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Delivering seabed geodiversity information through multidisciplinary mapping initiatives: experiences from Norway

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Abstract

Geology is a core component of two major multidisciplinary seabed-mapping initiatives in Norway (MAREANO, Marine Base Maps for the Coastal Zone). Helped by Norway's Nature Diversity Act, which acknowledges geological and landscape diversity alongside biodiversity, geological information has gained recognition nationally as part of an essential foundation for knowledge-based management, both in the coastal zone and offshore. Recently, international focus on the United Nations Sustainable Development Goals has led to the proposal of Essential Geodiversity Variables, a framework for geological (geodiversity) information, intended to stand alongside Essential Variables already defined for climate, biodiversity and oceans (limited to ocean physics, biochemistry, biology and ecosystems). Here, we examine to what extent map products from the Geological Survey of Norway generated under these multidisciplinary mapping initiatives fit within this framework of Essential Geodiversity Variables, and how well it is suited to information on marine geodiversity. Although we conclude that the framework is generally a good fit for the marine-relevant Essential Geodiversity Variable classes (geology and geomorphology), we examine opportunities for further highlighting quantitative geodiversity information. We present preliminary examples of substrate diversity and morphological diversity and discuss our experience of geological mapping as part of multidisciplinary initiatives. We highlight many benefits, which far outweigh any perceived or real compromises of this approach in monetary, practical and scientific terms.

1. Introduction

Geodiversity (Gray 2004) is generally regarded as the abiotic equivalent of biodiversity. Encompassing diversity in rocks, sediments, landforms and physical processes that underpin our environment, or more simply the diversity of geological and geomorphological phenomena in a defined area (Johansson *et al.* 2001), it is equally applicable in the marine realm as on land. Despite the term 'geodiversity' being coined almost 30 years ago (Sharples 1993; Wiedenbein 1993), the importance of geodiversity remains far less well acknowledged or celebrated (Gray 2021) than its biotic counterpart 'biodiversity', which gained far more political traction and public interest. Milton's (2002) statement 'Diversity in nature is usually taken to mean diversity of living nature …', which has been highlighted by several authors on geodiversity (e.g. Gray 2011; Brilha *et al.* 2018), remains just as true today, not least in relation to marine benthic habitats. Areas of rich plant and animal life on the seabed are frequently highlighted as biodiversity hotspots attracting the interest of nature conservation, whilst abiotic diversity, and specifically geodiversity, occurring over spatial scales beyond the camera lens, attracts less interest. Geodiversity and biodiversity are often linked, with diversity hotspots often co-located, but this is not always the case. Over nearly two decades of multidisciplinary seabed mapping in Norway, we have frequently observed, particularly from underwater video surveys, that changes in seabed geology coincide with changes in the associated benthic communities. However, we

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Abbreviations:

CMECS: United States Coastal and Marine Ecological Classification Standard
EGVs: Essential Geodiversity Variables
EOVs: Essential Ocean Variables
EVs: Essential Variables
GDCs: Geodiversity Components
IMR: Institute of Marine Research
MAREANO: Marine AREAl database for NOrwegian sea areas
NGU: Geological Survey of Norway
NiN: Nature in Norway
SDGs: Sustainable Development Goals

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also observe geological diversity that is important to highlight regardless of any known connection with biodiversity, as well as in areas where the seabed biota is undocumented.

Even though a connection between geodiversity and biodiversity is generally recognised, it is not so easily quantified, at least in consistent terms. This is partly linked to inconsistencies in the use of terminology and to what extent users perceive a need to align with concepts of biodiversity – see recent summary by Gray (2021) and insight into potential oversimplification issues from Erikstad (2013). Regardless of any ongoing terminology debates, there seems to be growing interest in using geodiversity as a surrogate for biodiversity (e.g. Hjort *et al.* 2012; Tukiainen *et al.* 2016), whilst potential cost savings and added value of such an approach have been noted in terrestrial settings (Bailey *et al.* 2017). This is a particularly attractive prospect in the marine realm, where accessibility and high associated costs with offshore surveys often limit the taxonomic inventories required to quantify biodiversity. By contrast, at least certain components of geodiversity can be mapped with the aid of remote sensing, preferably supplemented with limited *in-situ* observations (ground-truthing). In this sense, geodiversity mapping may offer an important foundation for identifying areas of conservation priority. This adds weight to the argument that geodiversity should be a priority for nature conservation (e.g. Chakraborty & Gray 2020).

Geodiversity has recently attracted attention in relation to the 17 United Nations Sustainable Development Goals (SDGs; e.g. Brilha *et al.* (2018)) with the development of the Essential Geodiversity Variables (EGVs) framework proposed by Schrodt *et al.* (2019) to supplement earlier Essential Variables (EVs) defined for climate, biodiversity and oceans (e.g. Bojinski *et al.* 2014). In relation to seabed mapping, we stress that the Essential Ocean Variables (EOVs) currently defined are based on The Global Ocean Observing System (2022), as such they do not include variables relevant to seabed geology but are limited to ocean physics, biochemistry, biology and ecosystems. Furthermore, they include only two variables of possible interest for seabed mapping in high latitudes: seagrass cover and composition as well as macroalgal canopy cover and composition, with coral reefs currently focussed on tropical rather than cold-water corals.

EGVs are defined by Schrodt *et al.* (2019) as abiotic state and process variables that relate to geology, geomorphology, soils and hydrology and which are:

1. Relevant to natural resource management and human well-being, conservation or ecology.
2. Complementary to the other suites of EVs.
3. Feasible and cost effective to measure.

Whilst soils and hydrology are less relevant in the marine environment, we can still use the remainder of the proposed EGV framework and assess its application in settings other than the terrestrial applications for which it was first conceptualised. The EGV concept is still relatively new, and we may expect some refinement and further development over the coming years, perhaps including adaptation towards seabed mapping. Establishing EGVs as part of a suite of EVs promotes the need to consider geodiversity as a core component of nature, alongside biodiversity, and to do so through consistent terminology. Without incorporating geodiversity, we risk undervaluing nature (Gray 2012) and may fail to recognise important geosystem services derived from geodiversity (Gray 2021).

Here, we aim to assess to what extent the major seabed-mapping initiatives in Norway currently deliver geodiversity information in relation to the EGV framework. We restrict our focus to map products published and/or developed by the Geological Survey of Norway (NGU). Specifically, we aim to:

- assess to what extent existing NGU marine geology products from Norway's multidisciplinary seabed-mapping initiatives fit into the EGV framework.
- provide some examples of how selected NGU products can better highlight geodiversity.
- discuss the extent to which mapping geology as part of multidisciplinary seabed-mapping initiatives helps delivery of geodiversity information and the relevance of the EGV framework to this.

2. Geodiversity as part of multidisciplinary seabed-mapping initiatives in Norway

Norway has made great strides in seabed mapping over the past couple of decades, benefiting from improvements in survey technology and IT infrastructure over the same period, which have been so fundamental in supporting the acquisition of increased knowledge of the seabed. Government and local or regional funding supports for these mapping initiatives have been substantial, reflecting the importance of coastal and offshore resources to the Norwegian economy. Here, we outline two of the largest initiatives currently underway, both of which NGU is a core partner.

