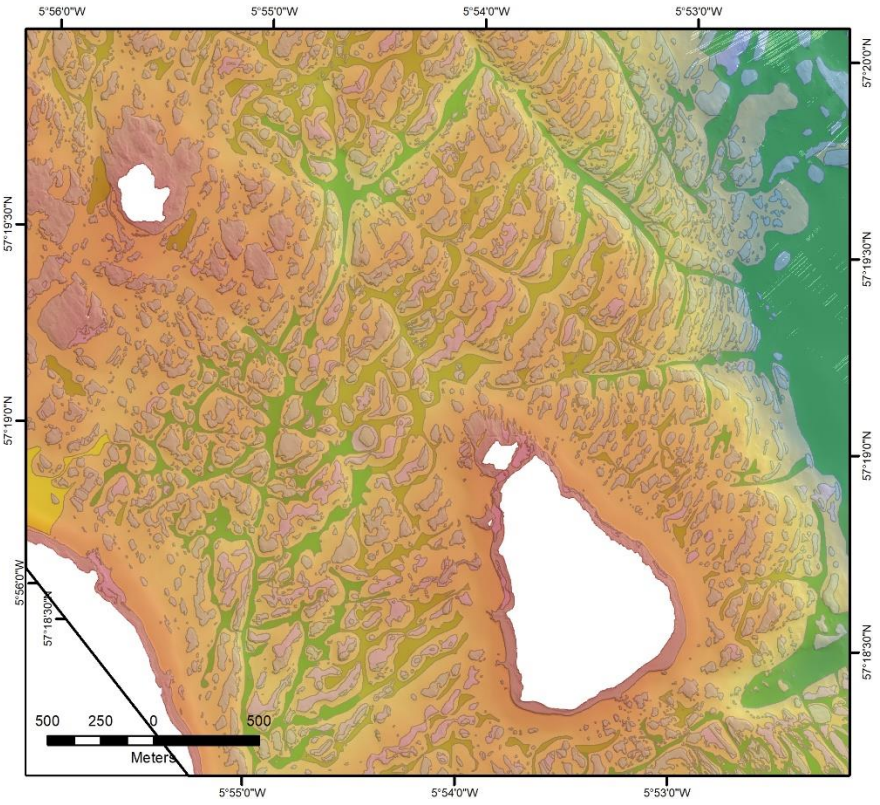
British Geological Survey

Reprocessing of CHP Datasets (HI 1567 &1570) and Seafloor Substrate Interpretation for Selected Areas: Inner Sound off Skye on the West Coast of Scotland

Environmental Change, Adaptation and Resilience

Commissioned Report CR/21/080



BRITISH GEOLOGICAL SURVEY

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Reprocessing of CHP Datasets (HI 1567 &1570) and Seafloor Substrate Interpretation for Selected Areas: Inner Sound off Skye on the West Coast of Scotland

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Keywords

Conservation; Seafloor substrate; sea-bed sediments; Marine Protected Area; West Coast of Scotland.

Front cover

Bathymetric raster with mapped areas of sea-bed substrate from an area of interest around Longay and Sgeir Dhearg, Inner Sound, Skye. Bathymetry data were acquired as part of the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

Bibliographical reference

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Foreword

This report forms part of a commissioned study of selected areas of the Inner Sound off Skye on the west coast of Scotland undertaken by the British Geological Survey on behalf of NatureScot (formerly known as Scottish Natural Heritage) and Marine Scotland. This report covers the processing methodology for Civil Hydrography Programme (CHP) supplied multibeam echosounder data for areas HI1567 and HI1570), the production of multibeam bathymetry, hillshade, slope, aspect and rugosity raster layers, an updated sea-bed substrate interpretation using the EUNIS lexicon of three areas specified as part of the contract. The update of the sea-bed substrate interpretation has been based on multibeam backscatter data, the multibeam bathymetry layers listed above, existing British Geological Survey sea-bed samples, client supplied sea-bed samples and video data, and other external datasets made available to us by project partners.

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Summary

This report describes the methodology for the processing of multibeam echosounder bathymetry, production of multibeam echosounder layers (bathymetry, hillshade, slope, aspect and rugosity) for display and interpretative purposes. Furthermore, an overview of the sea-bed substrate interpretation undertaken by the British Geological Survey (BGS) for three selected areas within Inner Sound off Skye on the west coast of Scotland is provided.

1 Introduction

The Marine (Scotland) Act 2010 and the Marine and Coastal Access Act 2009, collectively known as the "Marine Acts", provide the framework to help balance competing demands on our marine environment, combining growth of offshore industries with the need to conserve marine habitats and species. Scotland's National Marine Plan (The Scottish Government, 2015), provides an overarching legislative framework for implementation of these Marine Acts, both protecting the marine environment and enabling sustainable development of existing and emerging marine industries. This requires a holistic approach that values both geodiversity and biodiversity and the interactions between them (Gray *et al.*, 2013).

The area covered by Scotland's seas is 608,000 km^2 from Mean High Water Springs (MHWS) limit out to the limit of the claimed UK Continental Shelf, over 7.5 times the size of Scotland's land area (Baxter *et al*., 2011). In 2020, the Scottish Marine Protected Area (MPA) Network covered approximately 37% of Scottish seas, comprising 244 sites. The MPA network supports the Scottish Government's vision of a clean, healthy, safe, productive, and biologically diverse marine and coastal environment, managed to meet the long-term needs of nature and people (The Scottish Government, 2018). Marine Scotland is also seeking to improve the protection given to important habitats and species (termed Priority Marine Features - PMFs) outside the MPA network (Marine Scotland, 2018). The Bute House Agreement between the Scottish Government and the Scottish Green Party, proposes the delivery of new management measures in key coastal biodiversity locations outside of MPAs by March 2024 at the latest (Scottish Government, 2021a).

The overall aim of this project, which incorporated the processing and interpretation of multibeam echosounder data with available physical and video seafloor data, is to produce sea-bed substrate maps for three study areas within the Inner Sound (offshore east coast of Skye) and the adjacent west coast of the Scottish mainland (Table 1; Figure 1). These three areas encompass the Red Rocks and Longay urgent MPA (Scottish Government, 2021b) and six discrete 'illustrative' PMF management zones[1].

In order to meet the project objectives, the BGS undertook:

- Re-processing of received multibeam bathymetry data (HI1567 and HI1570) using QPS Qimera software.
- Production of multibeam echosounder raster layers comprising bathymetry, hillshade, slope, terrain ruggedness (VRM) and aspect in WGS84 UTM Zone 30N for import into ArcGIS.
- Expert interpretation of sea-bed substrate using the EUNIS definition of sediment classes for three study areas utilising all available sea-bed samples (BGS and client supplied), video data supplied by NatureScot, backscatter intensity raster layers, multibeam bathymetry layers and derived raster layers as listed above.

The layers and interpretations produced by the BGS will be used by NatureScot and Marine Scotland to inform various marine nature conservation initiatives.

[1] See https://marine.gov.scot/information/priority-marine-features-pmf-consultation-july-2018 and https://marinescotland.atkinsgeospatial.com/nmpi/default.aspx?layers=1648

Study area	Location	Task	CHP HI number	Maximum / minimum water depths	Area (nearest km^2)
Area 5	Red Rocks and Crowlins	Bathymetric data reprocessing and generate associated layers, EUNIS sea-bed substrate interpretation.	HI1567 and HI1570	1 m resolution grid: +3.7 m to -246.6 m 0.5 m resolution grid[2]: +2.4 m to -174.6 m	8421 km^2
Area 17	Inner Sound / BUTEC	Bathymetric data reprocessing and generate associated layers, EUNIS sea-bed substrate interpretation.	HI1570	1 m resolution grid: -0.5 m to -117.2 m 0.5 m resolution grid: -0.4 m to -117.3 m	2820 km^2
Area 18	Pabay S. Inner Sound	Bathymetric data reprocessing and generate associated layers, EUNIS sea-bed substrate interpretation.	HI1567	1 m resolution grid: +0.9 m to -36.5 m 0.5 m resolution grid: +0.9 m to -36.5 m	325 km^2

Table 1 Overview of the three areas of interest within the Inner Sound off Skye on the west coast of Scotland.

[2] Note the resolution of the 0.5 m bathymetric grid does not cover the deepest (<~120 m depth), central section of Area 5.

