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Highlighting broad-scale morphometric diversity of the seabed using geomorphons

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Abstract

Morphometric diversity is an important component of overall seabed geodiversity. Automated methods for classification of morphometric features (ridges, peaks, valleys etc.) provide a convenient way of classifying large volumes of data in a consistent and repeatable way and a basis for assessing morphometric diversity. Here, we apply 'geomorphons', a pattern recognition approach to morphometric feature classification, to 100 m resolution multibeam bathymetry data in the Barents and Norwegian Seas, Norway. The study area spans depths from a few metres to nearly 6000 m across several geological settings. Ten unique morphometric features are delineated by the geomorphon analysis. From these results, we compute the variety of features per 10 km^2. This simple 'geomorphon richness' measure highlights broad-scale morphometric diversity across the study area. We compare the richness results with terrain attributes and across physiographic regions. Our results provide new regional insights, which together with more detailed information will help guide follow-up surveys as well as identifying diversity hotspots, which may require special management.

Introduction

Geodiversity (Gray 2004) has many facets, or geodiversity components (Bailey *et al.* 2017), including the diversity of morphometric features (ridges, peaks, valleys etc.). These can be mapped from topographic data using single or combined terrain attributes derived from digital elevation or bathymetry data or by expert interpretation of shaded relief (MacMillan & Shary 2009; Lecours *et al.* 2016). Alternatively, they may be delineated using specifically designed feature detection algorithms (e.g. Dikau 1989; Wood 1996; Jasiewicz & Stepinski 2013).

Morphometric features identified by these methods are often called 'landforms'. Here, we avoid this term, which is widely used in a broader sense and which has proved difficult to define and adopt consistently even within the fields of geomorphology and geomorphometry (Evans 2012). They are also frequently described as geomorphological classifications, but such features need to be put in context with their geological setting and/or the process(es) by which they have been formed for the purposes of geomorphological mapping. This important distinction is emphasised by Dove *et al.* (2016, 2020) and Nanson *et al.* (2022, 2023) in their two-part approach to geomorphological mapping, whereby morphometric features are mapped first, followed by geomorphological interpretation where viable.

Irrespective of the geomorphological origin of seabed morphometric features, their detection and classification using automated, algorithm-based methods offer a convenient starting point for estimating their diversity. Numerous methods have been proposed for morphometric feature detection (MacMillan & Shary 2009). The pattern recognition approach of geomorphons (Jasiewicz & Stepinski 2013) is adopted here. This offers a more complete and computationally efficient classification than earlier approaches

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Abbreviations:

CMECS: United States Coastal and Marine Ecological Classification Standard
MAREANO: MArine aREAl database for NOrwegian sea areas
NGU: Geological Survey of Norway (Norges geologiske undersøkelse)
VRM: vector ruggedness measure

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(e.g. Dikau 1989; Wood 1996; Fisher *et al.* 2004; Schmidt & Andrew 2005), which need to be combined to capture a complete set of morphometric features and can struggle when applied to large data sets. The algorithm detects 498 geomorphons, which are reduced to the ten most frequent and commonly recognisable features (flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley and pit) through reclassification (Jasiewicz & Stepinski 2013). The number of classes may nevertheless be changed to match user needs via user-defined lookup tables (e.g. Masetti *et al.* 2018; Masetti 2022). The geomorphon approach has existed since 2013, but it has only recently seen uptake in the marine environment (e.g. Dekavalla & Argialas 2017; Di Stefano & Mayer 2018; Masetti *et al.* 2018; Novaczek *et al.* 2019; Sowers *et al.* 2020). Geomorphons also appear to have only recently been explored as a basis for terrestrial geodiversity assessments (Bailey *et al.* 2017; Pál & Albert 2021; Vörös *et al.* 2021) and to our knowledge have not been applied in assessments of seabed geodiversity, besides the recent study by Dolan *et al.* (2022).

