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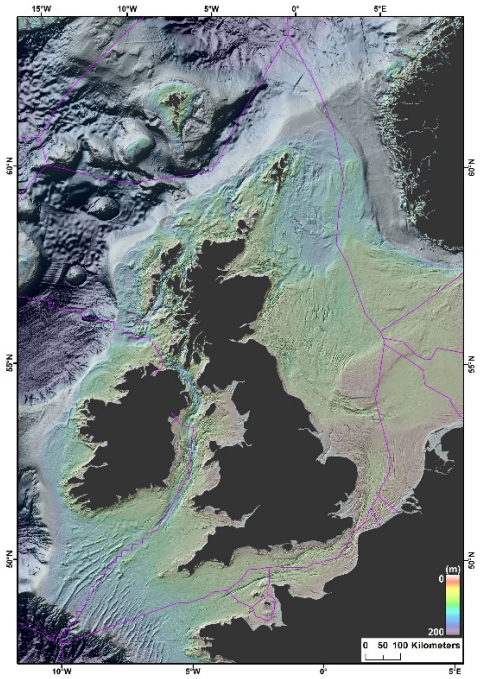
Seabed Geomorphology: a two-part classification system

Marine Geoscience Programme
Open Report OR/16/001



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Seabed Geomorphology: a two-part classification system

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Front cover
Bathymetry (EMODNET)

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Foreword

This report is the result of an initiative led by the British Geological Survey (BGS) to establish a new classification system for Seabed Geomorphology. Geomorphological maps and spatial products that result from this initiative are intended to serve as enabling resources for research, educational, commercial, and marine spatial planning purposes, much like the existing BGS 1:250k map series (e.g. Seabed Sediment and Quaternary Mapping - http://www.maremap.ac.uk/index.html).

Concurrent to the finalisation of the BGS classification system, collaboration with marine mapping partners in Europe has highlighted the wider interest and demand for characterising seabed geomorphology. This is the case at both the pan-European level with the members of EMODnet planning to address geomorphology in greater detail over the next few years, and more regionally along the NW European margin, where a partnership between national mapping programmes MAREANO – Norway, INFOMAR - Ireland, and MAREMAP - UK (MIM), has been established to consider best practice in geomorphological mapping. This includes the classification of features, but also identifying fit-for-purpose data preparation and automated detection/mapping protocols that will improve mapping accuracy and reduce user bias. As a first step, the MIM group have adopted and are testing the BGS two-part classification. Feedback from the group has improved the classification system and ensured that it is applicable across the diverse environments of the NW European margin, and applicable at multiple scales. In this report we present Version 1 of the classification system. It is likely that future versions will be released via the broader MIM partnership.

Acknowledgements

In addition to the BGS and MIM scientists who contributed to this report, the development of this classification system has benefitted from communication with a number of other groups and individuals. We would like to acknowledge the EMODnet Geomorphology working group for useful discussions on seabed features, and we would particularly like to thank Daniel Praeg (OGS-Trieste), Steve McCarron (Maynooth Univ.), and Colm O'Cofaigh (Durham Univ.) for providing helpful feedback on early drafts of the classification scheme, when it addressed only glacial features. We thank Jeremy Everest (BGS) for a helpful review of this report.

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1 Summary

The BGS has developed a two-part classification system ('Morphology' and 'Geomorphology') to facilitate work on a new 'Seabed Geomorphology' mapping initiative, and this classification system is the focus of this report. As stated in the Foreword, the rationale and the basic framework of the classification system were conceived and established within BGS, but recent collaboration within the MAREANO-Norway, INFOMAR-Ireland, and MAREMAP-UK (MIM) partnership has led to significant improvement of the classification system, and this report. To further support this effort, existing BGS GIS tools (SIGMA) have been adapted to apply this two-part classification system for more efficient geomorphological mapping in the marine environment.

This report:

- provides a brief background on seabed mapping and characterisation, as well as how this science has been addressed historically within BGS;
- describes the current motivation to conduct seabed geomorphological mapping, and the requirement for a new set of tools to facilitate this work;
- describes the logical framework that underpins the classification system;
- outlines the attributes of the classification system, how it can be applied, and discusses the advantages and limitations of the approach.

It is anticipated that through testing and usage, the classification system will be revised and improved over time, with updated versions released through MIM partnership. It is also planned that a further 'user guide' report will be produced for the classification system and the GIS tools, including thematic details (e.g. background information on 'coastal' or 'glacial' features) and a feature glossary.

2 Background

Detailed and accurate mapping of the seabed is important for a number of user-groups (research, commercial, conservation and policy). For example: i) the ever increasing activity in the offshore renewables industry has demonstrated a critical need for improved characterisation of shallow geology for appropriate site selection and foundation design; ii) the designation of marine protected areas (MPAs) requires the identification and mapping of benthic habitats that are underpinned by the geological substrate; iii) to understand the environmental processes that formed and actively govern the marine environment, scientists and marine spatial planners require more accurate and up-to-date geological interpretations at multiple scales; and iv) marine policies and environmental legislation, e.g. Marine Strategy Framework Directive, can only be enforced where the most accurate information is available. New, extensive high-resolution bathymetry datasets are enabling significant insights into the geology of the seabed and shallow sub-seabed. In contrast to terrestrial settings, the increasing availability of high-resolution data in the marine environment is leading to many features being revealed and described for the first time. This calls for an observational mapping approach, which is analogous to that which may have been applied on land over a century ago. For example, swath-bathymetry datasets (~1-10 m resolution) not only permit scientists to better distinguish the genetic origin of seabed features, but also cover sufficiently extensive areas to allow feature assemblages to be understood in the broader context of environmental systems (Figs. 1, 2) (e.g. Dove et al., 2015).