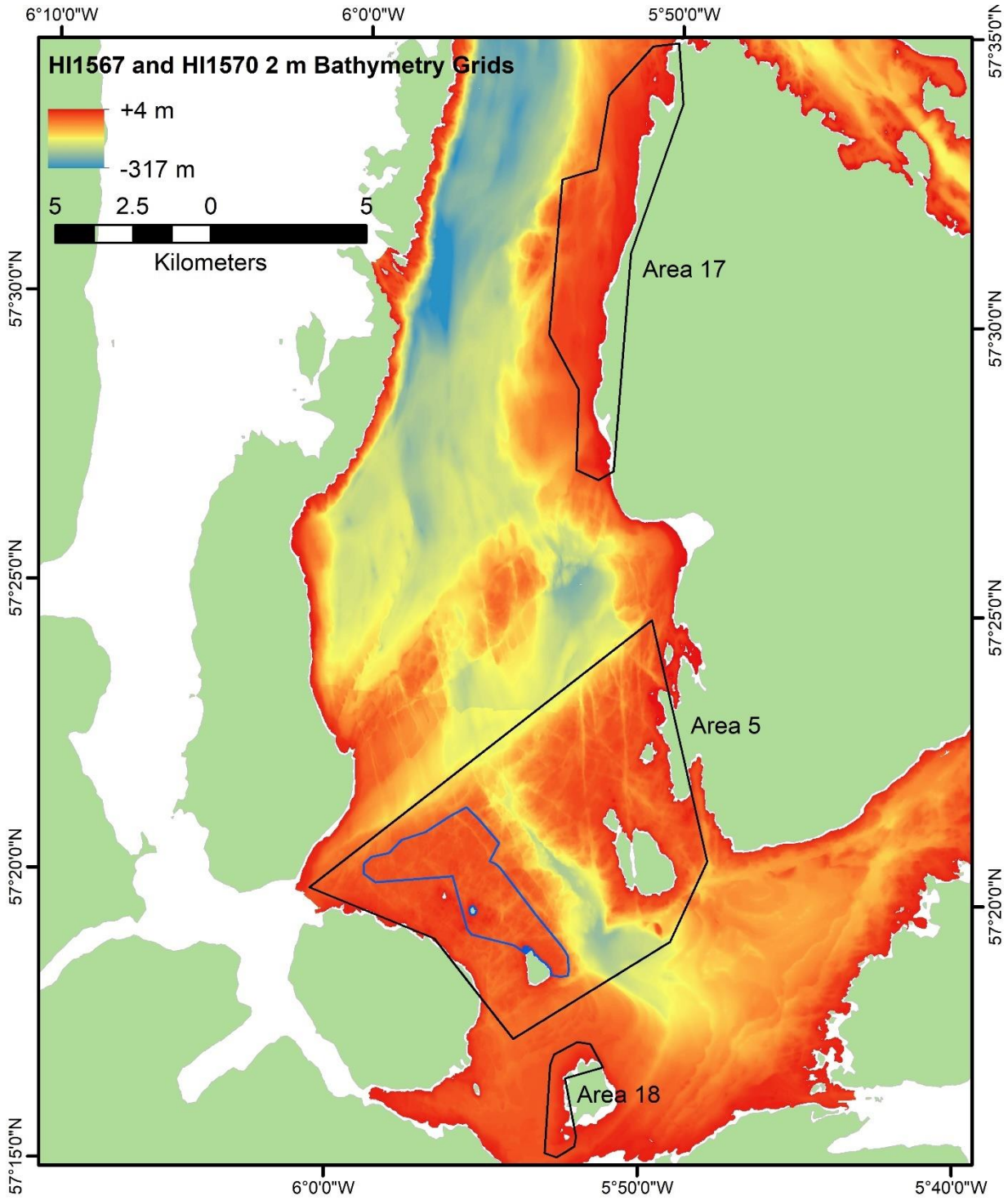


Figure 1 Location the three study areas (5, 17 and 18) indicated by the black boxes, explored during this project. Multibeam bathymetry acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) from surveys HI1567 and HI1570 were made available to the BGS through an agreement with the MCA via NatureScot. The boundary of the Red Rocks and Longay urgent MPA (December, 2021) is delineated by the blue box within Area 5.

2 Multibeam Echosounder Data Processing

The primary dataset used for the study was the high-resolution multibeam echosounder (MBES) dataset acquired by the Maritime & Coastguard Agency (MCA) in 2019 on behalf of the Civil Hydrography Programme (CHP). NatureScot supplied a UKHO (United Kingdom Hydrographic Office) derived CARIS project to the BGS for reprocessing to higher resolutions. The BGS investigated what was possible and depending on depth and line/data density could reprocess to a maximum resolution of 0.5 m x 0.5 m. In water depths exceeding ~100 m, a resolution of 0.5 m was not achievable due to the low density of data points, as a result, layers of 1.0 m x 1.0 m resolution were also created.

The MBES survey area Hydrographic Instruction HI1567 data were originally gridded at 2.0 m x 2.0 m resolution, and were subsequently reprocessed by the BGS to create a dataset at a resolution of 0.5 m x 0.5 m, and a dataset at 1.0 m x 1.0 m. The MBES survey area Hydrographic Instruction HI1570 data were supplied as two datasets originally gridded at 2.0 m x 2.0 m resolution (water depths of +3.9 m to -140.9 m), and 4.0 m x 4.0 m (water depths of +0.9 m to -246.6 m). The HI1570 data were also reprocessed by the BGS to create a dataset at a resolution of 0.5 m x 0.5 m, and a dataset at 1.0 m x 1.0 m.

The reprocessed data delivered to NatureScot comprises:

HI1567:

- The 0.5 m x 0.5 m resolution rasters were subdivided into 30 “tiles” for data management purposes (Figure 2).
- The 1.0 m x 1.0 m resolution rasters were subdivided into 14 “tiles” for data management purposes (Figure 3).

HI1570:

- The 0.5 m x 0.5 m resolution rasters were subdivided into 26 “tiles” for data management purposes (Figure 4).
- The 1.0 m x 1.0 m resolution rasters were subdivided into 8 “tiles” for data management purposes (Figure 5).

The processed bathymetric data were exported as ESRI ArcGRIDS (.asc format), ASCII XYZ files and Geotiff format for each Hydrographic Instruction survey area. Final grids for each of the three areas of interest were analysed in ESRI ArcGIS, additional layers of slope, hillshade and aspect (see Appendix 1) were derived from the bathymetric data in ArcGIS using the 3D Analyst extension. Hillslope was calculated using an azimuth of 45° and an altitude of 25° for study areas 5, 17 and 18. Layers depicting terrain roughness, or rugosity, were derived from the bathymetric data in ArcGIS using the Benthic Terrain Modeler extension (Walbridge *et al.*, 2018).

The backscatter intensity data for HI1567 and HI1570 were not processed further by the BGS and were used during this project as the original 1.0 m x 1.0 m grids as supplied through the CHP data delivery.

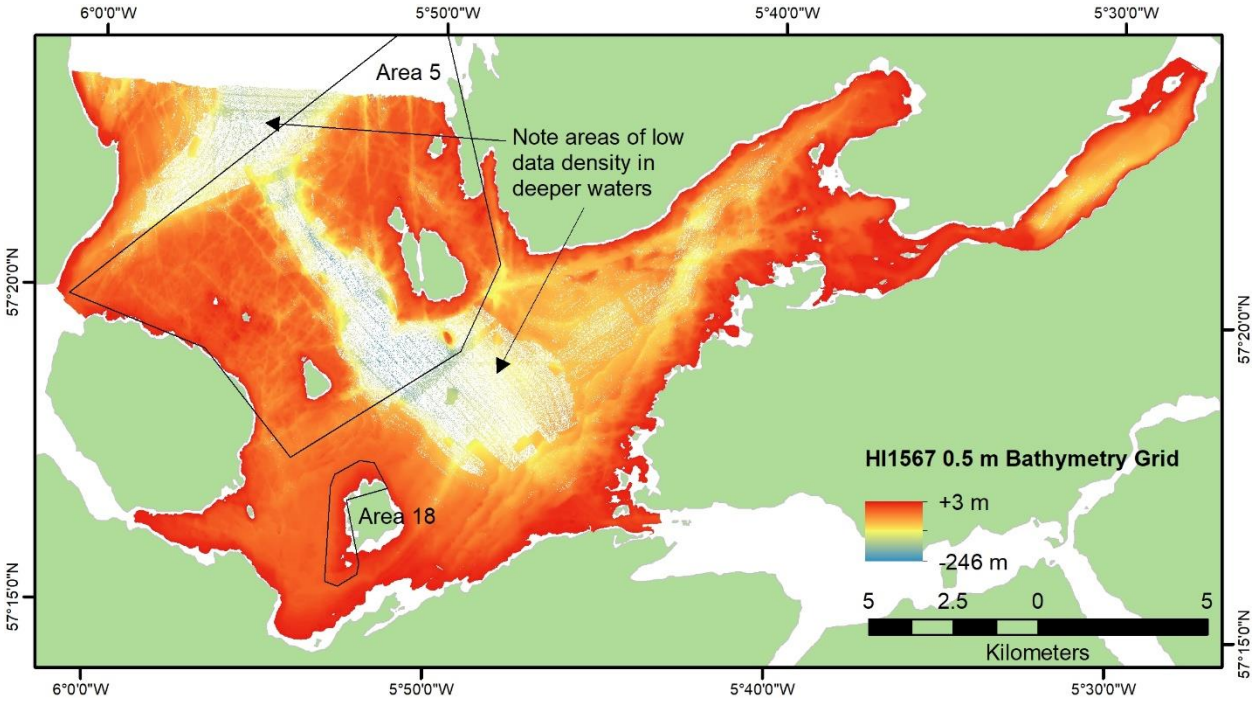


Figure 2 Overview multibeam bathymetry map of survey HI1567 reprocessed by the British Geological Survey (BGS) to a resolution of 0.5 m x 0.5 m. Study areas are indicated by the black boxes. These multibeam echosounder data were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