As well as contributing to a broader suite of geodiversity-related information, characterising morphometric diversity of the seabed has intrinsic value and can be particularly useful when investigating new areas. In Norway, the offshore seabed mapping programme MAREANO (Bøe *et al.* 2020) has focussed on the continental shelf and slope but has recently begun mapping the deep Norwegian Sea, adding to earlier bathymetric mapping, with a view to providing information for sustainable management. This deep-sea area is far from flat and featureless. Much of the terrain is far more extreme than the previously mapped shelf and slope areas – notably the hills and mountains of the Mid-Atlantic Ridge and depths of nearly 6000 m at Molloydjupet (Molloy Deep) west of Svalbard. Before attempting any follow-up surveys to further characterise the seabed geology and habitats, it is important to appreciate just how morphometrically diverse the deep-sea terrain is. Alongside more detailed studies of the terrain, it is useful to conduct broad-scale analyses, which facilitate comparison with more familiar areas on the shelf and slope, and even on land.

Classification of morphometric features and assessment of their variety gives an insight into the morphometric diversity of an area, which complements information from traditional terrain attributes (slope, ruggedness, relative relief etc.). A research challenge in classifying these features is to develop methods that are repeatable and can be applied to very large data sets without overreliance on (often subjective) expert interpretation. Sowers *et al.* (2020) used geomorphons as a foundation for classifying geomorphological units. Using the United States CMECS geoforms (Federal Geographic Data Committee 2012) at 100 m resolution bathymetry, they showed that useful results can be obtained even from relatively coarse data. Here, we use geomorphons to extract morphometric features on the Norwegian seabed, using bathymetry data at this same resolution. We explore whether this approach provides a useful basis for quantifying broad-scale morphometric diversity, through determination of geomorphon richness per unit area (10 km^2). This is then compared with examples of terrain attributes associated with morphometric diversity. Furthermore, we examine how geomorphon richness varies by physiographic region.

Methods

Bathymetry data

Multibeam bathymetry data were compiled and supplied by the Norwegian Mapping Authority Hydrographic Service (Kartverket) for the MAREANO programme. This compilation (August 2021) combines bathymetry data from the MAREANO programme and related surveys. For this broad-scale study of the Norwegian and Barents Seas, the data were resampled to 100 m resolution using bilinear interpolation. The elevation void fill function in ArcGIS v.10.8.1 was used to fill gaps in bathymetry data coverage of up to 2 km to minimise morphometric feature detection artefacts. Such gaps appear only sporadically in the data, usually confined to older surveys over steep terrain.

Geomorphon analysis

Geomorphon analysis was conducted using the BRESS toolbox (Masetti *et al.* 2018; Masetti 2022), a free standalone tool developed specifically for applying the method to bathymetry data. Masetti *et al.* (2018) and Jasiewicz & Stepinski (2013) detail the geomorphon algorithm while Masetti's (2022) user manual describes practical use of the BRESS toolbox. Here, we provide an overview of the main user-defined settings.

BRESS classifies into the original ten, or optionally six (default), five or four morphometric features (see lookup tables in Masetti 2022). We use ten classes; this maintains the discrimination between convex and concave slopes (termed "spur" and "hollow" by Jasiewicz & Stepinski 2013) and maximises the number of different features for our morphometric diversity assessments.

The inner and outer radii of the search annulus determine how near and far the algorithm will 'look' in each of eight directions. These settings affect not only which morphometric features will be detected but also the impact of noise or artefacts in the bathymetry data on the results. Sowers *et al.* (2020) found that while the default BRESS values of inner/outer radii of 5/10 grid nodes work reasonably well using 100 m resolution data, radii of 3/15 grid nodes provided results that were better matched with those that would be obtained by expert delineation of deep-sea terrain (>200 m depth). In this study, we use this same outer radius but increase the inner radius to seven grid nodes to help reduce the effects of noise in much of our older multibeam data from the deep-sea area. We notice that other data resolutions can be accommodated by adapting the radii used, while maintaining the distances considered.

The other main user-defined setting is the flatness threshold (see Jasiewicz & Stepinski 2013). Sowers *et al.* (2020) showed that adapting this setting, and thereby what the algorithm considers flat, is useful for delineation of specific morphometric features. For this study, which focuses on using geomorphons as a basis for assessing morphometric diversity, we maintain a constant (default) flatness value for consistency across all areas. We recognise that this may lead to the under- or over-estimation of morphometric features, depending on the terrain, but it serves the purpose for a preliminary analysis. For more detailed analysis, with a view to geomorphological mapping, adjustments to the flatness parameter would be prudent.