Mapping the geomorphology of the seabed provides a fundamental and effective means to characterise this important element of the marine environment. The science of geomorphology addresses the general configuration of the earth's surface, in this case in a submarine setting, with

the purpose of describing the nature of landforms/bedforms, and their relationship to the underlying geology. Geomorphological analysis enables a better understanding of the environmental processes recorded at the earth's surface as the physical characterisation (form and other attributes e.g. symmetry) of landforms may be used to distinguish feature origin, as well as describe their development and evolution through time. Geomorphological maps combined with other marine datasets, e.g. ground-truthing and shallow seismic data, allow for considerably improved geological characterisations and predictions of associated geotechnical properties.

The concept of mapping seabed geomorphology is not inherently innovative or ground-breaking. Terrestrial geomorphology is a well-established field of science (e.g. Hubbard and Glasser, 2005; Summerfield, 2014), and within the marine environment for example, mapping submarine glacial landforms has become the most useful and common method to reconstruct the extent and dynamics of former marine-based ice-sheets (e.g. Dowdeswell et al., in press). Geomorphology has also been demonstrated to exert significant control on the character and distribution of benthic habitats (e.g. Harris et al., 2011). What is novel here, and useful/necessary for survey organisations, is to have the means to describe the geomorphology of the seabed in a consistent, and where appropriate, standardised way. This requires the development of a new classification system that is: i) applicable to multiple and diverse environments, and ii) sufficiently detailed and interpretive to be informative, but not so detailed that features are over-interpreted, and/or become mired in disputed designations or definitions.

New high-resolution and extensive datasets also result in large, and exponentially increasing data volumes. This requires that BGS, together with other survey, research, and industry-based scientists supplement classical mapping with improved methodologies. Adapting to this challenge requires innovative data acquisition, processing, and interpretation techniques, including: image analysis, statistical approaches, and automated-feature-detection protocols (e.g. Gafeira et al., 2012; Cazanave et al., 2013; Ismail et al., 2015). Incorporating these tools will form an important component in the effort to produce better geomorphological map products.

3 Previous work

3.1 OBSERVATIONS

While this is not intended to be an exhaustive review of all significant efforts to characterise seabed geomorphology, there is evidence that as soon as surveyors and geoscientists began acquiring data which yielded images/profiles of the seabed, they also began making inferences on the environmental origins and associations of the features observed. The first hydrographic surveys relied on lead-line surveys (17th century – mid-20th century) that provided a series of point observations of water depth, but carried significant navigational uncertainties. As an example, the early expeditions led by Wyville Thomson demonstrated the seabed was not a 'barren waste', but a diverse physiographic environment with equally diverse flora and fauna (Thompson, 1874). This was followed by the unprecedented *Challenger* expedition, which over ~20 years and 50 reports laid the foundations for modern hydrography and oceanography.

The 1930s saw the development of single-beam echo sounders (SBES), providing the first acoustic images of the seabed, and with increasing volumes of data, provided greater scope for describing the nature of the seabed, e.g. examining the origin of submarine canyons (Daly, 1936). In the 1950s and 1960s, increasing bathymetric observations enabled the first global-scale characterisation of seabed geomorphology: the production of physiographic charts, at first for individual ocean basins (e.g. Heezen et al., 1959), and then ultimately for the global seabed (less than 73° latitude) (Heezen and Tharp, 1977). This painstaking cartographic work conducted

