour and erosional pluck marks, at slightly higher velocities (<0.4 m s^{-1}). Large crag-and-tails have been mapped in the northern Irish Sea, around Lambay and St. Patrick's Island, or Rockabill, that act as obstacle to current flow. Crag-and-tails were mapped using Method 1 at a resolution of 20 m/pixel.

3.4.6. Megaridges

The Celtic Sea is dominated by a system of huge shelf-crossing ridges, which are the largest landforms on the Irish continental shelf. In the Irish sector, these ridges are up to 200 km long, 15 km wide and ~60 m high. Two interpretations for their formation have been proposed in the past: the ridges were regarded as tidal features, now moribund, formed during lower sea level (Belderson et al., 1986; Stride, 1982). Another interpretation sees the ridges formed by glaciofluvial processes (Praeg et al., 2015, 2019). Lockhart et al. (2018) proposed a third alternative, where the megaridges include post-glacial tidal deposits covering a partially eroded pre-existing glacial topography. The Celtic Sea megaridges were mapped using Method 1 at a 20 m/pixel resolution.

3.4.7. Scours and obstacle and comet scours

Scouring by marine currents is observed throughout the bathymetry data close to the coastline and more diffusely in the Irish Sea. Deep scours form when tidal flow is amplified through funnelling of tidal energy, for example between islands (Figure 7). In some cases, directional net sediment transport produces sediment tailings or accumulations (somewhat like ebb or flow deltas) at the end of the scour (Figure 7A). Scours are also formed in the presence of flow obstacles (e.g. rocky crags or shipwrecks) leaving obstacle and comet scours. Numerous unidirectional comet scours were mapped offshore Bantry