Geomorphon richness

The diversity of morphometric features was assessed by calculating the variety of geomorphon classes within a unit area. This calculation of 'geomorphon richness' employs a fishnet polygon grid as the basis for zonal statistics calculations, reporting the variety of classes within each polygon (Dolan *et al.* 2022). Here, using ArcGIS 10.8.1 with Spatial Analyst, we used a *c.* 10 km^2 fishnet (3200 × 3200 m), which suits broad-scale assessment, and calculated the geomorphon richness of an integer version of the BRESS classification output, which had first been subject to a majority filter (8 neighbours).

Terrain attributes and marine landscapes

To explore the complementary information given by geomorphon richness, we generated two examples of terrain attributes: relative relief and VRM (Sappington *et al.* 2007). Both are commonly associated with morphometric diversity. Relative relief was generated for a standard 1 × 1 km area using focal statistics (range) in ArcGIS 10.8.1 Spatial Analyst, while VRM was calculated via the spatialEco package in R (Evans 2020) for a 3 × 3 cell analysis neighbourhood. We also compare geomorphon richness to the NGU's marine landscape map, providing a semi-automatic classification of the major physiographic regions (Elvenes 2014).

Results

Figure 1 shows the geomorphon classification for the entire study area. Inset maps highlight the features captured for several example areas with different morphologies in various geological settings. Near Molloydjupet (Fig. 1a), slopes dominate the extreme terrain, but peaks, ridges, valleys and shoulders are also effectively captured, as well as a few flat areas, including at the deepest part. On the Mid-Atlantic Ridge (Fig. 1b), we see a complex morphology featuring all geomorphon classes. Of note is the delineation of volcanic cones as peaks. Figure 1c highlights an area of the deep Norwegian Sea area mapped by older multibeam surveys with noisy data. Here, we see that besides real (larger) features, the algorithm has classified noisy data (corrugations visible in shaded relief) as morphometric features, despite our best efforts to find an appropriate setting for the inner radius. At the Barents Sea shelf edge (Fig. 1d), we see how larger morphometric features are effectively detected, including the Sopphola-Steinbitryggen hill-hole pair, the shelf edge and variations in slope morphology. However, several less prominent features are classed as flat. This is a good example of an area where adjustment of the flatness parameter may allow detection of more features. Alternatively, analysis of higher resolution data may complement these results. At Malangsdjupet (Fig. 1e), the neighbouring strandflat (crystalline bedrock), banks and continental slope, we see effective delineation of the relatively flat bank areas (Malangsgrunnen and Sveinsgrunnen) from the morphometrically diverse coastal and continental slope areas.

Figure 2 shows the geomorphon richness results. Although quite a coarse resolution, this figure complements the information in Fig. 1 by highlighting areas of high and low morphometric diversity. The inset figures (a–e) show the richness for each example area, and the results of the relative relief calculations are included for reference. Here, we see that morphometric features are effectively captured both in areas of high and low relative relief. As we might anticipate from Fig. 1, area b on the Mid-Atlantic Ridge is the most morphometrically diverse. We also see that diversity is overestimated in area c due to the noisy data leading to a high geomorphon richness. Elsewhere, the summaries reflect the features shown in Fig. 1. Most importantly, the richness map highlights regional differences in the morphometric diversity: a property that is not immediately apparent from the geomorphon classification or terrain attribute maps. We gain a new appreciation of

