WORKING GROUP ON MARINE HABITAT MAPPING (WGMHM)

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Contents

i Executive summary

The Working Group on Marine Habitat Mapping (WGMHM) coordinates the review of habitat classification and mapping activities in the ICES area and promotes the standardization of approaches and techniques.

For the second consecutive year, WGMHM have held a joint meeting with the Working Group on Deep-Water Ecology (WGDEC) with a shared term of reference. The specific request to WGMHM in 2020 was to provide maps of VME elements in the North Atlantic. VME elements are defined as geomorphological features that provide habitat for VMEs. In addition, WGMHM undertook a series of examinations of each element to understand the strength of association between VME elements and specific VME habitats. The results of this analysis highlighted the following issues with the use of VME elements:

1) Elements are also listed without clear rule-sets for their consistent identification and delineation (i.e. a specification that states the acceptable input data sets, working resolution, underlying data quality, exact method to produce terrain derivatives and the thresholds for delineating features).
2) The strength of association between specific elements and individual VME habitats is often poor.
3) Where the strength of association is high, the footprint of the VME element is excessively large (as either a small number of large units or numerous small units) and unlikely to be useful for the fine-scale delineation of spatial advice.

To make VME elements more useful for the provision of management advice, further work must be undertaken to refine the physical conditions captured by each element. This can be done by either narrowing the definitions of VME elements or by including more physico-chemical parameters. However, this progression fundamentally represents an *ad-hoc* approach to what Predictive Habitat Models (PHMs, also known as Habitat Suitability Models) do in an objective, efficient and sophisticated way. It is recommended that PHMs remain the primary method for investigating where VME habitats are likely to occur in areas lacking VME observations.

ii Expert group information

Expert group name	Working Group on Marine Habitat Mapping (WGMHM)
Expert group cycle	multiannual
Year cycle started	2018
Reporting year in cycle	3/3
Chair	James Asa Strong, UK
Meeting venues and dates	4–7 May 2020, online meeting, 11 participants
	3–7 June 2019, Palma de Mallorca, Spain, 4 participants
	22–24 May 2018, Hamburg, Germany, 8 participants

1 Mapping and validation of VME Elements

For the second consecutive year, the working groups on marine habitat mapping (WGMHM) and deep-water ecology (WGDEC) have held a joint meeting with a shared ToR (D). WGMHM produced a document in 2019 detailing the advantages and disadvantages of species and habitat distribution modelling for supporting the identification of VMEs and the advice provided to ICES (ICES, 2019). The 2019 report from WGMHM also included a 'road-map' for implementing the production and use of species and habitat distribution modelling within the workflow that generates advice for the protection of VMEs. The 2019 report provided by the WGMHM has also been requested by other initiatives, such the new European iAtlantic project.

Despite the ever-increasing number of studies modelling VMEs and supporting documents advocating their use, ICES has informed WGDEC and WGMHM that they are not yet ready to integrate modelling of VMEs into the advice drafting process – this is based on understandable issues relating to the timely delivery of products and the current lack of a minimum standard for modelled outputs. Based on the need to provide supporting evidence for an imminent VME workshop, ICES have suggested that they will consider the use of VME 'elements' to support advice. Elements are geomorphological features that provide habitat for VMEs. Elements stem from the UNGA resolutions that call for the protection of VMEs (59/25; 61/105) and specifically mentions seamounts. The FAO guidelines, which operationalise the UNGA resolutions, also list additional elements (FAO, 2009):

1) submerged edges and slopes (e.g. corals and sponges);
2) summits and flanks of seamounts, guyots, banks, knolls, and hills (e.g. corals, sponges, xenophyophores);
3) canyons and trenches (e.g. burrowed clay outcrops, corals);
4) hydrothermal vents (e.g. microbial communities and endemic invertebrates); and
5) cold seeps (e.g. mud volcanoes for microbes, hard substrates for sessile invertebrates).

NAFO has interpreted elements from these same set of guidelines. The combined NAFO and NEAFC Elements are below:

- Isolated seamounts;
- Steep-slopes and peaks on mid-ocean ridges;
- Knolls;
- Canyon-like; and
- Steep flanks >6.4°.

VME elements were initially discussed within WGDEC in 2013 (ICES, 2013). Analysis from the Flemish Cap as well as results reported by Heifetz *et al.* (2005) and Vetter *et al.* (2010) are provided as evidence for the relationship between geomorphological elements and VME habitats. The primary objective for the WGMHM was to provide the distribution of these VME elements within the NEAFC/European Seas area. In addition, WGMHM also undertook a series of examinations of each element to understand the strength of association between VME elements and specific VME habitats. Specific objectives for WGMHM were:

- Provide the spatial distribution of as many VME elements as possible with the NEAFC area – where possible, this will rely on existing geomorphological datasets (e.g. the Grid Arendal global geomorphology classification (Harris *et al.*, 2014);
- Examine at the availability of existing geomorphological glossaries that can be used to define VME elements;

- Where VME elements have to be identified and delineated by WGMHM, establish an objective rule-set for their generation.
- Investigate whether hydrothermal vents can be included as a VME element;
- Assess the number of VME observations, by type, that fall in and outside of the footprint of the elements.
- Examine the typical; footprint (area) size of units of VME elements to understand the efficiency of VME containment; and
- Discuss the use of elements (pros and cons), future work and validation required for the continued use of VME elements.

2 VME elements delineated and assessed by WGMHM

The existing VME elements considered by the WGMHM are listed in Table 1 along with any existing definition that is specific to that VME element with a working definition adopted by WGMHM for the analysis. It was also apparent that other geomorphological features, identified by Harris *et al.* (2014), might also have merit as VME elements. These additional geomorphological features, termed Candidate Elements here, we also examined to understand their relationship with observations of VME habitats. The generation of the candidate and existing elements relied heavily on the GRID-Arendal Global Geomorphological map provided by Harris *et al.* (2014). These methods used in Harris *et al.* (2014) have been directly quoted in Tables 3 and 4 when this data source has been used. The methods used by the WGMHM to derive new Elements are also included in Tables 3 and 4. Example maps of the selected VME Elements are provided in Figure 1.

As a relatively unexplored concept, many of the VME elements lacked exact definitions (for use as a tool for considering the distribution of VMEs), rule-sets to derive/delineate the Elements (except for the 'Steep flanks 6.4°' Element) and peer-review studies demonstrating the explicit link between VME elements and VME habitats or indicators. It is recommended by WGMHM that the following steps be taken to validate and standardize the use of VME elements:

- Link VME elements to an existing geomorphological glossary so that definitions remain standardized between studies.
- If the geomorphological glossary does not provide specific instructions on how to derive the feature of interest, a rule-set must be written so that VME elements are consistently delineated and transferable between areas.
- The relationship between VME elements and VME habitat and indicator species should be proven and quantified. Once quantified, it can be used to weight the use of different elements in order of effectiveness. This report starts this validation process but further work will be needed to extend this analysis (as well as update it when new VME observations are reported).

Table 1. Existing and working definitions for VME elements considered by WGMHM.

VME elements	Provided or associated definition explicitly linked to the Element	Definition used for the production of VME elements by WGMHM	Comment
Isolated seamounts	Topography that rises 1000 m or more from the surrounding seabed (WGDEC, 2013).	Seamounts are "a discrete (or group of) large isolated elevation(s), greater than 1000 m in relief above the seafloor, characteristically of conical form "(IHO, 2008, and adopted by Harris *et al.*, 2014).	Other sources of Seamount information area available [1]
Steep-slopes and peaks on mid-ocean ridges	None found by WGMHM.	Slopes greater than 6.4 degrees that are on mid-ocean ridges (WGMHM working definition).	
Knolls	Topographic features of that rise less than 1000 m from the surrounding seabed (WGDEC, 2013).	Not required – Element not investigated by WGMHM.	
Canyons	None found by WGMHM.	A steep-walled, sinuous valley with V-shaped cross sections, axes sloping outwards as continuously as river-cut land canyons and relief comparable to even the largest of land canyons (Shepard, 1963). To be considered 'large' canyons, canyons must extend over a depth range of at least 1000 m and to be incised at least 100 m into the slope at some point along their thalweg. (Harris and Whiteway, 2011).	
Steep flanks 6.4°	Areas of 6.4° or greater are classified as slopes (WGDEC, 2013)	Areas of 6.4° or greater are classified as slopes (WGDEC, 2013)	
Hydrothermal	None found by WGMHM.	Active Submarine Hydrothermal Vent Fields as determined by the InterRidge Global Database	

[1] Alternative Seamount databases
Yesson C, Clark MR, Taylor M, Rogers AD (2011). The global distribution of seamounts based on 30-second bathymetry data. Deep Sea Research Part I: Oceanographic Research Papers 58: 442-453. doi: 10.1016/j.dsr.2011.02.004. Data URL: http://data.unep-wcmc.org/datasets/41
https://data.unep-wcmc.org/datasets/41
Global Seamount Database
http://www.soest.hawaii.edu/pwessel/smts/
INFOMAR Deepwater Atlas
Dorschel, B., Wheeler, A., Monteys, X. & Verbruggen, K. (2010) Atlas of the Deep-Water Seabed: Ireland. ISBN: 978-90-481-9375-2. Springer Science & Business Media. https://doi.org/10.1007/978-90-481-9376-9
https://www.infomar.ie/rd-and-education/publications/atlas-deep-water-seabed-ireland

Table 2. Existing and working definitions for candidate VME elements considered by WGMHM.

VME elements	Provided or associated definition explicitly linked to the Element	Definition used for the production of VME elements by WGMHM	Comments
Guyots	Not currently considered a VME element	Guyots are an isolated (or group of) seamount (s) having a comparatively smooth flat top. Also called table mount(s) (IHO, 2008).	
Escarpments	Not currently considered a VME element	Escarpments are an elongated, characteristically linear, steep slope separating horizontal or gently sloping sectors of the sea floor in non-shelf areas. Also abbreviated to scarp (IHO, 2008).	Escarpments, like basins, overlay other features (i.e. other individual features may be partly or wholly covered by escarpments). Thus, features like the continental slope, seamounts, guyots, ridges and submarine canyons (for example) may be sub-classified in terms of their area of overlain escarpment.
Glacial troughs	Not currently considered a VME element	Shelf valleys at high latitudes incised by glacial erosion during the Pleistocene ice ages form elongated troughs, typically trending across the continental shelf and extending inland as fjord complexes (Hambrey, 1994). The largest of these features are glacial troughs, characterised by depths of over 100 m (often exceeding 1000 m depth) and are distinguished from shelf valleys by an over-deepened longitudinal profile that reaches a maximum depth inboard of the shelf break, thus creating a perched basin on the shelf with an associated sill (Hambrey, 1994).	

Table 3. Method used to derive the VME elements considered by WGMHM.

VME elements	Method of calculation
Isolated seamounts	From Harris *et al.* (2014): delineated by on the SRTM30_PLUS model and the adhered to the requirement that seamounts are "of conical form", thus distinguishing "seamounts" (having a length/with ratio of ~2) from ridges (having a length/width ratio ≥2).
Steep-slopes and peaks on mid-ocean ridges	Slopes greater than 6.4 degrees that are contained within the GRID-Arendal 'Ridge' feature polygons.
Knolls	NA
Canyons	Canyon delineation by Harris *et al.* (2014) was based on a combination of automated and expert interpretation of the SRTM30_PLUS model. Topographic position index for the SRTM30_PLUS model was calculated for 3, 5 and 10 cell radiuses. For each TPI raster layer, cells with a value of greater than 50 were extracted and converted to vector layers. These three vector layers were then merged to form a single layer that formed the basis for guiding further refinement of the canyons layer. The TPI derived canyon layer was overlaid with 100 m contours generated from the STRM bathymetry. The polygons were then refined to better capture the shape of canyon features, to remove areas that were clearly not canyons and add canyons that were missed. Two categories of submarine canyon were mapped separately: shelf incising canyons; and blind canyons. Shelf incising canyons have heads that cut across the shelf break, and in which there are landward-deflected isobaths on the continental shelf. Blind canyons are those which have heads that are wholly confined to the slope, below the depth of the shelf break
Steep flanks 6.4°	Slope was derived from a 2019 GEBCO bathymetry grid (15 arc seconds) and the ESRI ArcMap Calculate Slope tool (Average Maximum approach[2] with a 3 x 3-neighbourhood window). The resulting raster was then 'Reclassified' into a binary surface depending on whether slope angles were above or equal to/greater than the 6.4° threshold. The resulting raster surface was converted to a polygon shapefile.
Hydrothermal vents	InterRidge version 3.4 (Beaulieu, 2013) provides active submarine hydrothermal vent fields as point data. WGMHM buffered these points using a radius of 500 metres. This is accepted as an arbitrary choice by WGMHM and in need of further refinement.

[2] Burrough, P.A., and McDonell, R.A. 1998. Principles of Geographical Information Systems (Oxford University Press, New York.

Table 4. Method used to derive the candidate VME elements considered by WGMHM.

Candidate elements	Method of calculation
Guyots	The seamount base layer was used to mask the SRTM30_PLUSmodel. The gradient of the resulting grid was calculated (ArcGIS 10 DEM Surface Tools (Jenness *et al.*, 2012) Slope with computation method = 4-cell method. The gradient was classified into areas of <2° and areas of > 2°. The areas less than 2° were converted into vector layers. Where these occurred at the top of sea-mounts and were greater than a minimum size threshold (10 km^2) they were flagged as possible guyots. These possible guyots were then visually checked and either classified as a guyot or a seamount.
Escarpments	Escarpments were calculated based on the gradient of the SRTM30_PLUS model. Gradient was calculated (ArcGIS 10 DEM Surface Tools (Jenness *et al.*, 2012) Slope, Slope computation method = 4-cell method) and classified into areas of gradient greater than 5° and less than or equal to 5°. A majority filter (ArcGIS 10 Spatial Analyst Generalisation Majority Filter, Number of neighbours = 8, Replacement threshold = half) was run twice over to remove small sized pixelation in the classified grid. Areas of the filtered grid with gradient greater than 5° were converted to a vector layer. The area of the individual feature polygons was calculated and features of <100 km2 were deleted; similarly holes in features smaller than 100 km2 were filled. Finally, the resulting vector layer was smoothed (ArcGIS 10 Smooth Polygon tool (Smoothing Algorithm = PAEK, Smoothing tolerance = 2 nautical miles).
Glacial troughs	Glacial troughs were digitised by hand based on 50 m contoured data for the Antarctic and 10 m contoured data for other shelf areas (Harris *et al.*, 2014).