2.1 MAREANO

The Norwegian seabed mapping programme MAREANO (Marine AREAl database for NOrwegian sea areas) started in 2005 with a focus on offshore mapping. The programme is government-funded and receives annual contributions from two ministries (The Ministry of

Trade, Industry and Fisheries and The Ministry of Climate and Environment) through the national budget. Since 2005, nearly 1.4 billion NOK (*c.* 135 million EUR) have been invested in MAREANO's marine mapping. MAREANO maps bathymetry, seabed substrates, biodiversity, habitats and pollution in seabed sediments. The multidisciplinary mapping is carried out by three collaborating institutions: the Norwegian Hydrographic Service (part of the Norwegian Mapping Authority), NGU and the Institute of Marine Research (IMR). Since 2005, the seabed has been surveyed using acoustic remote sensing (multibeam bathymetry, backscatter, water-column data and sub-bottom-profiler data), whilst geology, biology and chemistry have been mapped via *in situ* video surveys and physical sampling. As an example, seabed sediments (grain size) maps have been made for areas covering 270 000 km^2. Until 2010, the programme focussed its efforts on the Barents Sea, before moving to include the Norwegian Sea and areas around Svalbard. In 2019, MAREANO mapped about 69 000 km^2 in the deeper parts of the Norwegian Sea, including several areas on the mid-Atlantic Ridge using acoustic remote sensing. Follow-up *in situ* surveys are planned in the coming years to ground truth the acoustic data and acquire more detailed visual and acoustic data using underwater survey platforms. In 2022, MAREANO is also starting work in the North Sea.

MAREANO produces a range of thematic map products. Geological maps (e.g. Bellec *et al.* 2017) include seabed substrate maps such as acoustic backscatter, grain size, sedimentary environment and genesis (Fig. 1), intended for use at regional scales of

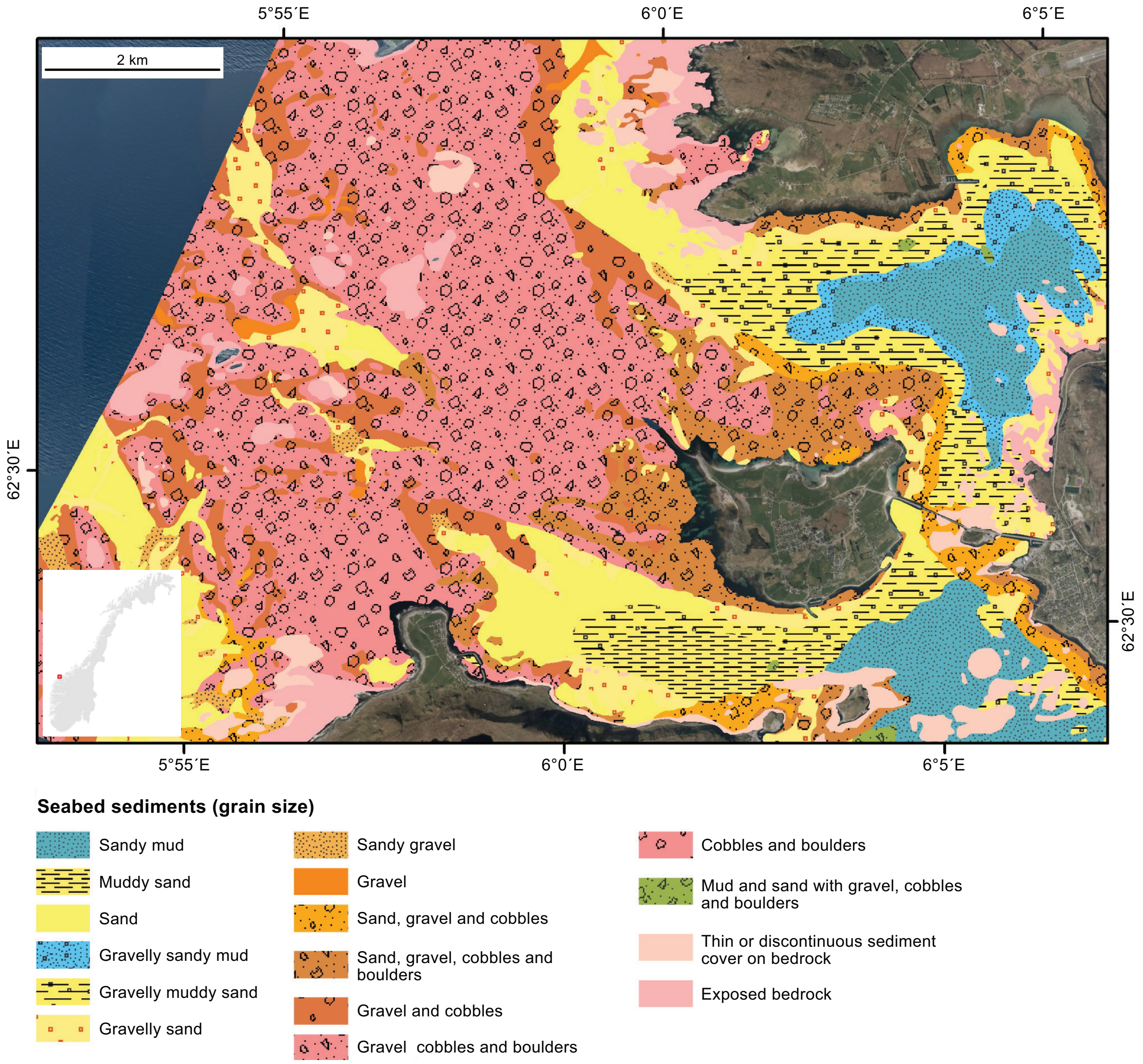

Fig. 1 Example of detailed (1:20 000) seabed sediments (grain size) map from the southern part of Nordre Sunnmøre, one of the pilot areas for Marine Base Maps for the Coastal Zone. Background image: Norge i bilder WMS from *www.geonorge.no.*

1:100 000–1:250 000, depending on the volume and quality of survey data in each area. Geomorphological maps show the distribution of marine landscapes and landforms, including cold-water coral mounds predicted from topography. A suite of maps depicting geochemical composition and characteristics are also produced. The methods used for the production of these map products are outlined by Bøe *et al.* (2020). The geological maps are used further to develop benthic habitat maps, which fuse biological, geological and oceanographic information. MAREANO results are disseminated free of charge through *www.mareano.no, www.ngu.no* and many other portals, and data and results can also be obtained through *www.geonorge.no.* The multidisciplinary maps and data generated by MAREANO contribute to the scientific knowledge base for national ocean management plans. They are used widely by management institutions, petroleum and fisheries industries, academia and the public.

2.2 Marine base maps for the Coastal Zone

From 2020 to 2022, the Norwegian Mapping Authority, NGU and IMR are also collaborating on another coordinated pilot project for seabed mapping and data distribution: Marine Base Maps for the Coastal Zone. The methodology is partly based on previous marine base-map projects by NGU (Elvenes *et al.* 2019; Bøe *et al.* 2020) and draws on experience from MAREANO as well as previous work of the partner institutions. The project produces a range of hydrography, geology, biology, nature type and geochemistry maps in three example areas to lay the groundwork for a national coastal mapping programme. A proposal for extending the pilot to a national programme, which will map approximately 100 000 km^2 of seabed in coastal Norway, was delivered to the Norwegian government in 2021 with a view to starting in 2023. This mapping is estimated to take 15–20 years within the proposed framework at a cost of around 4 billion NOK (*c.* 400 million EUR). Amongst the most notable conclusions from a recently conducted socio-economic analysis of this proposal, the financial investment is very profitable. Furthermore, when the mapping is complete, the invested amount can be saved every year due to cost savings and smart decisions informed by comprehensive baseline knowledge of the seabed. In other words, the mapping will pay for itself over time and would mean a financial loss if not conducted.

Geological thematic maps from Marine Base Maps for the Coastal Zone are like those produced in MAREANO spanning geology (grain size, sedimentary environment and genesis; Fig. 1) and geomorphology (landforms). They are produced at a finer scale of 1:20 000 through expert interpretation of all available data providing the necessary higher level of detail for coastal management. Additionally, several applied thematic maps including anchoring conditions, diggability and accumulation basins have been developed from the main geological map products. Surface sediment samples and short cores from accumulation basins are analysed for organic and inorganic components to evaluate levels of contamination and temporal evolution (past 100–200 years).

