

National Programmes: Geomorphological Mapping at Multiple Scales for Multiple Purposes

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Abstract A better understanding of marine geomorphology is a common goal for seabed mapping programmes, with various mapping approaches, methodologies and challenges associated with systematically describing geomorphological features. To address these issues, and highlight the overall value of geomorphological mapping, a group of representatives from the seabed mapping programmes of the geological surveys of Norway, Ireland and the United Kingdom have formed a partnership to share their knowledge, expertise and technologies. Here we describe

MIM partnership: MAREANO-INFOMAR-MAREMAP.

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the first year of collaboration by outlining the background to and motivation for the groups' national seabed mapping programmes, and presenting several case studies as well as tests to potentially adopt a harmonised classification scheme.

1 Introduction

In December 2015, representatives from the seabed mapping programmes of Norway, Ireland and the UK (MAREANO, INFOMAR and MAREMAP respectively) formed a partnership (MIM) to cooperate on advancing best practice for geological seabed mapping by sharing experiences, knowledge, expertise and technology. One of the key areas identified for collaboration concerned the challenges inherent in geomorphological mapping. In addition to sharing expertise and developing effective mapping approaches, it was agreed that the group would work towards a harmonised geomorphological classification scheme. In this chapter we report on the results of MIM's first year of collaboration by (i) describing the background and motivations of national programmes to characterise seabed geomorphology, (ii) introducing and discussing the developing classification system, and (iii) presenting several case studies from Norway, Ireland, and the UK to demonstrate the various advantages, challenges and overall value of geomorphological mapping of the seabed.

While the three survey programmes in the MIM group differ in terms of history, formation and governance, all are charged with geological mapping of their respective sovereign seabed areas to meet the needs of a variety of end-users and stakeholders, often at multiple scales. Norway and Ireland lay claim to the largest (2.1 million km²) and second-largest (850,000 km²) seabed areas in Europe respectively, yet neither had an established seabed survey programme until late last century, coincident with the widespread availability of high-resolution multibeam echosounder system (MBES) seabed mapping technology. In the 1990s and the beginning of the twenty-first century, several proposals for an extensive seabed mapping programme were presented to the Norwegian Government, but it was not

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until development of the first plan for integrated ocean management that the pressing need for greater knowledge of the benthic environment was recognised, leading directly to the establishment of the MAREANO programme in 2005 (<http://www.mareano.no>). Meanwhile, the Irish Government contracted a commercial company in 1996, to survey the continental margins to the west of Ireland as part of a submission to the United Nations Convention on the Law of the Sea, which set the criteria for determining the extent of a nation's sovereignty, and which required accurate and verifiable mapping. Subsequently, in early 1999, a proposal was put to the Irish Government outlining the importance of a national seabed survey to manage and identify the opportunities presented by Ireland's extensive seabed territory. The decision was made to first focus on surveying those waters deeper than 200 m resulting in the establishment of the Irish National Seabed Survey. In 2006, the deep-water programme was succeeded by an inshore programme that was renamed as INFOMAR (Integrated Mapping for the Sustainable Development of Ireland's Marine Resource; <http://www.infomar.ie>).

In contrast to Ireland and Norway, there was a broad understanding of the seabed geology in the UK prior to the widespread availability of MBES data. Between the late 1970s and early 1990s, mainly driven by the need to support the developing offshore oil and gas industry, the British Geological Survey (BGS) undertook a regional, reconnaissance sampling and geophysical survey programme. The broad-scale information provided by this programme brought significant scientific, commercial, and policy value but the need for more detailed information and research on which to base commercial and policy decisions has ensured regular MBES-based mapping of the UK seabed over the last circa 15 years. Recently, other marine organisations in the UK have increasingly shared their MBES data. These new 'open data' policies and data-sharing agreements resulted in the establishment of the UK Marine Environmental Mapping Programme (MAREMAP) in 2010 which pools and integrates the resources and expertise of a number of marine science organisations across the UK (<http://www.maremap.ac.uk>).

While the three surveys in the MIM group conduct similar mapping activities, their main motivations are variable. For example, both Norway and the UK have significant offshore oil and gas and other maritime industries (e.g. aquaculture, offshore renewables). As a consequence, the MAREANO programme caters particularly to the requirement for new knowledge about the seabed in relation to integrated management plans for the North Sea, Norwegian Sea and Barents Sea, with a special emphasis on ecosystems and habitat/biotope mapping. Similarly, MAREMAP responds to the regular requirement for detailed and accurate mapping of the seabed to serve multiple purposes (research, commercial, conservation, and policy), but this impetus is greater now than ever before as increasing development of the seabed has paralleled the growing awareness of valuing the marine ecosystem, and the need to establish Marine Protected Areas (MPAs).

Ireland's maritime economy, however, is far less developed than its neighbours, so the primary motivation for the INFOMAR programme is the need to underpin opportunities for marine economic growth, the 'Blue Economy', by providing data, products

(e.g. databases, charts, physical habitat maps) and services (marine decision support tools) to support marine spatial planning (MSP) and infrastructural development.