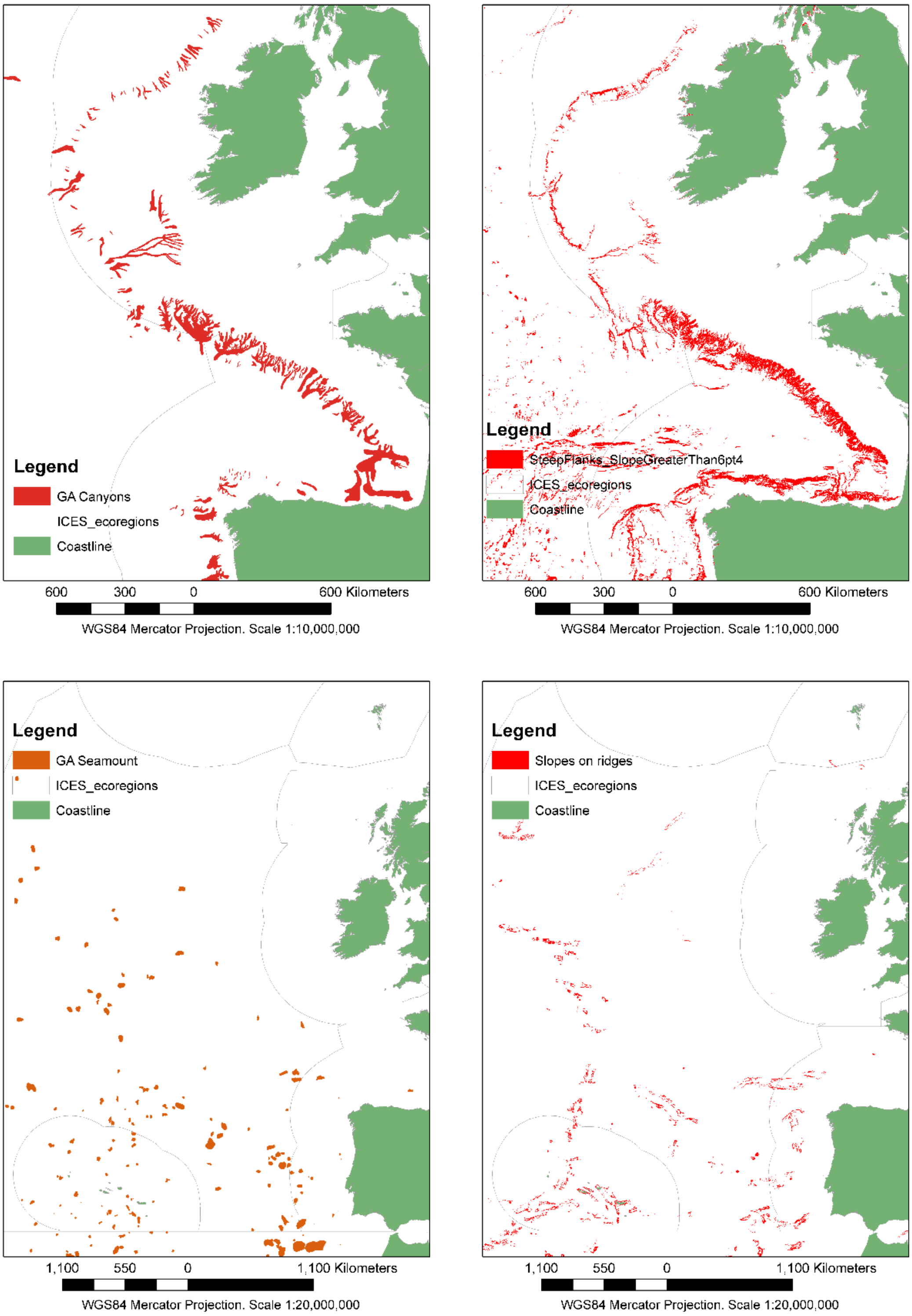

Figure 1. Example VME element maps of Canyons (top left), steep flanks greater than 6.4 degrees (top right), Seamounts (bottom left) and (slopes on ridges (bottom right). Of the canyons, 6% were described as being blind and the 94% were shelf incising.

3 Delivery of VME elements to WGDEC

The results from the spatial analysis of VME observations within elements highlighted nine geomorphic features of interest. These features included the following:

1. Seamounts
2. Canyons
3. Guyots
4. Steep slopes on ridges
5. Ridges
6. Escarpments
7. Glacial troughs
8. Flanks (slopes > 6.4°)
9. Continental slope

The request from WGDEC was to provide a spatial dataset displaying these geomorphic features (i.e. VME elements) within ICES Ecoregions. The source data for these layers (Tables 2 and 4), came from the Seafloor Geomorphic Features Map (created through collaboration between Geoscience Australia, GRID-Arendal and Conservation International) and the General Bathymetric Chart of the Oceans (GEBCO). Most of the elements were downloaded as vector files from the Blue Habitats website. “Flanks” and “Steep slopes on ridges” were generated using GEBCO bathymetry. Slope was derived from the bathymetry data and a prescribed threshold of 6.4° was used to extract steep slope areas. These data were clipped to the extent of the area of interest and converted into vector format. The “Ridge” element's shapefile was used to extract the steep slopes that were contained within the extent of ridges.

Both data sources display data at a global scale and needed to be clipped to the extent of the ICES Ecoregions (Figure 2). A 10 km buffer around the extent of the ecoregions was incorporated allowing any features on the boundary of an ecoregion to be included in the compiled data. In addition, a second dataset displaying the extent of the elements within the NEAFC region was also prepared.

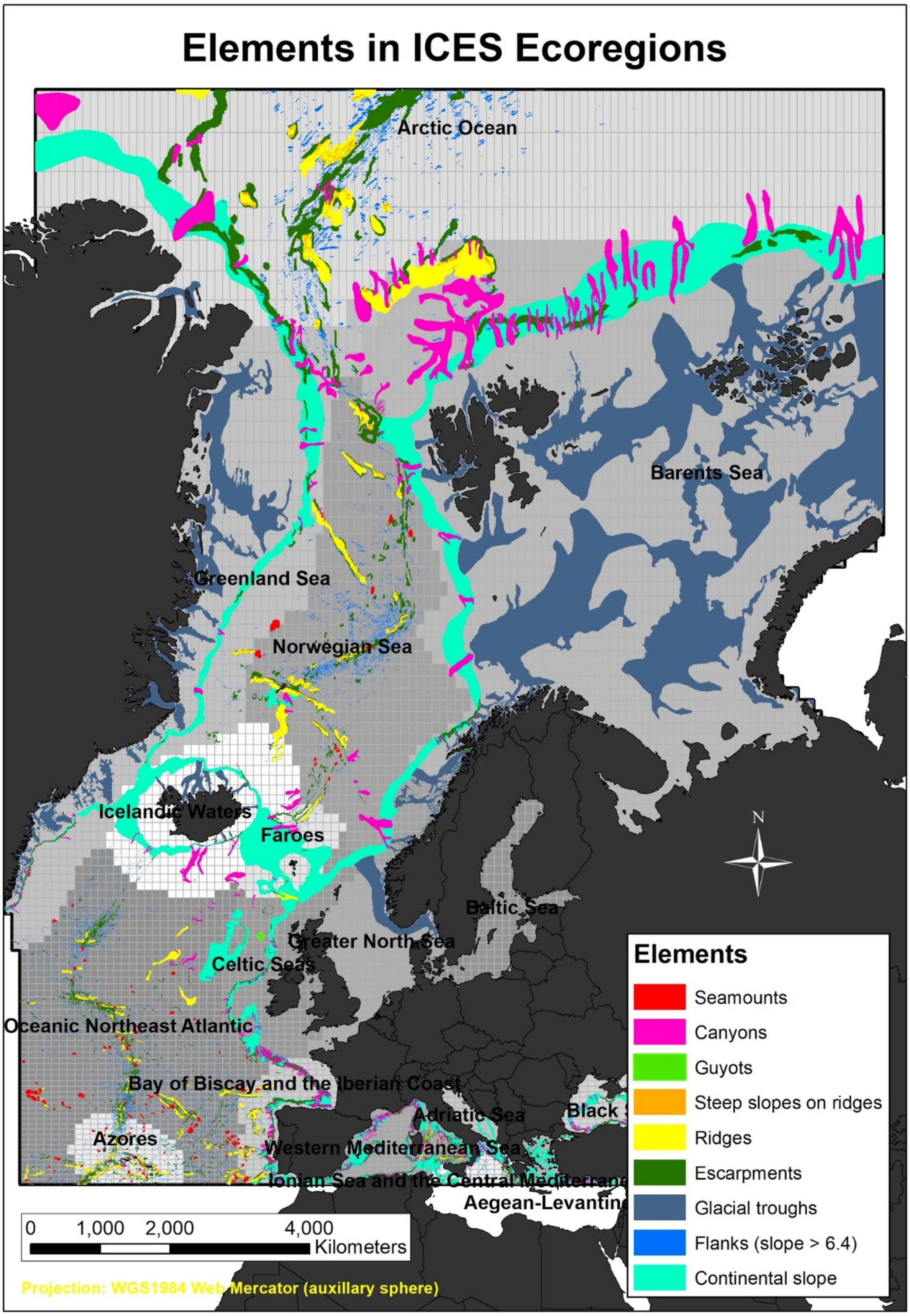

Figure 2. Distribution of VME elements within the ICES ecoregion.

The area of each element within the ICES Ecoregion was calculated using the Mollweide Equal Area projection. Any differences between the original area in the source data and the recalculated area in the region of interest was due to features being clipped by the boundary of the ICES Ecoregion. The ZIP file associated with this report contains the distribution of the requested and candidate elements. It is recommended that the distribution of elements be regularly updated as elements are more clearly defined and as better data sources become available. The quality and spatial resolution of the bathymetry data used for the calculation of steep flanks was found to be influential for the detection and expression of sloped areas. For example, it was found that improvements made to the 2020 GEBCO resulted in the detection of 20% more sloped areas (greater than 6.4°) when compared with the 2019 GEBCO dataset (Figure 3a and 3b). As such, it is important to specify the sources of data that should be used for deriving elements as well as the working resolution of the analysis. The topic of data quality and the influence it has on the expression of VME element units is discussed in more detail below.

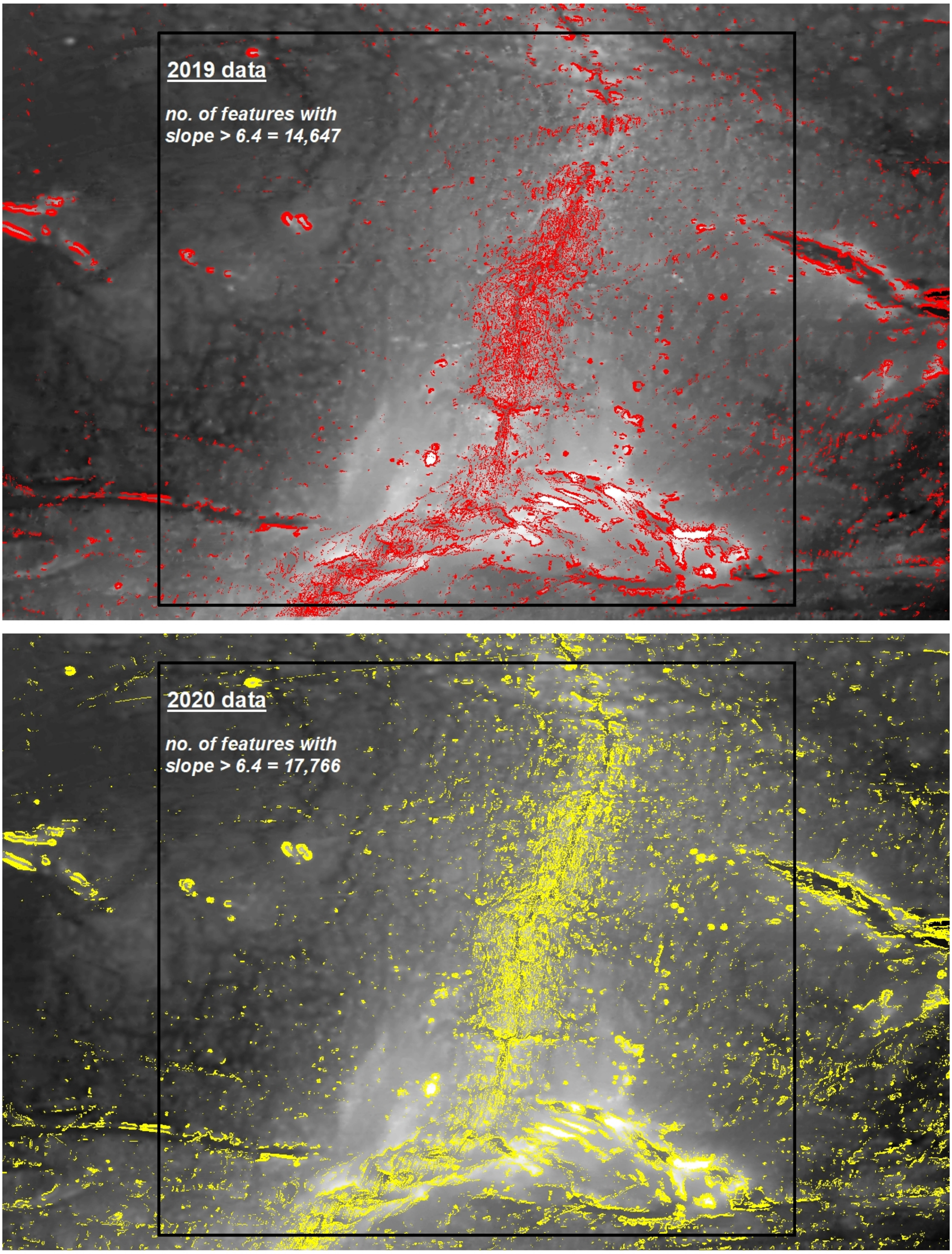

Figure 3a and 3b. Sloped areas greater than 6.4° derived from the GEBCO 2019 bathymetry (top) and GEBCO 2020 bathymetry (bottom).

4 Linking VME elements to existing geomorphological glossaries

VME elements rely on the use of existing and wide-recognised geomorphological features. To enable users to identify and delineate these features consistently, it is important to link VME elements to either specific definitions, ideally from existing glossaries, or exact rule-sets for elements derived from terrain variables. Mapping the geomorphology of the seabed provides an effective means to characterise this important element of the marine environment. Despite the availability of high-quality swath bathymetry, there have been few attempts to structure the way we characterise bedform/landform-scale features observed in high-resolution data. The only two existing glossaries used to describe the geomorphology of the seabed in a consistent, standardised way are:

1. Hydrographic Dictionary

International standards documents produced by the International Hydrographic Organisation (IHO) include the 'Standardization of undersea feature names' (IHO and IOC, 2013), and 'Hydrographic 'Dictionary' (IHO, 1994). The 'feature names' list includes a list of 'generic terms' and associated definitions. The 'Hydrographic dictionary' includes over 7,000 terms relating to all aspects of hydrography. Taken together, these IHO documents incorporate fewer geomorphological features than one might observe at seabed (Dove *et al.*, 2016).