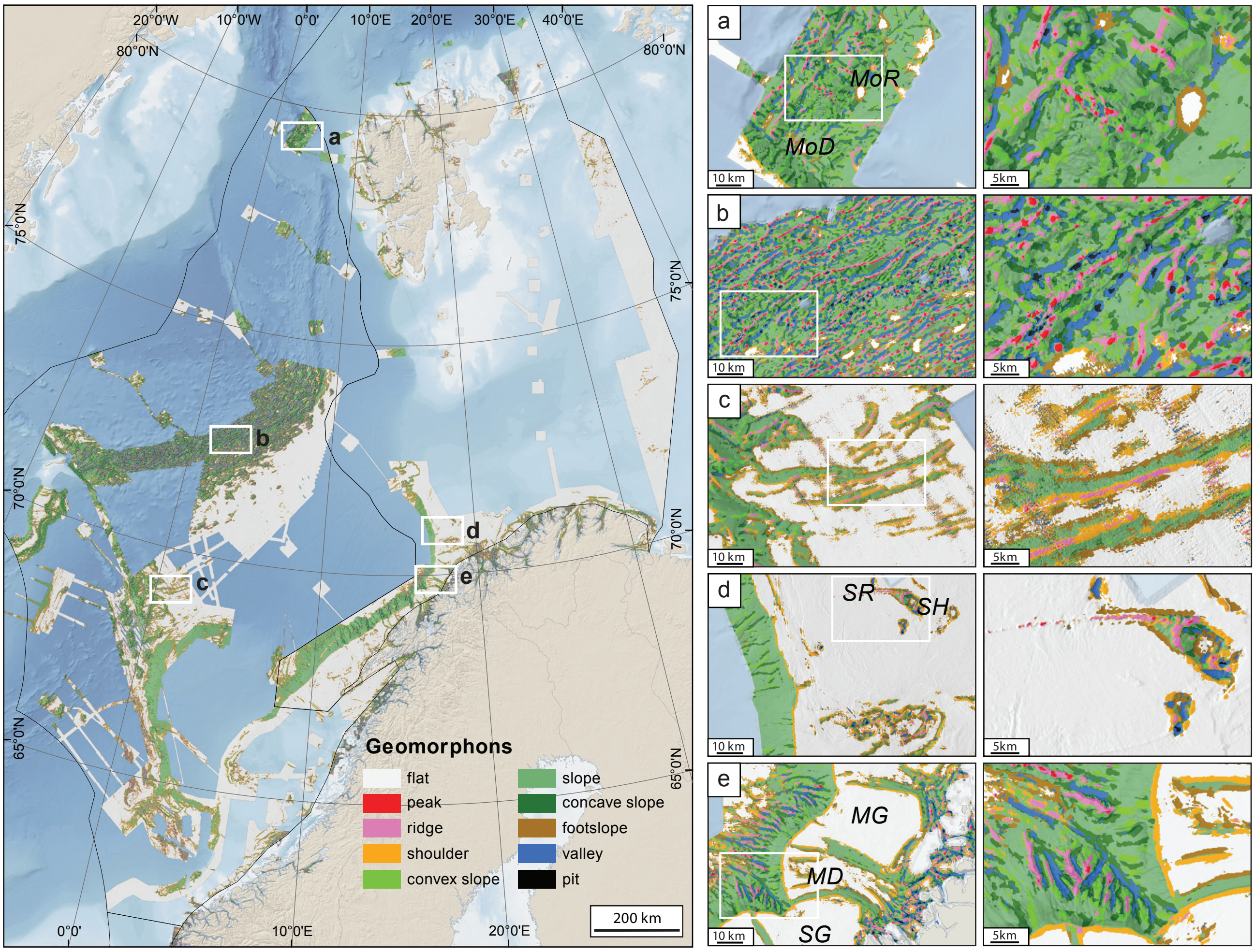

Fig. 1 Geomorphon classification of the study area in the Norwegian and Barents Seas. The geomorphon classes are shown as a semi-transparent layer over greyscale hillshade. Inset maps (**a**–**e**) show details of the geomorphon classes at several example locations. Multibeam bathymetry: Kartverket. Background bathymetry (blue shaded relief): GEBCO Bathymetric Compilation Group (2019). Abbreviated place names: **MoR**: Molloyryggen. **MoD**: Molloydjupet. **SR**: Steinbitryggen: **SH**: Sopphola. **MG**: Malangsgrunnen. **MD**: Malangsdjupet. **SG**: Sveinsgrunnen.

where diversity hotspots are, and how much more diverse they are than previously mapped areas. Furthermore, where we see apparently high diversity in unexpected places (e.g. deep sea plain), we are alert to the reasons for this, such as poor data quality.