Notwithstanding these differences, all three survey programmes have in common that they are directed to carry out mapping activities which support a diversity of end-uses including MSP, MPAs, identification of landslide hazards, habitat-mapping, fisheries and numerous other commercial, policy and research interests. In addition, European projects such as MESH (Development of a framework for Mapping European Seabed Habitats), MESH-Atlantic, GeoSeas and EMODnet-Geology (European Marine Observation and Data Network; <http://www.emodnet-geology.eu>) have spurred mapping efforts and allowed participation in the development of agreed international standards for production of socio-economically important maps.

2 Geomorphological Mapping—Approaches and Challenges

Geomorphological mapping provides a fundamental and effective means to characterise the seabed, an important interface between the geological substrate and the water column where a range of biological, chemical, and hydrodynamic phenomena are dependent on both the morphological and geological character of the seabed. While information on seabed morphology/geomorphology is useful for a wide range of end-uses (e.g. habitat mapping, engineering, fisheries etc.) and therefore a priority for seabed surveys, production of such maps has not always been straightforward.

Until recently, geomorphological mapping in the UK has been data-limited, in terms of high-resolution MBES bathymetry, and complicated by the large number of organisations who acquire and hold such data. It is estimated that only c.30% of the UK's seabed has been mapped by MBES in contrast to the extensive BGS repositories of ground-truthing and other seabed information. Increased availability of MBES data, however, is enabling UK scientists to better distinguish the genetic origin of seabed features and, with datasets covering sufficiently extensive areas, allows feature assemblages to be understood in the context of broader environmental systems. This progress has been facilitated by the formation of MAREMAP and aforementioned data-sharing and coordination efforts. Conversely, the Irish survey has prioritised the collection and processing of bathymetric data, having mapped over 85% of its seabed. Geomorphological and other secondary mapping has been an auxiliary activity; finite resources meant that such work was carried out piecemeal and was usually project-driven. Furthermore, a paucity of ground-truthing has been an issue for Ireland due to the prioritisation of MBES data collection. However, an increase in, and optimisation of ground-truthing campaigns is a priority for INFOMAR going forward.

The Norwegian survey has also collected extensive MBES datasets and though only c. 10% of the seabed area has been surveyed to date, this is a significant achievement considering the size of the Norwegian marine area and the relatively recent establishment of the survey programme. MAREANO routinely collects both video-line and seabed sampling data and produces a wide range of interpretive mapping including maps delineating the distribution of larger physiographic regions (landscape types) and smaller geomorphic features (landforms). Landscape-type mapping is conducted in a semi-automatic manner using GIS-tools (Elvenes et al. 2013), while detailed geomorphological mapping has, hitherto, been produced for the most part by manual digitisation based on expert interpretation. This is particularly labour- and cost-intensive as the occurrence of many seabed features (e.g. biogenic mounds, iceberg ploughmarks) can number in the thousands for some areas of the Norwegian continental shelf. MAREANO has now started exploring automated methods as described in the case study below.

In general, production of interpretive, geomorphological mapping from data collected for bathymetric purposes presents a number of challenges, common to most mapping organisations. Collection of sufficient and appropriate ground-truthing is particularly problematic as marine territories are vast and the cost of seabed sampling is very high. However, optimisation of sampling strategies is being explored by another working group within the MIM partnership and is not discussed here.

More fundamentally, bathymetric data can vary in terms of quality and resolution e.g. MBES data acquired for hydrographic charting purposes versus regional-scale bathymetric compilations. The ubiquity of artefacts in bathymetric data can make delineation of features in the processed output problematic, particularly when using semi-automated techniques. Artefacts may result from increases in the signal-to-noise ratio caused by changes in MBES settings or poor weather or sea conditions. Perhaps surprisingly, it is also worth noting that data acquired to meet International Hydrographic Office (IHO) bathymetric standards may not always be best-suited for geomorphological mapping; this is discussed further in the INFOMAR case study below.

Another issue for mapping programmes is that maps may need to cover areas with substantial changes in water depth. This results in significant variability in the resolution of the underlying data due to the increase in size of the MBES footprint with depth and the concomitant decrease in data density. While resolutions of the order of metres are possible for the shelf (<200 m depth), this is reduced to the order of tens of metres, at best, in 4000 m water depths (ship borne MBES). This significantly impacts on the minimum size of detectable features. Resolvability issues are further compounded by the fact that the MBES frequencies required for deeper waters also result in a reduction in the accuracy of depth measurements.

While more data are welcomed, increasing data volumes requires that traditional, expert manual interpretation be supplemented with more time-efficient and, potentially, more accurate semi-automated approaches (e.g. image-based and statistical methods). These approaches can reduce mapping subjectivity and bias, but

manual interpretation is still frequently used to sense-check semi-automated outputs and characterise natural complexity and detail that may have gone undetected.

Finally, a key challenge for national mapping programmes is the need to produce map products for diverse users, at multiple scales as is discussed in the MAREMAP case studies below. With marine spatial planners, developers and researchers requiring more accurate and up-to-date geological information at multiple scales, there is a need to develop consistent mapping and geomorphological classification approaches. Based on work carried out by BGS, development of such a scheme has been one of the key activities of the MIM group.