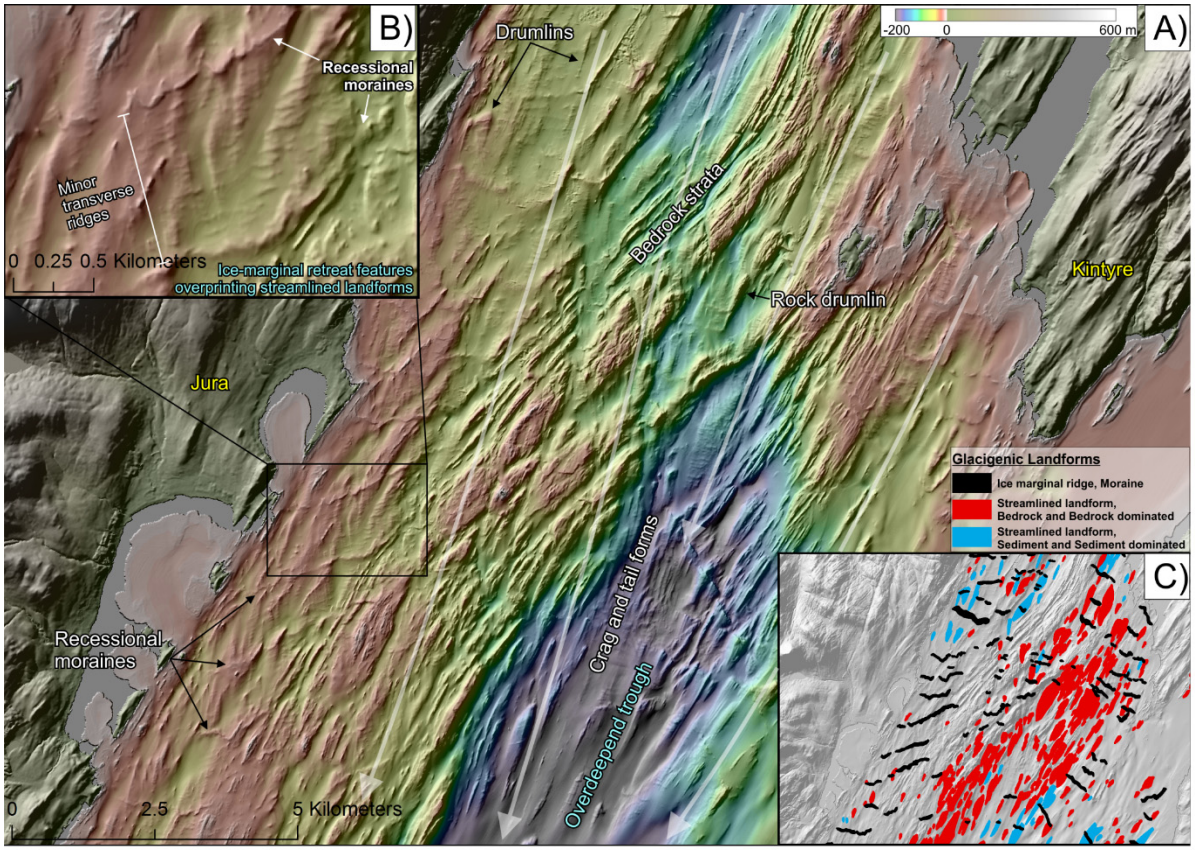

Figure 2: *Bathymetry data from the Sound of Jura reveal an assemblage of glacially streamlined landforms and moraines overlying commonly exposed bedrock strata. Panel C) shows the local glacial landform interpretation, and how morphological character may infer sub-surface characteristics (i.e. degree of presence/absence of bedrock in landforms.*

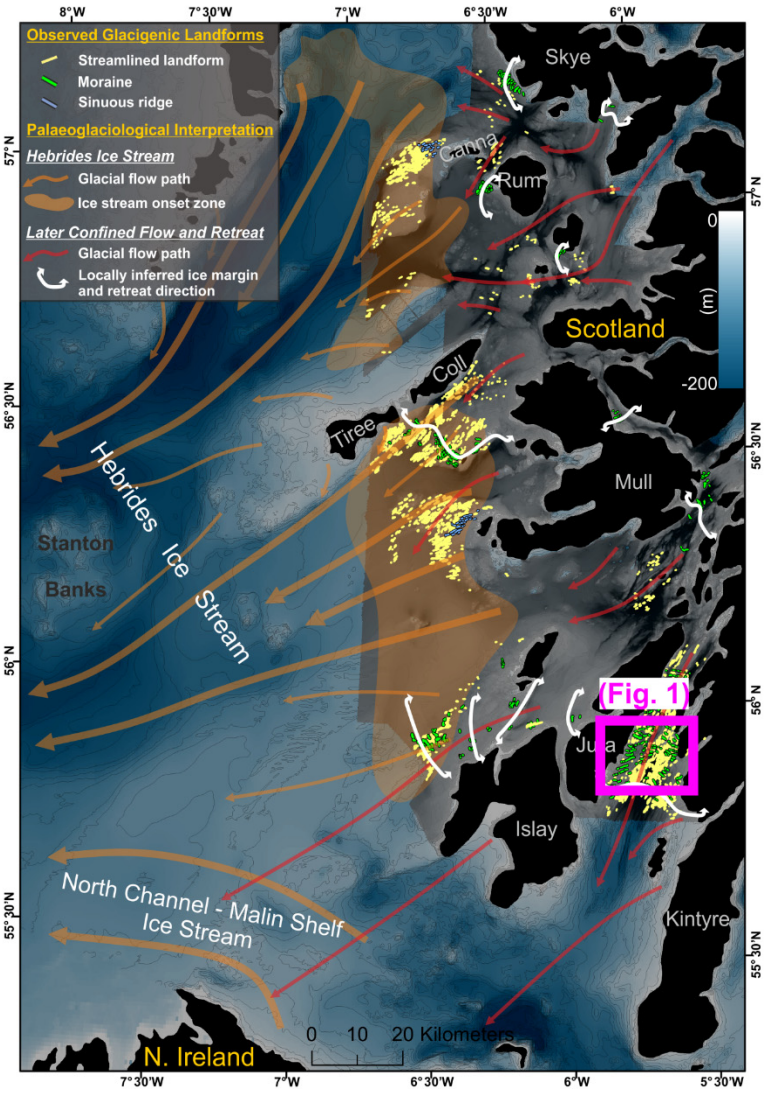

Figure 1: *Regional interpretation of ice sheet flow and retreat based on geomorphic interpretation. Extensive bathymetry data enable feature-scale landform assemblages to be placed in context of broader environmental systems.*

by Marie Tharp and Bruce Heezen demonstrated the great variation in seabed morphology/configuration, and through this, also made significant contributions to the contemporaneous plate-tectonic revolution.