The geological maps are used further within the project to produce nature-type maps according to Nature in Norway (NiN; see section 2.3). The geological information is used alongside hydrographic and oceanographic variables to provide environmental predictor variables, which are combined with classified observations of major and minor nature types (determined from biological and environmental characteristics) from video data.

All geological maps are published online at *www.ngu.no* and are also available via other national and international portals, including *www.mareano.no*. Some examples of geological map products are shown in Figs. 1 and 2. Other multidisciplinary results from the pilot project are available from The Norwegian Mapping Authority and IMR. Whilst the pilot project is active, they are also available through the dedicated portal *marinegrunnkart.avinet.no*.

2.3 Other initiatives in Norway relevant to seabed geodiversity

Scandinavian countries have generally been recognised as forerunners in the promotion of geodiversity, with the work of Johansson (2001), which highlights the (terrestrial) geodiversity of the region, being highly praised by Brilha *et al.* (2018). In Norway, the Nature Diversity Act (Ministry of Climate and Environment 2009) came into force in 2009. This Act aims to promote conservation and sustainable use of the 'full range of variation of habitats and landscape types'. It means that geological and landscape diversity have been officially recognised alongside biological diversity, but also that information on their spatial distribution must exist for successful implementation of the Act. The need for this type of information began to be addressed through initiatives such as The Norwegian Programme for Mapping of Marine Habitats (Bekkby *et al.* 2011), which ran from 2007 to 2019. This National Programme was designed to provide information on nature types selected under DN Handbook 19 (Direktoratet for naturforvaltning 2007). This programme included aspects of geological mapping, geological features and geodiversity, with NGU contributing maps of carbonate (shell) sand occurrences and ice marginal deposits.

The need for information related to the Nature Diversity Act also led to the development of NiN, to provide a unified framework for delivering the required knowledge. The NiN framework facilitates classification and description of nature across terrestrial, freshwater and

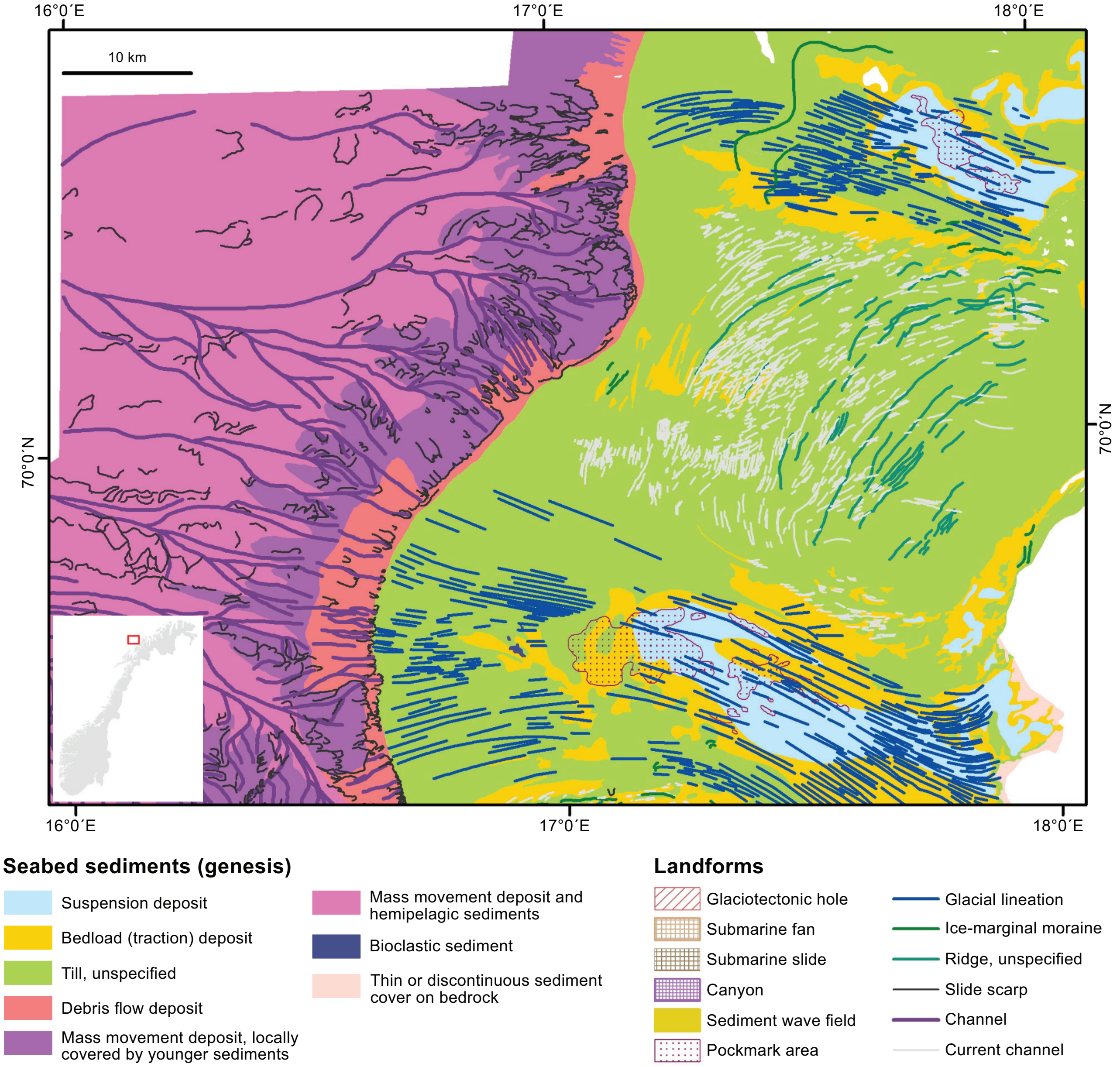

Fig. 2 Example of regional scale (1:100 000) seabed sediments (genesis) map produced for MAREANO at Malangsgrunnen and surrounding area. Interpreted landforms are overlain.

marine systems and has become the national standard for publicly funded mapping initiatives. Whilst the majority of the NiN documentation is in Norwegian (Halvorsen *et al.* 2016), the approach was recently summarised for the international scientific community by Halvorsen *et al.* (2020), who present NiN as an implementation of the broader 'EcoSyst' framework. NiN includes several mechanisms for describing geological and geomorphological attributes, which are intended to feed into various proposed EVs, including EGVs. Whilst NiN has provided many opportunities and raised the bar for nature-type mapping, there remains scope for further development and practical testing of the system, especially in marine environments. Erikstad (2013) discussed geodiversity as a comprehensive framework for management and conservation issues with special reference to Norway, citing NiN and similar approaches as part of the solution. Through this discussion, the importance of maintaining geodiversity as a descriptor rather than merging it with management value is highlighted. This distinction is important across all aspects of NiN and extends nicely to geological mapping within the ongoing projects we focus on here.

3. EGVs – a new concept for seabed mapping?

The EGV concept (Schrodt *et al.* 2019) highlights the need for consistency and proposes four main classes for organising geodiversity information: geology, geomorphology, soils and hydrology. Many of the staple products of geological surveys and related institutions around the world are easily represented under these themes. However, these traditional products may be overlooked by users who perceive their interest to be focussed on other aspects of nature, for example, biodiversity. By elevating geological information to the same level as other EVs through EGVs, Schrodt *et al.* (2019) help make geological information more visible in key global management arenas such as the United Nations Sustainable Development Goals. Here, we examine the extent to which information relating to each EGV class is already provided by NGU's marine geological mapping, through initiatives like MAREANO and Marine Base Maps for the Coastal Zone and evaluate scope for further development.