2. Seafloor Geomorphic Features Map

The global seafloor geomorphic features map has been created through collaboration between Geoscience Australia, GRID-Arendal and Conservation International. The digital map displays 29 geomorphic features derived from coarse bathymetric compilations. The data were used to broadly assess global submarine geomorphology (Harris *et al.*, 2014).

The British Geological Survey (BGS) developed a two-part classification system ('Morphology' and 'Geomorphology') to facilitate work on a new 'Seabed Geomorphology' mapping initiative. The first part of this classification scheme is a list of morphological features with glossary definitions and associated example diagrams. The classification scheme structures the way the geomorphology of the seabed is described and addresses the current lack of a standardised method to do this at a broad range of scales. A recent collaboration within the MAREANO-Norway, INFOMAR-Ireland, and MAREMAP-UK (MIM) partnership, together with Geoscience Australia, has led to significant improvement of the BGS classification system. A second version is currently in press. The WGMHM recommends that existing and future VME elements be linked to feature specific definitions, ideally from the same glossary. Based on the recent update of the BGS/MIM glossary and its inclusion of scalar issues, WGMHM recommends this glossary for use with the VME elements.

5 Examining the strength of association between VME Elements and VME habitats and indicator observations

Although mooted some time ago, VME Elements have yet to be widely adopted and have therefore received little development. The value of Elements as a supporting evidence for the zonation of protected areas for VMEs hinges on the assumption that Elements represent VME habitat and are therefore disproportionately important when compared with other geomorphological features or alternative seabed delineations. To test this relationship, VME habitats observations (ICES VME database extraction 30/04/2020) were overlaid and connected with each Element and candidate Element to obtain the percentage of VME observations contained within each Element. The average footprint area of units of each Element containing one or more VME observations was also reported. The average area of units of each Element is indicative of the efficiency of VME capture by each Element. For example, an Element that captures a high proportion of VME observations and has a relatively small unit footprint area can be considered an effective tool for protecting VMEs. However, an alternative Element may also capture a high proportion of VMEs but do this within a large footprint area. The latter example may well prove to have a strong association with certain VMEs but the large footprint may make it an ineffective tool for the fitting of tailored, protected areas.

It is also assumed that the physical environment that supports specific VME habitats is likely to change geographically and especially between water bodies/ecoregions. To test the basic spatial transferability of VME elements, each VME observation was also attributed with an ecoregion. The ecoregion selected for this test was the Marine Ecoregions and Pelagic Provinces of the World (2007, 2012)[3]. This ecoregion classification had both the extent required and a small number of open ocean classes (a larger number of ecoregions would greatly complicate the analysis). The modified ecoregions maintained the 'subarctic Atlantic', ' North Atlantic Transitional', and 'North Central Atlantic Gyre' regions before merging all other regions into a coastal/shelf ecoregion. The modified ecoregion maps used to attribute the VME observation is shown in Figure 4. The distribution of VME habitat and indicator observations (2020) is shown in Figure 5.

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[3] The Nature Conservancy (2012). Marine Ecoregions and Pelagic Provinces of the World. GIS layers developed by The Nature Conservancy with multiple partners, combined from Spalding *et al.* (2007) and Spalding *et al.* (2012). Cambridge (UK): The Nature Conservancy. DOIs: 10.1641/B570707; 10.1016/j.ocecoaman.2011.12.016. Data URL: http://data.unep-wcmc.org/datasets/38
https://data.unep-wcmc.org/datasets/38

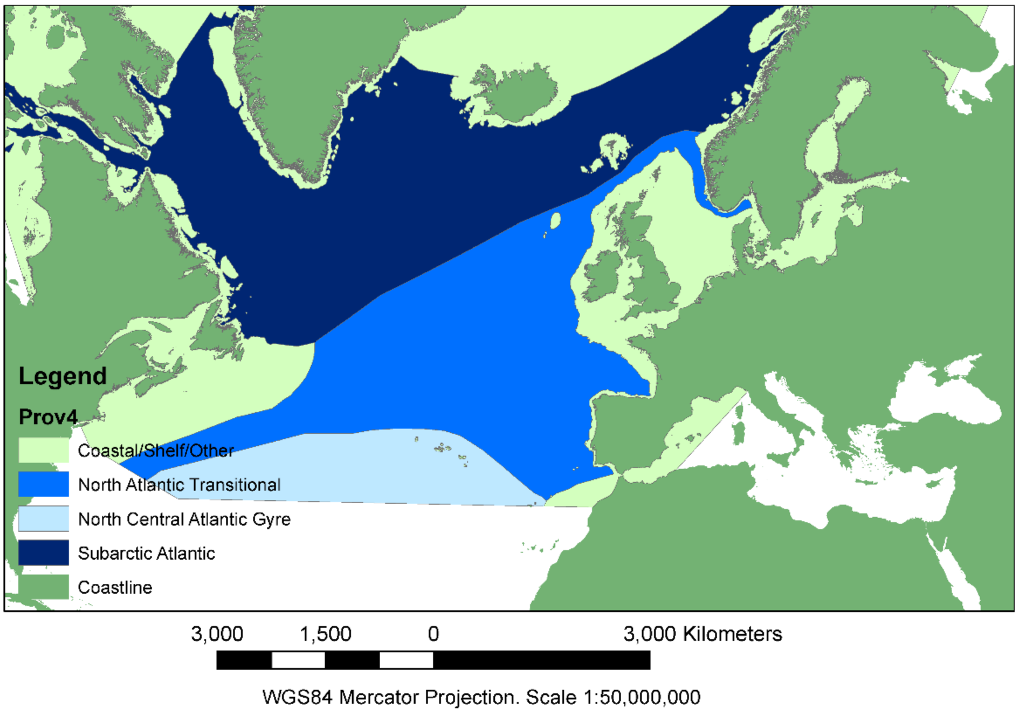

Figure 4. Modified ecoregion used to stratify the test of spatial transferability of VME Elements. The original ecoregions were provided by The Nature Conservancy (2012). Marine Ecoregions and Pelagic Provinces of the World. GIS layers developed by The Nature Conservancy with multiple partners, combined from Spalding *et al.* (2007) and Spalding *et al.* (2012).

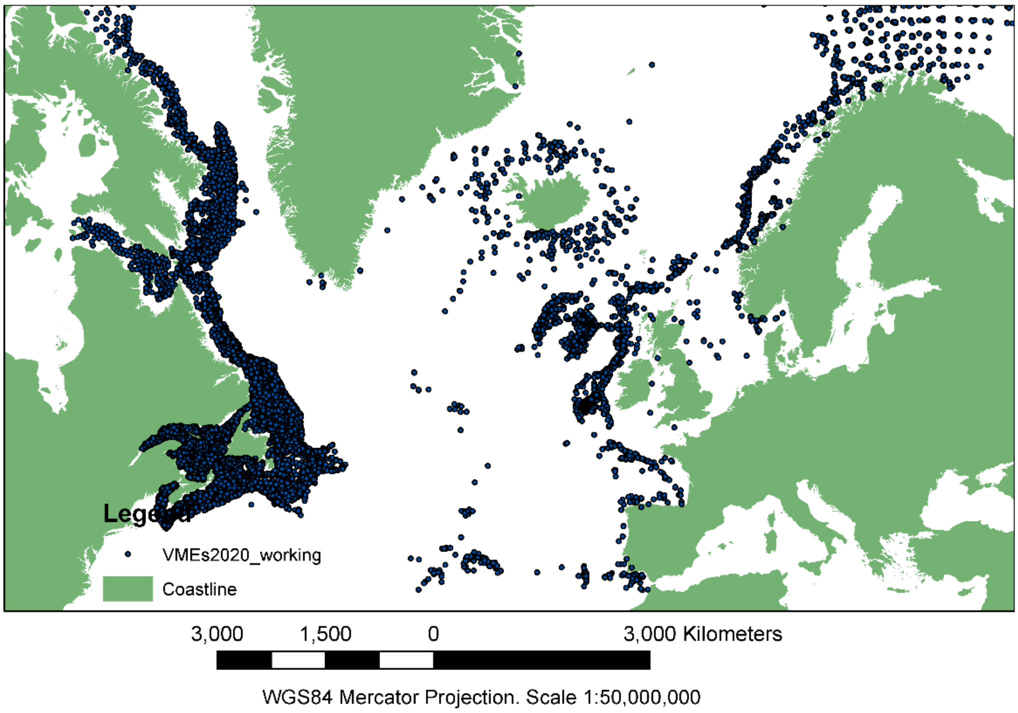

Figure 5. Distribution of the majority of the VME habitat and indicator records in the North Atlantic (as of 30/04/2020).

6 Strength of association between VME element and VME observations

Seamounts, steep slopes and peaks on mid-ocean ridges and hydrothermal vents capture relatively few VME habitat observations (Table 5). By contrast, canyons captured 23% of the available VME habitat type observations present in the 2020 ICES VME database. The steep flanks element overlapped with the greatest number of VME observations, and was particularly effective at capturing Anemone aggregations, coral gardens and stalked crinoid aggregations. The strength of association between VME habitat type observations and Elements has been subdivided into four broad provinces (namely Sub-arctic Atlantic, Transitional Atlantic, North Central Atlantic Gyre and a final province that covers shelf, coastal and other provinces – this output is large and is included in Annex 3).

The candidate elements provide a comparison with the current selection of VME elements (Table 6). It is noteworthy that continental slopes included in the GRID-Arendal data (Harris *et al.*, 2014) capture 59% of the VME habitat observations and 53% of the VME indicator observations. Both escarpments and glacial troughs also overlap with a substantial number of VME habitat and indicator observations. Ridges and guyots appear not to overlap with a significant number of VME observations and do not represent suitable candidates for inclusion in the adopted VME Elements list.

The average footprint area of each element provides some useful information about the efficiency of capture for each element. Ideally, elements would overlap many VME observations with a relatively small footprint (Table 7). However, elements that have a relatively large footprint area may be less useful for the recommendation of small and fitted management areas. The individual units of hydrothermal vents (buffered to 500 m) and those of steep slopes and peaks on mid-ocean ridges are relatively small. Seamount units that overlap with VME habitat observations generally have a large footprint (~720 km^2) when compared with the previous elements. Units of canyons and steep flanks have the largest mean area at 3000 and 4000 km^2 respectively (although units in this context is somewhat arbitrary and dependent on the scale and method of calculation). Steep flanks have the largest unit footprint area as well as the greatest number of individual units (in excess of 100 000 units). Due to the very high number of individual steep flank units, the proportion of actual units that overlap with VME habitats is very low at just 0.2%. Hydrothermal vents and canyons appear to be relatively efficient method of capturing VME habitats based on the proportion of element units that overlap with VME observations and typical unit area.

The units of continental slope (i.e. defined as the area between the shelf edge and the upper limit of the continental rise) provided by Harris *et al.* (2014) have an extremely large average footprint size, which explains why this candidate element captures a large proportion of the VME observations and has a relatively small number of units. Guyots appear to have a small unit size and a high probability of containing a VME. However, there are very few guyots within the analysis area and they therefore fail to overlap with many VME overall (Table 8). As discussed above, escarpments and glacial troughs overlap with a large proportion of both the VME habitats and indicators. Both candidate elements achieve this overlap using relatively large average footprint areas (13 500 and 55 400 km^2 respectively).

The relationship between elements and VME observations varies significantly between the broad ecological provinces used here. For example, canyons in the North Atlantic Transitional province capture 23% of the local VME habitats but encompass 80% in the coastal/shelf/other province. As one would expect, the number of element units differs greatly between provinces. For example, the North Atlantic Transitional province has 168 canyon units but none in the North Central Atlantic Gyre province. The division of elements by province or ecoregion may represent a way of stratifying, and thereby focus the application of elements within a specific area. Further work is required to understand why the strength of association between elements and VME habitat observations differs between provinces. It is likely that broad oceanographic changes between the water bodies that dominate these provinces is likely to modify the value and availability of habitat within the elements for specific VME habitats.

To summarise, unless element units have a very large footprint area or are very numerous, they typically fail to have a strong overall association with VME habitats. Should elements be used for management, it is recommended that only individual element units that overlap with a specific number of VME observations be used. Equally, elements should also be picked that have, on average, the smallest unit areas so that spatial measures are fitted as closely as possible to the VMEs. It is acknowledged that some elements do represent a useful and ecologically meaningful unit of management, e.g. the use of a specific canyon or seamount as a managed area.

Table 5. Percentage of VME habitat observations captured by each Element. Summary statistics present the overall percentage between all VME habitats and indicators by Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME Habitats	**Isolated seamounts**	**Canyons**	**Steep-slopes and peaks on mid-ocean ridges (greater than 6.4)**	**Steep flanks greater than 6.4 degrees**	**Hydrothermal vents**
Anemone aggregations	0.0%	88.0%	0.0%	68.0%	0.0%
Cold-water coral reef	0.0%	13.9%	0.0%	32.8%	0.0%
Cold seeps	0.0%	17.6%	0.0%	0.0%	0.0%
Coral Garden	0.0%	49.3%	0.0%	66.6%	0.0%
Deep-sea Sponge Aggregations	0.0%	1.9%	0.2%	3.2%	0.0%
Hydrothermal vents/fields	3.7%	0.0%	0.0%	18.5%	100.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	0.0%	17.1%	0.0%	16.9%	0.0%
Stalked crinoid aggregations	0.0%	66.7%	0.0%	83.3%	0.0%
Tube-dwelling anemone aggregations	0.0%	11.2%	0.0%	29.0%	0.0%
Xenophyophore aggregations	0.0%	29.3%	0.0%	46.3%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	1	2959	10	4221	27
Percentage of all VME *habitat* observations captured by the Element	0.0%	22.7%	0.1%	32.3%	0.2%
Co-occurrence of VME *indicator* observations and the VME Element	105	4620	347	7388	0
Percentage of all VME *indicator* observations captured by the Element	0.2%	8.3%	0.6%	13.3%	0.0%