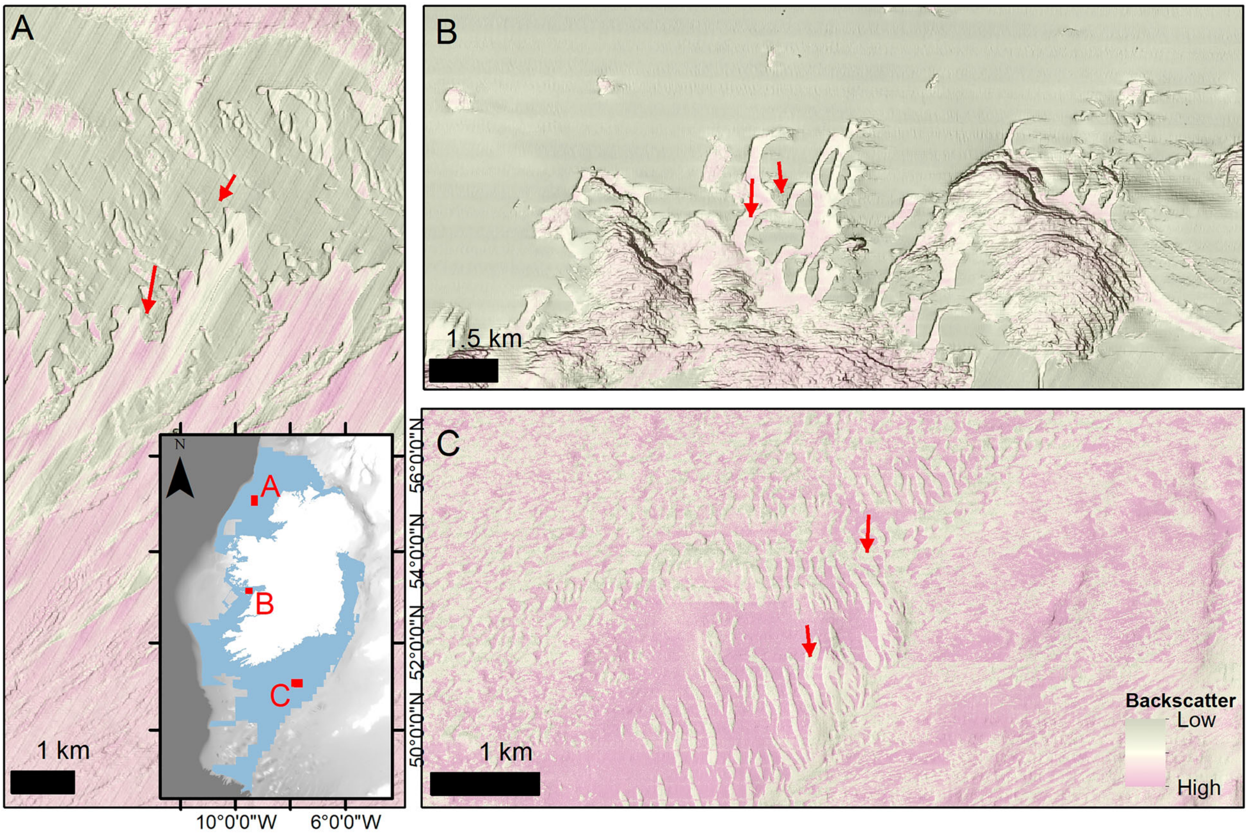

Figure 8. Examples of sorted bedform, with backscatter values superimposed on hillshades (multidirectional, exaggeration ×10) (A) Sorted bedforms on the Malin shelf. (B) Sorted bedforms in Galway Bay, close to bedrock outcrop (described by McCullagh et al. (2020) as 'scours'). (C) Pervasive pattern of sorted bedforms in the Celtic Sea.

Bay in association with sediment ribbons (see section 3.4.2 and Figure 5). Finally, significant deeps are observed at the extremities of trochoidal dunes (Figure 7C), where scour mechanisms are intensified by the strengthened vortices around the edges of the bedforms (Van Landeghem, Uehara, et al., 2009). Scours were mapped using Method 1 at a resolution of 20 m/pixel.

3.4.7.1. Sorted bedforms. Smaller scale and shallow scour depressions in correspondence and at the edges of modern soft sediment sheets occur across much of the shallow shelf region in a variety of shapes, sizes, and configurations: in some occasions they are elongated and narrow, while in others they are broad and rounded. In places, separate scour depressions have merged with adjacent depressions, forming larger eroded areas that often contain crescentic or lobated flat-topped erosional patches of the uppermost sandy sea-floor sediments. In the Celtic Sea, the lobated patches almost ubiquitously cover the central part of the region (Figure 8). Mappers of the Irish shelf have previously observed these features in Galway Bay in proximity to bedrock outcrops and on the Malin shelf bisecting sand ribbons, and interpreted them as erosional features, suggesting they may be formed by local-non-uniform flow over and around the topographic obstacle (cf. 'scours', McCullagh et al., 2020) or downslope erosional processes that remove finer sediments (cf. 'furrows', Evans et al., 2015). On the basis of their morphology and sediment zonation we interpret these features as sorted bedforms (Cacchione et al., 1984; Murray & Thieler, 2004). Sorted bedforms are recurrent in sediment-starved coastal and inner shelf settings where they are indicators for hydrodynamic conditions (Diesing et al., 2006; Liu et al., 2018; McMullen et al., 2015).

Several mechanisms may concur in the formation of sorted bedforms. Murray and Thieler (2004) suggested that these depressions are formed and maintained under high-energy shelf conditions by the interaction between repetitive cyclic loading imposed by high-amplitude, long-period waves and roughness elements on coarse sediment. Near-bed turbulence causes resuspensions and exposes the suspended sediments to erosion by currents. Consequently, accumulations of fine material separated by patches of coarse sediments tend to be constituted. For example, offshore Donegal Bay depression floors correspond to exposed relict Pleistocene moraine deposits and indicate that the muddy Holocene sands have been completely removed. When perpendicular to the shoreline (Figure 8(B)) the scours ('cross-shore swaths' *sensu* (Oakley et al., 2009)) may be formed from the down welling of seaward flowing water during storms. Other factors affecting the formation and migration of these landforms include longshore currents, combined current and orbital forces, subsurface stratigraphy and sediment supply (Liu et al., 2018). Areas with pervasive sorted bedforms have been mapped as fields (areas) manually. Sorted bedforms are also clearly visible on the substrate map provided by the INFOMAR programme (https://www.infomar.ie)