In Table 1, we have organised existing marine geological map products from NGU under the EGV framework to assess the extent to which we are already mapping EGVs. The EGV classes most relevant to seabed geology are 'Geology and Geomorphology'. Under the EGV class 'Geology', NGU's seabed map products fit naturally under 'Unconsolidated deposits', with multiple map products providing a range of information per class. Under current seabed-mapping initiatives, we do not specifically produce maps relating to 'Hardrock, fossil & mineral distribution' or 'Geophysical processes', although some existing map products from NGU are somewhat related to these topics. Under the 'Geomorphology' EGV class, we deliver several products, which fit well as 'Landform distribution' EGVs. We have indicated the management or policy relevance for each of the EGV classes based on those that NGU currently map for seabed-mapping initiatives. There is potential for developing additional, geodiversity-relevant map products related to several EGVs, which will be discussed further in section 3.1. Several maps planned for future production by NGU (e.g. sediment thickness maps, volume of sand or gravel deposits) will also provide additional relevant map products.

The EGV classes for 'Soils' and 'Hydrology', proposed by Schrodt *et al*. (2019), are less relevant to marine geology and are not included in Table 1. Soil properties that would be important on land are generally absent and the relevant geological attributes, for example, chemistry and physical state, are captured under 'Geology – unconsolidated deposits'. Hydrology too is largely irrelevant in the marine environment, except for submarine artesian wells, which are not mapped by NGU.

According to Schrodt *et al.* (2019), EGVs should be (1) relevant to natural resource management and human well-being, conservation or ecology, (2) complementary to the other suites of EVs and (3) feasible and cost effective to measure. Generally, all our seabed maps relating to geology and geomorphology fulfil criteria (1) and (2). This is the very reason they are produced by NGU and are essential outputs funded through the major seabed-mapping initiatives. These geological map products form the basis for several applied or derived map products tailored specifically for various users and for nature-type mapping and management of the ocean areas.

Whilst the EGV classes proposed by Schrodt *et al.* (2019) are comprehensive, we also note scope for including an anthropogenic EGV class. Such information may be adequately highlighted separately on land and may have been deliberately omitted as an EGV class for this reason or because it is not purely related to geodiversity. However, in the marine realm, which can tend to be 'out of sight, out of mind', there may be benefits to including this class under the EGV umbrella. We have added some example features of geological relevance for further consideration, which are particularly relevant to EGV criterion (1) in the seabed mapping.

Criterion (3) takes on a new meaning in the marine realm as compared to land. Despite recent technical advances, seabed mapping is still an expensive exercise, particularly offshore, where large research vessels are needed. Approximately 1.4 billion NOK (*c.* 135 million EUR) have been invested in MAREANO (offshore) at a cost of *c.* 5000 NOK/km^2 – nearly 500 EUR/km^2 (all products included, i.e. hydrography, geology, biology, habitats and chemistry), whilst estimates for the proposed coastal mapping programme are around 50 000 NOK/km^2 – nearly 5000 EUR/km^2. It should be noted that the coastal mapping delivers a much larger suite of map products and is far more detailed than the MAREANO mapping (scale 1:20 000 versus 1:100 000 and coarser) and that multibeam surveys are considerably more costly in shallow waters.

On land, whilst detailed geological mapping still requires considerable effort and fieldwork, a lot of first-pass geodiversity information can now be gained from satellite data and other relatively low-cost remote sensing and observations. By contrast, most of the seabed remains hidden from satellite imagery, requiring acoustic or other remote sensing methods to map the underwater topography and other acoustic indicators of seabed geological attributes (e.g. multibeam backscatter and sub-bottom profiler data). This generally requires access to suitable boats or other survey platforms which are expensive, especially in offshore and Arctic (ice-influenced) waters.

The mapping methods vary in their efficiency, cost-effectiveness and feasibility by water depth and practical considerations. Furthermore, because acoustic remote sensing provides only a proxy to seabed geology,

Table 1 Comparison of Essential Geodiversity Variables (EGVs; Schrodt et al. 2019) with existing marine geological map products from the Geological Survey of Norway (NGU).

Original (from Schrodt *et al*. 2019)				Marine (this paper)	
EGV class[1]	EGV	Definition	Examples	Seabed examples[2]	Marine policy or management relevance
Geology	Hardrock, fossil and mineral distribution	Geological materials and their spatial distribution	Natural resources (e.g. coal, gas and ore)	NGU bedrock maps cover land and some sea areas[3]	Sustainable management Spatial planning Blue growth Green transition Nature conservation/ protection Pollution management Geohazard assessment Climate change
	Unconsolidated deposits	Surface distribution of parent materials resulting from geomorphological processes	Distribution or scarcity of materials (e.g. sand). Dynamics of surface materials (e.g. sedimentation).	**Standard products:** Seabed sediments (grain size) Seabed sediments (genesis) Sedimentary environment (present day erosion/deposition areas) Accumulation of organic carbon Sedimentation rates Maps of chemical elements and compounds (organic and inorganic) Bioclastic sediments (offshore) Likely occurrences of coral reefs (offshore) Shell-sand deposits (coastal areas) Chemistry/pollution Gas seeps **Applied/derived map products:** Sediment fractions Sand and gravel resources Anchoring conditions Diggability Accumulation basins Submarine slides NiN-specific environmental variables Translated maps (e.g. EMODnet classes)	
	Geophysical processes	Variability of the intensity of geophysical processes	Earthquakes Volcanic eruptions Earth radioactivity Thermal energy Land subsidence	No specific maps[4]	
Geomorphology	Landform distribution	Landforms and their spatial distribution	Distribution of landforms resulting from erosion, transport and sedimentation Dynamics of geohazards	Landforms (geomorphology) Marine landscapes (physiographic regions) Submarine landslides Translated maps (e.g. EMODnet landforms)	Sustainable management Spatial planning Nature conservation/ protection Geohazard assessment
Human influence[5]	*Anthropogenic*	–	–	*Information on several human activities, e.g. dumping, dredging and trenching are currently included in the seabed-sediment maps (grain size and genesis) but could be extracted as separate themes*	*Human impact* *Nature conservation/ protection* *Pollution management*

[1] EGV classes Soil and Hydrology proposed by Schrodt *et al.* (2019) are not included in this table. [2] Based on NGU maps produced for MAREANO/ Marine Base Maps for the Coastal Zone. Maps are available from *https://www.ngu.no/en/topic/map-viewers,* with options for download and map services also available. [3] Further development of these products is not part of current seabed-mapping initiatives. [4] Some NGU products are related to geophysical processes but fall more naturally under unconsolidated deposits or geomorphology. [5] Potential 'human influence' EGV class added, which is not part of Schrodt *et al*.'s original EGV classes.

it must be backed up by ground-truth data such as video and physical samples. The number of observations required is linked to the complexity of the area and the level of mapping detail required (spatial and thematic). This is generally a trade-off between available funds, information requirements and practical considerations. In the case of MAREANO and Marine Base Maps for the Coastal Zone, a further consideration is that the ground-truthing campaigns are designed not only to meet the needs of geological mapping (verifying backscatter signatures, observing topographic features, etc.) but also to provide information for biological and habitat mapping as well as geochemistry. This multidisciplinary approach facilitates cost-effective use of resources and paves the way for multiple map products spanning many EVs, as well as collaboration on products of common interest, for example, habitat maps and geochemistry, ultimately delivering a comprehensive suite of information for management and other users. The multidisciplinary mapping approach inevitably leads to compromises as compared to single-objective mapping, but overall, our experience is that the benefits (also economic) far outweigh the limitations (see also section 4).