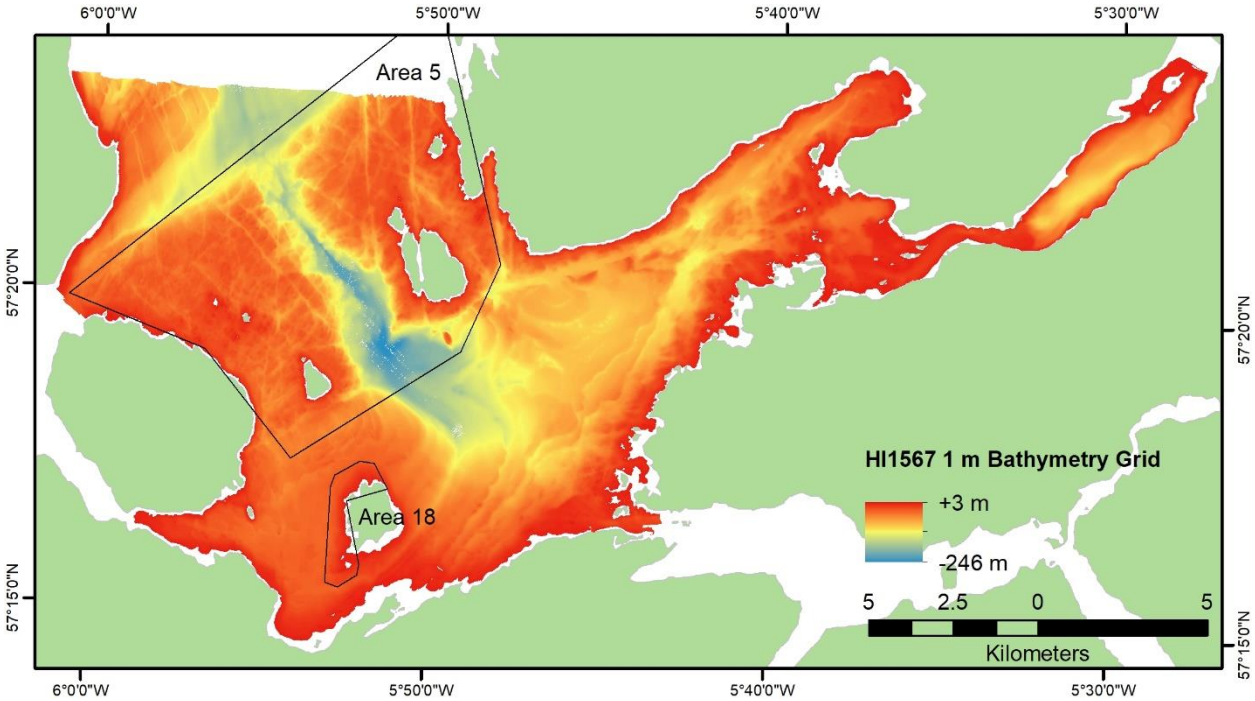


Figure 3 Overview multibeam bathymetry map of survey HI1567 reprocessed by the British Geological Survey (BGS) to a resolution of 1.0 m x 1.0 m. Study areas are indicated by the black boxes. These multibeam echosounder data were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

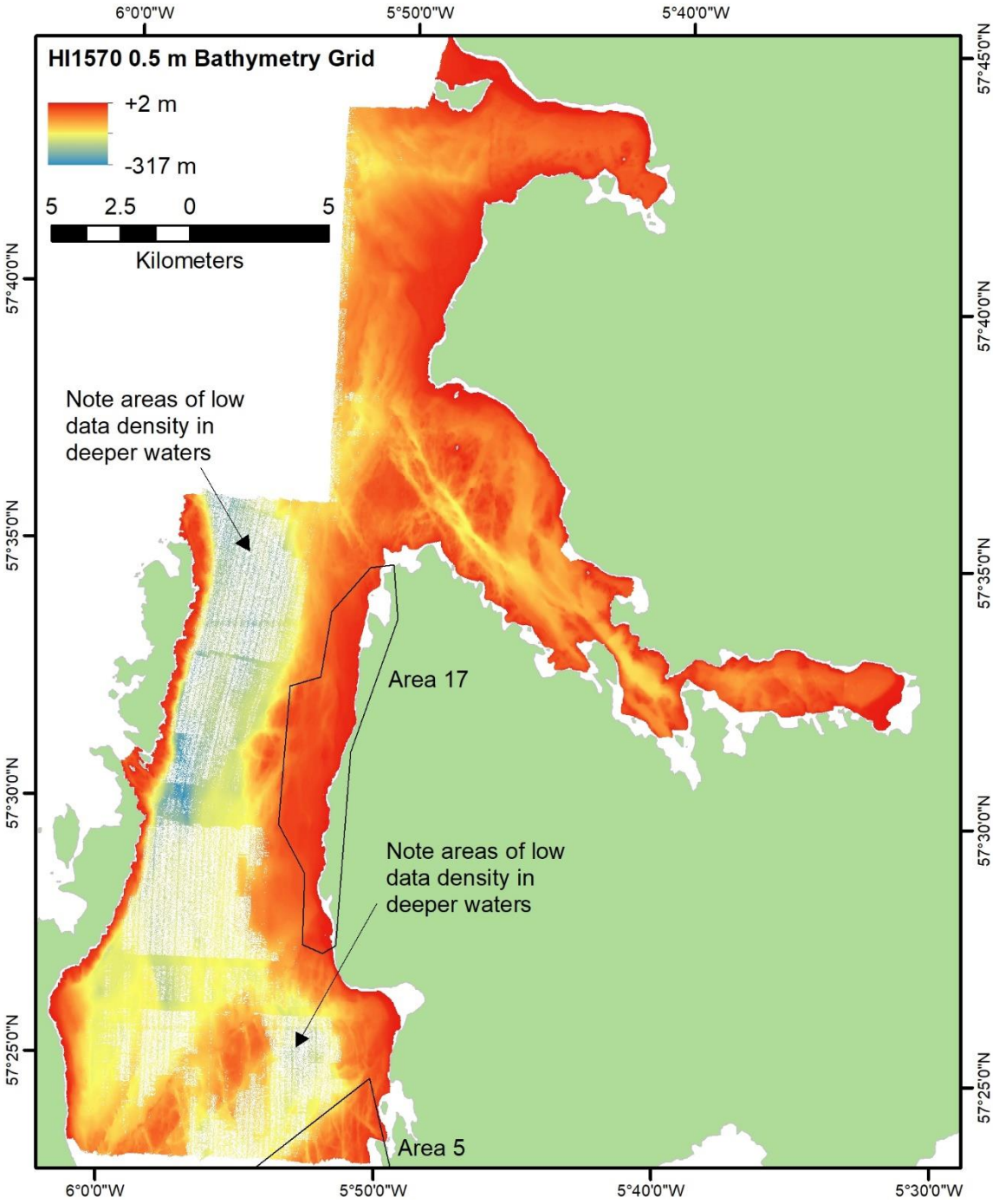


Figure 4 Overview multibeam bathymetry map of survey HI1570 reprocessed by the British Geological Survey (BGS) to a resolution of 0.5 m x 0.5 m. Study areas are indicated by the black boxes. These multibeam echosounder data were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