3.5. Fluid flow process

3.5.1. Pockmarks

Circular to elongated crater like features identified particularly in soft, fine-grained seafloor substrates and interpreted as pockmarks are direct indicators of fluid seepage at the seafloor (Hovland & Judd, 1988). They are found isolated, occurring in groups referred to as 'pockmark fields' or as large chains of craters known as 'pockmark trains'. Pockmarks were mapped using Method 2 at a resolution of 10 m/pixel but 5 m/pixel bathymetry was also consulted to improve precision in pockmark-rich areas. In three locations – Dunmanus Bay, Bantry Bay and at the River Boyne estuary, where pockmarks have been identified by other authors (Jordan et al., 2019; O'Reilly et al., 2021; Szpak et al., 2015) but occur in swarms of very small features (less than 25 m in diameter) the field was mapped instead of the single units. The largest field of pockmarks on the Irish continental shelf is the Malin Deep Pockmark Field, which occurs approximately 70 km offshore northwest Ireland and has been extensively mapped and studied by previous authors (Dunlop et al., 2010; Evans et al., 2015; Gafeira et al., 2018; Garcia et al., 2014; Monteys et al., 2008; Szpak et al., 2012) (Figure 9(A)). The area lies in a complex structural setting, delimited to the North by the Stanton Banks Fault and to the south by the Malin Terrace. Pockmarks are distributed in groups predominantly in the vicinity of main structural lineaments (Szpak et al., 2012). A total of 517 Malin pockmarks were mapped in this study, against the more conservative 212 mentioned by Szpak et al. (2012) or the 154 identified manually by Evans et al. (2015). A great number of pockmarks is also present in the Western Irish Sea Mud Belt (WISMB), related to shallow gas accumulation (Coughlan et al., 2019; Croker et al., 2005; Yuan et al., 1992). Some of the pockmarks in the area present mounds in their central part, which may represent MDAC crusts (Coughlan et al., 2021) (Figure 9(C)). A field of numerous newly identified rounded but shallow and flat depressions have been mapped south of the Aran Isles, and have been tentatively interpreted as pockmarks. Using a 5 m resolution grid, we have identified 530 features, however many more tiny pockmarks are observable at finer resolutions (Figure 9(B)). The larger features can reach more than 200 m in diameter and present sometimes