The introduction of side-scan sonars (SSS) brought about a new element to seabed mapping, the ability to 'sense' significantly smaller features than was previously possible, even though SSS yield backscatter (intensity of acoustic return) data rather than bathymetry (depth) data. SSS data not only imaged features at higher resolution (10s cms), they provided imagery in a broader swath rather than along single 2D profiles. While initially intended for military applications, the technology had value to geoscientists, and opened up the capacity to image individual bedforms and better understand associated sedimentary and hydrodynamic processes (e.g. Belderson et al., 1972, Stride, 1982).

With the increased usage and availability of SBES and SSS, there followed initiatives to classify sedimentary bedforms and compare them with fluvial analogues (e.g. Ashley, 1990), much like this report describes an initiative to describe geomorphology using the increased availability of of multibeam echo sounder (MBES) data. From efforts such as this, it is clear that the classification of features does not simply represent a 'stamp- collecting' exercise, but through careful categorisation and compilation, yields important information on the variation of features (e.g. 'bedform continuum'), and provides the ability to discriminate between the multiple environmental processes that constrain their development. SSS data are still of relevance today as not only do they typically provide higher-resolution data than hull-mounted MBES systems, they also give a 'slant-range' view of the seabed, which is of use for imaging upstanding features that may be less apparent in MBES data e.g. unexploded ordinance (UXO) and wreck mapping.

From the 1990s onward, survey-scale interpretations of geomorphology have primarily been based on MBES data (as well as Lidar data in the coastal zone), which provide a swath of co-registered bathymetry and backscatter data. As in the past, the resulting scientific progress has been distinctively data driven, both in terms of data quality and coverage. As described earlier, swath bathymetry data provide an extraordinary opportunity to image the seabed and understand the environmental processes that formed and actively govern that environment. Because of this, the last 20-30 years have seen a remarkable rush in academic and commercial work using these data to describe the seabed from the coastal environment (e.g. Finkl et al., 2005; Gavrilov et al., 2005; Moore et al., 2009), to the continental shelves (e.g. Clarke et al., 1996; Todd et al., 1999; Kenyon and Cooper, 2005; Dove et al., 2015), continental slopes (e.g. Driscoll et al., 2000; Mosher et al., 2010; Dolan et al., 2008), and deep-ocean basins (e.g. Edwards et al., 2001; Hillier and Watts, 2007).

3.2 CLASSIFICATION

The availability of high-quality swath bathymetry has led to a step-change in our understanding of numerous aspects of marine geology, and that is why it is somewhat surprising that there has been no significant attempt (to our knowledge) to structure the way we describe the geomorphology of the seabed. The application of geomorphic classification schemes in terrestrial geoscience is after all common place, including both manual and automated classification approaches (e.g. MacMillan and Shary, 2009). One partial exception to this in the marine environment are the international standards documents produced by the International Hydrographic Organisation (IHO), including the 'Standardization of undersea feature names' (IHO and IOC, 2013), and 'Hydrographic 'Dictionary' (IHO, 1994). Apart from giving guidance on the appropriate way to name new features, the 'feature names' list includes a list of 'generic terms' and associated definitions. These 'generic terms' are relevant here and primarily fall into our 'morphology' (e.g.

'ridge') classification tree rather than our 'geomorphology' tree (e.g. 'abyssal hill'). The 'Hydrographic dictionary' includes several further terms that relate to features in our 'geomorphology' classification (e.g. 'sandwave'), though the greater than 7,000 terms in this dictionary relate to all aspects of hydrography. Taken together, these IHO documents incorporate fewer geomorphological features than one might observe at seabed (and that we've attempted to include here), but the primary point of difference is that features are simply listed in alphabetical order rather than presented in a structure relevant to their origin or morphology. Nevertheless, we make a point of incorporating all relevant features listed in IHO standards, and adopt their glossary definitions where they cannot be improved upon.

Within the field of benthic ecology, geomorphology is also indirectly addressed through 'terrain attributes' (e.g. slope, rugosity, etc), which are regularly incorporated into predictive models of the distribution of benthic habitats (e.g. Wilson et al., 2007; Lecours et al., 2016). While certainly of use, these terrain attributes only relate to aspects and/or derivatives of the morphology, and do not address the process-origin of features, their potential mobility/erodibility (i.e. geotechnical properties), or their association with the underlying geology.