3.1 Highlighting geodiversity using EGVs

Besides seeing how well our products fit into the EGV classes and provide a basis for geodiversity related information, we are interested in how far the EGV framework goes towards highlighting geodiversity *per se.* At face value, the framework seems to highlight relevant information from which one can gain insight into geodiversity through geological mapping but is not prescriptive as to how to provide geodiversity information directly in the form of (semi-) quantitative indices. We are mindful of comments by Erikstad (2013) who, in discussing the need to measure diversity, points out that simple solutions such as counts of different units can be problematic due to oversimplification. This may be particularly concerning if these metrics are used outside the original intended context and used to associate value. We note that the EGV concepts appear to build on earlier work by several of the authors who contributed to Schrodt *et al.*'s (2019) paper where the term 'Geodiversity Components' (GDCs) is used to refer to quantified geofeatures (Bailey *et al.* 2017) across similar themes (Geofeature categories) via calculations of coverage, richness or other dimensions. GDCs are inherently tied to the scale at which these various measures of geodiversity are studied. Calculations applicable to mid- to broad-scale geodiversity in the context of land management are discussed by Pellitero *et al.* (2015) who summarise many of the approaches reported in previous literature. One of the most common methods measures is richness per unit area, which has also been used in marine geological applications (e.g. Kaskela & Kotilainen 2017) for various components of their geodiversity assessment.

Through various projects, NGU has recognised the need to adapt traditional geological map products to end users and for onward use. Several examples of applied maps derived from categorical maps of surficial sediments are reported by Elvenes *et al.* (2019; e.g. anchoring conditions, diggability, etc.). Whilst none of these specifically highlight or quantify geodiversity yet, they, nevertheless, demonstrate a need to translate geological information into more readily digestible formats for a variety of end users. Figure 3 summarises some

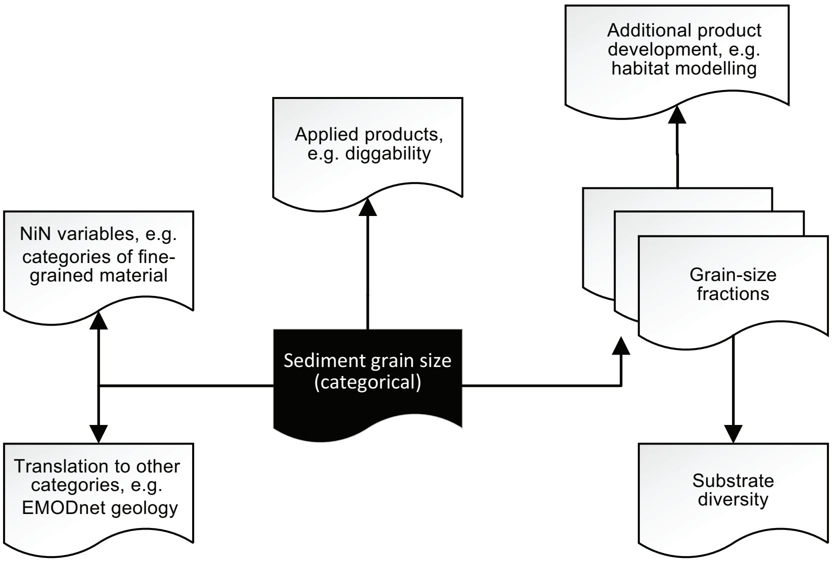

Fig. 3 Conceptual diagram showing how applied map products may be developed from a traditional marine geological map (categorical sediment grain-size map). These applied products may be better suited to onward use for various purposes. They illustrate one way in which we may make essential geodiversity variables (EGVs) even more relevant for sustainable development.

ways in which a traditional sediment grain-size map may be converted into alternative forms to suit a variety of purposes. Whilst we recognise potential risks of overgeneralising geological information by reducing it to estimates of component parts of geodiversity (or GDCs), we also recognise a perhaps greater risk of not making it accessible enough by letting it remain hidden in traditional map products, which may not match the needs of an expanding suite of end users. The development of additional map products is an ongoing process at NGU and has recently included several that specifically target geodiversity. Here, we preview two of these maps, which highlight substrate diversity and morphological diversity.

3.1.1 Substrate diversity

The difference in inherent grain-size diversity between grain-size categories is well known to a geologist familiar with a given system of grain-size classes, such as those used by NGU (Bøe *et al.* 2010; Bellec *et al.* 2017; Elvenes *et al.* 2019; Geological Survey of Norway 2022). However, the differences in relative composition, and, hence, the likely diversity of substrates available within each of the different sediment polygons, may not be clear to all end users.

Similarly, the spatial variation of a particular grain-size fraction (e.g. mud content) may be obscured by traditional classifications and map symbology. Conversion of the original categories to a suite of maps showing the spatial distribution of constituent fractions can be invaluable for many applications, aiding onward use of the geological maps. For example, van Son *et al.* (2020) used the proportion of hard substrate estimated from NGU's maps to model the spatial distribution of kelp biomass. This work used interpolated estimates of the sediment-fraction distribution (using kriging); however, we have found that for many applications, including MAREANO biotope modelling, a simple translation per polygon is sufficient. A lookup table listing the fractional content per class is provided for reference (see Supplementary File S1) including all classes used to date in NGU maps; this updates the version used in van Son *et al.*'s (2020) study. Alternatively, we may translate categorical grain-size maps into other categorical schemes for onward use, for example, NiN fine-material content classes (Norwegian Biodiversity Information Centre 2022), or to facilitate harmonisation with international data, for example, EMODnet geology substrate classes (Kaskela *et al.* 2019; Vallius *et al.* 2020).

Conversion of traditional maps to new formats also provides opportunities for highlighting relationships between sediment properties and aspects of geodiversity, which may, otherwise, be rather hidden. For example, following conversion of our categorical sediment map to component fractions, we can quantify substrate diversity by calculating the entropy between layers. Although often applied to probability layers, for example, for quantifying between class uncertainty in habitat (Dolan *et al.* 2021) or soil mapping (Hengl *et al.* 2017), the entropy method is generic and can be applied to our estimates of sediment fractions derived from the categorical sediment map. Figure 4 illustrates how NGU's categorical grain-size maps can be translated into constituent fractions and used to produce a map of substrate diversity. Since Shannon Entropy has previously been applied as a measure of geodiversity between adjacent units within a neighbourhood radius (e.g. Read *et al.* 2020), we emphasise that here we are determining the entropy of the values of co-located pixels between our five overlapping raster layers representing the fractions. Whilst a neighbourhood version could theoretically be applied to a categorical sediment map, it would fail to yield meaningful information on substrate diversity since the classes themselves have intrinsic diversity. Such an analysis would thereby only yield class diversity, highlighting transition zones between categories.

3.1.2 Morphological diversity

Similar concepts apply to landforms and other geomorphic features, and it is important to recognise that landform diversity, whilst often linked to substrate diversity, may also be independent. For example, where landforms are covered by recent deposits of fine material, or where landforms (or bedforms) occur at finer scales than the changes in sediment properties, for example, sandwave fields. The mapping of landforms is often rather selective, based on project demands, mapping traditions, map scale and the possibility of reliable interpretation from available data and observations. The degree of generalisation of landforms is often not standardised from project to project, nationally and even less so internationally, making harmonisation challenging, for example, for EMODnet (Vallius *et al.* 2020). To help standardise geomorphological mapping, NGU has recently contributed to a two-part classification system for geomorphological features led by the British Geological Survey (Dove *et al.* 2016, 2020), which separates morphological classification (part 1) from geomorphological interpretation (part 2). The applied study by Nanson *et al.* (2022) further highlights the many benefits to such an approach, which we will not repeat in detail here. However, we note how the two-part approach lends itself naturally to opportunities to map morphological diversity separately from the diversity of geomorphic features, which are tied to specific geological processes.