3 Seabed Geomorphological Classification

The science of seabed geomorphological mapping is developing rapidly, but as this publication also demonstrates, the field is now well established, with its own, very active sub-disciplines. To an extent, these sub-disciplines have developed independently of one-another with researchers deriving from different scientific backgrounds. While this is advantageous for understanding the variable environmental processes recorded at the seabed, it also results in scientists using different terminology and relying on inconsistent classification criteria. Despite the relative youth of the modern field, i.e. common usage of high-resolution MBES bathymetry (1990s-present), it is perhaps surprising that there have not been (as far as we are aware) more concerted efforts to develop more integrated and coherent mapping approaches. Marine scientists have after all been interpreting the nature of the seabed for as long as they have been surveying it (e.g. Thompson 1874). The first half of the twentieth century saw the development and use of single-beam echo sounders (SBES), and it was the accumulation of these data that enabled the compilation and production of the first global-scale depiction of the seabed (Heezen and Tharp 1977). This work was particularly important because it demonstrated that through presenting and characterising the variation in seabed morphology, scientists could extract further scientific value, in this case significantly contributing to the plate tectonic revolution.

The field continued to progress through the application of side-scan sonars (SSS) (e.g. Belderson et al. 1972), MBES for bedform and regional-scale studies (Clarke et al. 1996), satellite altimetry for continental and global-scale studies (Smith and Sandwell 1997), and most recently with AUVs (Wynn et al. 2014), as well as LiDAR (Finkl et al. 2005) and satellite-derived imagery for coastal environments. While typically based on good science and observation, these mapping efforts commonly employ inconsistent mapping principles without reference to geomorphological standards, since very few exist. This has merit in advancing our understanding of the seabed, but neglects the value of implementing robust classification criteria to ensure accurate seabed characterisation and, perhaps more importantly, to enable comparison and integration between different geographic regions, data types, and mapping scientists. Such classification resources are more common in terrestrial

(e.g. Nanson and Croke 1992) and planetary geomorphology (Barlow et al. 2000), as well as within benthic habitat mapping (e.g. Greene et al. 1999).

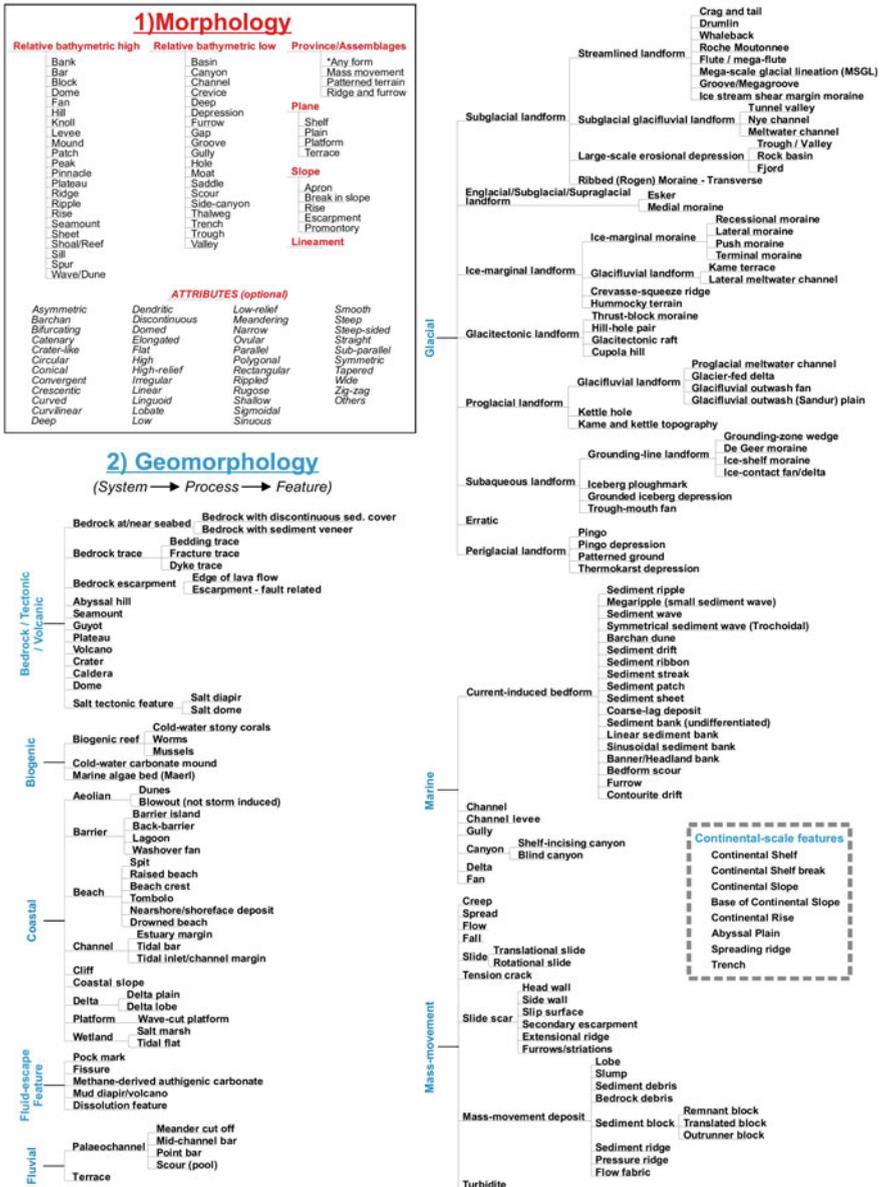
The scientific community has of course not entirely ignored the value of applying standards in submarine geomorphology. A notable early example was the publication by Ashley (1990) in which marine bed forms were compared with fluvial analogues and classified. There are also standardised International Hydrographic Organisation (IHO) feature lists (IHO and IOC 2013), but importantly these lists are limited when it comes to diversity of features, and do not organise features in a structure that is relevant to their origin or morphology. The field of benthic habitat mapping itself has provided probably the greatest impetus to develop standardised ways of describing the seabed in the recent years. While this has largely focussed on hard substrates and seabed sediment character, there has been increasing recognition of the importance of seabed geomorphology in understanding the distribution of benthos (e.g. Harris et al. 2011). It is perhaps global-scale studies, however, which prove most instructive for progressing our characterisation of submarine geomorphology in more complex systems at finer scales. Because of the availability of continuous, albeit lower-resolution, bathymetric models, scientists have been able to adopt more systematic approaches in characterising the seabed, to examine for example the global distribution of seamounts (e.g. Hillier and Watts 2007), or more widely to assess global seabed geomorphology (Harris et al. 2014).