Table 6. Percentage of VME habitat observations captured by each Candidate Element. Summary statistics present the overall percentage between all VME habitats and indicators by Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME Habitats	**Slope (Grid Arendal)**	**Escarpment**	**Glacial trough**	**Ridges**	**Guyots**
Anemone aggregations	100.0%	100.0%	0.0%	0.0%	0.0%
Cold-water coral reef	61.9%	46.4%	14.5%	0.0%	0.5%
Cold seeps	52.9%	0.0%	11.8%	0.0%	0.0%
Coral Garden	89.4%	64.8%	5.5%	0.4%	0.6%
Deep-sea Sponge Aggregations	47.7%	3.1%	23.8%	0.5%	0.0%
Hydrothermal vents/fields	0.0%	40.7%	3.7%	7.4%	0.0%
Mud and sand emergent fauna	100.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	25.7%	16.5%	43.3%	0.0%	0.0%
Stalked crinoid aggregations	100.0%	83.3%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	48.6%	16.8%	29.9%	0.0%	0.0%
Xenophyophore aggregations	97.6%	46.3%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	7753	4493	2611	33	37
Percentage of all VME *habitat* observations captured by the Element	59.4%	34.4%	20.0%	0.3%	0.3%
Co-occurrence of VME *indicator* observations and the VME Element	29431	10605	8742	704	52
Percentage of all VME *indicator* observations captured by the Element	53.0%	19.1%	15.7%	1.3%	0.1%

Table 7. Mean area (km²) of VME Element units occupied by VME habitat observations. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME Habitats	Isolated sea-mounts (km²)	Canyons (km²)	Steep-slopes and peaks on mid-ocean ridges greater than 6.4 (km²)	Steep flanks greater than 6.4 degrees (km²)	Hydrothermal vents (km²)
Anemone aggregations	-	7447	-	8879	-
Cold-water coral reef	-	1906	-	7760	-
Cold seeps	-	5792	-	-	-
Coral Garden	-	3120	18	7085	-
Deep-sea Sponge Aggregations	-	1040	137	306	-
Hydrothermal vents/fields	726	-	-	4103	1
Mud and sand emergent fauna	-	-	-	-	-
Seapen fields	-	6974	-	7578	-
Stalked crinoid aggregations	-	173	-	12	-
Tube-dwelling anemone aggregations	-	382	-	172	-
Xenophyophore aggregations	-	335	-	247	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	726	3019	77	4016	1
Total number of Element units within analysis area	364	715	3307	103653	42
Element units containing VME habitat observations	6	90	25	170	17
Percentage of units with VME habitat observations	1.6%	12.6%	0.8%	0.2%	40.5%

Table 8. Mean area (km²) of Candidate Element units occupied by VME habitat observations. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Candidate Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitat type	**Slope (Grid Arendal) (km²)**	**Escarpment (km²)**	**Glacial trough (km²)**	**Ridges (km²)**	**Guyots (km²)**
Anemone aggregations	12790233	30897	-	-	-
Cold-water coral reef	12230326	30251	169686	-	1728
Cold seeps	12790233	-	40688	-	-
Coral Garden	11977950	31017	90390	7617	1728
Deep-sea Sponge Aggregations	12182013	2189	102679	6145	-
Hydrothermal vents/fields	-	19445	16510	1567	-
Mud and sand emergent fauna	12790233	-	-	-	-
Seapen fields	12342636	29261	109006	-	-
Stalked crinoid aggregations	12790233	2073	-	-	-
Tube-dwelling anemone aggregations	7409029	1602	80830	-	-
Xenophyophore aggregations	11518312	1836	-	-	-
Summary area statistics by VME Element					
Average area of occupied units (km²)	10801927	13506	55435	1394	314
Total number of Element units within analysis area	20	1295	89	174	3
Element units containing VME habitat observations	13	89	39	22	1
Percentage of units with VME habitat observations	65.0%	6.9%	43.8%	12.6%	33.3%

7 Slope ranges compared across VME elements and within VME observations

VME elements are defined based on geomorphological characteristics and each element may consist of a range, or a certain distribution, of slopes. Since slopes may be more directly linked to types of VME habitats, rather than the geomorphological classifications themselves, the distribution of slopes within each VME element may reflect to what extent elements support various types of VME habitats. In figure 6 the distribution of slopes derived from the GEBCO bathymetric dataset is shown for each of 8 VME elements, for the total area covered by each element type (Figure 6a - left) as well as for the locations of all individual VME records (Figure 6b - right).

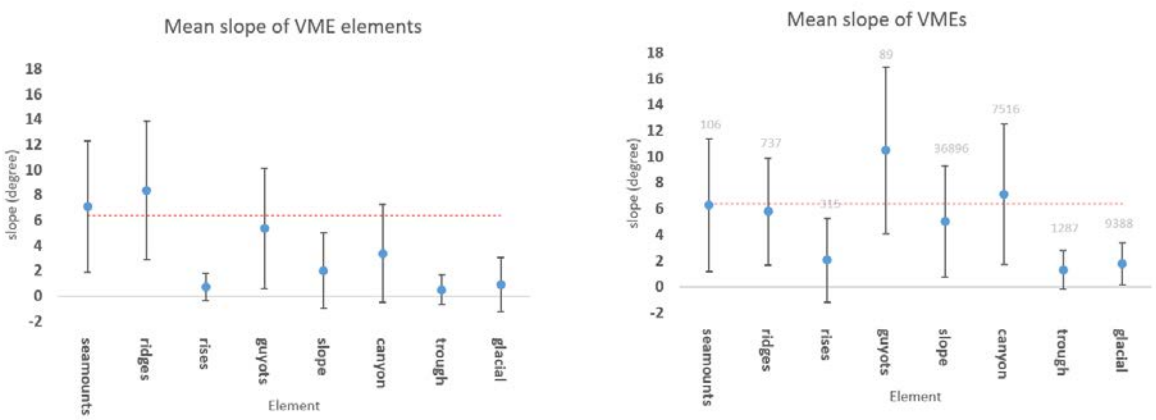

Figure 6a and 6b. Left (6a): mean and standard deviation of slopes (from GEBCO) within each of eight selected WME elements. Right (6b): mean and standard deviation of slopes for all WME records (2019). The red lines indicate the 6.4 degree slope threshold.

The general pattern is that distribution of slopes among and within VME elements are similar when comparing the overall distribution of slopes of the total area of VME elements and the distributions of slopes of individual VME records, however with some exceptions. For seamounts, ridges, guyots and canyons, distributions of slopes for VME records among elements are very similar with mean slopes close to 6.4 degrees. For the VME element type "canyon" there are some deviations with generally steeper slopes of recorded VMEs compared to the mean slope of total areal coverage of the VME element, indicating that the element type "canyon" may need to be more narrowly defined.

Similarly, for the VME element steep flanks (greater than 6.4 degrees) are generally considerably higher for VME records compared with the VME element total area, indicating that this element also may need to be more narrowly defined. For VME elements including rises, troughs and glacial troughs, mean slopes and distribution are generally smaller and at a similar range, and distinguishable from the other steeper element types. To conclude, using just slope (at a resolution of 15 arc seconds), the eight VME elements and candidate elements can only resolve slope characteristics that may explain differences in VME observations in just two major groups. In order to ensure VME elements are capturing the conditions occupied by VMEs, the VME elements canyon and steep flanks (greater than 6.4 degrees) need to be more narrowly defined. For candidate elements, rises and guyots there may be a basis for a similar conclusion, however the number of VME observations is too sparse.

8 Association between specific VME habitats and slope at several scales

Slope is the only terrain analysis parameter that is mentioned explicitly in the definition of VME elements, where a threshold value of 6.4 degrees is used to define steep flanks. In marine environments, slope is not measured directly, but is instead derived from the analysis of digital bathymetric models (DBMs) which usually represent depth as values in a regular grid. The resolution of available DBMs depends on the data source. In the deep-sea, high-resolution (<50 m) DBMs are derived from multibeam echosounder data, but these are costly to obtain and are available only in some areas. For broader areas, data products like GEBCO (Weatherall *et al.* 2015) and SRTM15+ (Tozer *et al.* 2019) combine available multibeam data with satellite altimetry and other data to produce global DBMs with resolutions above 500 m.

The value of slope at a given location depends on the resolution of the DBM and the size of the analysis grid, as well as on the specific algorithm used to compute the slope (Wilson *et al.* 2007). Here we explored the distribution of slope values observed at locations where VME habitats have been recorded in the ICES VME database. For this analysis, we used bathymetric data from the General Bathymetric Chart of the Oceans (GEBCO 2020 grid, Weatherall *et al.* 2015), a global relief model with a resolution of 15 arc-seconds. We obtained data between 34°N and 78.5°N, and between 78°W and 20°E, which includes the entire North Atlantic. The data was projected using a Lamberts Equal Area projection centered at 56°N and 29°E and bilinearly interpolated to obtain a grid with a resolution of 500 m, which is a similar cell size to the original data.

Slope was calculated using the function "r.param.scale" in the GRASS GIS software (GRASS Development Team 2018). This function implements a multi-scale approach to calculate terrain parameters from a digital elevation model by fitting quadratic parameters to processing windows of uneven cell numbers. For this analysis, we obtained the slope, defined as the magnitude of maximum gradient, using windows of 3x3, 9x9 and 27x27 cells, equivalent to spatial scales of 1.5, 4.5 and 13.5 km. Slope values for the same location obtained using different window sizes are correlated but with a high degree of variance (Figure 7).

Figure 7 (B-D) shows the distribution of slope values at reported locations of VME Habitat Types, using slope estimates using the three window sizes. Slope values in general decreased with increasing window size. This is not surprising, as increasing the spatial scale in which slope and other terrain analysis parameters are calculated is equivalent to obtaining estimates after smoothing the bathymetry data with a moving window average. Notably, a high proportion of VME habitat records were from locations with slopes less than 6.4°. This was expected for VME habitats associated with sedimentary bottoms like seapen fields, but it was also the case for other habitats. When using slope values calculated at a spatial scale of 13.5 Km, practically all records originated from areas with less than 6.4° of slope.

Next we examined the distribution of slope values at reported locations of VME Habitat Types with five geomorphic features that can be considered as VME elements (Figure 8). Geomorphic features were derived by Harris *et al.* (2014) through a spatial analysis of a global DBM. Here we only utilised slope values computed at a scale of 1.5 km. The distribution of slope values and VME Habitat types differed among the five geomorphic features analysed. For example, VME habitats reported within escarpments included many cold-water coral reefs observed at slopes between 3 and 17°, while most records from within glacial troughs consisted of anemone and deep-sea sponge aggregations observed at slopes less than 5°.

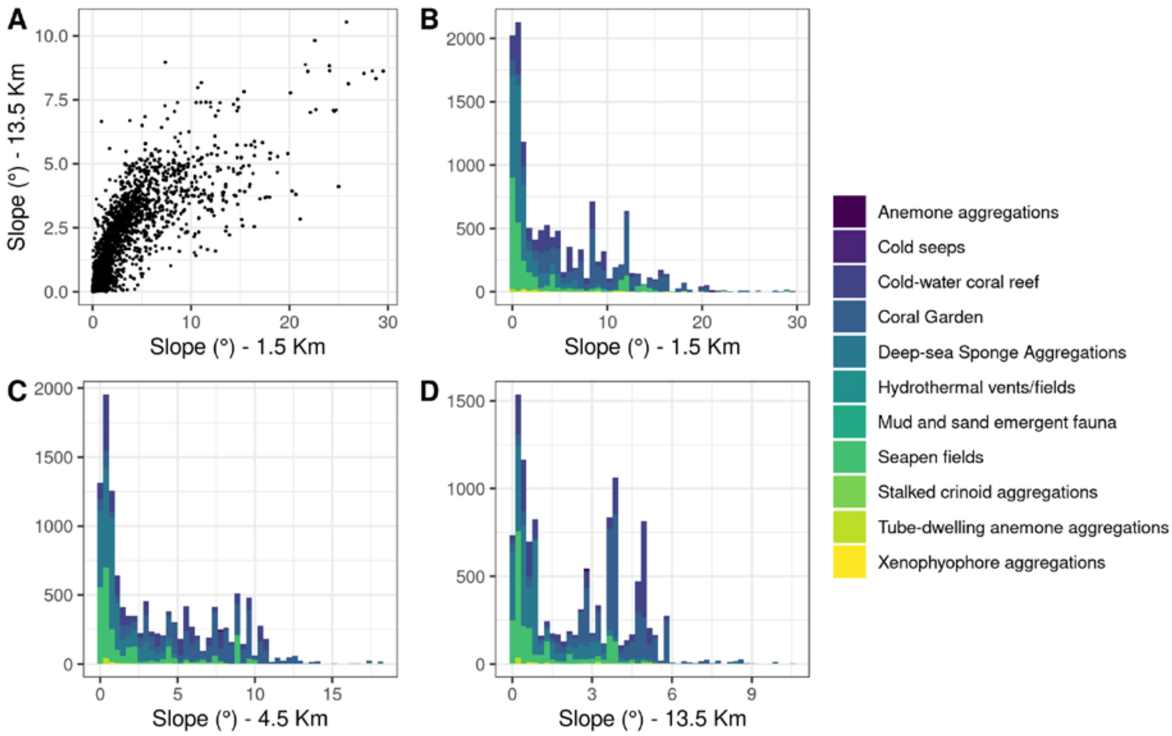

Figure 7. A. Scatterplot showing the slope values calculated from GEBCO 2020 bathymetry data at two spatial scales: 1.5 Km (using a three cell-moving window) and 13.5 Km (using a 27 cell-moving window). B-D. Distribution of slope values at locations where VME Habitat Types were reported in the ICES VME database. Slopes were computed at three different spatial scales: 1.5, 4.5 and 13.5 Km, corresponding to the use of a 3, 9 and 27 cell-moving window, respectively.