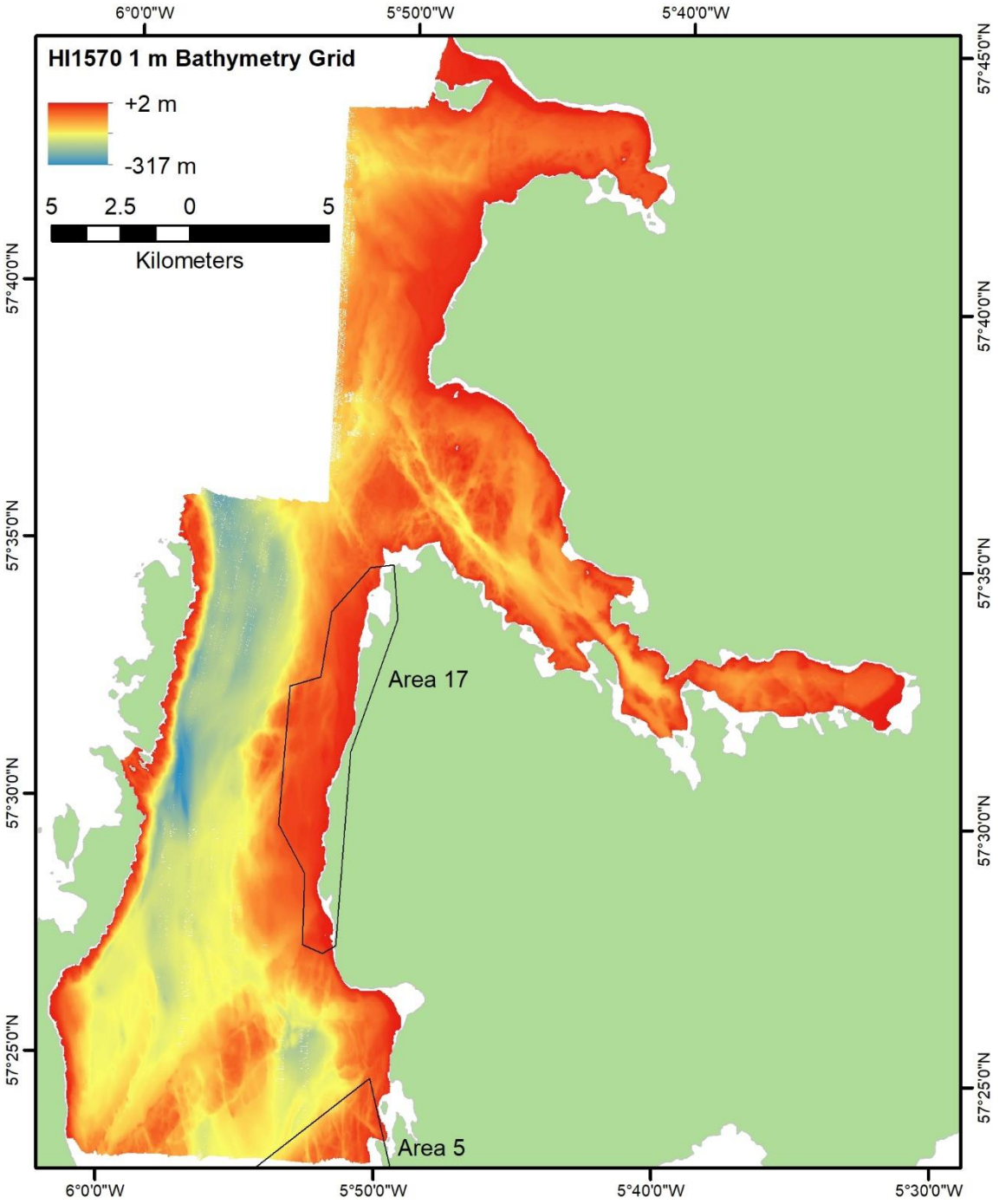


Figure 5 Overview multibeam bathymetry map of survey HI1570 reprocessed by the British Geological Survey (BGS) to a resolution of 1.0 m x 1.0 m. Study areas are indicated by the black boxes. These multibeam echosounder data were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

3 Sample Data

3.1 SEA-BED SAMPLE DATA

The BGS sea-bed sample database and samples acquired as part of the HI1567 and HI1567 surveys are based on analysis of approximately the top 0.1 m veneer of sea-bed sediments. These samples have predominantly been acquired using a shipek grab, with some analyses conducted on core samples where available. The samples were analysed for their particle size and percentage compositions obtained for mud, sand and gravel. These results were converted into a modified sea-bed sediment classification based on Folk (1954) based on the gravel percentage and sand to mud ratio. For the purposes of this project, these analyses have also been converted into EUNIS sediment classes as defined by the modified Folk (1954) classification of Long (2006) (Table 2; Figure 6).

Only a total of seven BGS sea-bed samples and two HI1567 sea-bed samples were found to be coincident with Area 5. Only one sea-bed sample was acquired within Area 17 as part of the broader HI1570 survey. These comprise the following sediment classes: Muddy Sand (1), Slightly Gravelly Muddy Sand (1), Gravelly Muddy Sand (2), Gravelly Mud (1), Muddy Sandy Gravel (2), Gravelly Sand (1), and Gravel (2).

No physical sea-bed samples have been sourced for Area 18.

Station	Area	Latitude (N)	Longitude (W)	Folk (1954)	EUNIS Class (Long, 2006)
HI1567-10 (CHP)	5	57.37007	-5.85793	Gravelly Sand	Coarse Sediment
HI1567-11 (CHP)	5	57.34462	-5.88572	Gravelly Mud	Mixed Sediment
+57-06+168 (BGS)	5	57.37117	-5.90583	Slightly Gravelly Muddy Sand	Mud and Sandy Mud
+57-06+169 (BGS)	5	57.388	-5.87367	Gravel	Coarse Sediment
+57-06+4 (BGS)	5	57.35844	-5.90813	Gravelly Muddy Sand	Mixed Sediment
+57-06+3 (BGS)	5	57.35384	-5.88321	Gravelly Muddy Sand	Mixed Sediment
+57-06+57 (BGS)	5	57.29333	-5.90167	Muddy Sand	Mud and Sandy Mud
+57-06+167 (BGS)	5	57.331	-5.90483	Muddy Sandy Gravel	Mixed Sediment
+57-06+27 (BGS)	5	57.32767	-5.98252	Muddy Sandy Gravel	Mixed Sediment
HI1570-7 (CHP)	17	57.5663	-5.86592	Gravel	Coarse Sediment

Table 2 Overview of sea-bed sediment samples within the three areas of interest.

3.2 GROUND-TRUTHING DATASETS SUPPLIED BY NATURESCOT

NatureScot provided access to ground-truthing datasets held internally to compliment the BGS data holdings for the interpretation and mapping of sea-bed substrate (Figure 7). Biological data made available for use include Marine Recorder data (points and straight line [in/out]) and any existing feature polygon data from the GEMS database, supplemented with complex shape vessel track polylines (where relevant and available) and example seabed imagery (video or stills) with associated interpretive reports.

General, qualitative observations on the composition of the sea-bed sediments were made from the video transect data rather than quantitative analysis as that was beyond the scope of this study. These general observations helped confirm and guide some of the new boundaries interpreted in the three study areas but are not included in this report.