NGU is working to further develop this two-part approach with particular focus on glacial landforms. Additional work aims to align the two-part classification with the recently revised landform list for NiN (part of the NiN descriptive system), which lists landforms by

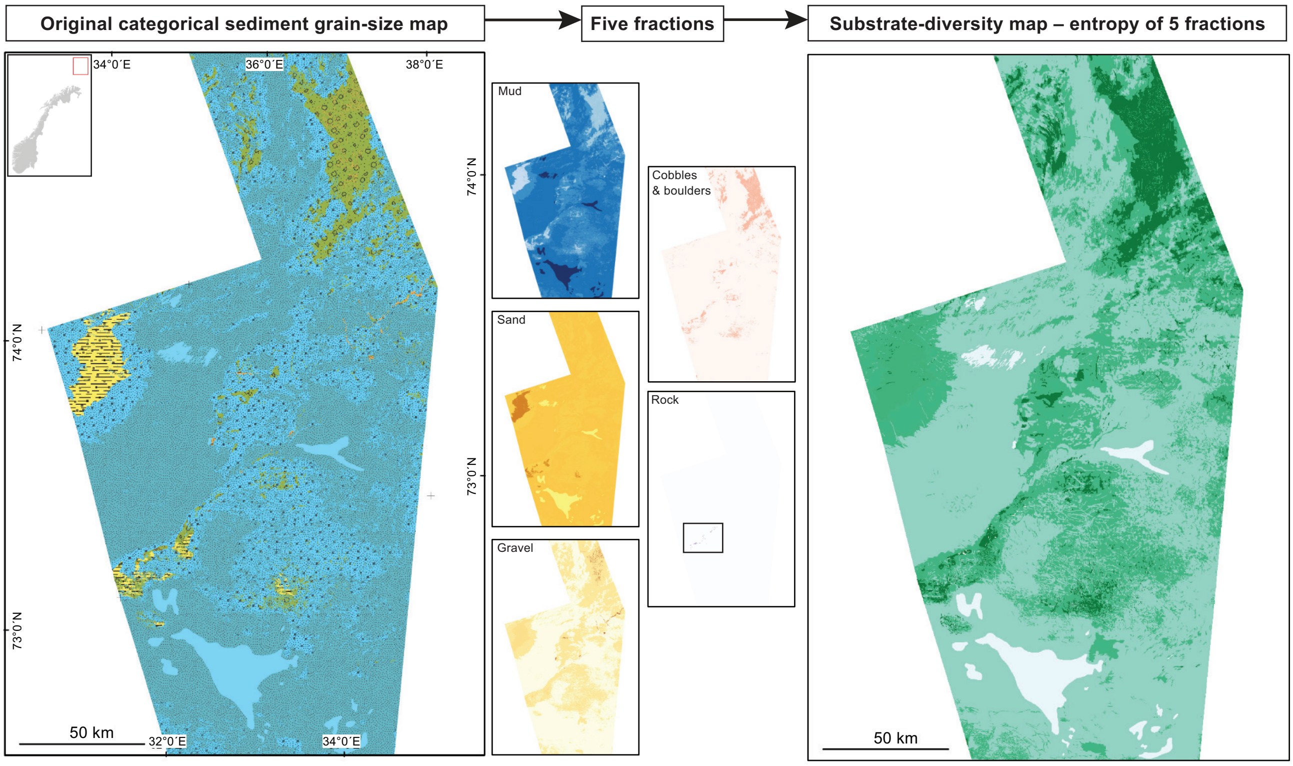

Fig. 4 Example showing how Geological Survey of Norway (NGU)'s sediment grain size map may be converted to five component fractions (mud, sand, gravel, cobbles, and boulders and rock), where darker colours indicate higher percentage content. Note that in this figure, rock is only non-zero within the black box where it occurs very locally (few pixels only). A preliminary substrate diversity map is computed from these fractions using the entropy between the five fractions; darker colours indicate higher diversity. In the sediment grain-size map, blue shades indicate mud-rich sediments, yellow indicates sandy sediments and green indicates coarser mixed sediments. The full legend is available at *www.ngu.no/Mareano/Grainsize.html* and in Supplementary File S1.

geological process and will be published in the next version of NiN (expected 2023). This is a far more comprehensive landform list than that currently implemented in NiN or by NGU and provides a solid foundation for further work.

Morphological diversity is included in the GDCs used by Bailey *et al.* (2017) who employed geomorphons (Jasiewicz & Stepinski 2013) to map landform units. The geomorphon approach uses computer vision techniques to analyse raster digital terrain models and is well suited to automated mapping of morphometric units, offering several advantages of earlier approaches (e.g. Fisher *et al.* 2004). Bailey *et al.* (2017) used the geomorphon classes to obtain coverage estimates of each morphometric type per unit area as a predictor of biodiversity. Coverage estimates are a perfectly viable form of geodiversity metric for seabed mapping too, but we argue that a more intuitive impression of the spatial variation of morphometric diversity can be gained by using morphometric richness estimates at spatial scales relevant for various applications.

Using the BRESS toolbox (Masetti *et al.* 2018), which presents an implementation of the geomorphon method specifically targeted to bathymetry (and optionally reflectivity) data, we have explored the potential of this method for mapping morphometric features in a variety of geological settings. The results are encouraging, across a range of bathymetric data resolutions, and using various options for the number of morphometric classes. Sowers *et al.* (2020) recently used BRESS to show how geomorphons can be used to classify coarse (100 m) bathymetry data to help map broad scale geomorphology linked to the United States Coastal and Marine Ecological Classification Standard (CMECS; Federal Geographic Data Committee 2012).

In Fig. 5, we show how geomorphon classification can be applied to data of different resolutions to gain a nested impression of morphometric features. This may aid expert interpretation of landforms, or as is our focus here, these classifications may be used to compute geomorphon richness (and optionally patchiness). This may allow us to highlight morphological diversity in a more complete way than via traditional (selective) landform mapping (Fig. 5a).

Our example includes geomorphon classification applied to two resolutions of the same data. We use the 10-class option as per the original method of Jasiewicz & Stepinski (2013) and employed by Bailey *et al.* (2017), though other options are available via BRESS. Geomorphon settings (inner radius 50 m, outer radius 200 m,