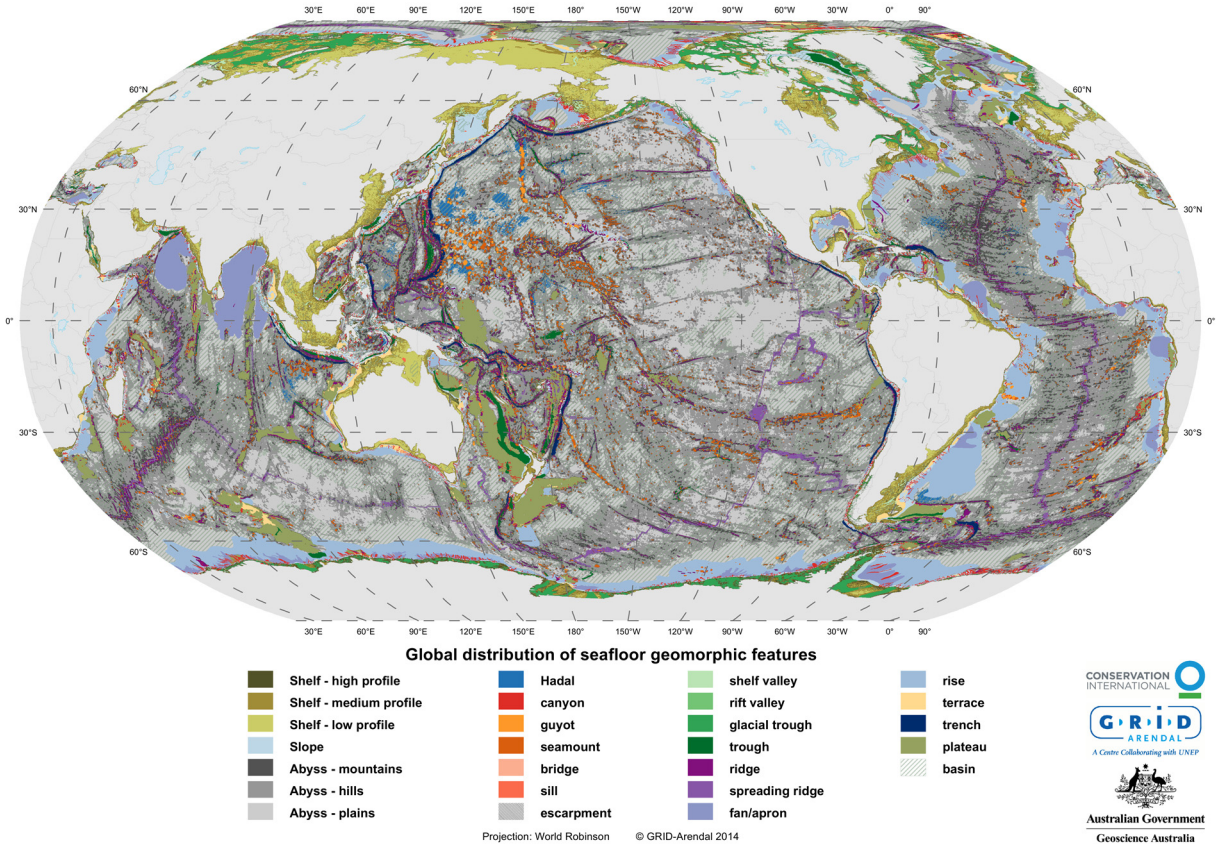

Figure 3: *Geomorphic features map of the world's oceans. Reproduced from Harris et al. (2014).*

Surprisingly, it is at the global scale where there have been systematic attempts (methodologically at least) to classify seabed geomorphology, which presumably relates to the availability of suitable data. Global bathymetry datasets are produced by extrapolating ship-borne bathymetric transects (broadly and irregularly spaced) according to satellite altimetry data (e.g. Smith and Sandwell, 1997, Becker et al., 2009). These bathymetry models are of coarser km-scale resolution, but because they are continuous they enable a consistent logical mapping approach to be applied to the data. This has been undertaken for example to look at the global distribution of seamounts (e.g. Hillier and Watts, 2007), and more broadly to assess global submarine geomorphology (Harris et al., 2014) (Fig. 3). It is this systematic approach that is required to identify, describe, and classify features at a broader range of scales, from characterising bedform/landform-scale features observed in high-resolution data (e.g. swath bathymetry), to continental-scale features

observed in coarser bathymetric compilations. Considering the substantial attention paid to the classification of deposits and the distribution of sediment at seabed (e.g. Kostylev et al., 2001; Diesing et al., 2012; Lark et al., 2015), it seems timely (if not overdue) to develop a classification system that facilitates the consistent classification of seabed geomorphology. This is especially the case considering the increasing availability of high-resolution MBES data (e.g. Fig. 1), as well as meso-scale regional bathymetry models (Fig. 4) (based on compilations of SBES data and MBES data where available - e.g. EMODnet-Bathymetry) that support detailed geomorphic description and interpretation. It is also worth noting that this approach can apply below the seabed, where 3D seismic data depict buried surfaces recording environmental processes similar to those observed at seabed, providing further information on the architecture of the seabed and shallow sub-seabed (e.g. Andreassen et al., 2007).