As well as visually assessing the geomorphons and their richness, we examined how the morphometric diversity varies by landscape type. The results are summarised in Fig. 3 where we show the mean geomorphon richness by landscape type, with mean relative relief and ruggedness for reference. Fjords, the strandflat and marine hills and mountains exhibit the highest values of geomorphon richness. The two former types have moderate relative relief and ruggedness at the analysis scales used, while hills and mountains alongside canyons have the highest relative relief and slightly higher ruggedness values. Ruggedness values are generally low and due to the data resolution will not capture local variations, which may be linked to the, often fractal, morphology. Relative relief is a useful indicator of how extreme the terrain is but does not appear to have a direct link to geomorphon richness at the scales analysed.

Discussion and conclusions

We have applied geomorphons to classify 100 m resolution multibeam bathymetry data over large parts of the Barents and Norwegian Seas, Norway. We used this result to calculate geomorphon richness – a measure of morphometric diversity based on the variety of geomorphon classes per 10 km^2. This has allowed us to gain initial insight into morphometric diversity hotspots (e.g. Mid-Atlantic Ridge; Figs 1a, 2a), which may be linked to high biodiversity, as well as identifying areas where the diversity is overestimated due to poor data quality (e.g. Figs 1c, 2c). Our results will help prioritise follow-up surveys to document surficial geology and benthic habitats using sampling and video as well as highlight areas where high resolution acoustic surveys (which would allow detection of finer-scale morphometric features)