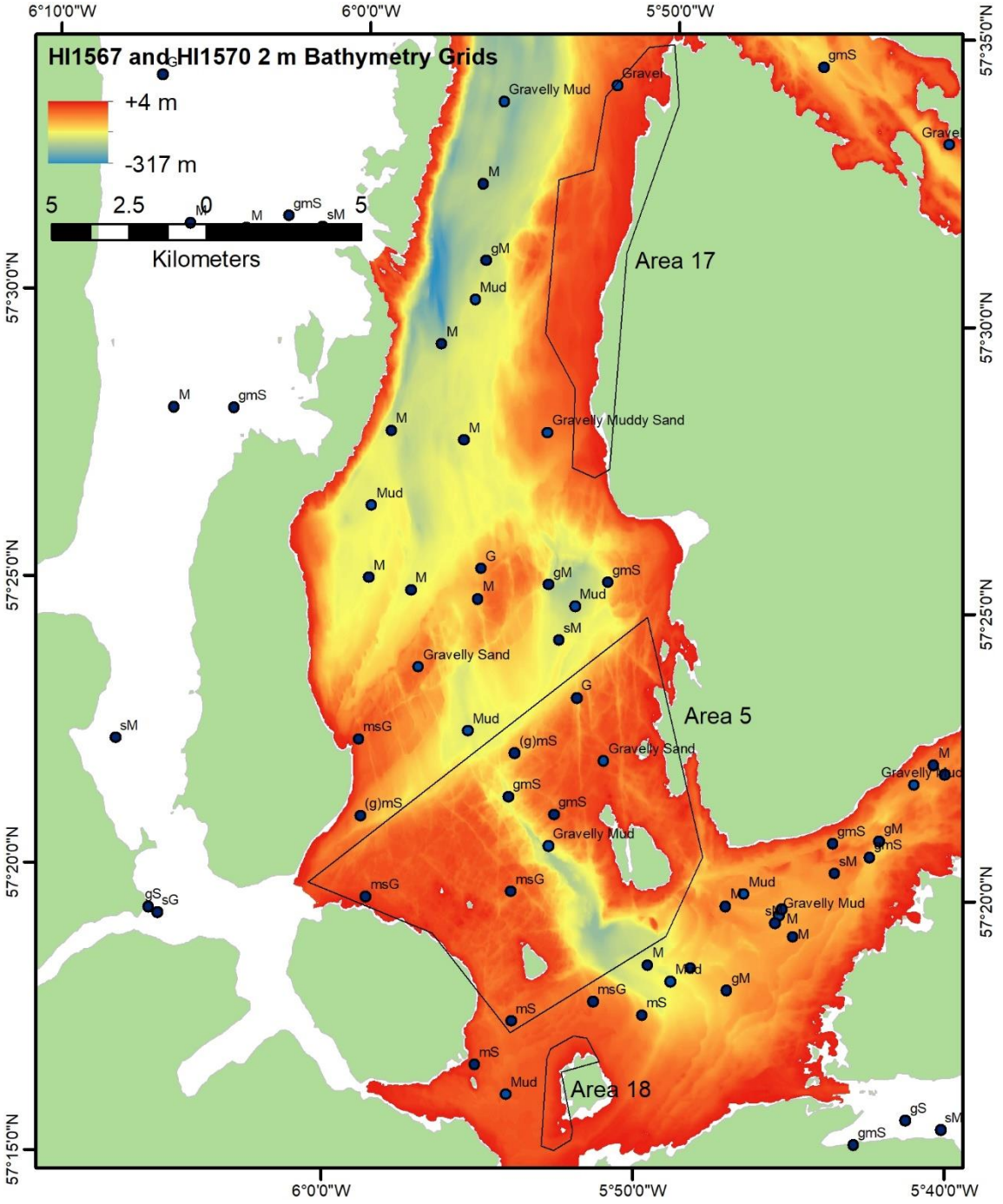


Figure 6 Overview of sea-bed sediment samples within the three areas of interest and across the broader area that are included here for context. Data sourced from the British Geological Survey and sea-bed samples acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot. Multibeam echosounder data were also made available to the BGS through the same agreement with the MCA via NatureScot.

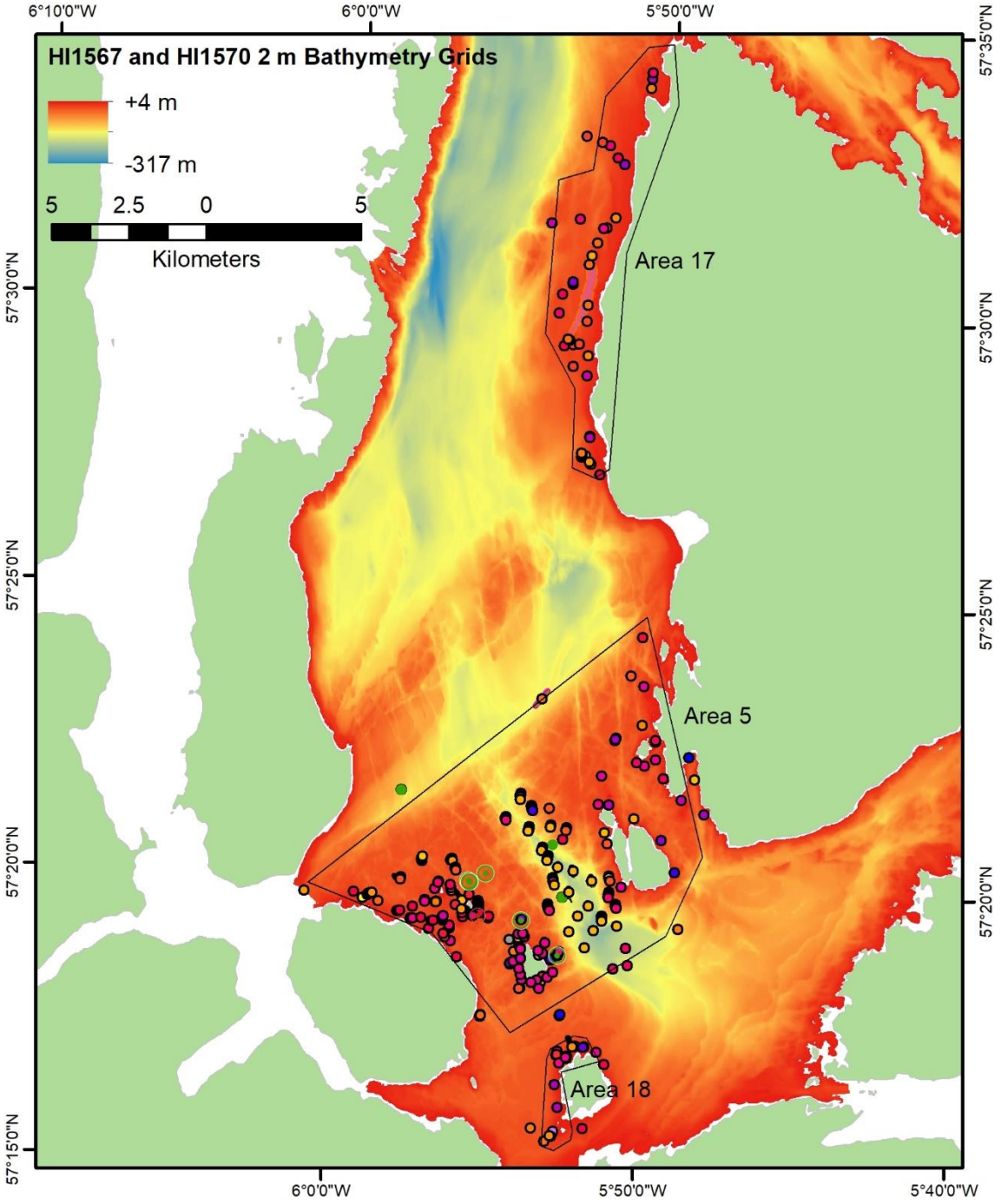


Figure 7 Location of biological data compiled and made available by NatureScot. Qualitative observations from these datasets were used to inform the interpretation and mapping of sea-bed substrate during this project. Multibeam echosounder data were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

4 Sea-bed Substrate Interpretation

4.1 METHODOLOGY

The final sea-bed substrate map was interpreted at a scale of around 1:5000, although some areas were mapped at a finer resolution (e.g. locations with confirmed glacial moraines detected on the seabed). According to basic principles on the relationship between presentation scale, data resolution, and detectable feature size (Tobler, 1988) a map presented at 1:5000 may include individual features as small as 5 m x 5 m. The mapping resolution of this project is 1:5000 with the smallest features mapped around 5 m in diameter.

The final product is based on a semi-automated mapping approach, summarised as entailing an automated, clustering-based method, analysing bathymetric derivatives (relative bathymetric highs and lows at multiple spatial resolutions) to detect and delineate seabed features. This automated step is followed by manual attribution of the predicted line-work and minor editing. This approach is effective in that it uses computational power to produce detailed linework using consistent rule-sets, but then employs the expertise of the geoscientist to classify the features, and 'sense-check' the predicted results.

The workflow for the semi-automated method can be summarised as follows:

4.1.1 Computation of Relative Distance to Mean Value (RDMV)

Relative bathymetric highs and lows are determined at multiple spatial scales. This is accomplished by calculating the 'relative deviation from mean value' (RDMV) from the bathymetry data, using the TASSE geospatial toolbox (Lecours, 2015). RDMV is calculated over search areas (or 'neighbourhoods') of 5, 21 and 89 cells to resolve geomorphic features of varying size. For example, for this study bathymetry data (0.5 m spatial resolution), RDMV at 5 cells searches a circular area with a radius of 2.5 m to calculate relative bathymetric position at each 0.5 m^2 cell, and at a neighbourhood of 89 cells, searches a circular area with a radius of 44.5 m (Figure 8).

This process was undertaken on both the 0.5 m and the 1 m resolution bathymetric datasets for each of the three study areas.