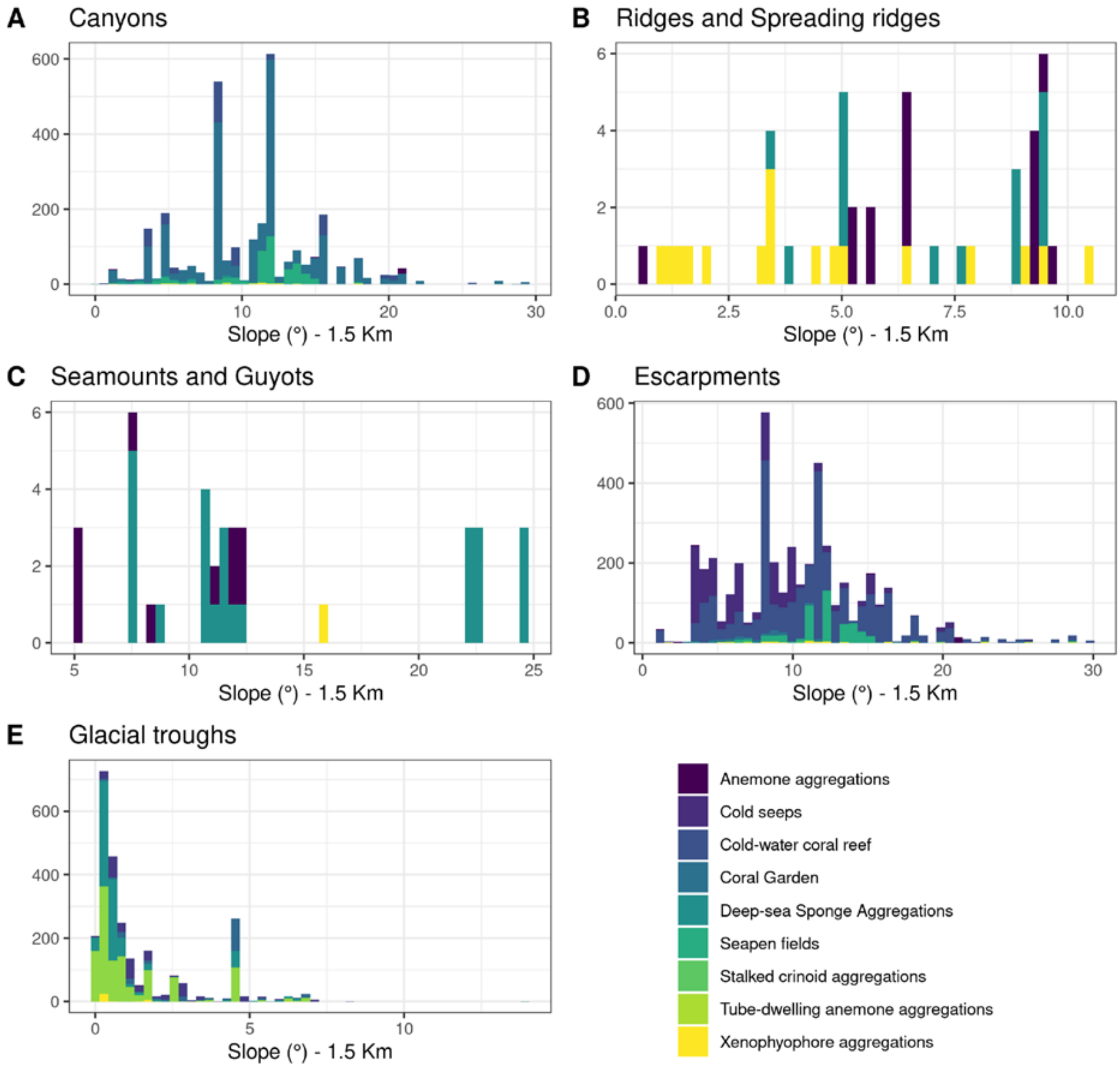

Figure 8. Frequency of records of nine VME habitat types reported within five geomorphologic elements: A) canyons, B) ridges and Spreading ridges, C) seamounts and guyots, d) escarpments, and e) glacial troughs, plotted as function of the bottom slope measured at a spatial scale of 1.5 Km. Geomorphologic elements are as defined in Harris *et al.* (2014).

9 Association between the quality of bathymetry and the delineation of slopes, and consequently, VME elements

The way the seafloor is captured by environmental variables such as depth is dependent on both the resolution and the quality of our data. A low quality data set can be of high spatial resolution in terms of pixels, but still represent a low-resolution view of the environment. To show the effect of this slope derived from the latest GEBCO grid was compared for areas with high quality depth (direct measurements from multibeam sonars), and low quality depth (indirect measurements such as interpolated depth and predicted depth based on satellite gravity data). The VME observations themselves were also evaluated to indicate how depth data quality might interfere in our understanding of the connection between the features we capture in models and geomorphological features such as the VME elements, and the quality and resolution of the data we have at hand.

The latest 2020 GEBCO grid was downloaded, including the uncertainty layer accompanying the depth grid. All data analysis took place in R 3.6.1. Depth and uncertainty data were clipped to the outer extent of the modified provinces (which was also converted to raster format at the GEBCO resolution), and reprojected to Mollweide equal area projection. Slope was calculated using a 9-cell window (3x3), and reclassified to above or below 6.4 deg. A raster stack with area of interest (four modified provinces), reclassified slope and depth quality was computed and converted into a data frame. Data was grouped by area and quality, and the cover of slope was computed. The total cover of each slope class was computed by multiplying the extent of each cell (average of 283 m x 409 m in equal area projection) with the number of cells in each group, and summary statistics was derived for GEBCO quality vs slope by areas, as well as GEBCO quality by areas. Additionally, the VME observations were connected to the quality grid to compute statistics of VME observations and GEBCO depth quality.

The analysis of the connection between VME observations (both habitats and indicators), high slope areas and depth quality show that a majority of the VME observations (86%) are located in areas where the data quality of the underlying GEBCO depth grid is relatively high, while for the area as a whole higher quality depth data is only available for 38% of the seafloor (Figures 9, 10 and 11). The analysis also shows that there is a correlation between the amount of slope found in an area and the underlying depth data quality. The proportion of Slope > 6.4 degrees was 75% higher in areas with high quality depth data compared with low quality depth data (Figure 12).

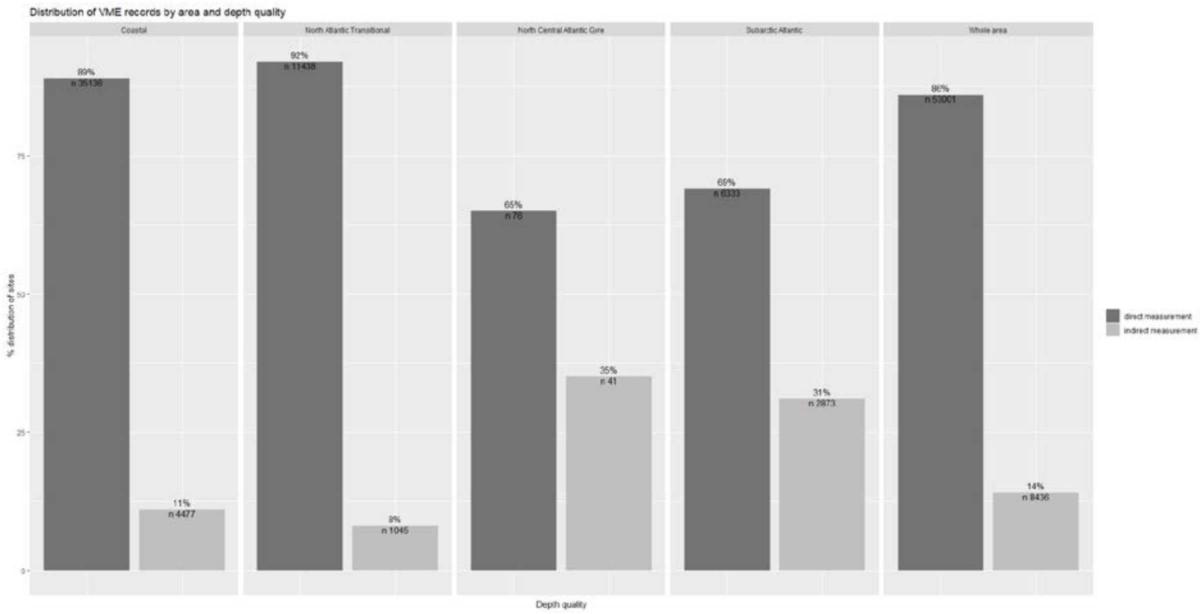

Figure 9. VME observations by GEBCO 2020 depth quality by province areas. A majority of the observations in all areas are located in places where the GEBCO depth grid has good quality.

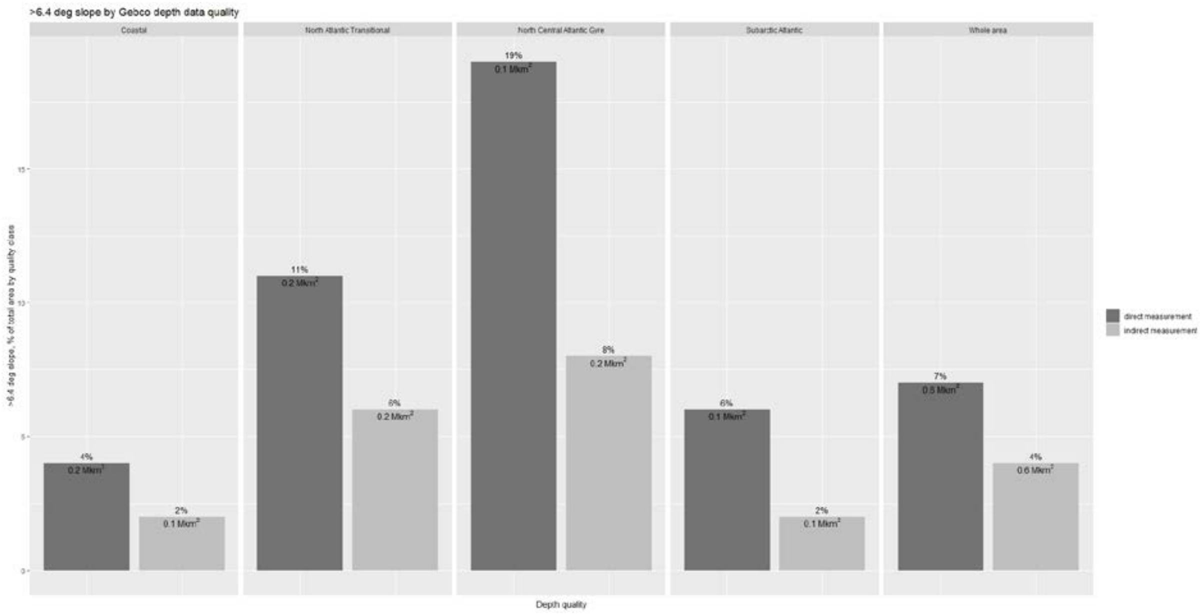

Figure 10. Areas with Slope >6.4 degree computed from the GEBCO 2020 grid by province areas and GEBCO depth quality. The proportion of high slope areas is significantly higher in places where the GEBCO depth grid is supported by good quality. In the whole region, 7% (0.6 million km^2 of a total of 8 million km^2) of areas with good data quality was covered by >6.4 degree slope, while only 4% (0.6 million km^2 of a total of 13.3 million km^2) of the areas with low data quality was covered by >6.4 degree slope.

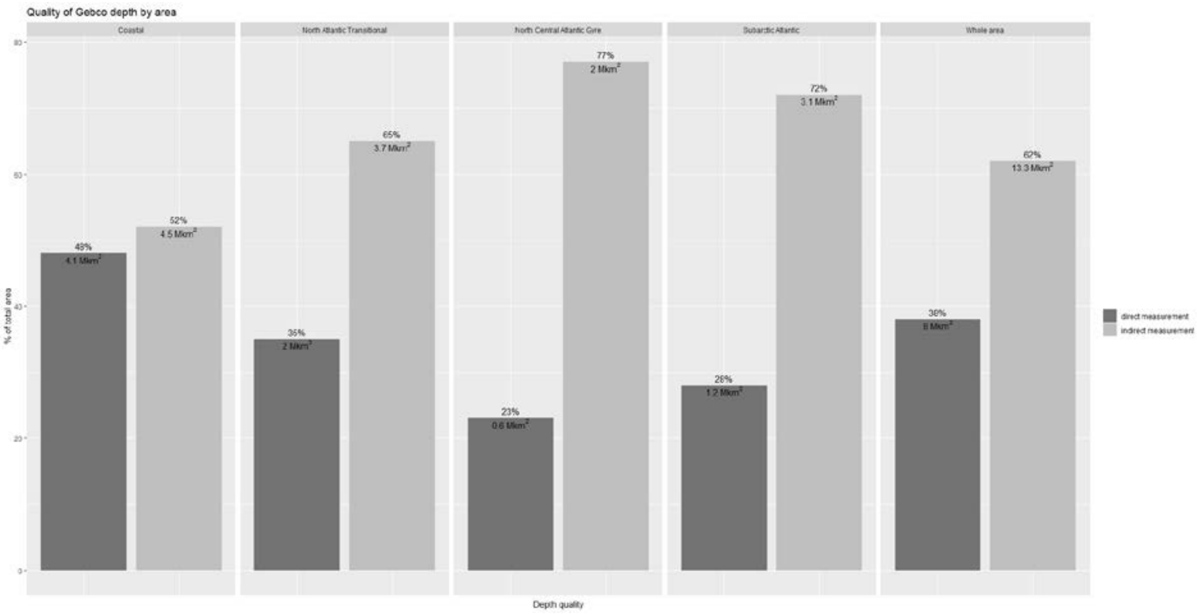

Figure 11. GEBCO depth quality by TNC area. Overall 62% (13.3 million km²) in the region was covered by lower data quality (indirect measurements) while 38% (8 million km²) was covered by higher data quality (direct measurements)

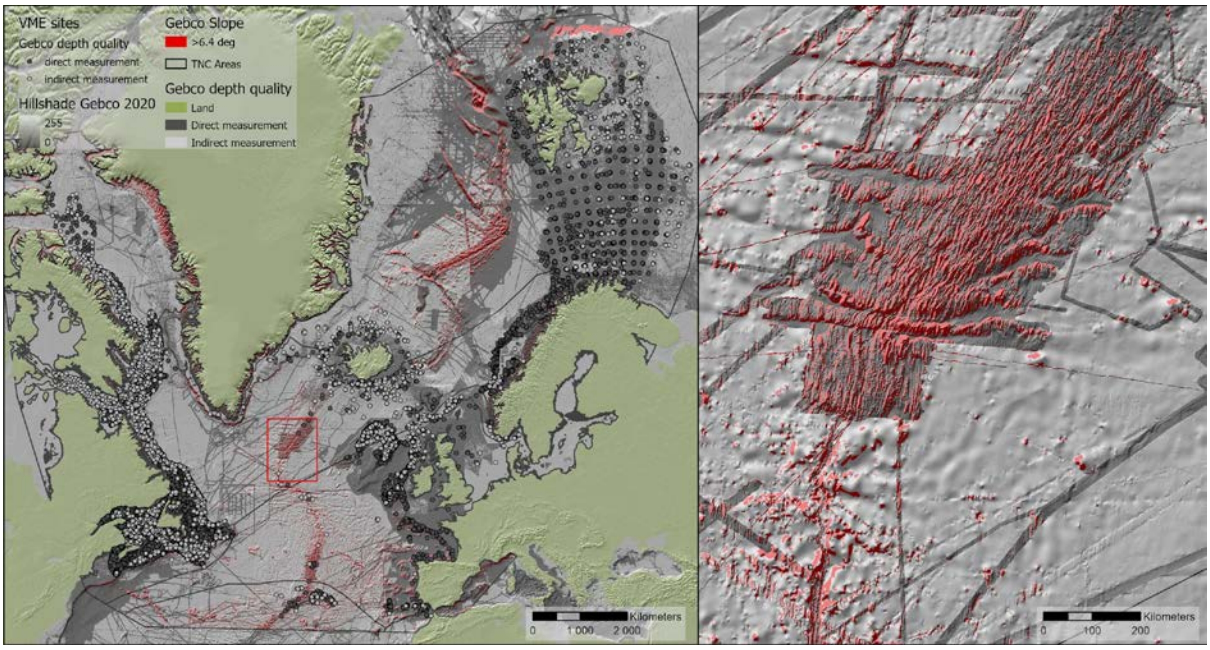

Figure 12. Map showing GEBCO 2020 depth data quality, VME stations and areas with slope >6.4 deg. Hillshade and slope is computed with the GEBCO 2020 depth grid. Visual inspection of the maps indicates how the occurrence of high slope is related to the quality of the depth data in many but not all areas.