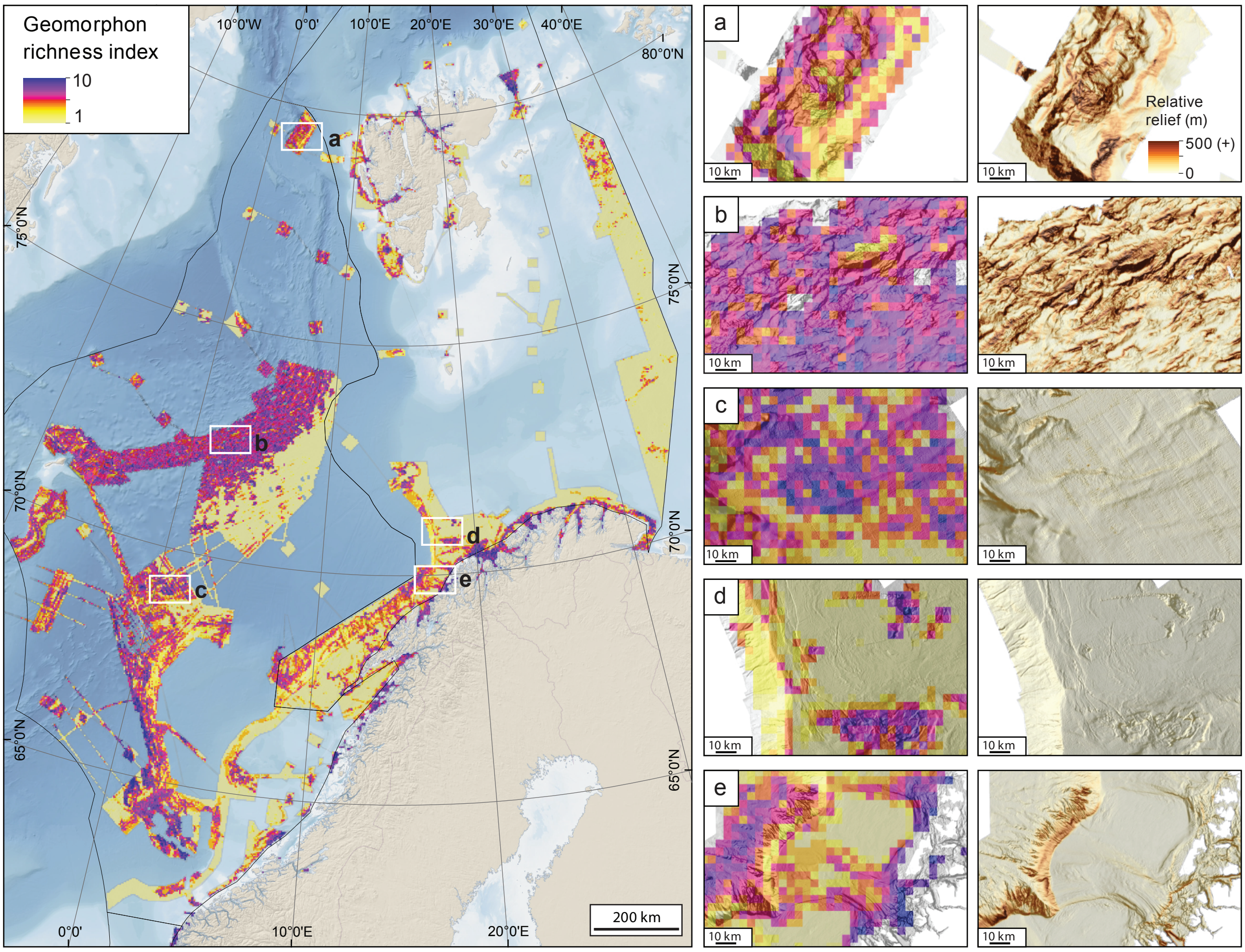

Fig. 2 Geodiversity overview and detailed inset maps (areas **a**–**e**) showing geomorphon richness (**left**) and relative relief (**right**). The colour ramps are common for all areas. Note that the maximum value for the colour ramp of relative relief has been limited to 500 m to aid visualisation. Values of up to 1248 m (up to 948 m in area a and up to 1087 m in area b) occur within the data set, but extreme values are rare. A maximum–minimum stretch has been applied as opposed to standard deviation or another stretch that will distort perception of the range of values. Multibeam bathymetry: Kartverket. Background bathymetry (blue shaded relief): GEBCO Bathymetric Compilation Group (2019).

would be particularly useful. This type of information can help sustainable management of the seabed and aid the design of marine protected areas. It is important that geodiversity is included in such management and conservation efforts (Schrodt *et al.* 2019; Tukiainen & Bailey 2022), especially as this information may be available well in advance of biological data.

Quantitative methods for highlighting geodiversity are currently sparse. To promote geological information on national and international stages like the UN Sustainable Development Goals, a concerted effort to remedy this is needed, particularly in the marine environment. We hope that preliminary results such as those presented here will help spur on such development and provide an initial basis for comparison with biological data and biodiversity estimates. Here, we compared geomorphon richness with examples of terrain attributes intuitively associated with morphometric diversity (and hence often with biodiversity). This showed that high morphometric diversity can occur in regions of high and low relative relief and ruggedness, but that low morphometric diversity seems to be associated with low values of these terrain attributes. Furthermore, we examined how geomorphon richness varies by marine landscape, confirming that fjords, the strandflat and marine hills and mountains exhibit the highest diversity.

Our analysis was limited to a single resolution, relatively coarse data set. This was a practical solution for analysis of a large area, encouraged by the useful results obtained by Sowers *et al.* (2020) with data of the same resolution. Following limited testing, we adopted fixed values for BRESS user-defined settings across the entire study area to gain a first impression of how successful the method might be. Further fine-tuning or splitting of areas may help make the classification truer to the real morphometric features present, for example by further reducing the effects of noise and better highlighting less distinct features. Since this is challenging for a large area, a more promising approach may be to