It is this systematic approach that is applied and advanced here to develop the means to describe the geomorphology of the seabed (metres—100s kilometres scale features) in an accurate, robust, and consistent way. This is particularly useful for mapping organisations, and requires a flexible new classification system that is applicable to multiple and diverse environments. The approach should be both sufficiently detailed and interpretive to be informative, but not so detailed that features are over-interpreted or mired in disputed designations or definitions.

In this context, and in response to the increasing requirement for seabed characterisation for multiple purposes and at multiple scales, the BGS developed a two-part Seabed Geomorphology classification system ('Morphology' and 'Geomorphology') to facilitate this work. Feedback on the evolving classification system from expert groups (e.g. submarine glacial geomorphology) demonstrated that other programmes (e.g. MAREANO and INFOMAR) and marine data networks (e.g. EMODnet) across Europe were also directing attention to geomorphology. As a result of this shared interest, one of the first activities of the MIM partnership has been to provisionally adopt the BGS approach and, through testing and revision, collaboratively improve the classification system (Dove et al. 2016). Version 1 of this classification is presented in Fig. 1.

A central objective of the classification system is to communicate useful and specific geological information while also providing an objective physical description of the seabed. Early attempts to include both elements in a single, logically-consistent classification proved either excessively complicated or overly prescriptive, broadly resulting from the non-unique relationship between morphology and feature origin. The solution was to employ two independent

Two-part geomorphological classification system



hierarchical classification trees, ‘Morphology’ and ‘Geomorphology’. ‘Morphology’ features are those characterised by their physical attributes (e.g. shape, size, texture) and ‘Geomorphology’ features are those defined by their process origin and/or the principal environment in which they were formed; e.g. ‘Biogenic’ features are formed primarily by biological processes and ‘Glacial’ features are formed in a glacial environment. Simply put, ‘Morphology’ provides the fundamental, objective description of the feature(s) whereas ‘Geomorphology’ provides an interpretation of the feature(s). Employing this two-step approach is robust as well as flexible because it allows the mapper to separate physical observations and descriptions from their informed interpretations, in effect better future-proofing their work. This is particularly relevant in the marine environment where mapping is heavily dependent on remotely-sensed data, due to the relative paucity of ground-truthing data.

Morphological forms are organised into two broad groups: ‘Relative bathymetric high’ or ‘Relative bathymetric low’, together with several other features that do not fit into the ‘high’ or ‘low’ categories (i.e. plane, slope, and lineament features as well as provinces/assemblages of features). Further morphological attributes (e.g. ‘sinuous’) may also be appended to feature designations to assign greater detail. The geomorphological classification tree presently incorporates 8 environmental systems/themes: Biogenic, Coastal, Fluid-escape, Fluvial, Glacial, Marine, Mass-movement, and Bedrock-Tectonic-Volcanic, with the intention to eventually incorporate ‘Anthropogenic’ (Fig. 1).

To demonstrate how the two independent classification trees might be used to map a single feature, we give the example of a ‘Sediment wave’ below:

- (1) Morphology: ‘Bathymetric high’ \gg ‘Wave/Dune’ \gg ‘Curvilinear wave/dune’
- (2) Geomorphology: ‘Marine’ \gg ‘Current-induced bedform’ \gg ‘Sediment wave’.

A feature may be designated at any hierarchical level, ensuring that it is mapped at a level of precision consistent with the intrinsic nature of the feature, the data quality and confidence of interpretation. A set of bespoke GIS tools, modified from those originally developed by BGS for terrestrial mapping (SIGMA—<http://www.bgs.ac.uk/research/sigma/home.html>) are also being developed to implement the new classification system. These tools will enable more efficient mapping as well as provide a means to incorporate further quantitative (e.g. height, maximum slope) and qualitative (e.g. active vs. moribund, free-text comments) attributes, again adding to the flexibility of the approach.

The classification system provides a logical and consistent framework on which to base seabed geomorphological characterisation. Although a primary objective of the MIM partnership is to develop and collate good-practice mapping techniques and methodologies (e.g. automated numerical and imaged-based protocols vs. expert interpretation), it is intended that this classification system can function independently, and is applicable regardless of the mapping methodology that is used.