Considering the clear connection between what an environmental variable captures and the underlying data quality shown in the comparison of high slope areas versus depth data quality, it is of great importance that data quality is included when VME elements and/or habitat suitability models are considered for spatially explicit management advice. The fact that a majority of VME observations are in areas where the underlying depth data model is of high quality further complicates the issue. An observational dataset that is distributed evenly between high and low data quality areas is currently not available, hence one runs the risk of making conclusions for the whole region that are only applicable for less than half the region.

One way to mitigate the risk of drawing poor conclusions for the whole area is to develop environmental variables that have the same underlying level of quality (e.g. use of a full coverage low data quality surface rather than a surface that varies in quality across its extent) in addition to the best available data approach. Perhaps then different slope thresholds can be used depending on the underlying data quality. The same could apply for spatial models, e.g. one model with best available information and one built using surfaces of equal data quality. More work and thought into how this is best managed is needed.

10 Relative importance of geomorphological variables versus other environmental variables in examining the distribution of VME habitats at a broad-scale

The 2020 WGMHM workshop mainly focused on VME element and the implicit use of geomorphological features for capturing area that are likely to contain VME habitats. However, previous studies have also demonstrated the importance of other environmental variables as drivers for VME species distribution (Mortensen *et al.*, 2001; Wheeler *et al.*, 2007; Davies and Guinotte, 2011, Morato *et al.*, 2019, Sundahl, 2020, Burgos, 2020). Niche modelling using available species occurrence data and the best environmental parameter candidate was used to assess the relative importance of physical (geomorphological variables) and other environmental variables in describing the variance within VME habitat observations.

VME habitat records were used to extract the corresponding values from environmental raster layers (Table 9). The final data set consisted of nine variables on 8289 records. Principal component analysis was used as an exploratory tool to summarize and to visualize the results. PCA was performed using R statistical software. The results are shown in the Figure 13 and Table 10.

Table 9. Environmental variables used for PCA analysis.

Variables	Sources
Particulate organic carbon flux at 100-m depth (epc100, mg C m-2 d-1)	Morato *et al.*, 2019. https://doi.org/10.1111/gcb.14996 Data availability : https://doi.pangaea.de/10.1594/PANGAEA.911117 Used data : variables computed under present-day (1951-2000) environmental conditions climate projections (RCP8.5 scenario) for the North Atlantic Ocean
Bottom water dissolved oxygen concentration (µmol kg-1)	
pH, and potential temperature (°K)	
Near seafloor aragonite (Ωcal)	
Near seafloor calcite (Ωcal)	
Potential temperature (°K)	
Sea surface salinity	Copernicus portal
Bathymetry	GEBCO
Slope	

The first three dimensions account for approximately the total variation in the dataset with eigenvalues of 41.4, 22.6 and 13.9% respectively. Variable markers displayed as arrows in correlation biplots (Figure 13) as well as the contribution of variables (Table 10) highlight that environmental variables, pH, calcite and aragonite form the first dimension, followed by temperature and oxygen for the second dimension. Bathymetry and slope, the two proxies of geomorphological variables, appear to be represented by the third dimension. Clearly, variables associated with dimensions one and two explain the majority of the variance within the VME observations. Bathymetry and slope explain a smaller amount of variance when the analysis is conducted at this scale. It was reported that aragonite saturation was exclusively selected for scleractinians, whereas calcite saturation was selected for octocorals (Morato *et al.*, 2019).

Other environmental variables that could affect VEM occurrences or density should be included in further work. For instance, strong and prevailing near bottom currents should be included as they are related to food supply, larval dispersal and smothered by sediment deposition (Davies *et al.*, 2009). In addition, *Lophelia* has been shown to be related to specific surface chlorophyll a concentrations (Sundahl *et al.*, 2019). However, as a quick first-pass over the data, it is apparent that bathymetry and slope are less important in explaining variance when compared with other environmental variables. Predictive Habitat Models (PHMs, also known as Habitat Suitability Models) typically include a broad array of environmental variables and include other terrain variables. This again suggests that VME elements in their current form may not capture VME habitat particularly well.

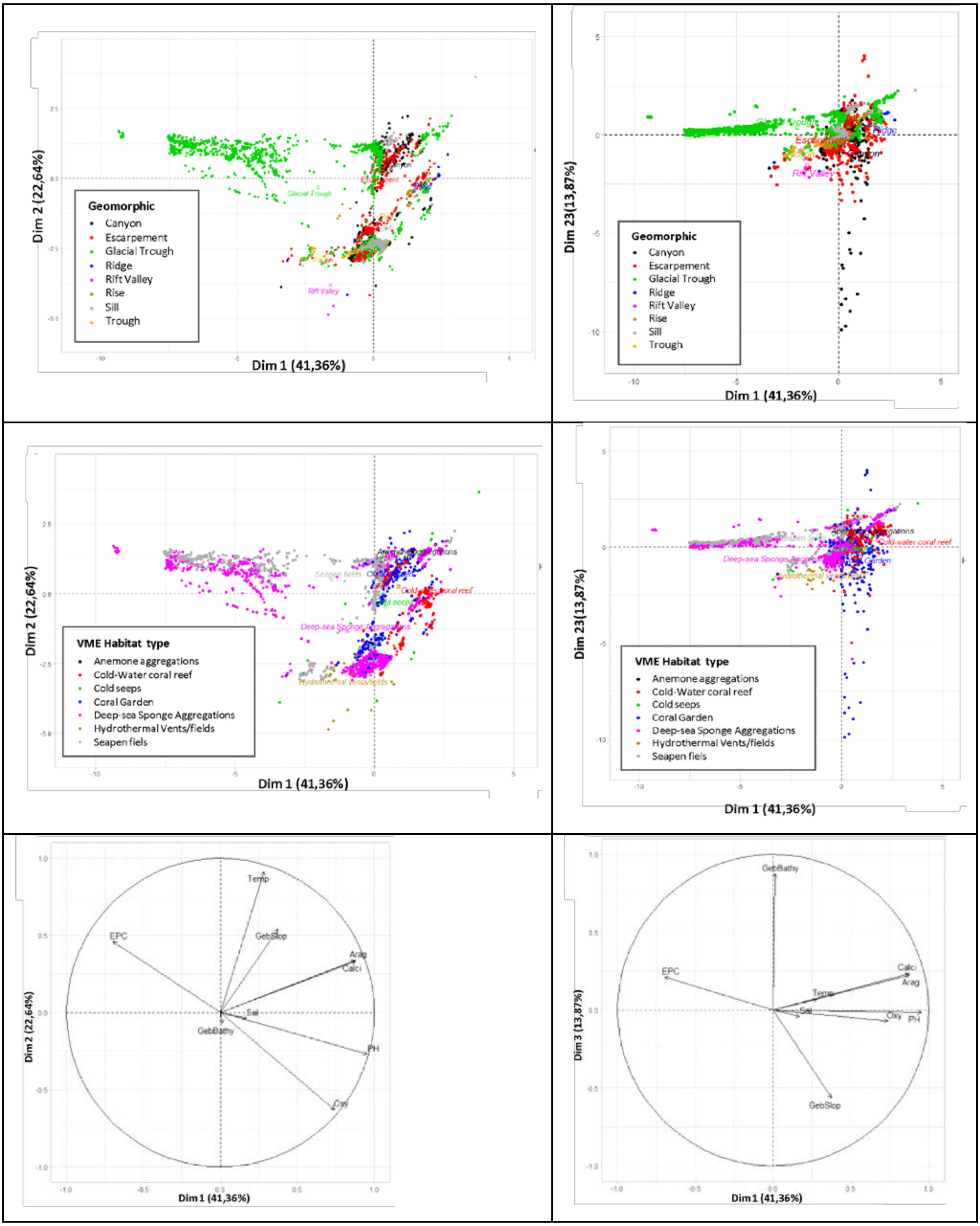

Figure 13. Principal component analysis (PCA) used as a tool to explore patterns in a dataset linking VME habitat types to environmental variables : Particulate organic carbon flux at 100-m depth (EPC), Bottom water dissolved oxygen (Oxy), pH, potential temperature, surface salinity (Sal), Near seafloor aragonite (Arag), Near seafloor calcite (Calci), Depth (GebBathy) and slope (GebSlop). Geomorphologic (Top) and VME habitat types (In the middle) qualitative variables are used as supplementary elements.

Table 10. Contribution of explored variables to the data set variance for the three most important dimensions (Dim1=41.36, Dim2=22.64, Dim 3=13.87).

	Dim.1	Ctr	Cos2	Dim.2	Ctr
	Cos2	Dim.3	Ctr	Cos2	
PH		0.952	**24.342**	0.906 ǀ -0.270	3.575
	0.073 ǀ -0.016	0.019	0.000		
Temperature	0.283	2.152	0.080 ǀ	0.914	**41.036**
	0.836 ǀ	0.071	0.406	0.005	
SSS		0.170	0.773	0.029 ǀ -0.037	0.066
	0.001 ǀ -0.041	0.132	0.002		
Oxygen		0.740	14.725	0.548 ǀ -0.628	**19.328**
	0.394 ǀ -0.071	0.399	0.005		
EPC		-0.698	13.096	0.487 ǀ	0.459
	10.323	0.210 ǀ	0.213	3.620	0.045
Calcite		0.875	**20.560**	0.765 ǀ	0.332
	5.416	0.110 ǀ	0.236	4.471	0.056
Aragonite	0.875	**20.582**	0.766 ǀ	0.339	5.641
	0.115 ǀ	0.225	4.070	0.051	
Slope		0.374	3.768	0.140 ǀ	0.541
	14.365	0.293 ǀ -0.564	**25.437**	0.318	
Bathy		0.011	0.003	0.000 ǀ -0.071	0.250
	0.005 ǀ	0.876	**61.445**	0.767	

11 Discussion

As per the WGDEC request, WGMHM have delivered the estimated distribution for the following VME elements; (i) canyons; (ii) seamounts; (iii) steep flanks greater than 6.4 degrees; (iv) steep-slopes and peaks on mid-ocean ridges; and (v) hydrothermal vents. It was not possible at this point to delineate the knolls. Candidate VME elements that also have a relatively strong association with VME habitat types, namely escarpments and glacial troughs, have also been provided.

Analysis conducted by the WGMHM on the underlying concept of VME elements has highlighted some limitations in their use for management of VME habitats. The main weaknesses relates to the use of just geomorphological features for the delineation of VME habitat. This is further compounded by the use of arbitrary or locally relevant thresholds for defining VME elements. Elements are almost exclusively geomorphological features or variables that do not include other environmental information that is known to influence the distribution of VME habitats. An analysis of the distribution of the VME observations in relation to a suite of oceanographic variables (e.g. temperature, salinity, aragonite, calcite and primary production) with geomorphological variables (depth and slope) using Principal Component Analysis revealed that most of the variance within the VME observations is explained by oceanographic variables whilst depth and slope explain relative little variance. This relationship is likely to vary with scale. At a local scale, it is likely that bathymetry and its derivatives will be more important for explaining variance. However, the analysis conducted here was at the scale of the entire north Atlantic. When operating at this, and large regional scales, it is apparent that geomorphology is of less value in explaining the distribution of VME habitat types. This would suggest that the reliance of VME elements on physical variables/bathymetry derivatives results in a relatively poor expression of conditions suitable for VME habitats when operating at a broad spatial scale.

Analyses also examined the level of overlap within the physical variables between VME elements, i.e. are individual elements delineating unique habitat or is there commonality between elements? Slope is a variable that is common to almost all of the VME elements and was therefore selected for further analysis. The value ranges for slope overlap substantially between VME elements. For example, steep flanks will also be present in canyons, seamounts, steep-slopes and peaks on mid-ocean ridges and knolls. As such, individual VME elements do not specifically relate to discrete physical conditions and this leads to spatial overlap between VME elements. Based on the overlap analysis and strength of association, it is likely that some VME elements have varying levels of redundancy. It is recommended that more work be conducted to refine the definition of the VME elements and to either weight or reduce the list of elements - this list may vary between provinces, spatial scales and VME habitat type.

The reliance on slope, and thresholds of slope angles, for defining some elements is a significant weakness unless the method for deriving estimates of slope are carefully stated. It has been shown above that the calculation of slope is highly dependent on the resolution of the bathymetric grid selected. As such, regardless of the source of the bathymetry, the working resolution of the bathymetric grids used for the slope calculation must be specified and bound to the VME element definitions that use components of seabed slope. The underlying data type (modelled/remotely sensed from satellites versus observed by single-beam and multibeam echosounders), and hence quality, has also been shown to influence the calculation of slope, i.e. higher slope values area more likely to occur when the underlying bathymetry data is sourced from survey rather than from modelled or remotely sensed (satellite altimetry) sources. In addition, the number of slope units also increases as data quality improves, e.g. a 20% increase in the number of discrete units of slope (>6.4 degrees) when using the 2020 GEBCO data compared with the 2019 data. As such, the quality of sloped areas and probability of high slope angles occurring will vary between data sets and spatially within data sets.

Although this report is recommending that VME elements are defined using quantitative thresholds, it is of great importance that these thresholds are carefully fitted so that they reflect real ecological transitions that influence the distribution of VME habitats. An analysis of the presence of VME habitat types along gradients of slope revealed that the 6.4 degree threshold did not correspond to any natural transitions or breaks within the VME observations. This analysis was repeated over several resolutions of bathymetry, which again highlighted the influence of resolution on the expression of slope. In summary, many of VME habitat observations were seen to occupy slope angles less than 6.4 degrees. It is understood that the 6.4 degree threshold was appropriate for delineating VME habitat at one site but it appears to have little transferability within the North Atlantic. Further work is therefore required to establish which thresholds reflect ecologically important changes within the environment and whether these thresholds are truly transferable to all VME habitats within the management area.

As the association between VME elements and habitat observations is broad and the footprint of most elements large, it is likely that the use of VME elements will result in the delineation of large areas where VME habitats are likely to occur. In modelling terms, this equates to a very high rate of false positive classifications as well as high rate of false negatives based on the abundance of VME observations on slopes less than 6.4 degrees. The high rate of false positives associated with VME elements may not be a hindrance if precautionary principles are being followed. However, should the footprint of the VME elements overlap high-value fisheries, the high level of false positives may result in an unacceptably high level of socio-economic impact given the certainty of the zoning process.