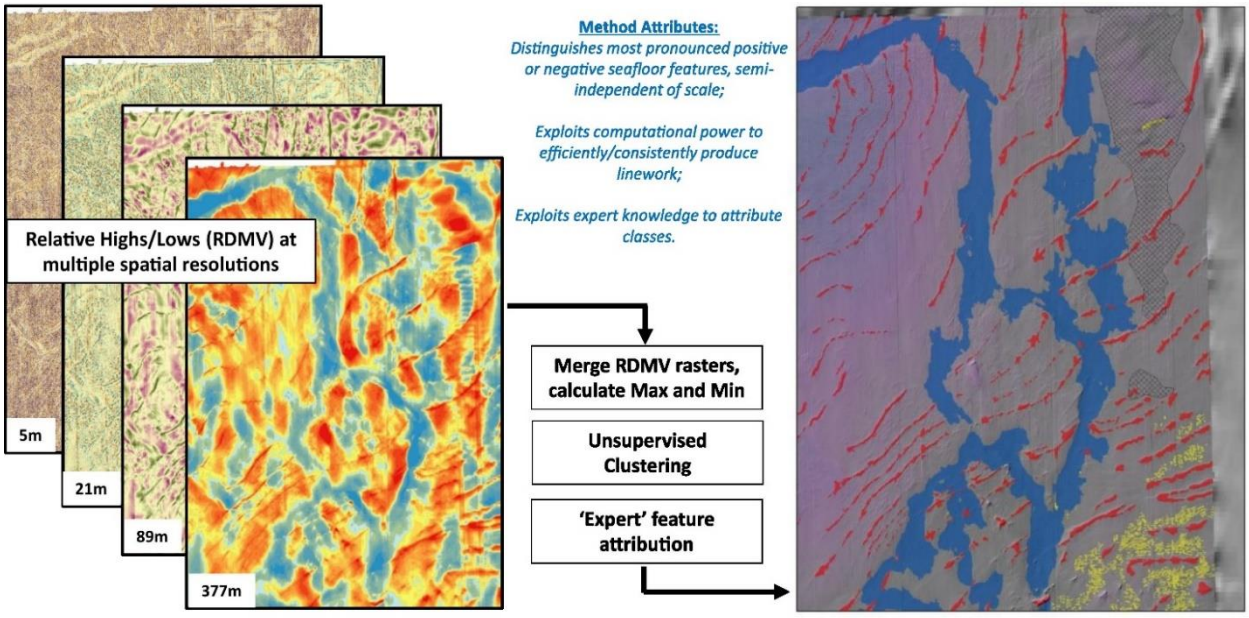


Figure 8 Semi-automated mapping of seabed geomorphology summary. Data example from Dove *et al*. (2021) for a study area located East of Orkney. Note this project did not produce a RDMV raster at a resolution of 377 cells due to the finer resolution of multibeam bathymetry data available for this project.

4.1.2 Merging of the RDMV Rasters

The three RDMV rasters (produced at 5, 21 and 89 cells) are merged together, whereby in each location either the maximum value (i.e. to resolve bathymetric highs) or the minimum value (i.e. to resolve bathymetric lows) are preserved. This is achieved using the ”Mosaic to New Raster” function within the “Data Management Tools” toolbox from ESRI ArcGIS.

This process was undertaken on both the 0.5 m and the 1 m resolution bathymetric datasets for each of the three study areas. This has the desired effect of extracting the most pronounced morphological forms at seabed, frequently corresponding to discrete geomorphic features.

4.1.3 ESRI ArcGIS ISO Cluster Unsupervised Classification Tool

This tool is part of the multivariate classification toolset available through the Spatial Analyst ArcGIS Toolbox extension. The tool uses an iterative clustering procedure, also known as a migrating means technique, to find the natural groupings of cells of shared properties. Clusters of 3 and 6 classes were produced for each produced maximum and minimum merged raster dataset (see section 4.1.2).

4.1.4 Raster to Polygon Conversion

The classified raster obtained from the above steps was converted to a vector polygon shapefile to produce a final, fully attributed, topologically clean, smooth vector dataset.

The resultant classified output represents a numeric, thematic map. The number of classes created is simply an over-estimation of the potential number of sediment types or morphological features present in the study area. The user can analyse the resulting map and change the number of classes until satisfied all likely changes in seabed substrate or morphology have been represented.

4.1.5 Expert Judgement

The vectorised output of the semi-automated process was reviewed manually to assign EUNIS sediment classifications. Knowledge of the geological history of an area means the expert can 'sense check' the outputs. Polygons can be amended, modified and merged to best represent the acoustic data (taking account of derived layers of slope, topographic roughness or rugosity, and backscatter intensity), available ground-truthing samples and take account of the geological expert judgement.

4.2 AREA 5

The automated production of relative bathymetric highs and lows described in section 4.1, using the 0.5 m resolution bathymetric dataset, was essential to delineate areas of bedrock outcrop at the seafloor, glacial deposits such as moraines, and linear depressions caused by structural faults across the platform areas. Layers created using the 1 m resolution dataset were used in areas occupied by the overdeepened trough (>~120 m water depth) that dominates the central portion of the study area. These boundaries were cross-referenced with layers of backscatter intensity and terrain ruggedness (Figure 9a-f) to produce the resultant sea-bed substrate map (Figure 10).

The dominant sediment class across the entire area is ‘Mixed Sediment’, found extensively across the large, upstanding bedrock platforms surrounding Longay, Sgeir Dhearg, Sgeir Thraid and the Crowlin Islands. The extensive bedrock platforms comprise Torridon Group sandstones, siltstones and mudstones with Jurassic strata to the south and Jurassic/Triassic strata to the north of these conspicuous bedrock platforms. This bedrock dominated submerged landscape comprises crag-and-tails, flutes, quarried stoss slopes and rock drumlins indicating palaeo-ice stream flow to the northwest (Figure 11b-e). Superimposed on this glacially streamlined, or modified, sea-bed are a number of irregular ridges, commonly perpendicular or near perpendicular to the streamlined bedrock landforms (Figure 11b-e). These subtle ridges, interpreted as recessional moraines, some of which can be classed as ‘boulder moraine’ belt, are frequently observed on upstanding bedrock highs, commonly 2-5 m in height, 10-20 m wide

and 80-380 m in length. These features were deposited during overall ice-sheet retreat into the Inner Sound around 16.5–16 calendar ka BP (Bradwell *et al*., 2021).

These assemblages of glacially streamlined landforms and superimposed ice-marginal landforms provide a clear record of ice flow, and subsequent ice-sheet retreat across the region.

General observations made from the video transect data strongly suggest that interpreted glacial moraines are likely to comprise boulders, cobbles and mixed gravels and sands (e.g. Figure 11f). This is supported by the backscatter intensity return and the texture of the 0.5 m resolution multibeam bathymetry data.