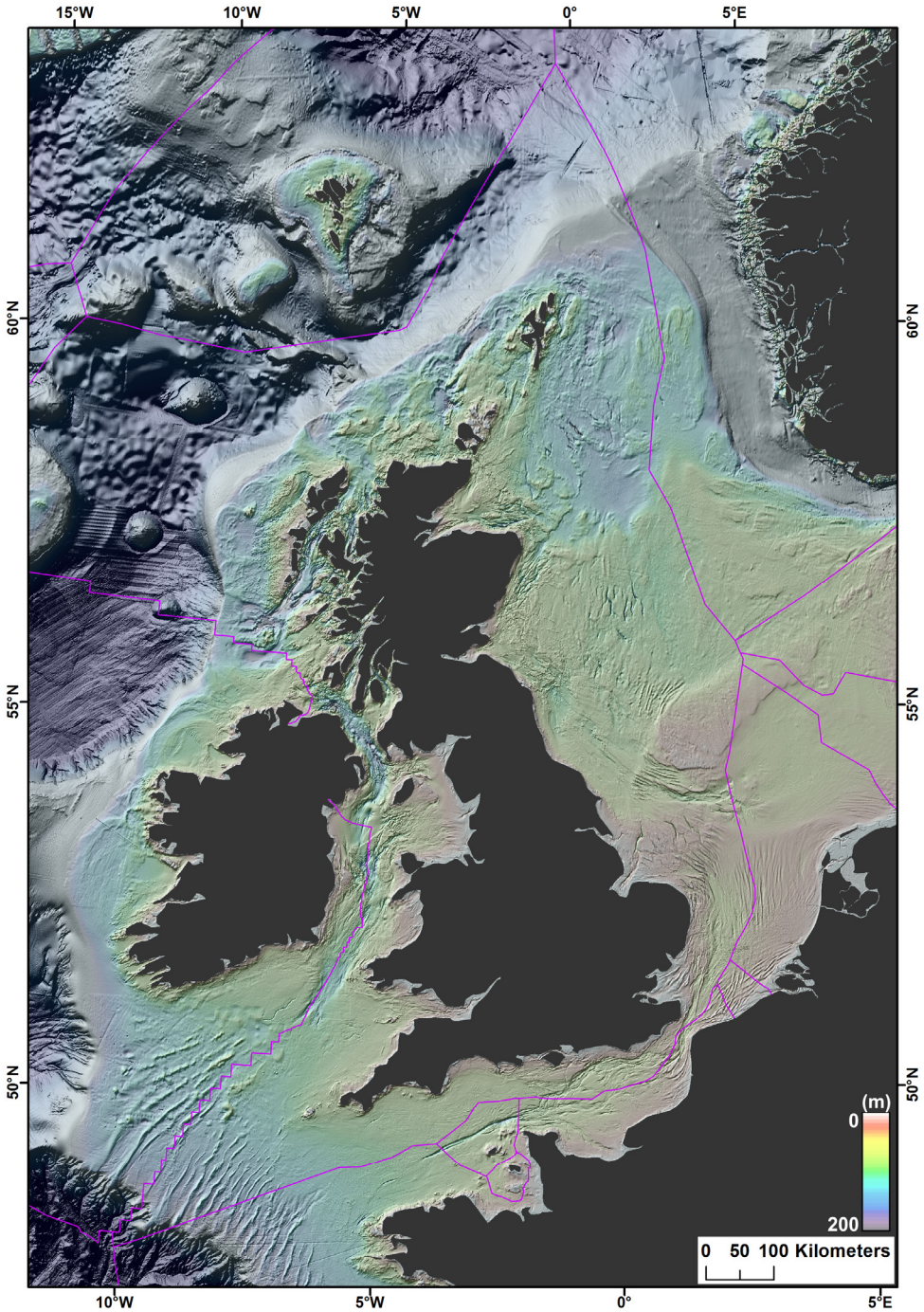

Figure 4: *Bathymetry offshore of the UK and surrounding areas (~150m resolution). Source: European Marine Observation and Data Network (EMODnet). Colour scale clipped to emphasise relief inboard of the continental shelf break. Pink lines delineate national maritime boundaries.*

3.3 DEVELOPMENT OF SEABED GEOMORPHOLOGY MAPPING WITHIN BGS

Between the late 1970s and early 1990s, the BGS undertook a systematic survey programme of geophysics and ground-truthing across the UK offshore (Fannin, 1989), which resulted in the publication of a series of 1:250,000 scale maps (e.g. British Geological Survey, 1991), regional reports (e.g. Cameron et al., 1992), and associated peer-reviewed publications. Many of the 1:250k Quaternary and Seabed Sediment maps included inset maps of bedforms, more often than not focussed on mobile-sediment features (e.g. sediment waves). Through a number of commissioned projects, these disparate maps have been collated to produce a single layer of bedforms (e.g. Strategic Environmental Assessments (SEA) - https://www.gov.uk/guidance/offshore-energy-strategic-environmental-assessment-sea-an-overview-of-the-sea-process; Westhead et al., 2014), but these maps are based primarily on SBES and SSS data and cannot match the detail provided by interpretation of swath bathymetry. Further to this, BGS geoscientists have produced numerous geomorphological maps through commissioned projects, for end-purposes including: offshore renewables, Oil & Gas platforms, cable/pipeline routes, and marine protected areas.

In 2005, BGS ran a pilot 'Seabed Geology' project to utilise all available data to produce maps of the seabed geology, including seabed sediments and geomorphology. Within the case study area, there was little swath bathymetry data available at the time, but detailed interpretations were made as high-resolution observations of bedforms on SSS data were extrapolated according to regional-scale bathymetric surfaces (50-100m resolution) produced by re-gridded single-beam surveys. The intrinsic challenge with this approach was that the mapping effort was excessively time-consuming, and therefore prohibitively expensive. Nevertheless, a prototype geomorphology scheme was developed as part of the project. The classification system presented in this report reflects an evolution of that process, but is fundamentally changed as the previous scheme was primarily a catalogue of features that in some instances were defined by geomorphology (e.g. moraines), and in other instances by morphology (e.g. linear depressions). Separately, land survey geologists in BGS started work in the mid-2000s on compiling a glossary of glacial landforms, and these features are also incorporated here.