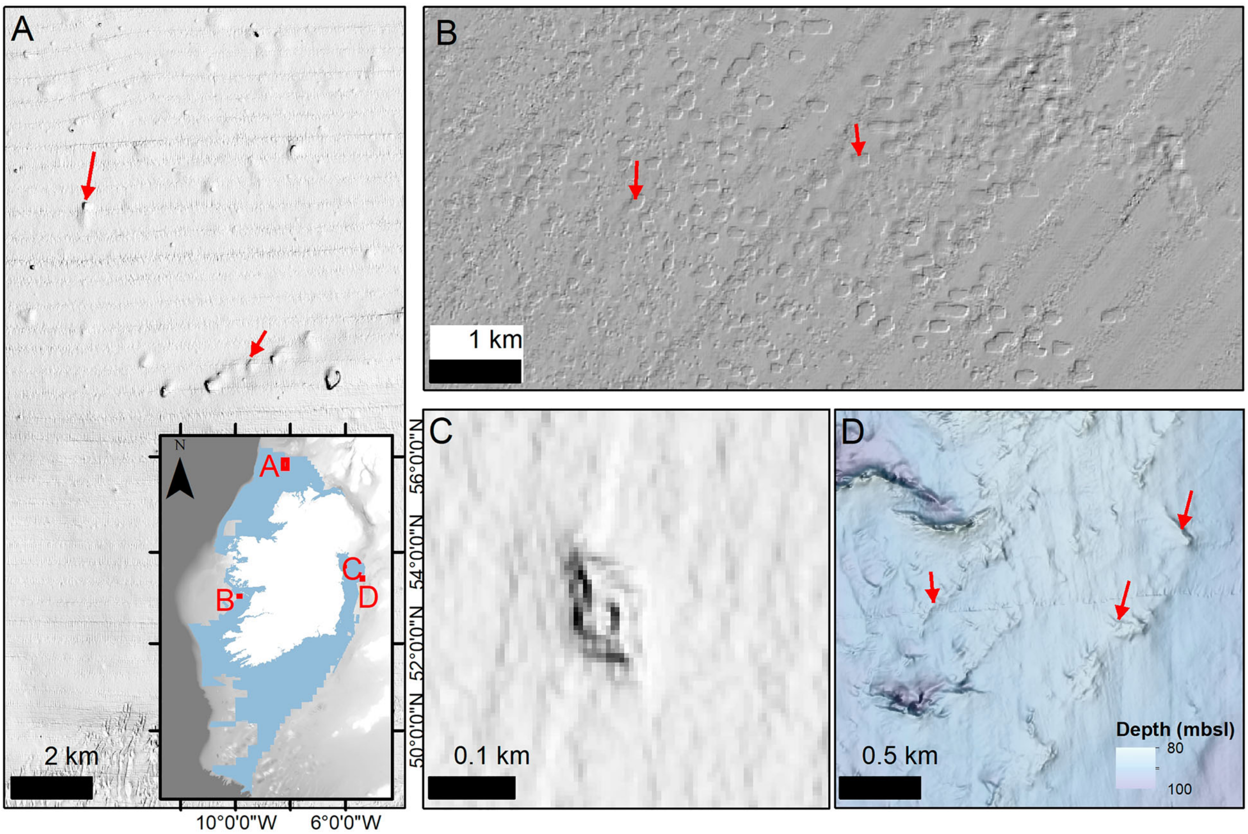

Figure 9. (A) Pockmarks and pockmark trains in the Malin Deep. (B) Newly identified shallow pockmarks south of the Aran Isles. (C) Pockmark presenting an internal mound, potentially a MDAC. (D) Sub-parallel mounds and ridges that may be authigenic carbonate in origin.

oblong or ellipsoidal shapes. They are also all very shallow (ca. 50–100 cm depth) and have an unusual flat and regular floor. Smaller pockmarks are instead generally rounded and, albeit still not deep, have a V-shaped profile. The larger features seem to be formed by the coalescence of the smaller pockmarks (e.g. Michel et al., 2017), and indeed stages of merging are observable in tightly packed groups.

3.5.2. Outcropping methane-derived authigenic carbonate (MDAC)

Within the Codling Fault Zone in the Irish Sea a series of mounds and short ridges forming distinctive bathymetric highs within a dynamic and extensive dune field is interpreted as methane authigenic carbonate outcrops (Croker et al., 2005; Judd et al., 2007). Approximately 15 carbonate features were previously identified by O'Reilly et al. (2014) and Van Landeghem et al. (2015), while Coughlan et al. (2021) identified a further two mounds which exhibit a roughly circular shape with a diameter of 60 m which may be MDACs. In this study, we designate ~14 additional features (reaching a number of ca. 30 as in Croker et al. (2005)), that based on their morphological similarity and proximity with the carbonate mounds identified previously, probably share the same formation mechanism. Other ridge-like and mound-like features to the Northeast of the Codling Fault Zone share similar morphologies to the MDACs (Figure 9(D)), however in the absence of groundtruthing we prefer a general interpretation as bedrock outcrops.

4. Discussion

The ISSGM (v2023) illustrates the variety of landforms and processes active on the Irish continental shelf, including new and all previously mapped units. Together with the contents of this paper, the map stands as a critical review and harmonised collation of existing geomorphological literature on the Irish continental shelf. This study has also revealed places of potential geological interest where ground-truthing is lacking or completely absent, and identified landforms whose interpretation remains ambiguous, indicating avenues for potential future work. In this last sections of the paper, we will draw some final considerations and outline potential future lines of investigation, subdividing the mapped shelf into four separate regions (cf. Figure 1), which, albeit sharing a common shallow marine nature, show distinctive traits and geomorphological characteristics.