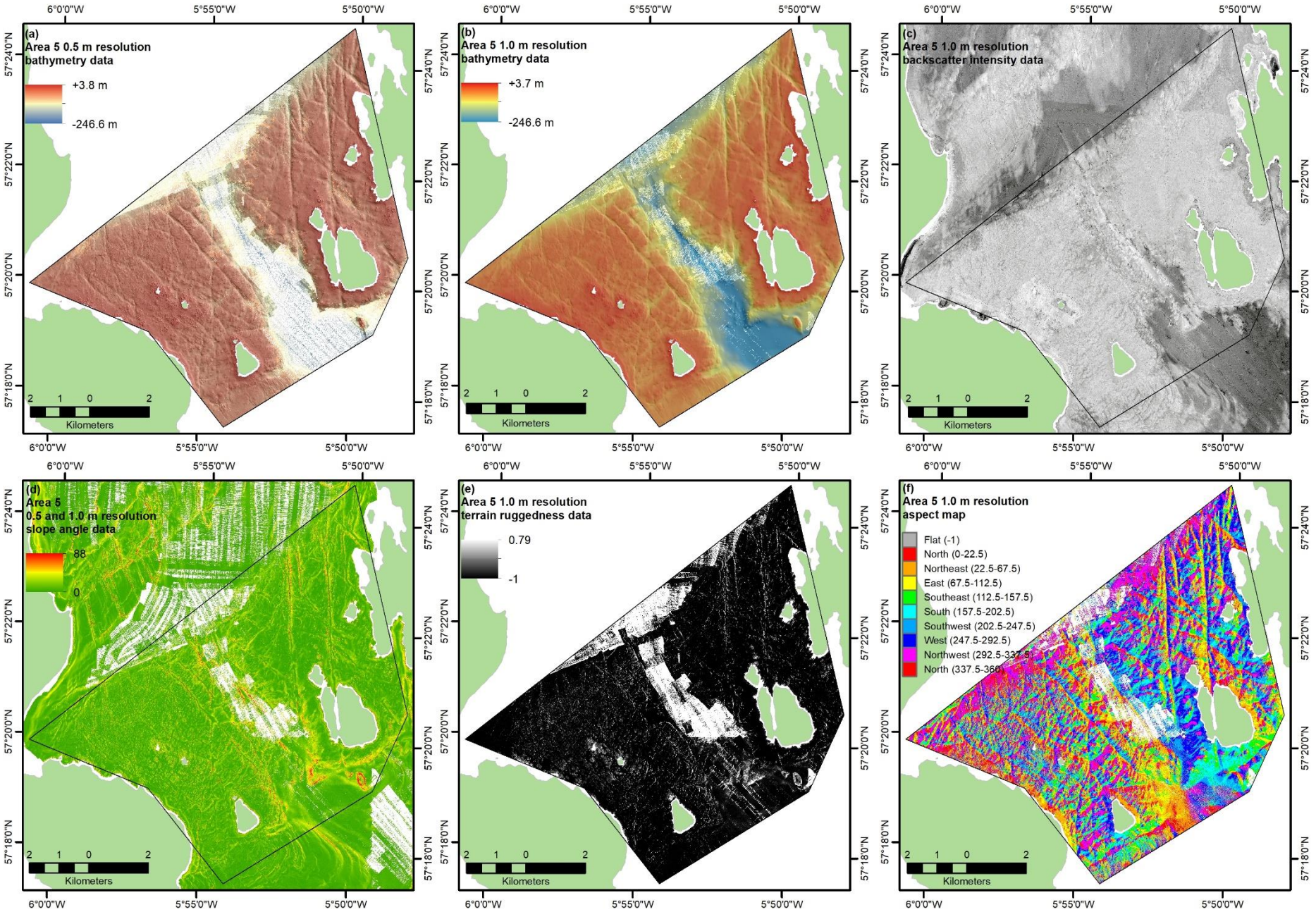
These 'Coarse Sediment' moraine features may potentially provide particularly favourable Flapper Skate egg habitat of interest for marine conservation management. Preliminary observations from NatureScot-led remote video sampling in 2021 indicate that areas of boulder and cobble moraine deposits on and around the margins of numerous crag-and-tails and rock drumlins on the platform off NE Scalpay (e.g. Figure 11g) are also used by Flapper Skate for egg-laying (NatureScot *pers comm*.). These localised deposits are likely a result of glacial erosion of in situ bedrock and cannot be distinguished from the adjacent or underpinning bedrock due to similarities in their acoustic signatures.

Only one submarine landslide was identified during the course of this project, in Area 5, located approximately 300 m west of Eilean Beag (Figure 12b). The headwall is ~105 m wide and the feature is ~250 m in length. It is likely this landslide may have occurred immediately after ice-sheet retreat and fluctuating stress conditions shortly after ~16 ka BP (Bradwell *et al*., 2021).

'Mud' and 'Mud and Sandy Mud' dominate the sediment assemblages of topographic lows, representing a number of faults, some of which have been subsequently exploited by glaciers to form over-deepened channels. Two large pockmarks were identified in Area 5, approximately 600 m south of Eilean Mòr within the soft sediments of the main overdeepened channel, or fjord, in the south of the area of interest. Each feature is around 200 m in diameter and 10.5 m deep, located 122 to 133.5 m water depth (Figure 12c).

Next page:

Figure 9 Overview of data and derived layers for Area 5. a) Reprocessed multibeam bathymetry data at 0.5 m x 0.5 m resolution; b) reprocessed multibeam bathymetry data at 1.0 m x 1.0 m resolution; c) backscatter intensity data as supplied through the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot; d) slope angle derived from the 0.5 m grid with the 1.0 m grid underlain to infill data gaps; e) terrain ruggedness (VRM), or rugosity, derived from the 1.0 m grid; f) aspect derived from the 1.0 m resolution bathymetry grid.


(a)
Area 5 0.5 m resolution
bathymetry data
+3.8 m
-246.6 m
(b)
Area 5 1.0 m resolution
bathymetry data
+3.7 m
-246.6 m
(c)
Area 5 1.0 m resolution
backscatter intensity data
(d)
Area 5
0.5 and 1.0 m resolution
slope angle data
88
0
(e)
Area 5 1.0 m resolution
terrain ruggedness data
0.79
-1
(f)
Area 5 1.0 m resolution
aspect map
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)
2 1 0 2
Kilometers
6°0'0"W
5°55'0"W
5°50'0"W
57°24'0"N
57°22'0"N
57°20'0"N
57°18'0"N

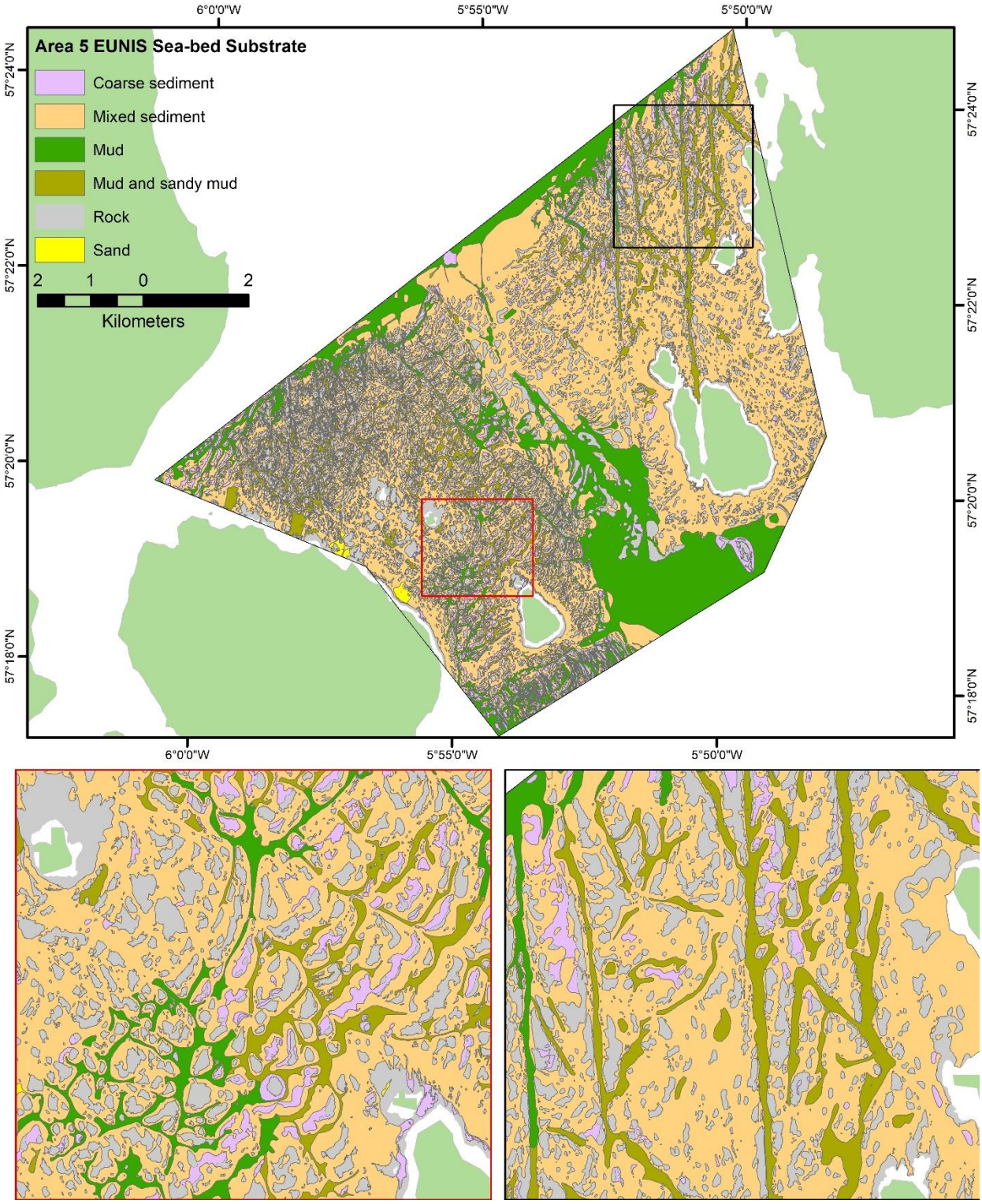


Figure 10 Overview of the sea-bed substrate interpretation in Area 5 undertaken by the BGS for this project using EUNIS sediment classes. This work is undertaken primarily using the 0.5 m resolution bathymetry data. The coloured boxes indicate the location of the two inset maps. The red inset map shows examples of crag-and-tails and rock drumlins preserved on the platform around northern Longay and Sgeir Dhearg, with mud-rich sediments infilling depressions caused by faults. The pink 'Coarse Sediments' indicate the presence of glacial moraines preserved on the topographic highs. The black inset map shows the prevalent structural fabric of the Torridon Group bedrock units, depicted by the fault network forming topographic lows now infilled with mud-rich sediment.