In summary, it is important that the points raised in this report are carefully considered before committing to the use of Elements in forming advice - a summary of the main points are provided below:

1. Although VME elements have been provided, it is noted that the definition for each VME element is inadequate to ensure the exact reproduction of elements.
2. Elements are also listed without clear rule-sets for their consistent calculation (i.e. a specification that states the acceptable input data sets, working resolution, underlying data quality, exact method to produce terrain derivatives and the thresholds for delineating features).
3. The strength of association between specific elements and individual VME habitats is often poor.
4. Where the strength of association is high, the footprint of the Element is excessively large (either as a small number of large units or numerous small units) and unlikely to be useful for the fine-scale delineation of spatial advice.
5. Based on the above issues, WGMHM does not recommend the use of VME elements without further refinement. We have however provided VME element maps for the imminent Workshop on EU regulatory area options for VME protection (WKEUVME). It is likely that this workshop will also provide additional insights into the value of VME elements within marine management.

To make VME elements more useful for the provision of management advice, further work must be undertaken to refine the physical conditions captured by each element. This can be done by either narrowing the value range of existing variables used to define an element or by including more physico-chemical parameters. However, this progression fundamentally represents a manual approach to what Predictive Habitat Model (PHMs) modelling techniques do in an objective, efficient and sophisticated way. It is recommended that PHMs remain the primary modelling method for investigating where VME habitats are likely to occur in areas lacking VME observations. The benefit of PHMs is that the fitting of VME habitat signatures is built-up from the VME observations themselves rather than using expert-driven, top-down rules that currently define VME elements. The WGMHM does acknowledge that VME elements do represent an attractive source of evidence for supporting management advice. On first pass, VME elements do have an intuitive simplicity that is easy to apply and attractive. Their simplicity also provides greater transparency, which allows the method to be communicated quickly to both specialist and non-specialist. Furthermore, VME elements attempt to capture multiple VME habitat types within each element. A similar approach using PHMs would either require multiple models of individual habitats or multi-species modelling approaches, both of which represent a significant workload when compared with the use of VME elements. Rather than adopt VME elements because of these positive points, the challenge for marine habitat mapper and modellers is to transfer these advantages to PHMs, i.e. making modelling techniques quicker to produce, clearer and more intuitive for end users and covering a great breadth of VME habitats, species and traits. The proposed application of the ICES benchmarking progress and development of standards for the acceptance of PHMs outputs in ICES advice will also contribute to a greater acceptance of these products.

To summarise, if VME elements are to be used within advice drafting process, further work that should be prioritised includes:

- Shortlist existing and candidate elements based on their strength of association with VMEs and their spatial properties;
- Link Elements to an existing geomorphological glossary – suitable glossaries have been discussed within this report;
- If the methods for delineating the elements are not implicit within the definition, provide a rule-set for the consistent calculation of elements; and
- Consider refining elements with more specific value ranges or including more environmental variables but be aware that this is fundamentally a manual approach to geostatistical modelling that cannot compete against the quality and specificity of existing, automated approaches.

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Annex 1: List of participants

2020 meeting

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2019 meeting

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2018 meeting

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Annex 2: WGMHM Resolutions

The **Working Group on Marine Habitat Mapping** (WGMHM), chaired by James Strong, UK, will work on ToRs and generate deliverables as listed in the Table below.

	MEETING DATES	VENUE	REPORTING DETAILS	COMMENTS (CHANGE IN CHAIR, ETC.)
Year 2018	22-24 May	Hamburg, Germany	Interim report by 1 August	
Year 2019	3-7 June	Palma de Mallorca, Spain	Interim report by 1 August	Meeting in association with WGDEC
Year 2020	4-8 May	by corresp/ webex	Final report by 1 July	physical meeting cancelled - remote work (jointly with WGDEC)

ToR descriptors

TOR	DESCRIPTION	BACKGROUND	SCIENCE PLAN CODES	DURATIO N	EXPECTED DELIVERABLES
A	Report on progress in international mapping programmes (including OSPAR and HELCOM Conventions, EMODnet, EC and EEA initiatives, CHARM, Mesh-Atlantic and other projects).	Capturing the presence and work of large international mapping projects is importance because (i) the WGMHM report becomes a useful 'state of the art' summary of marine habitat mapping activity, (ii) the presentations from these projects helps spread best-practice, standardisation and collaborative working within the group, and (iii) other presentations highlight relevant mapping work that may benefit the large international programmes.	3.4	3 years	Annual updates and final report
B	Review and synthesise key results from national habitat mapping during the preceding year, as well as new on-going and planned projects focusing on particular issues of relevance to the rest of the meeting. Provide National Status Report updates in geographic format in the ICES webGIS.	The current extent of marine habitat mapping and modelling means that maps are meeting at international boundaries. It is important that maps are joined internationally and in a standardised manner. This requires an understanding of the extent and distribution of habitat mapping within nation states. Equally, WGMHM are often interested in specific habitats and wish to be kept informed of specific mapping exercises on these habitats, e.g. deepwater habitats or cold water corals. The reporting of national mapping is also the primary mechanism for encouraging WG	3.4	3 years	Annual updates and final report. Submission of of survey metatdata to ICES Data Center

		members to submit survey metadata files to the various data archiving centres. The National Progress reports also states whether member countries have purchased significant survey items, such as ships, AUVs and sonars. This provides a good opportunity for others to identify useful resources for international colloboration.			
C	Summarise recent advances in marine habitat mapping and modelling techniques, including field work methodology, and data analysis and interpretation.	This ToR provides the main avenue for mappers to coomunicate new or improved techniques to the other scientists present (and captured in the report). As such, this ToR is essential for spreading best practice and developing new methods.	3.3	3 years	Annual updates and final report. The 2018 intersessional work will be directed towards producing our first marine habitat mapping best practice document (1–2 methodological topics only)
D	Review practise about the use of habitat maps, for example mapping for the MSFD, marine spatial planning, and management of MPAs; and assess the ability to use habitat maps for monitoring of the environment.	To encourage the diversification of the WGMHM, the group also consider how marine habitat maps are used for scientific and management purposes. Members of the group are often the creators of these maps and have important insights into how the maps can be used. Equally, it gives marine managers an opportunity to suggest how maps are best presented to support clarity and value for management purposes.	6.2	3 years	Annual updates and final report. The WGMHM also made a substantial contribution to the ICES Special Request Advice 'EU request for guidance on how pressure maps of fishing intensity contribute to an assessment of the state of seabed habitats' Published 4 July 2016
E	The identification of sources of information (e.g. bathymetry, oceanography, fisheries or socio-economic) that can be used for the production and enrichment of marine habitat maps.	Many of the remotely sensed and modelled outputs that are of value to marine habitat mappers is available online. Although much of this information is centralised in large data archives, other information remains dispersed on the web. This ToR seeks to collate the important data soueces that are of value for marine habitat mapping into one database.	3.2	Year 1	An annually updated database listing important data sources suitable for marine habitat mapping

F	Identify and advance theoretical aspects of habitat mapping (e.g. landscape ecology, supply-side ecology, implications of scale etc.).	This ToR is to provide an opportunity for EG members to address the theoretical aspects of marine habitat mapping. As a science in its infancy, it is important that underpinning concepts are challenged and re-evaluated.	4.1	Years 1 and 2	Important presentations and discusses summarised in annual reports. Scientific publication assessing the influence of classification schemes on marine habitat mapping (to be submitted in md December 2017 to ICES Journal of Marine Science)

Summary of the Work Plan

Year 1	Draft and finalise the "Recommended Operating Guidelines for Assessing and Communicating Confidence in Marine Habitat Mapping
Year 2	Conduct a joint meeting with the working group on deep-water ecology (WGDEC) and collaborate a significant joint output, e.g., geo-spatial modeling of the distribution of Atlantic Vulnerable Marine Ecosystems".
Year 3	Annual reporting for remaining ToRs and comissioning of new intersessional papers and database.

Supporting information

Priority	These ToRs are essential for maintaining the WG as a focused and relavent group for marine habitat mapping. The ToRs also contribute to the disemination of innovative ideas and best practice. This in turn improves the quality and quantity of marine habitat maps.
Resource requirements	The only resouces required will be the occassional use of ICES HQ meeting rooms.
Participants	The Group is normally attended by some 10 - 15 members and guests.
Secretariat facilities	None.
Financial	No financial implications.
Linkages to ACOM and groups under ACOM	There are no obvious direct linkages.
Linkages to other committees or groups	There is a very close working relationship with Working Groups on Benthic Ecology, Deep-Water Ecology, Marine Planning and Coastal Zone Management and Spatial Fisheries Data.
Linkages to other organizations	EMODnet bathymetry and EMODnet seabed habitats.

Annex 3: Strength of association and element area analyses subdivided by province

Table 1. Percentage of VME habitat observations captured by each Element within the North Atlantic Transitional province. Summary statistics present the overall percentage between all VME habitats and indicators by Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the North Atlantic Transitional province	Isolated seamounts (km^2)	Canyons (km^2)	Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km^2)	Steep flanks greater than 6.4 degrees (km^2)	Hydrothermal vents (km^2)
Anemone aggregations	0.0%	100.0%	0.0%	77.3%	0.0%
Cold-water coral reef	0.0%	18.4%	0.0%	45.2%	0.0%
Cold seeps	0.0%	20.0%	0.0%	0.0%	0.0%
Coral Garden	0.0%	48.3%	0.0%	73.3%	0.0%
Deep-sea Sponge Aggregations	0.0%	2.7%	0.4%	8.5%	0.0%
Hydrothermal vents/fields	0.0%	0.0%	0.0%	0.0%	0.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	0.0%	37.7%	0.0%	39.0%	0.0%
Stalked crinoid aggregations	0.0%	66.7%	0.0%	83.3%	0.0%
Tube-dwelling anemone aggregations	0.0%	15.6%	0.0%	36.4%	0.0%
Xenophyophore aggregations	0.0%	29.3%	0.0%	46.3%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	0	2003	3	3105	0
Percentage of all VME *habitat* observations captured by the Element	0.0%	33.1%	0.0%	51.3%	0.0%
Co-occurrence of VME *indicator* observations and the VME Element	98	759	312	2258	0
Percentage of all VME *indicator* observations captured by the Element	1.0%	7.5%	3.1%	22.3%	0.0%

Table 2. Percentage of VME habitat observations captured by each Candidate Element within the North Atlantic Transitional province. Summary statistics present the overall percentage between all VME habitats and indicators by Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the North Atlantic Transitional province	Slope (Grid Arendal) (km^2)	Escarpment (km^2)	Glacial trough (km^2)	Ridges (km^2)	Guyots (km^2)
Anemone aggregations	100.0%	100.0%	0.0%	0.0%	0.0%
Cold-water coral reef	88.0%	71.3%	1.1%	0.0%	0.9%
Cold seeps	80.0%	0.0%	0.0%	0.0%	0.0%
Coral Garden	97.9%	70.1%	0.3%	0.0%	1.0%
Deep-sea Sponge Aggregations	93.1%	5.2%	6.4%	1.4%	0.0%
Hydrothermal vents/fields	0.0%	100.0%	0.0%	0.0%	0.0%
Mud and sand emergent fauna	100.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	41.6%	38.1%	12.5%	0.0%	0.0%
Stalked crinoid aggregations	100.0%	83.3%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	67.5%	23.4%	26.0%	0.0%	0.0%
Xenophyophore aggregations	97.6%	46.3%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	5108	3342	232	12	37
Percentage of all VME *habitat* observations captured by the Element	84.3%	55.2%	3.8%	0.2%	0.6%
Co-occurrence of VME *indicator* observations and the VME Element	5034	2617	6	612	52
Percentage of all VME *indicator* observations captured by the Element	49.7%	25.8%	0.1%	6.0%	0.5%

Table 3. Percentage of VME habitat observations captured by each Element within the coastal/shelf/other province. Summary statistics present the overall percentage between all VME habitats and indicators by Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the coastal/shelf/other province	Isolated seamounts (km^2)	Canyons (km^2)	Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km^2)	Steep flanks greater than 6.4 degrees (km^2)	Hydrothermal vents (km^2)
Anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Cold-water coral reef	0.0%	14.7%	0.0%	32.5%	0.0%
Cold seeps	0.0%	22.2%	0.0%	0.0%	0.0%
Coral Garden	0.0%	67.2%	0.0%	69.4%	0.0%
Deep-sea Sponge Aggregations	0.0%	0.0%	0.1%	1.2%	0.0%
Hydrothermal vents/fields	0.0%	0.0%	0.0%	7.1%	0.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	0.0%	1.7%	0.0%	1.3%	0.0%
Stalked crinoid aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	0.0%	0.0%	0.0%	10.0%	0.0%
Xenophyophore aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	0	872	1	1031	0
Percentage of all VME *habitat* observations captured by the Element	0.0%	19.3%	0.0%	22.8%	0.0%
Co-occurrence of VME *indicator* observations and the VME Element	0	3723	8	5043	0
Percentage of all VME *indicator* observations captured by the Element	0.0%	10.1%	0.0%	13.7%	0.0%

Table 4. Percentage of VME habitat observations captured by each Candidate Element within the coastal/shelf/other province. Summary statistics present the overall percentage between all VME habitats and indicators by Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the coastal/shelf/other province	**Slope (Grid Arendal) (km²)**	**Escarpment (km²)**	**Glacial trough (km²)**	**Ridges (km²)**	**Guyots (km²)**
Anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Cold-water coral reef	35.6%	31.6%	44.3%	0.0%	0.0%
Cold seeps	33.3%	0.0%	22.2%	0.0%	0.0%
Coral Garden	79.1%	72.2%	16.5%	0.0%	0.0%
Deep-sea Sponge Aggregations	2.3%	1.1%	61.3%	0.1%	0.0%
Hydrothermal vents/fields	0.0%	21.4%	7.1%	7.1%	0.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	9.7%	1.2%	70.3%	0.0%	0.0%
Stalked crinoid aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	0.0%	0.0%	40.0%	0.0%	0.0%
Xenophyophore aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	1293	1051	2269	2	0
Percentage of all VME *habitat* observations captured by the Element	28.6%	23.3%	50.2%	0.0%	0.0%
Co-occurrence of VME *indicator* observations and the VME Element	21153	7757	8000	18	0
Percentage of all VME *indicator* observations captured by the Element	57.4%	21.1%	21.7%	0.0%	0.0%