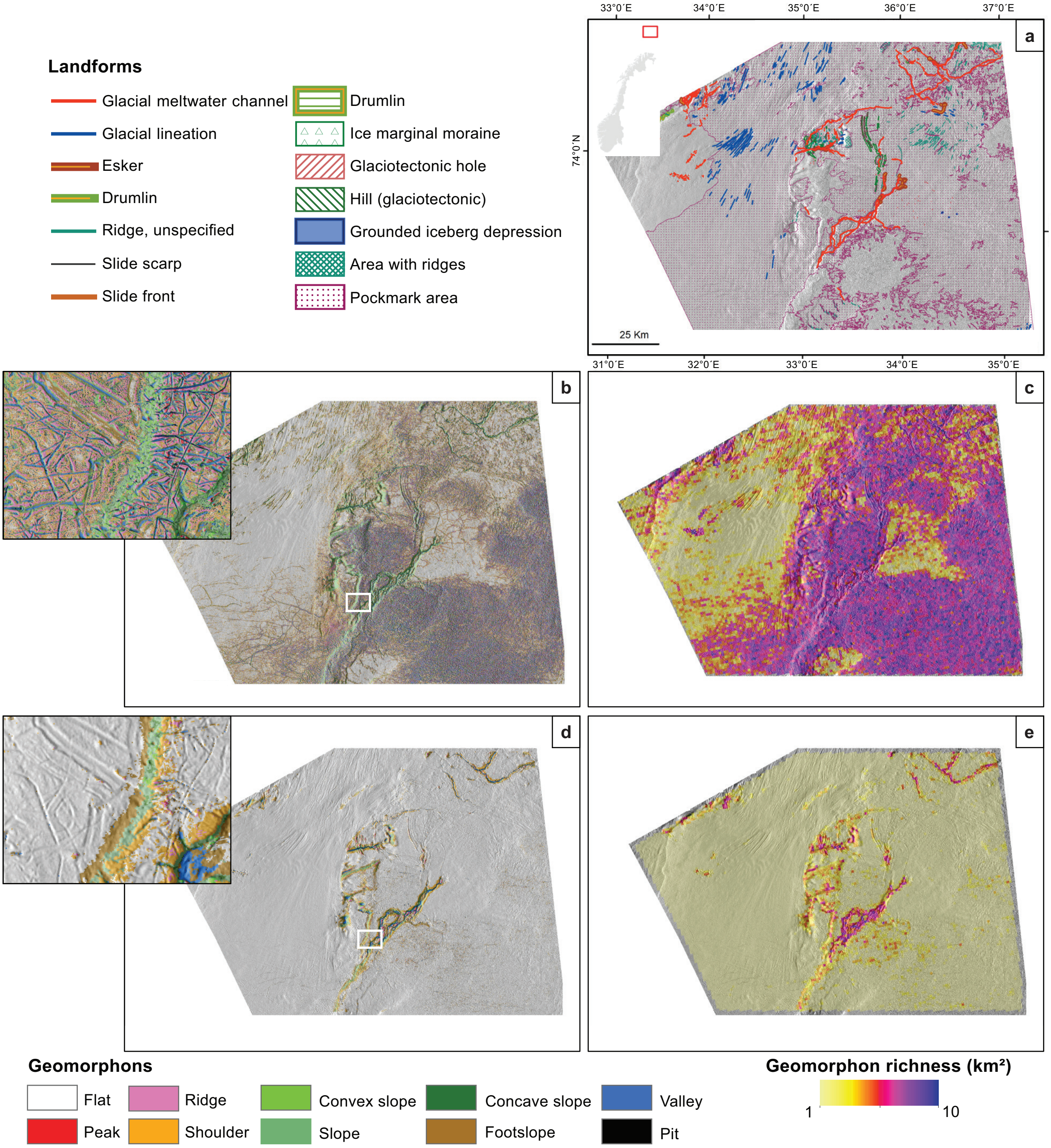

Fig. 5 Example area in the Barents Sea mapped by MAREANO, showing traditional landform mapping alongside morphometric feature classification using geomorphons at fine and broad scales. (**a**) Standard Geological Survey of Norway (NGU) landform map (offshore), which includes a combination of polygon and line features mapped by expert interpretation of bathymetric and supporting geological data. (**b**) Fine-scale geomorphon classification of 5 m bathymetry data. (**c**) Geomorphon richness showing the number of fine-scale geomorphon classes (from b) per km^2 (5 m grid). (**d**) Broad-scale geomorphon classification of 50 m bathymetry data. (**e**) Geomorphon richness showing the number of broad-scale geomorphon classes (from d) per km^2 (50 m grid).

other settings default) were first used to capture local features visible in the 5 m bathymetry data (Fig. 5b). Second, we applied a broader scale geomorphon classification to 50 m bathymetry data (resampled from the 5 m data using bilinear resampling). Here, we used the same length scales as used by Sowers *et al.* (2020; inner radius 300 m, outer radius 1500 m), adapted for a 50 m bathymetry grid, with other settings as default (i.e. no adaptation of the flatness parameter, as adjusted by Sowers *et al.* (2020)). Examining Fig. 5b (and inset), we see that fine-scale features, including iceberg ploughmarks and pockmarks, are effectively captured by the geomorphon analysis using local settings. Larger features, including the prominent glacial meltwater channels, are delineated by the broader scale analysis shown in Fig. 5d. The interpreted landform map (Fig. 5a), by contrast, includes selected features spanning these two scales. It links mappable morphological units to the geological process that created them, a step that requires expert interpretation and supporting data sets, for example, sub-bottom profiler data. Only those landforms in which MAREANO and NGU maps as standard are included, and only where sufficient information exists to determine their origin. Note that individual pockmarks are not mapped due to their immense numbers (Rise *et al.* 2014), but large areas of pockmarks are delineated in NGU maps as polygon features. Also, iceberg ploughmarks are not delineated in NGU maps since they are so widespread, diverse in form and scale, and often overlapping (e.g. Bjarnadóttir *et al.* 2016). Whilst the landform map gives invaluable geological information, it does not provide such a good basis for assessing morphological diversity as the morphometric features mapped using geomorphons, which can also serve as a valuable complementary map product.

The variety of morphometric features (geomorphon classes) within a given analysis neighbourhood can provide a measure of morphological diversity (richness). We use the explicit term ‘geomorphon richness’ here to avoid confusion. Several studies, across various applications, have used focal statistics for similar diversity estimations; however, our testing confirms that for focal analyses using larger neighbourhoods, the results become dominated by artefacts associated with the analysis window itself. This effect was noted by Wilson *et al.* (2007) in relation to terrain attributes and is just as applicable here. Whilst the roving window approach using focal statistics may be successful in some applications (e.g. Kaskela & Kotilainen 2017), the approach presented here is less computationally intensive or prone to artefacts, aiding analysis across many scales.

We convert the BRESS geomorphon output to integer, applying a majority filter to the results before computing diversity (this eliminates single pixels of a particular class, which are generally of little practical value). By overlaying a fishnet at the scale of interest, we can then extract the variety of geomorphon classes within each grid cell using zonal statistics. Here, we show results using a 1 km grid (Figs 5c, e), which provides an overview of geomorphon diversity (richness) at the mesoscale, *sensu* Greene *et al.* (1999) within the study area. For megascale analyses, such as a national level, summaries at a larger (e.g. 10 km) grid scale may be more suitable. The raster output from the zonal statistics can be set to the desired resolution for onward use. By default, the cell size is the same as the input raster.

In Norway, due to military restrictions on bathymetry data within the 12 nautical mile territorial boundary, 50 m analysis offers the minimum practical size for unified analysis of geomorphons on a national scale. This will fail to capture fine-scale features and, hence, their diversity. However, as we see from Fig. 5e, many important larger features are still captured, and this approach can give a very good indication of morphometric diversity when applied to larger data sets.

Further development of this geomorphon-based approach is ongoing at NGU, including examining ways in which it may support landform mapping, but initial results are promising. Results to date also suggest that the morphometric features detected using similar distance settings are consistent across data resolutions, depending on the information content of the data (i.e. coarse data cannot detect small features). In addition to providing a basis for diversity assessments, geomorphon-based morphometric classification provides a useful complement to the interpreted landform map. It may be used for onward product development, for example, habitat mapping (Wyles *et al.* 2022), or to aid the planning of ground-truthing cruises. Where we find high morphometric diversity and other environmental diversity, we may expect greater biodiversity and may, therefore, require greater sampling effort (van Son *et al.* 2015).