4.1. The Irish Sea

The geomorphology of the western Irish Sea seabed is the most complex, compared to that of the other three regions. The northern section is occupied by the West Irish Sea Mud Belt approximately from offshore Dundalk Bay to Lambay island, where the seabed is generally smooth and featureless excluding pockmarks, some tidal-induced scouring and linear basins (e.g. Peel Basin) possibly formed by a combination of tectonic and gas-seepage processes (Croker et al., 2005). At least half the area of the central and southern section of the region is covered by large units and fields of dunes, mainly transverse and trochoidal. The unusually high trochoidal dunes are the features that have received most attention in past studies. They are symmetrical and made up by coarse, poorly sorted sediments, which differentiate them from normal transverse dunes. They are also associated with linear or channel-like depressions (scours), from which they obtain abundant scoured mobile sediment (dislodged from the depression infill) that permits their subsistence (Van Landeghem et al., 2013). Further distinctive semi-circular scouring created around the edges of the dunes is considered to provide additional mobile fraction from the coarse lag deposits. In places however, semi-circular scouring occurs without an associated trochoidal dune (Figure 10). This is evident in deeper parts towards the centre of St. George's Channel (80–100 mbsl), where groups of subdued and irregularly alternating ridges and scours have been interpreted as extinct dune fields. Other semi-circular scouring recur elsewhere, sometimes in association with linear depressions and not far from coupled dune-scour sets (Figure 10). The existence of these features complicates the interpretation of the scouring. Were the lone scours created in the presence of a trochoidal dune now completely eroded away, or were they produced independently by other mechanisms?

In the remaining parts the modern day sandy and muddy sediment cover becomes thinner and scarcer, and the seabed is pervaded by irregular and rough topography which is probably linked to relict Late glacial processes and the Midlandian (Weichselian) glaciation. This topography proved the hardest to be interpreted, and might include modern and paleoscours on channelled glacial till of the Cardigan Bay formation (BGS, 1990), bedrock outcrops and authigenic carbonate mounds. A reliable identification of the latter is especially hard, as reliable identification is only possible in combination with video groundtruthing or seabed sampling.

4.2. The Celtic Sea

The almost planar and gently sloping bathymetry of the Celtic Sea is characterised by a sediment-starved, lightly bulging central section, corresponding roughly to the North Celtic Sea Basin (NCSB) (Rodríguez-Salgado et al., 2020). The basin seems to control Holocene sands and muds distribution, as sediment cover becomes progressively thicker away from the inverted