4 Approach: Two-part classification

Marine geoscientists are highly reliant on remotely-sensed observations due to the common paucity of ground-truthing data, hence we need approaches that most effectively exploit the available data. At the outset of the process, it was important to ensure that the classification system allowed for the communication of useful and specific geological information, while also providing an objective description of the seabed. Instead of collating all features into a single list or catalogue, it was also preferred to present features in a consistent logical framework (i.e. hierarchy) to inform on the physical/environmental processes that led to their formation (e.g. glacial vs. fluvial vs. submarine). However, initial attempts to integrate detailed geological interpretations together with objective morphological descriptions (e.g. ridge, channel, escarpment) within a single classification tree were unsuccessful as this required the scheme to become either excessively complicated (e.g. permitting sufficient variation of form), or excessively prescriptive (e.g. permitting insufficient variation of form). The end result of trying to merge objective and interpreted descriptions together was generally ineffective because of the non-unique relationship between morphology and process origin.

The solution presented here demonstrates that separating the two elements (geomorphology and morphology) provides a more straightforward, logically-consistent, and flexible means of mapping the seabed. Within this revised approach, two independent classification schemes are employed to describe the seabed: 1) Morphology and 2) Geomorphology. 'Morphology' features are those characterised by their physical attributes (e.g. shape, size, texture), while 'Geomorphology' features are those defined by their process origin, i.e. biogenic features are those that were formed primarily by biological processes, and glacial features are those that were formed primarily by

glacial processes. In a general sense, 'Morphology' provides the fundamental objective description of the feature(s), whereas 'Geomorphology' provides an interpretation of the feature(s). Employing these two independent classification schemes frees the mapper to describe features purely according to their morphology, or the environmental systems and processes that led to their formation.

Within the 'Morphology' classification tree, features are described at four hierarchical levels according to their general form (e.g. channel, ridge, etc), and optionally with separate morphological attributes (e.g. sinuous, streamlined, etc) (Fig. 5). Morphological forms are organised into two broad groups: "Relative bathymetric high' or 'Relative bathymetric low', together with several other features that don't fit into 'high' or 'low' categories (i.e. plane, slope, and lineament features as well as provinces/assemblages of features). There are also a series of morphological attributes (e.g. 'sinuous') that may optionally be appended to feature designations.

Within the 'Geomorphology' classification tree, features are also described at four hierarchical levels. Within this hierarchy features are typically described in increasing detail from environmental system (e.g. submarine), to environmental setting (e.g. shelf), to process (e.g. current-induced bedform) to bedform/landform type (e.g. sediment wave). At present, the classification tree incorporates 8 environmental systems/themes: **Bedrock/Volcanic/Tectonic, Biogenic, Coastal, Fluid-escape, Fluvial, Glacial, Marine**, and **Mass-wasting**, with the intention that '**Anthropogenic'** features will be incorporated at a later date (Fig. 5). This geomorphological classification was developed with the intention of characterising seabed features found in UK and NW European waters, and almost certainly excludes many features that may be found in other geographic areas (e.g. Mediterranean, tropics). Nonetheless, we believe that the classification system is sufficiently flexible and robust that such features could easily be appended where relevant.

To demonstrate how the two independent classification trees would be used to map a single feature, we give the example of a 'drumlin' below:

1) *Morphology: ('Bathymetric high' >> 'Mound' >> 'Streamlined mound');*
2) *Geomorphology: ('Glacial' >> 'Subglacial landform' >> 'Streamlined landform' >> 'Drumlin').*