4. Discussion

4.1 Multidisciplinary mapping and EGVs

In this section, we reflect on how our multidisciplinary mapping programmes have helped map Norway’s seabed geology and geomorphology, thus delivering EGV-relevant information (Table 1). NGU’s partnership with collaborating institutions (Norwegian Mapping Authority and Institute of Marine Research) has been invaluable in both MAREANO and the Marine Base Maps for the Coastal Zone pilot. Working under the same programme umbrella allows planning, execution and delivery of map products to be aligned, as well as meeting the needs of multiple end users. For instance, the geological mapping is very much dependent on multibeam echosounder data (bathymetry, backscatter and water column data). By partnering with the Norwegian Mapping Authority, who has the overall responsibility for this data acquisition and bathymetric data processing, we gain better quality data, which can be used for multiple purposes. Similarly, through the partnership with NGU and IMR, the Norwegian Mapping Authority (traditionally focussed on safety of navigation) gains insight into bathymetric data quality issues important for geological interpretation and use in habitat mapping, which may be irrelevant for hydrography. Examples could be data artefacts that lead to misleading terrain attributes (Lecours *et al.* 2017a, 2017b) or overenthusiastic data cleaning, which obscures real morphological features in deeper waters. Additionally, fuller use of backscatter and water-column data are made through partnerships. The backscatter data are an invaluable proxy to sediment type (given sufficient ground truthing) and fundamental to the development of good geological maps (which, in turn, feed into habitat and nature-type maps). Backscatter-processing expertise and links to international initiatives for improving data quality, for example, GeoHab backscatter working group (Lurton & Lamarche 2015), are more accessible to the Norwegian Mapping Authority, thanks to NGU's involvement. Water-column data are not only used to detect gas seeps, which themselves are an important nature type under NiN, but also of interest for the oil and gas industry and important for the study of natural pollution and links to climate change (Ruppel & Kessler 2017).

Fieldwork is more efficient and resource-effective through multidisciplinary cruises rather than multiple surveys for different objectives. Video surveys are jointly planned, and data are shared for geological and biological interpretation. Likewise, some samples are shared to meet different objectives (e.g. shared grab sample for sediment ground truthing and infauna sampling; shared multicore deployments for organic and inorganic chemistry and microplastics) making efficient use of ship time.

Additional uses of the geological map products are more easily realised in a multidisciplinary framework, where partners are aware of and closely connected with each other's work. Geological and bathymetric maps are used directly in habitat and nature-type mapping and may be adapted to suit specific purposes, thanks to the collaboration. This has helped cement geology as an integral part of nature-type mapping and contribute to the development of NiN, which, in turn, has benefits for nature conservation and management.

There may be a perceived risk that multidisciplinary mapping could hinder geological mapping due to a diluted focus. In our experience, this is unfounded; instead, it has been advantageous to be able to combine many and different data sets and work across disciplines. There have been few compromises, and those made have been largely outweighed by opportunities for additional mapping or follow-up studies (including by universities and other institutions outside the core programme partnership). There are also numerous less tangible benefits related to exchange of ideas and a greater common understanding between partner institutions that have arisen from the multidisciplinary approach. It is difficult to imagine how a single-discipline approach can meet the demand for knowledge that will be needed for effective and sustainable management of our planet's interconnected systems.

It is equally difficult to imagine how EVs for sustainable management in line with the United Nation's Sustainable Development Goals can be effective without the inclusion of EGVs alongside the other EVs. In this paper, we have seen how geological and geomorphological maps deliver such information and potential for developing additional map products that highlight geodiversity. As Norway and other Nordic countries continue to produce a thorough suite of geological and geomorphological map products that fall neatly under the EGV framework, we will see how EGVs provide a good platform for geological mapping on the global environmental stage. With geological surveys and similar institutions seeking to gain greater relevance for their work, the EGV 'brand' can be beneficial, just as we have witnessed with the development of NiN. Whether it can help secure funding for geological mapping is not a question we can answer, but we suggest it should be more of a help than a hinderance.

4.2 General comments on the EGV framework

There is still considerable scope for the development of the EGV framework. It is broad, quite generic and is not tied to specific map scales or products. We have shown that it is relatively easy to adopt the framework in 'well mapped' areas of the seabed such as those we have presented from Norway. Here, geological map products (mostly 1:20 000–1:250 000) are based on a comprehensive suite of data, and as we have shown, several of these have the potential to be translated to additional products that highlight geodiversity.

In areas with less complete data, either in terms of geographic coverage or information content, it may be more challenging to deliver useful EGV-relevant information on sediment properties. The scales at which geological map products can be produced are tied to the availability of a suite of data, which is, in turn, linked to cost and access limitations. Mapping generally combines remotely sensed data and ground-truth observations. Where observations are sparse, and/or remotely sensed data are coarse (pixel sizes of several hundred metres), the mapping scales may be in the order of 1:1 000 000 and coarser (e.g. 1:3 000 000 sediment grain-size map for the Barents Sea in Lepland *et al.* (2014)). Comparing this with MAREANO maps for the same region (e.g. via NGU's online map service *geo.ngu.no/kart/marin_mobil*), we emphasise how generalised the sediment classes are, and we are uncertain to what extent a useful level of geodiversity information can be obtained from coarser-scale seabed mapping such as this. We note, however, that Laverick *et al.* (2022) showed the potential for extending the suite of geological information from broad-scale maps (including Lepland *et al.* 2014) using predictive modelling. Despite their coarse resolution and inherent uncertainty, broad-scale geological maps (e.g. Lepland *et al.* 2014; Diesing 2020; Laverick *et al.* 2022) still provide invaluable information in areas where data are otherwise lacking and can help to prioritise follow-up studies.

Regarding seabed morphology, maps of classified morphometric features, interpreted landforms and landscapes (physiographic regions) are well matched to delivering EGV-relevant information across the entire range of mapping scales, for which topographic and supporting data are available. Here, we have shown how algorithms such as geomorphons may contribute to this effort and further lend themselves to quantitative assessments of diversity, alongside terrain attributes, for example, slope and relative relief, which provide complementary information.

Whilst more specific goals (including guidance on data requirements and mapping scales) for EGV product development may be sought by some, the open scope allows the EGV concept to be very inclusive. This is an important quality for global adoption. In our case, for mapping new and relatively inaccessible areas of the seabed, as well as those already subject to multiple user-group pressures, more complete links between EGVs and GDCs for quantifying seabed geodiversity will help to make the geological information more tangible. Here, we have shown some examples of how such product development might start, but there is a wealth of possibilities to be explored, including further links to biodiversity, which should be more easily realised through multidisciplinary mapping.

5. Conclusions

In this paper, we have provided an overview of the major seabed-mapping initiatives currently active in Norway. We set out to assess the extent to which these initiatives deliver geodiversity information in relation to the EGV framework. Specifically:

- We found that the existing map products deliver geological and geomorphological information that fits neatly within the EGV framework's geology and geomorphology classes. There are no obvious gaps in knowledge although there remains scope for development of additional products to meet more specific needs. Several of these could be derived from existing maps without significant additional effort (e.g. translation to sediment fractions); others require additional data (e.g. sediment thickness maps).
- We provided examples of how quantitative measures of geodiversity can be obtained from further development of existing products (substrate diversity) and through supplementary analysis of existing data (morphological diversity).
- We have highlighted how multidisciplinary seabed-mapping initiatives help delivery of geodiversity information, which fits the EGV framework by providing greater opportunities for effective mapping and knowledge development. The multidisciplinary approach helps cement geological information as part of an essential suite of information for sustainable management nationally. Translating this to a global stage, our experience supports the argument for EGVs standing alongside other EVs to provide knowledge for long-term global sustainable management.

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Additional information

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Competing interests

The authors declare no competing interests.

Author contributions

MFJD: conceptualisation, methodology (quantitative diversity examples), writing – original draft. RB: project administration, writing – review and editing. LRB: project administration, writing – review and editing.

Additional files

One additional file (Supplementary File S1) is available at *https://doi.org/10.22008/FK2/E0IPC9*.

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