Table 5. Percentage of VME habitat observations captured by each Element within the Subarctic Atlantic province. Summary statistics present the overall percentage between all VME habitats and indicators by Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the Subarctic Atlantic province	Isolated seamounts (km²)	Canyons (km²)	Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km²)	Steep flanks greater than 6.4 degrees (km²)	Hydrothermal vents (km²)
Anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Cold-water coral reef	0.0%	0.9%	0.0%	0.8%	0.0%
Cold seeps	0.0%	0.0%	0.0%	0.0%	0.0%
Coral Garden	0.0%	5.9%	0.0%	10.4%	0.0%
Deep-sea Sponge Aggregations	0.0%	3.2%	0.0%	1.6%	0.0%
Hydrothermal vents/fields	0.0%	0.0%	0.0%	0.0%	0.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	0.0%	10.0%	0.0%	0.0%	0.0%
Stalked crinoid aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Xenophyophore aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	0	84	0	65	0
Percentage of all VME *habitat* observations captured by the Element	0.0%	3.4%	0.0%	2.7%	0.0%
Co-occurrence of VME *indicator* observations and the VME Element	4	132	11	64	0
Percentage of all VME *indicator* observations captured by the Element	0.0%	1.6%	0.1%	0.8%	0.0%

Table 6. Percentage of VME habitat observations captured by each Candidate Element within the Subarctic Atlantic province. Summary statistics present the overall percentage between all VME habitats and indicators by Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the Subarctic Atlantic province	**Slope (Grid Arendal) (km²)**	**Escarpment (km²)**	**Glacial trough (km²)**	**Ridges (km²)**	**Guyots (km²)**
Anemone aggregations	100.0%	100.0%	0.0%	0.0%	0.0%
Cold-water coral reef	28.5%	0.9%	10.4%	0.0%	0.0%
Cold seeps	66.7%	0.0%	0.0%	0.0%	0.0%
Coral Garden	60.3%	5.9%	9.3%	0.0%	0.0%
Deep-sea Sponge Aggregations	61.1%	3.5%	1.0%	0.0%	0.0%
Hydrothermal vents/fields	0.0%	50.0%	0.0%	0.0%	0.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	70.8%	0.0%	5.0%	0.0%	0.0%
Stalked crinoid aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Xenophyophore aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	1334	81	110	0	0
Percentage of all VME *habitat* observations captured by the Element	54.4%	3.3%	4.5%	0.0%	0.0%
Co-occurrence of VME *indicator* observations and the VME Element	3223	183	736	38	0
Percentage of all VME *indicator* observations captured by the Element	38.1%	2.2%	8.7%	0.4%	0.0%

Table 7. Percentage of VME habitat observations captured by each Element within the North Central Atlantic Gyre province. Summary statistics present the overall percentage between all VME habitats and indicators by Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the North Central Atlantic Gyre province	Isolated seamounts (km²)	Canyons (km²)	Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km²)	Steep flanks greater than 6.4 degrees (km²)	Hydrothermal vents (km²)
Anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Cold-water coral reef	0.0%	0.0%	0.0%	0.0%	0.0%
Cold seeps	0.0%	0.0%	0.0%	0.0%	0.0%
Coral Garden	0.0%	0.0%	14.3%	85.7%	0.0%
Deep-sea Sponge Aggregations	0.0%	0.0%	100.0%	100.0%	0.0%
Hydrothermal vents/fields	11.1%	0.0%	0.0%	44.4%	0.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	0.0%	0.0%	0.0%	0.0%	0.0%
Stalked crinoid aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Xenophyophore aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	1	0	6	20	0
Percentage of all VME *habitat* observations captured by the Element	3.7%	0.0%	22.2%	74.1%	0.0%
Co-occurrence of VME *indicator* observations and the VME Element	3	6	16	23	0
Percentage of all VME *indicator* observations captured by the Element	3.3%	6.6%	17.6%	25.3%	0.0%

Table 8. Percentage of VME habitat observations captured by each Candidate Element within the North Central Atlantic Gyre province. Summary statistics present the overall percentage between all VME habitats and indicators by Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the North Central Atlantic Gyre province	**Slope (Grid Arendal) (km²)**	**Escarpment (km²)**	**Glacial trough (km²)**	**Ridges (km²)**	**Guyots (km²)**
Anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Cold-water coral reef	0.0%	0.0%	0.0%	0.0%	0.0%
Cold seeps	0.0%	0.0%	0.0%	0.0%	0.0%
Coral Garden	100.0%	71.4%	0.0%	100.0%	0.0%
Deep-sea Sponge Aggregations	100.0%	100.0%	0.0%	100.0%	0.0%
Hydrothermal vents/fields	0.0%	55.6%	0.0%	11.1%	0.0%
Mud and sand emergent fauna	0.0%	0.0%	0.0%	0.0%	0.0%
Seapen fields	0.0%	0.0%	0.0%	0.0%	0.0%
Stalked crinoid aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Tube-dwelling anemone aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Xenophyophore aggregations	0.0%	0.0%	0.0%	0.0%	0.0%
Summary statistics by VME Element					
Co-occurrence of VME *habitat* observations and the VME Element	18	19	0	19	0
Percentage of all VME *habitat* observations captured by the Element	66.7%	70.4%	0.0%	70.4%	0.0%
Co-occurrence of VME *indicator* observations and the VME Element	21	48	0	36	0
Percentage of all VME *indicator* observations captured by the Element	23.1%	52.7%	0.0%	39.6%	0.0%

Table 9. Mean area (km²) of VME Element units occupied by VME habitat observations within the North Atlantic Transitional province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the North Atlantic Transitional province	**Isolated seamounts (km²)**	**Canyons (km²)**	**Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km²)**	**Steep flanks greater than 6.4 degrees (km²)**	**Hydrothermal vents (km²)**
Anemone aggregations	-	7447	-	8879	-
Cold-water coral reef	-	1654	-	8874	-
Cold seeps	-	160	-	-	-
Coral Garden	-	3722	-	6391	-
Deep-sea Sponge Aggregations	-	-	171	310	-
Hydrothermal vents/fields	1121	-	-	-	-
Mud and sand emergent fauna	-	-	-	–	-
Seapen fields	-	6626	-	7770	-
Stalked crinoid aggregations	-	173	-	12	-
Tube-dwelling anemone aggregations	-	382	-	172	-
Xenophyophore aggregations	-	335	-	247	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	1121	2562	171	4082	0
Total number of Element units within analysis area	168	168	1293	31605	0
Element units containing VME habitat observations	2	34	2	56	0
Percentage of units with VME habitat observations	1.2%	23.2%	0.9%	0.3%	0.0%

Table 10. Mean area (km²) of Candidate Element units occupied by VME habitat observations within the North Atlantic Transitional province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Candidate Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the North Atlantic Transitional province	Slope (Grid Arendal) (km²)	Escarpment (km²)	Glacial trough (km²)	Ridges (km²)	Guyots (km²)
Anemone aggregations	12790233	34487	-	-	-
Cold-water coral reef	12130718	33574	80830	-	1728
Cold seeps	12790233	-	-	-	-
Coral Garden	11938611	30760	80830	7538	1728
Deep-sea Sponge Aggregations	11539964	2904	80830	5480	-
Hydrothermal vents/fields	-	7434	-	-	-
Mud and sand emergent fauna	12790233	-	-	-	-
Seapen fields	12123724	30418	80830	-	-
Stalked crinoid aggregations	12790233	2073	-	-	-
Tube-dwelling anemone aggregations	7409029	1602	80830	-	-
Xenophyophore aggregations	11518312	1836	-	-	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	11782129	16121	80830	6509	1728
Total number of Element units within analysis area	3	566	1	71	2
Element units containing VME habitat observations	3	13	1	2	1
Percentage of units with VME habitat observations	100.0%	5.8%	100.0%	15.5%	50.0%

Table 11. Mean area (km²) of VME Element units occupied by VME habitat observations within the coastal/shelf/other province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the coastal/shelf/other province	Isolated sea-mounts (km²)	Canyons (km²)	Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km²)	Steep flanks greater than 6.4 degrees (km²)	Hydrothermal vents (km²)
Anemone aggregations	-	-	-	-	-
Cold-water coral reef	-	2396	-	4763	-
Cold seeps	-	8608	-	-	-
Coral Garden	-	2092	-	9210	-
Deep-sea Sponge Aggregations	-	-	507	482	-
Hydrothermal vents/fields	-	-	-	-	-
Mud and sand emergent fauna	-	-	-	-	-
Seapen fields	-	11728	-	236	-
Stalked crinoid aggregations	-	-	-	-	-
Tube-dwelling anemone aggregations	-	-	-	-	-
Xenophyophore aggregations	-	-	-	-	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	-	6206	507	3673	-
Total number of Element units within analysis area	37	37	523	30953	0
Element units containing VME habitat observations	0	9	1	20	0
Percentage of units with VME habitat observations	0.0%	80.0%	0.0%	0.0%	0.0%

Table 12. Mean area (km²) of Candidate Element units occupied by VME habitat observations within the coastal/shelf/other province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Candidate Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the coastal/shelf/other province	Slope (Grid Arendal) (km²)	Escarpment (km²)	Glacial trough (km²)	Ridges (km²)	Guyots (km²)
Anemone aggregations	-	-	-	-	-
Cold-water coral reef	12790233	15860	159046	-	-
Cold seeps	12790233	-	40688	-	-
Coral Garden	12790233	32625	81092	-	-
Deep-sea Sponge Aggregations	12349650	812	102848	7538	-
Hydrothermal vents/fields	-	12952	16510	1939	-
Mud and sand emergent fauna	-	-	-	-	-
Seapen fields	12790233	679	113381	-	-
Stalked crinoid aggregations	-	-	-	-	-
Tube-dwelling anemone aggregations	-	-	80830	-	-
Xenophyophore aggregations	-	-	-	-	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	12702116	12586	84914	4739	-
Total number of Element units within analysis area	9	270	63	32	0
Element units containing VME habitat observations	2	15	21	2	0
Percentage of units with VME habitat observations	22.2%	13.7%	58.7%	18.8%	0.0%

Table 13. Mean area (km²) of VME Element units occupied by VME habitat observations within the Subarctic Atlantic province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the Subarctic Atlantic province	**Isolated seamounts (km²)**	**Canyons (km²)**	**Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km²)**	**Steep flanks greater than 6.4 degrees (km²)**	**Hydrothermal vents (km²)**
Anemone aggregations	-	-	-	-	-
Cold-water coral reef	-	4754	-	1538	-
Cold seeps	-	-	-	-	-
Coral Garden	-	3346	-	11	-
Deep-sea Sponge Aggregations	-	1248	-	126	-
Hydrothermal vents/fields	463	-	-	-	-
Mud and sand emergent fauna	-	-	-	-	-
Seapen fields	-	9159	-	-	-
Stalked crinoid aggregations	-	-	-	-	-
Tube-dwelling anemone aggregations	-	-	-	-	-
Xenophyophore aggregations	-	-	-	-	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	463	4627	-	558	-
Total number of Element units within analysis area	13	127	410	18942	0
Element units containing VME habitat observations	1	25	0	12	0
Percentage of units with VME habitat observations	7.1%	19.7%	0.0%	0.1%	0.0%

Table 14. Mean area (km²) of Candidate Element units occupied by VME habitat observations within the Subarctic Atlantic province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Candidate Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the Subarctic Atlantic province	**Slope (Grid Arendal) (km²)**	**Escarpment (km²)**	**Glacial trough (km²)**	**Ridges (km²)**	**Guyots (km²)**
Anemone aggregations	12790233	4568	-	-	-
Cold-water coral reef	12115927	5856	253306	-	-
Cold seeps	12790233	-	-	-	-
Coral Garden	10019580	2424	140919	-	-
Deep-sea Sponge Aggregations	12790233	1129	174689	-	-
Hydrothermal vents/fields	-	154	-	-	-
Mud and sand emergent fauna	-	-	-	-	-
Seapen fields	12790233	-	23493	-	-
Stalked crinoid aggregations	-	-	-	-	-
Tube-dwelling anemone aggregations	-	-	-	-	-
Xenophyophore aggregations	-	-	-	-	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	12216073	2826	148102	-	-
Total number of Element units within analysis area	3	136	25	10	0
Element units containing VME habitat observations	3	13	9	0	0
Percentage of units with VME habitat observations	100.0%	16.2%	56.0%	0.0%	0.0%

Table 15. Mean area (km²) of VME Element units occupied by VME habitat observations within the North Central Atlantic Gyre province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Element. Isolated seamounts and canyons are from Harris *et al.* (2014), slopes are derived from GEBCO data and hydrothermal vents are from the Inter-ridge database.

VME habitats in the North Central Atlantic Gyre province	**Isolated sea-mounts (km²)**	**Canyons (km²)**	**Steep-slopes and peaks on mid-ocean ridges (greater than 6.4) (km²)**	**Steep flanks greater than 6.4 degrees (km²)**	**Hydrothermal vents (km²)**
Anemone aggregations	-	-	-	-	-
Cold-water coral reef	-	-	-	-	-
Cold seeps	-	-	-	-	-
Coral Garden	-	-	18	608	-
Deep-sea Sponge Aggregations	-	-	18	608	-
Hydrothermal vents/fields	550	-	-	4103	-
Mud and sand emergent fauna	-	-	-	-	-
Seapen fields	-	-	-	-	-
Stalked crinoid aggregations	-	-	-	-	-
Tube-dwelling anemone aggregations	-	-	-	-	-
Xenophyophore aggregations	-	-	-	-	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	389	3019	77	4016	1
Total number of Element units within analysis area	145	145	1081	17594	0
Element units containing VME habitat observations	3	0	1	5	0
Percentage of units with VME habitat observations	2.1%	0.0%	0.8%	0.1%	0.0%

Table 16. Mean area (km²) of Candidate Element units occupied by VME habitat observations within the North Central Atlantic Gyre province. Summary statistics present: (i) the mean area across all VME habitat type; (ii) the total number of Candidate Element units within the area of analysis; (iii + iv) the number and percentage of these units containing VME habitat observations; and (v) the mean number of VME habitat observations within occupied units of each Candidate Element. All Candidate Elements are from Harris *et al.* (2014).

VME habitats in the North Central Atlantic Gyre province	Slope (Grid Arendal) (km²)	Escarpment (km²)	Glacial trough (km²)	Ridges (km²)	Guyots (km²)
Anemone aggregations	-	-	-	-	-
Cold-water coral reef	-	-	-	-	-
Cold seeps	-	-	-	-	-
Coral Garden	539	12414	-	7623	-
Deep-sea Sponge Aggregations	539	12414	-	7623	-
Hydrothermal vents/fields	-	32003	-	1195	-
Mud and sand emergent fauna	-	-	-	-	-
Seapen fields	-	-	-	-	-
Stalked crinoid aggregations	-	-	-	-	-
Tube-dwelling anemone aggregations	-	-	-	-	-
Xenophyophore aggregations	-	-	-	-	-
Summary area statistics by VME Element					
Average area of occupied Element units (km²)	10801927	13506	-	1394	314
Total number of Element units within analysis area	13	323	0	61	1
Element units containing VME habitat observations	1	2	0	2	0
Percentage of units with VME habitat observations	38.5%	2.5%	-	11.5%	0.0%