4 Case Studies

4.1 MAREANO, Norway—Automated Identification of Biogenic Reefs on the Norwegian Shelf

Coral reefs occur abundantly on the Mid-Norwegian shelf, particularly between 200 and 400 m depth along the continental shelf break and on morainic ridges (Fosså et al. 2002). Some coral reefs are elongated. Looking downstream, these have living ‘head’ colonies, which face the current, followed by a transition zone of recently-dead *Lophelia* colonies and gorgonians, blocks of dead *Lophelia* colonies with *Paragorgia arborea* and *P. resedaeformis* and a reef tail consisting of *Lophelia* rubble (Buhl-Mortensen et al. 2010). These elongated reefs form ridges composed mainly of biogenic material, ranging from mud through gravel to blocks. Circular reefs known as ‘mounds’ are similarly composed. Based on available ground-truthing, only a limited number of confirmed occurrences of live corals have been associated with the structures, though the sediments are clearly biogenic with a high proportion of coral-derived debris. This has called for a nomenclature based on sediment composition and geomorphology, rather than the presence of living corals; the non-living parts of these reefs are classified as ‘bioclastic sediments’ and are mapped out as a separate geological unit. Morphologically, both mounds and ridges are classified as ‘biogenic reefs’.

Maps of bioclastic sediments have received special attention, as these usually form the major parts of reefs, and can be identified using remote sensing (MBES bathymetry and backscatter) with limited visual and/or physical ground-truthing. Knowing the exact location of coral reefs is of major interest for integrated ocean management, because it forms the basis for legislative measures in order to protect the reefs. Since the 1990s, the official coral database managed by the Institute of Marine Research has been based mainly on visual observations of coral reefs using a remotely-operated vehicle or towed video platforms.

Mapping based on MBES data, gridded at 5 m and covering an area of 175,000 km² on the Norwegian shelf, reveals in excess of 100,000 mound and ridge structures, likely representing mounds and ridges composed of bioclastic sediments, which may or may not include living corals, normally found on the steepest slopes facing the current. Until now, mapping of biogenic mounds and ridges has involved delineating polygons containing one large structure or many small structures, based on expert interpretation and using manual digitisation (Bellec et al. 2014).

Scientists at MAREANO are now developing an alternative, automated mapping method based on a combination of MBES bathymetry and backscatter, processed and analysed using the object-based image analysis tool eCognition (version 9.2). Several test areas representing different geological settings have been trialled. In this case study, we present an area north of Skjoldryggen in water depths of 280–400 m (Fig. 2) for which ground-truthing includes 6 video lines, with a total length of nearly 3000 m, and 6 grab samples.

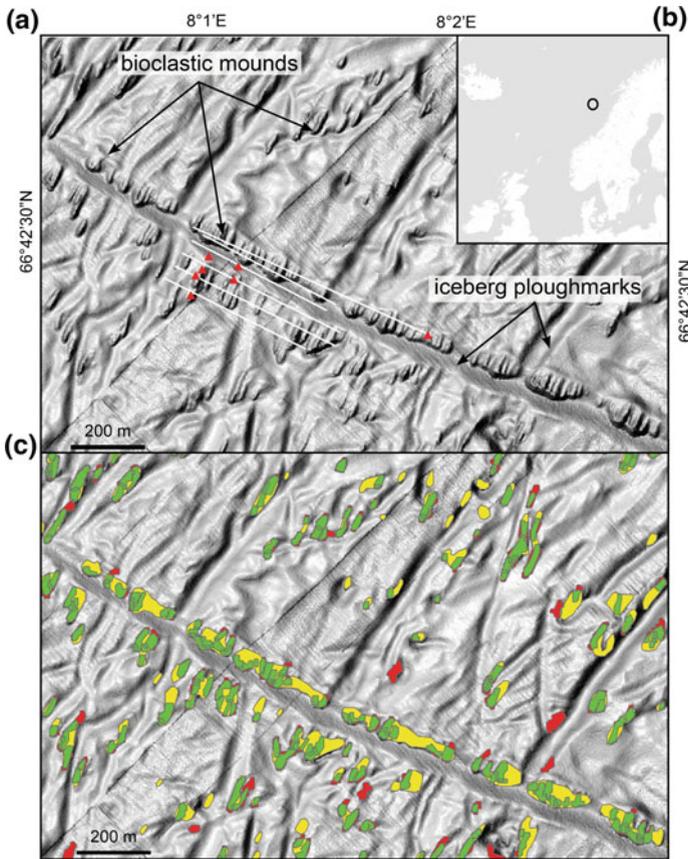


Fig. 2 **a** Overview of the study area. Water depth 295–305 m. Grayscale shaded relief image, 2 m grid, sun lightning from 315°, white lines indicate video lines, red triangles show grab samples. **b** Index map showing location of the study area. **c** Composite image comparing manual interpretation (MI) and eCognition classification (EC) of bioclastic mounds. Green intersection of MI and EC. Yellow mounds classified by MI, but not by EC. Red mounds classified by EC, but not verified by MI

In the study area, biogenic reefs represented by numerous mounds and NNE-SSW trending ridges with bioclastic sediments occur (Fig. 2a), typically up to 70 m long, 20–30 m wide and 10 m high. They occur particularly along the SSW-facing margins of iceberg ploughmarks, which are up to c. 100 m wide, up to c. 10 m deep and extend for several kilometres. The non-biogenic sediments are dominated by gravelly sand with cobbles and boulders. The ridges are thought to reflect development of coral reefs responding to the local hydrographic regime with a prevailing NNE current.