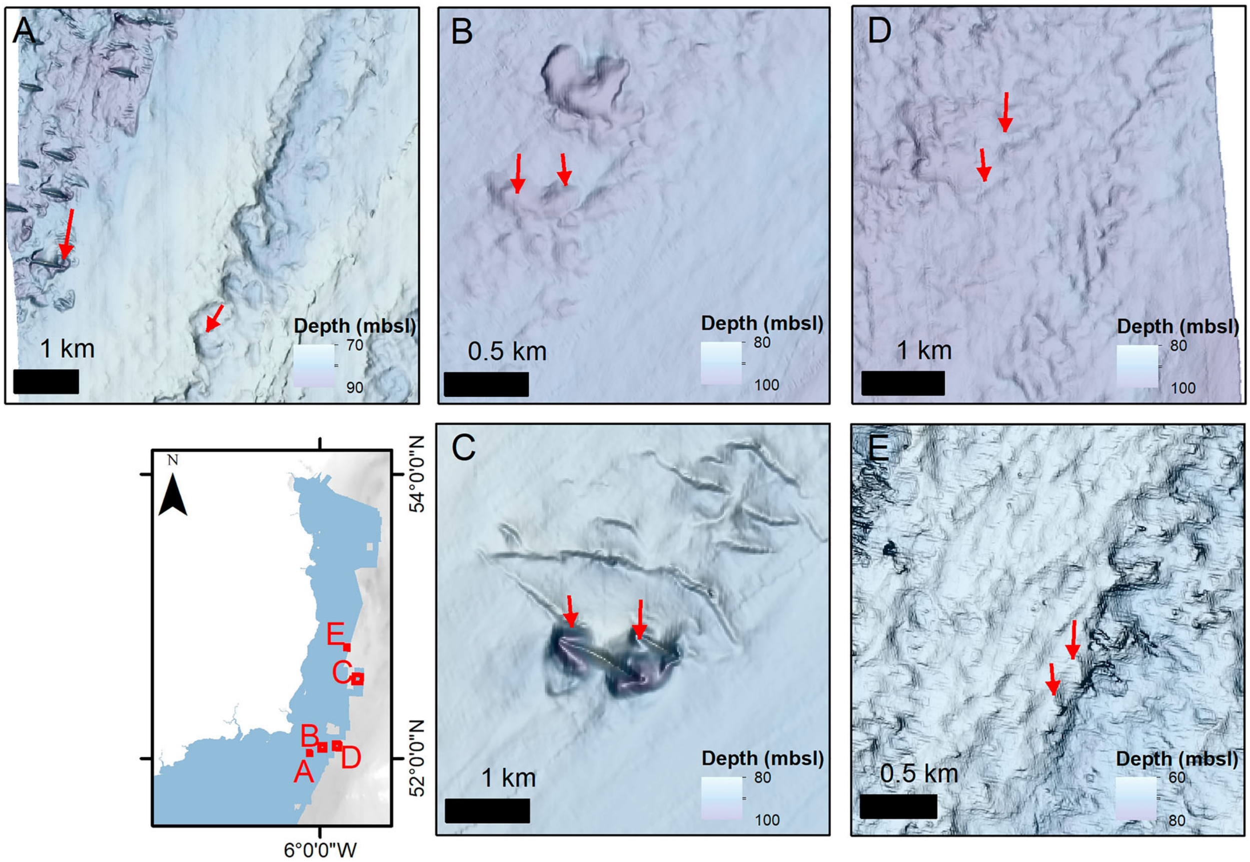

Figure 10. (A) Linear depressions in the Quaternary formation showing margins with semi-circular indentations. The depression on the left is occupied by trochoidal dunes, while that on the right is devoid of them. (B) Semi-circular scouring without any associated trochoidal dune, notice the shape and depth similarity with (C) semi circular scouring at the edges of trochoidal dune. (D) Relict-looking sub-parallel ridges that are tentatively interpreted as extinct dune fields. (E) Irregular topography common in the southern Western Irish Sea, red arrows indicate two mound features that might be gas-seepage features or bedrock outcrops. (A to D: resolution 10 m/ pixel, E: 5 m/ pixel; the bathymetry is superimposed on multidirectional hillshade, exaggeration ×10).

(and relatively higher) basin. A patchwork of superficial sandy sorted bedforms dominate the sediment-starved region, showing an overall migration towards the southwest. Studies in the Mediterranean and USA have shown that the coarse-grained floors of the depressions are rich in sessile fauna, while infaunal assemblages are prevalent in the fine-grained mobile sediment outliers and slivers, promoting regional faunal complexity (McMullen et al., 2015; Poppe et al., 2012). A more detailed study of the sorted bedforms and their mobility in the Celtic Sea may help understanding the faunal complexity and support commercial fishery.

Surprisingly, the Celtic Sea is relatively devoid of glacial morphologies, especially when compared to the northwestern region (i.e. Donegal and Malin shelf). Sparse moraine ridges and eskers have been identified close to the coastline (Giglio et al., 2022; Tóth et al., 2020), however the large GZWs that pervade the rest of the western continental margin are generally absent, possibly not preserved or not even formed in the central section (see discussion on rapid Irish Sea Ice Stream retreat in Giglio et al. (2021) and Scourse et al. (2021)). The formation of the tidal megaridges has also potentially modified the subglacial land system as described in Lockhart et al. (2018) and Scourse et al. (2021). The GZW we have tentatively identified as an extension of the features shown in Giglio et al. (2021) opens the possibility that some ice-marginal features might nonetheless exist, and that they are very subtle and/or covered by modern sediment.