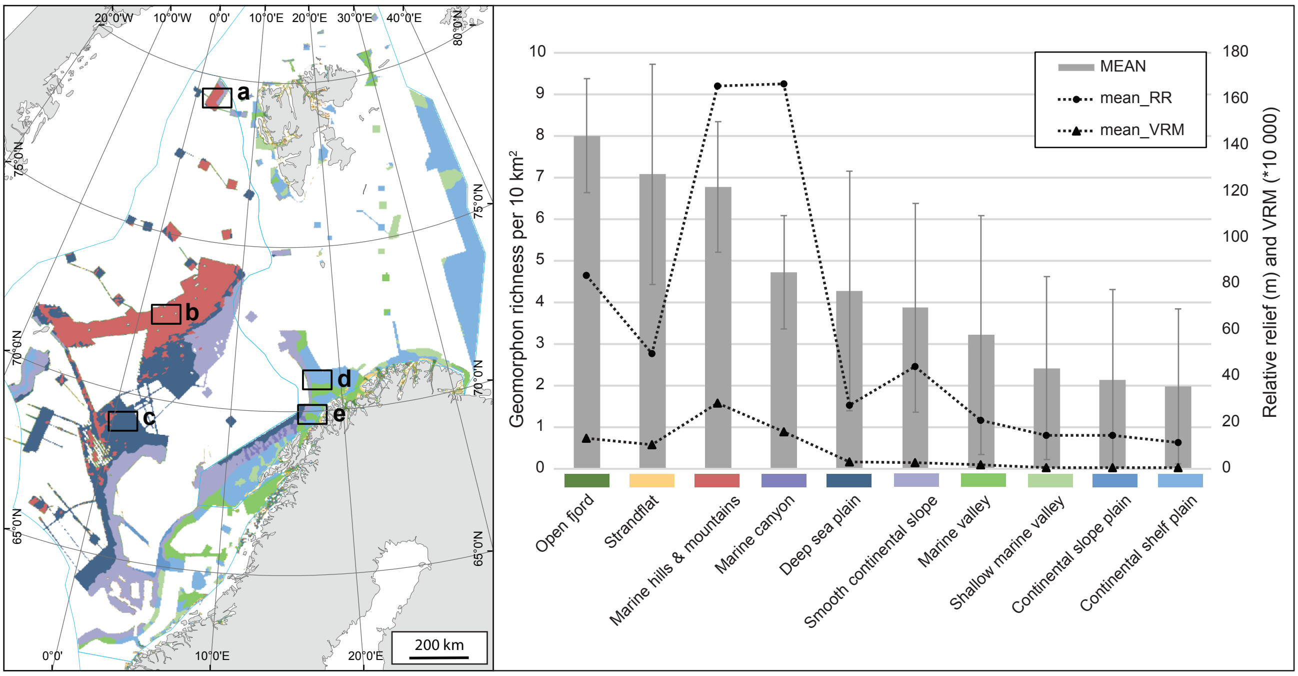

Fig. 3 Mean geomorphon richness per landscape type (error bars indicate standard deviation) and comparison with terrain attributes, relative relief (**RR**) and the vector ruggedness measure (**VRM**). Here, we show landscape types extracted for the study area. The full map, which is based on various sources of bathymetry data, is available at *https://www.mareano.no* and *https://www.ngu.no*. For further details on the landscape types, see *https://www.ngu.no/Mareano/Landscape.html* and Elvenes (2014). Areas a–e are indicated for reference to Figs 1 and 2.

combine broad-scale analysis, such as that conducted here, with local analyses based on more detailed data. This local analysis could be completed for most of the Norwegian continental shelf where multibeam bathymetry data are available at 5 m resolution or better. BRESS user-defined parameters may need to be modified (via additional testing) to best identify morphometric features of interest at this scale. Data for deeper areas are generally available at 25 m or coarser, so there is considerable potential for a finer resolution analysis at the best available resolution, if the study area is split into manageable sections (informed by e.g. depth or slope change thresholds) or tiled for computation purposes. It is worth noting that this finer resolution analysis (as per Dolan *et al.* 2022) will likely result in a higher diversity of geomorphons for many areas and by extension will result in changes to the geomorphon richness results. Analysis of the best available resolution data is, however, required for geomorphological interpretation. We hope that incorporating algorithm-based detection of morphometric features will aid our geological interpretation moving forward and support a two-part approach to geomorphological mapping (Dove *et al.* 2016, 2020; Nanson *et al.* 2023). More accurate estimates of morphometric diversity would be an invaluable parallel output from these analyses, alongside metrics of other components of geodiversity, supported by additional data and interpretation.

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Author contributions

MFJD: Conceptualization, methodology, writing – original draft; LRB: project administration, writing – review and editing

Competing interests

The authors declare no competing interests.

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