For automated delineation of the ridges, the workflow was as follows:

1. Terrain derivatives such as Bathymetric Position Index (BPI), curvature and slope were calculated from 5 m resolution MBES bathymetry using ArcMap and QGIS.
2. The terrain derivatives were imported to eCognition to form the basis of an image segmentation using an eCognition algorithm (Multiresolution segmentation with a scale parameter of 5 and compactness of 0.1).
3. A rule-based classification of the segmented objects of interest (mounds and ridges with bioclastic sediments) was then performed. In the case study, the criteria used were that BPI values (based a 5×5 and 20×20 windows) should be positive, mean slope should exceed 5° , standard deviation of slope should exceed 2.3° , standard deviation of curvature should exceed 12° m^{-1} and mean curvature should exceed 28° m^{-1} .
4. The classified data were exported to an ArcGIS polygon shapefile where a buffer of 3 m was added. This format ensures that the mound outlines can be integrated with other datasets in a desktop GIS environment or used as basis for WMS map services.
5. Finally intersect and union analyses were performed in ArcGIS to assess the performance of the classification against manual interpretation.

Preliminary results show that the classification using eCognition has a high, though not complete, overlap with ground-truthing (video, grabs) and expert-based manual interpretation (Fig. 2c). 98% of the predicted polygons intersect with the manually mapped polygons, while 2% of the predicted polygons are false. In terms of area, the predicted polygons make up 49% of the area of manually interpreted polygons. This means that the current parameters give a conservative prediction with very few classified polygons not verified by manual interpretation, but also that the current algorithm is not sufficiently sensitive to detect the more diffuse objects that can be identified by expert interpretation. Future work will include refining the choice of layers for segmentation, refining the rule sets for classification, and developing ways of representing confidence in the classified objects.

Delineation of individual reefs with bioclastic sediments has, until now, been too time consuming and thus beyond the capacity of the interpreters and the MAREANO budget. However, based on this trial, we now conclude that development of semi-automated methods will allow us to delineate individual reefs with high precision while expending far less time than for expert manual interpretation.

4.2 *INFOMAR, Ireland—Reprocessing of Bathymetric Data for Geomorphological Mapping*

The link between habitat heterogeneity, particularly morphological complexity and species diversity, has been well-established (e.g. Jumars 1976; Levin and Sibuet 2012). Seafloor habitat features, such as mounds and seamounts, are often given

special legislative protection to ensure they can continue to perform important eco-system services, for example by acting as nursery grounds for commercial fish species. However, deep-water features are, in general, significantly underrepresented in Marine Protected Areas (MPAs; Macmillan-Lawler et al. 2013). This underrepresentation may be even more pronounced than their analysis suggests as smaller and lower-relief features are usually poorly resolved for deeper waters, meaning that potentially important habitats may be missed (Robert et al. 2014). To support good policy decisions concerning deep and, indeed, all seabed areas seabed surveys must strive to produce the best maps possible from the data collected.

The first phase of the Irish seabed mapping programme focussed on deep-waters (>200 m) and revealed much morphological variety in the extensive (>0.5 × 10⁶ km²) seabed area surveyed. Details and bathymetric imagery were published in an Atlas (Dorschel et al. 2010) but the production of interpretive mapping such as geomorphology from the data is a relatively recent endeavour (Sacchetti et al. 2012; Thébaudeau et al. 2015).

All INFOMAR bathymetric data are processed to IHO standards. However, there are some significant differences between data that are sufficient for hydrographic purposes and data that are optimal for geomorphological mapping, one of the most significant being the acceptable level of noise and artefacts. To deal with these, geomorphologists often apply smoothing algorithms before further analysis, which can obscure those features at the artefact scale. Furthermore, bathymetric processing for hydrographic purposes has a number of implications for geomorphological mapping that it is important to be aware of. For example, hydrographic mapping aims to preserve the most shoal soundings to identify navigational hazards. While this is important in shallower waters, the same principles are often applied in deeper settings. Hydrographers will also try to preserve data density whereas, from a morphological perspective, preservation of underlying shape is more important. Additionally, hydrographers are not overly concerned with line-to-line artefacts as long as the depth differences are within the IHO specifications. Geomorphologists, however, prefer to minimise these artefacts even though this may call for a compromise on data density.

In the period since the Irish deep-water mapping programme was completed, data processing technology, particularly data visualisation, has advanced apace making detailed processing more practicable. Given these advances and the need to produce interpretive mapping, INFOMAR is currently exploring reprocessing of deep-water data specifically for this purpose.

To test the benefits of reprocessing, a pilot study area from the head of the Whittard Canyon was chosen (see Fig. 3). The area lies in 200–400 m water depth and is notable for large bedforms. Smaller bedforms are perceptible but, in the original images, are made indistinct by line artefacts of a similar size.

Reprocessing the data to reduce or remove artefacts involved several steps, including careful analysis and reapplication of the most appropriate sound-velocity profile calibrations, together with further manual correction for refraction effects. Subtle ship's roll effects were corrected and careful manual cleaning of the data was performed in accordance with the geomorphological principles outlined above.