The most striking Pleistocene morphology in the Celtic Sea are the palaeochannels. Channel location, as for that of the sorted bedforms, appears to be in part structurally controlled by the NCSB. Channels are in fact clearly incised around the NCSB, appearing in the western portion of the region and within ~40 km of the coastline, leaving a 'blank' space in the middle. We have mapped subtle traces of sinuous incisions also over the NCSB, suggesting that there might be other buried channels connecting the two separate networks. Further investigations in the shallow seismic stratigraphy of the region are required to confirm the interpretations, which would improve our understanding of the distribution and structural control of Pleistocene palaeodrainage in the Celtic

Sea region. Contention remains also over the re-interpretation of the rugged and linear morphologies to the east, previously interpreted as eskers by Giglio et al. (2021). While there seems to be evidence of bedrock and structural control in the area, and potential for gas-seepage features (Rodríguez Salgado, P. and Croker, P. pers. comm. 2021), only detailed ground-truthing can confirm the nature of these features.

4.3. The southwest

About 30% of the mapped Southwest seabed is covered either by bedrock outcrops or by bedrock only thinly covered by superficial sediment, making it the most bedrock-dominated seabed region around the coasts of Ireland. The most extensive outcrop is the Waulsortian platform offshore north Kerry, whose massive limestone beds appear to be affected by relict karstic processes. Stunning bedrock structures crop out south of the mouth of the Shannon and north of Loop Head. The Carboniferous lithologies in the area are Namurian shales and sandstones, which form monocline and pericline fold structures, and more competent Dinantian unbedded limestones (Sleeman & Pracht, 1999). The excellent exposure and clear details may permit the creation of a seamless bedrock map between offshore and onshore geology. Bedrock lithology has also an effect on the physiography of the region, as demonstrated by the preferential glacial erosion during the Pleistocene of softer Cork Group sedimentary successions, creating a jagged coastline in West Cork and Kerry. While glacial sediment infill and moraine succession is buried under Holocene sediment in the bays (e.g. Plets et al., 2015 in Bantry Bay), glacial successions crop out in the north of Kerry and west of Co. Clare, where we have mapped for the first time moraine ridges that appear to relate to the retreat pattern of the western Irish Ice Sheet after the Last Glacial Maximum (Roberts et al., 2020).

4.4. The northwest

The northwest Irish shelf, characterised by a diverse association of glacial landforms including GZWs, recessional moraines, iceberg ploughmarks and drumlins, is the Irish seabed region where these glacigenic forms have been best and most extensively preserved, permitting detailed studies on the extent and retreat pace of the British–Irish Ice Sheet in the area (e.g. Ó Cofaigh et al., 2019). In this review we have collected and assessed previous studies, confirming the general results but re-interpreting some of the features. In particular, the drumlins re-interpreted as recessional or Rogen moraines, located ~32 km northwest of Bloody Foreland in Co. Donegal, pose a problem as they complicate the palaeoglacial history shifting ice margin orientation from SW-NE (as drumlins) to WNW-ESE (as moraines). This area corresponds roughly with the suture zone between the 'Donegal' assemblage (Benetti et al., 2010) and the 'Scottish moraines' (Dunlop et al., 2010), and the ridges' orientation can be reconciled with a decoupling of two retreating lobes.

5. Conclusion

As Ireland enters a new era of development for offshore renewable energy, climate action and blue growth, the Irish Shelf Seabed Geomorphological Map (ISSGM) version 2023 will hopefully be of great use to many marine practitioners, providing the first coherent and complete geomorphological classification and systematic review of previous research findings. The ISSGM is available online on the Irish Marine Atlas (https://atlas.marine.ie) under the Geology Theme. The ISSGM features the first widespread application of semi-automated tools for shelf-wide marine geomorphological mapping, and could serve as a useful reference for future similar mapping endeavours in other countries. Finally, the map gives the first comprehensive picture of the range of processes that have sculpted the Irish continental shelf over the past tens of thousands of years and continue to modify it today.

Software

All the analysis was conducted on ESRI ArcGIS Pro v2.8.8 environment and using Python 3.6 to create personalised derivatives and delineations. QGIS 3.14 was utilised to create the *r.geomorphons* layers.

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