Two-part geomorphological classification system

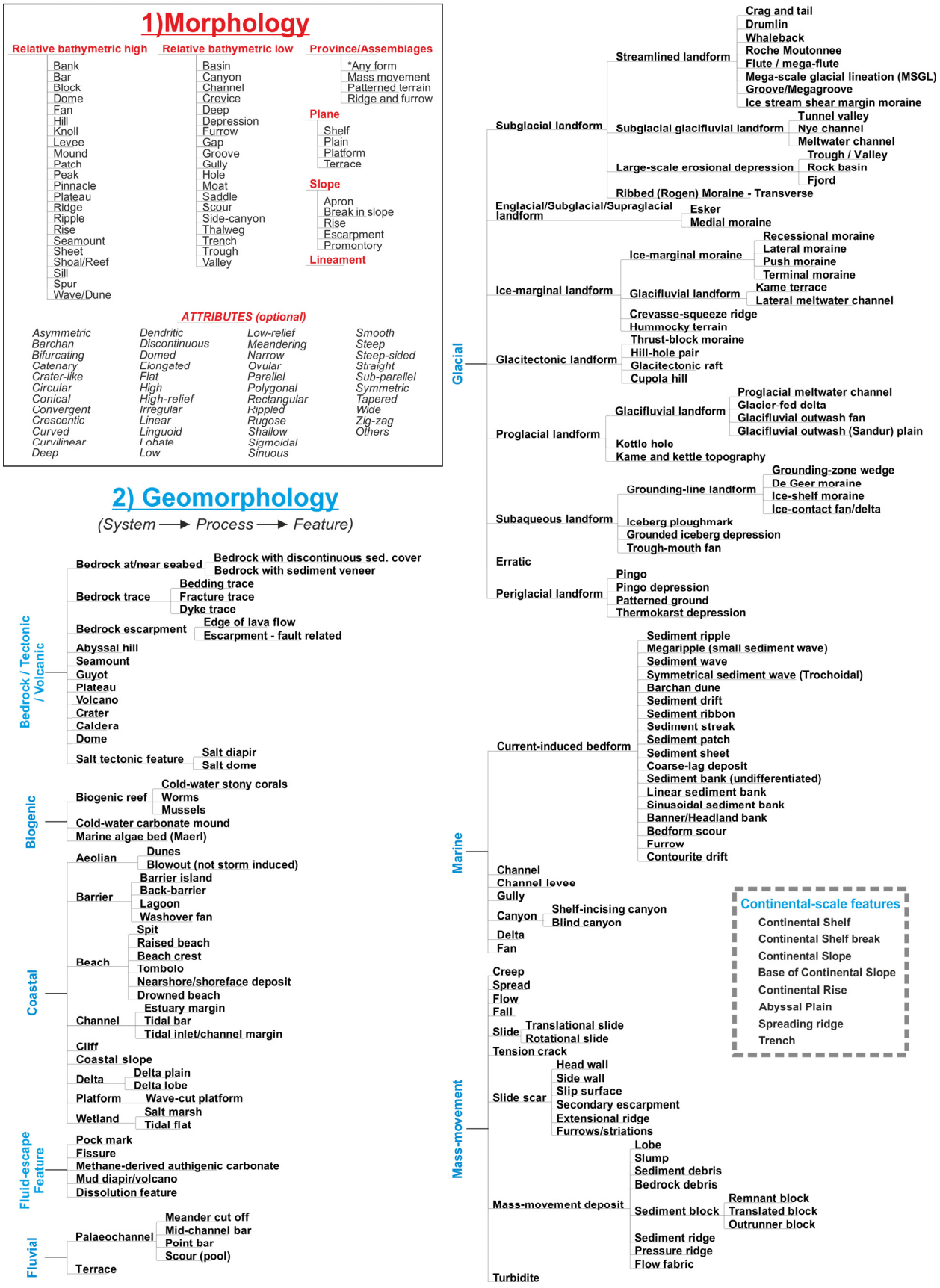

Figure 5. *Version 1 of the two-part Seabed Geomorphology system – Morphology and Geomorphology.*

4.1 FURTHER ATTRIBUTES OF THE TWO-PART CLASSIFICATION APPROACH:

- Features may be mapped at different hierarchical levels on both the 'Morphology' and 'Geomorphology' classification trees. This enables significant flexibility for the mapper to map features at greater or lesser detail according to the intrinsic nature of the feature(s), ensuring mappers can be confident in their interpretations. An example might be hummocky terrain that the geoscientist can confidently attribute to glacial processes (due to local context / surrounding features), but is uncertain whether the features result from subglacial or ice-marginal processes. In this instance, the feature could be mapped: 'Morphology' >> 'Province/Assemblage' >> 'Hummocky terrain'' ; and 'Geomorphology' >> 'Glacial';

- Every feature mapped will have a 'Morphology' classification, whereas only features in which the mapper has sufficient confidence in their interpretation will have a 'Geomorphology' classification. This follows from ensuring a justifiable scientific approach is applied to the mapping: i.e. observations and description are made before interpretation. By definition, any geomorphological feature has an associated morphology, but there are instances where the origin and environmental associations of a 'Morphology' feature(s) is unclear, so no 'Geomorphology' classification would be given. This also allows features to be assigned a 'Geomorphology' classification at a later date without remapping e.g. if additional information arises to support interpretation such as ground-truth data;

- Applying this two-step approach is flexible and robust because it allows the mapper to separate their basic observations and descriptions (Morphology) from their informed interpretation (Geomorphology), in effect better future-proofing their work. This is of use to the mapper and map users for a number of reasons: 1) A map user may disagree with some aspects of the interpretation, but could still make use of the 'Morphology' classification; 2) the origin of some seabed features may be ambiguous, despite having similar morphological characteristics ; 3) the map user might only want a map of the 'Morphology' classes, or components of the 'Morphology' (e.g. filter for seabed depressions only; and 4) the map user might want to view and filter for features associated with certain environmental systems only (e.g. fluvial systems), specific processes (e.g. fluid-escape features), or morphologies (e.g. scour). This is particularly useful as the origin of seabed features can be ambiguous, e.g. a bank of sediment can be produced through glacial or marine processes (or both), such that it is not always possible to distinguish between the two in the absence of ground-truth data;

- Each feature has an associated glossary definition (which are as yet incomplete, and will be published with a later version of the scheme);

- Apart from the independent 'Morphology' and 'Geomorphology' classifications, mapped features will incorporate a number of further quantitative (e.g. height, maximum slope, etc) and qualitative (e.g. active vs. moribund, free-text comments) attributes. This will be implemented through the associated SIGMA GIS tools. The SIGMA tools have been adapted to apply the two-part classification scheme and allow for efficient mapping of morphological and geomorphological features within an ArcGIS environment. The SIGMA tools will calculate several quantitative attributes (as described above) automatically and will allow for direct user input as well;

- Seabed geomorphological map products will be made available digitally. In the UK, this will be managed through the MAREMAP web portal (http://www.maremap.ac.uk/index.html). Maps will be presented with separate seabed Geomorphology and Morphology cartographic schemes, and map symbologies will reflect the respective hierarchical classification systems. Shapefiles will be downloadable to access further feature attributes.

5 GIS mapping tools

*At the time of publication, development of version 1 of the SIGMA GIS mapping tools is nearly complete (http://www.bgs.ac.uk/research/sigma/home.html). A brief user-guide will accompany the release of the GIS tools, and will be referenced in future versions of this report.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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