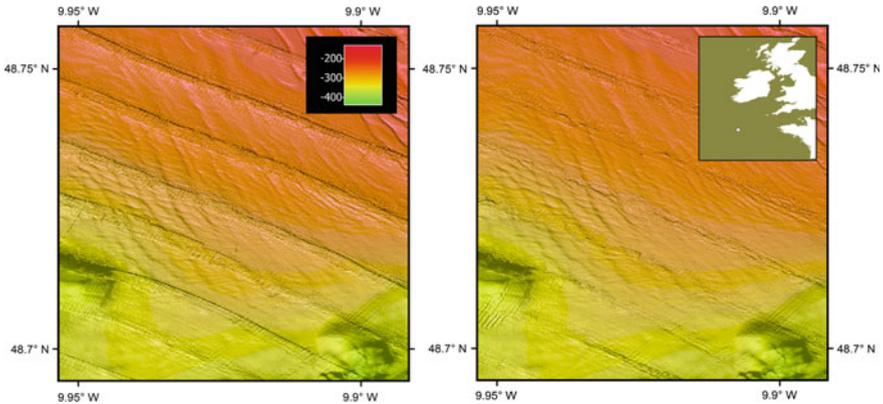


Fig. 3 Comparison of bedform area at the head of the Whittard Canyon located on the continental margin southwest of Ireland **a** before reprocessing of bathymetry for geomorphological mapping, where line-to-line and other artefacts partially obscure the bedforms which are of a similar scale **b** after reprocessing for geomorphological mapping where artefacts have been minimised and the bedforms better captured. Figures are shown in UTM29N and image settings chosen to exaggerate artefacts

Artefacts in the resulting image were found to be significantly reduced, making it possible to better identify the relatively smaller bedforms (Fig. 3).

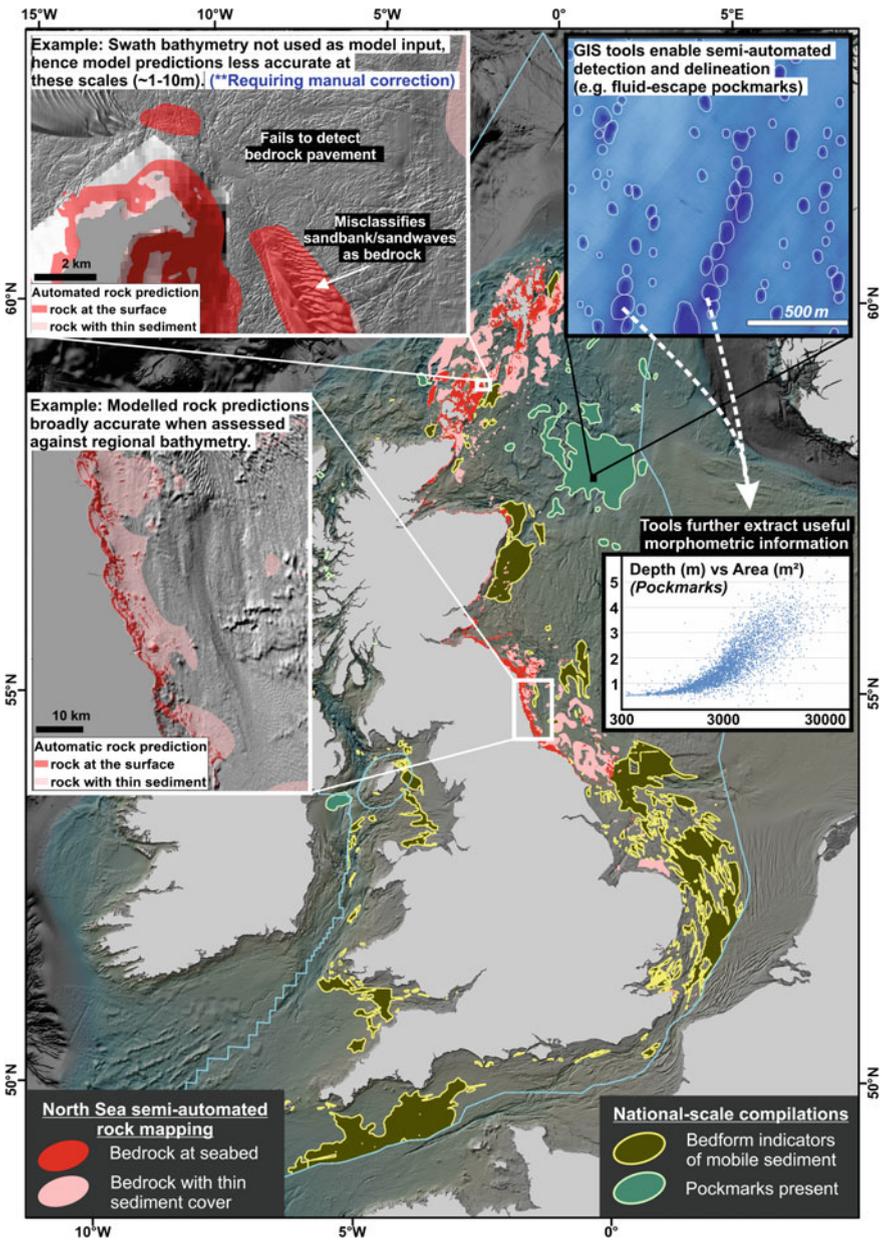
Finally, it should always be borne in mind that submarine geomorphology, even when produced by automated methods, is an interpretation. Confidence in this interpretation is partly a function of the quality and quantity of bathymetric readings. Currently, most geomorphological analysis is carried out using bathymetric grids of a particular resolution, often assumed to indicate the minimum size of feature detectable. However, a more accurate assessment can be made by considering three factors: data density (i.e. the number of bathymetric readings per grid cell); beam footprint, which increases in size from both shallower to deeper waters and with increasing swath angle, giving an incremental reduction in the ability to resolve smaller features; and vertical accuracy, which is primarily a function of the frequency of the MBES system. INFOMAR is currently exploring this kind of confidence information in addition to the development of quality control indices that could, in the future, be included in the map metadata to better support geomorphological and other interpretations made using INFOMAR bathymetric data.

4.3 MAREMAP, UK—Addressing Multiple End-Users at Multiple-scales

Here we present three examples of geomorphological mapping illustrating how MAREMAP addresses multiple end-uses at multiple scales for the UK offshore.

These examples describe different methodologies utilising variable data types (in terms of age and resolution) but employing a consistent, 'fit-for-purpose' mapping approach. We describe (a) a semi-automated seabed mapping tool that utilises high-resolution bathymetry data to identify and delineate features according to pre-determined criteria and extracts useful quantitative information (e.g. depth, orientation) relevant to the origin and potential activity of seabed features; (b) how existing data and information have been compiled and re-analysed to produce national-scale geomorphological map layers to underpin engineering constraint mapping for seabed development; (c) a mapping approach that combines semi-automated spatial prediction using multiple data-types with manual quality checks to predict the distribution of rock at seabed.

- (a) **Semi-automated seabed feature detection and characterisation.** Many distinct seabed features occur in vast and densely distributed numbers. Pockmarks (fluid-escape depressions) are one such example and in some areas of the North Sea more than 30% of the seabed is characterised by this type of morphology (Gafeira et al. 2012) (Fig. 4). Because manual mapping of these features is both time-consuming and subjective, BGS scientists developed a suite of semi-automated ArcGIS-based tools to more accurately and efficiently recognise, spatially delineate and morphologically describe seabed features. The tools also generate and store a range of morphometric attributes to an associated geodatabase. With more than 4500 pockmarks mapped on the UK continental shelf, these morphometric data have enabled unprecedented statistical characterisation of the features. Combined with geological and oceanographic information such analysis is greatly enhancing the understanding of their development, important for both geohazard assessment and potential climate change impact.
- (b) **National-scale compilation and constraint mapping.** National-scale geomorphological characterisation is required in the UK for both spatial planning and management purposes. One recent project with the Crown Estate (owner and/or effective 'landlord' of UK seabed) aimed to understand how the seabed and shallow sub-seabed geology (e.g. Quaternary thickness) constrains the design, installation, and operation of seabed infrastructure. For the geomorphological mapping component the approach was two-fold: compile and harmonise existing regional maps, and utilise the most recent bathymetric data to review and manually update the boundaries. These geological 'factor maps' (Fig. 4) were then combined with bathymetrically-derived morphological attributes (e.g. rugosity) to provide constraint parameters for specific seabed engineering activities using a rules-based scoring approach.
- (c) **Semi-automated regional mapping of rock outcrop.** The presence of hard-substrate is known to influence the distribution and character of benthic habitats and is, therefore, important to a range of groups with a stake in the seabed environment. Two regional studies (English Channel and Celtic Sea, North Sea) were recently conducted in collaboration with the Centre for Environment, Fisheries and Aquaculture Science and the Joint Nature



◀**Fig. 4** Examples of geomorphological mapping at national, regional, and local scales within the UK offshore. National-scale compilations include areas of pockmarks and mobile sediment bedforms. Regional, semi-automated bedrock mapping in the North Sea is also presented, (*left side insets*) depicting instances where automated predictions worked well, and where expert interpretation was required to correct inaccurate model predictions. Feature-scale characterisation of pockmarks also demonstrates the advantages of semi-automated mapping (*right side insets*) revealing how useful morphometric information may be extracted from objectively delineated features

Conservancy Council (JNCC) to delineate rock outcrops for accurate, robust and repeatable mapping using a two-step approach (Diesing et al. 2015; Downie et al. 2016). The first phase involved the development and application of a random forest ensemble model in which predictor variables included broad-scale bathymetry, bathymetric derivatives, hydrodynamic forcings, and a number of pre-existing map layers indicative of seabed properties (e.g. mobile sediment indicators). The model was trained and the most significant variables were retained to make probability predictions for the presence of rock at seabed.

The outputs were then reviewed in a GIS environment where knowledge-based enhancements were made in accordance with the character of the local/regional geological environment, and with reference to high-resolution MBES data sets and supporting information such as seabed sediment samples and maps, and industry reports (Fig. 4). Importantly, this step also identified incorrect predictions from the automated process, for example, the misclassification of sandbanks as bedrock due to their elevation/slope (Fig. 4 inset) and, conversely, failure to identify bedrock pavement due to lack of morphological variability. All modifications were documented through metadata, providing a feedback loop to the modelling phase to facilitate improved performance in future efforts.

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