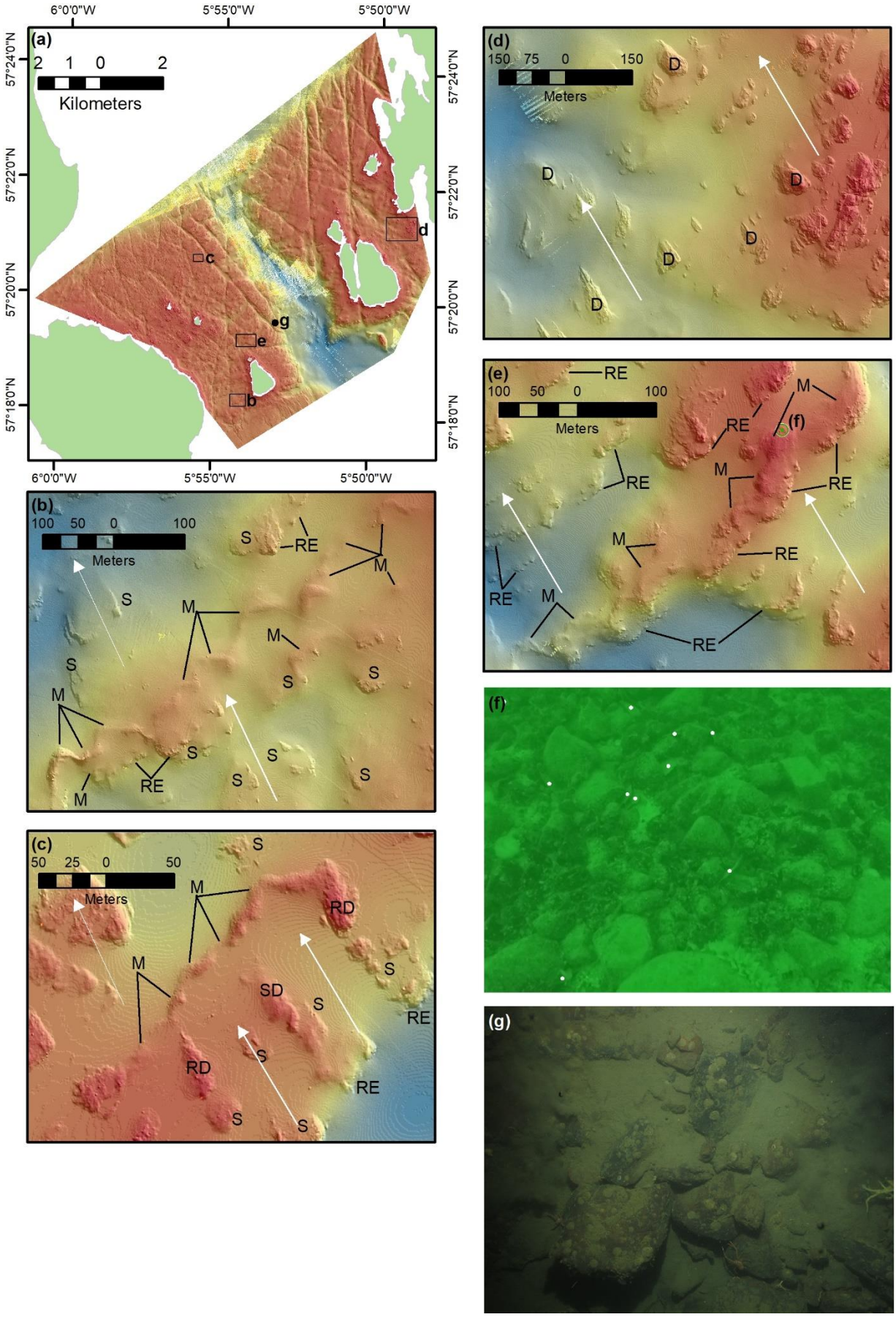


Figure 11 (a) Overview map showing location of inset maps and photographs. Examples of glacial landforms (b)-(e). (f) Boulder rich seafloor habitat (Station 48 2018 Marine Scotland Loch Alsh and Inner Sound survey) representing Flapper Skate egg-laying habitat (eggs indicated by white spots). For location see (e). (g) Example of localised areas of boulder- and cobble-rich moraine deposits around areas of

bedrock (Station FMA05-12 2019 SNH MSS Inner Sound Benthic Survey). For location see (a). Abbreviations: Glacial moraine (M), glacially streamlined bedforms like crag-and-tails (S) and drumlins (D), rock drumlins (RD), coarse sediment drumlins (SD) and quarried stoss slopes of glacially eroded bedrock escarpments (RE). Palaeo-ice flow direction is indicated by the white arrows. Photographs (f) and (g) made available by NatureScot. Multibeam echosounder data shown in (a)-(e) were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

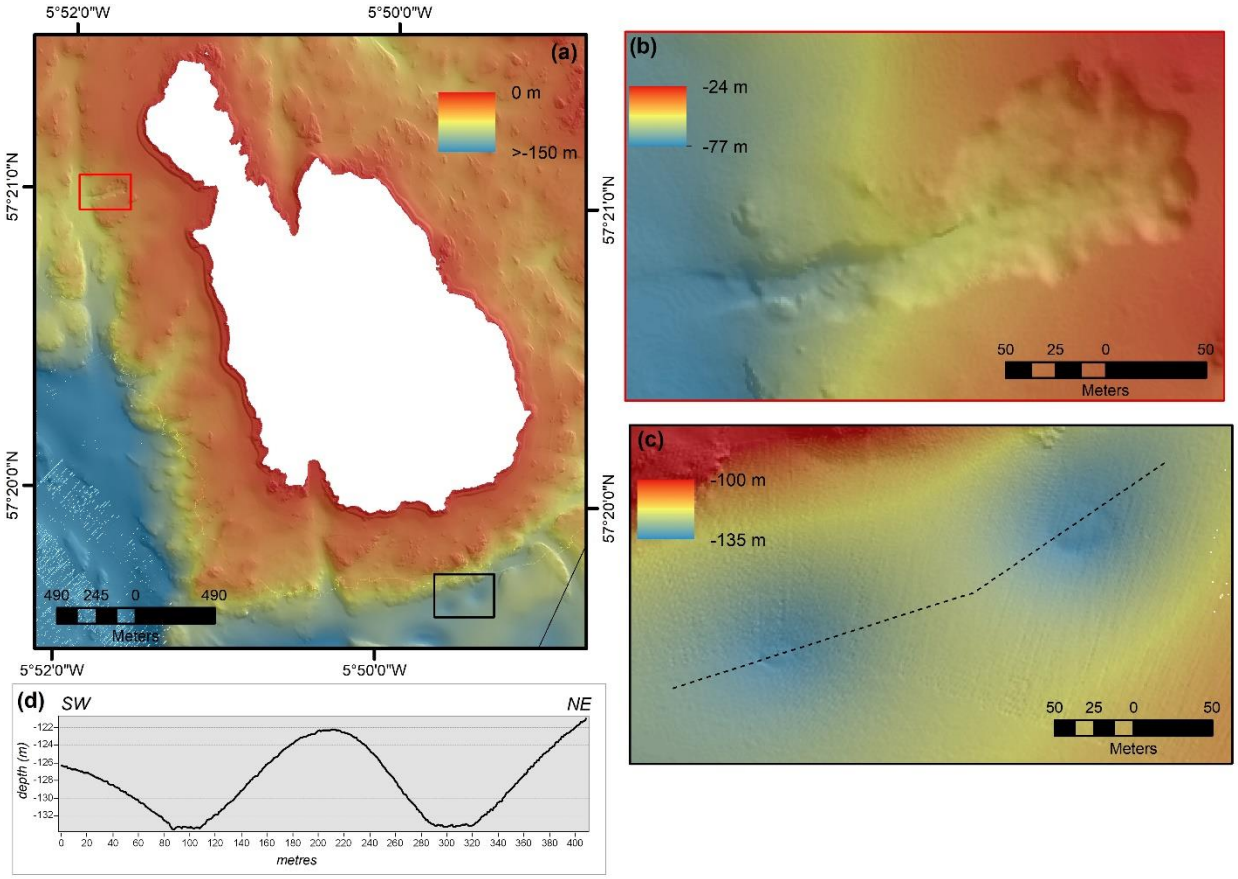


Figure 12 (a) Map showing 1.0 m resolution reprocessed bathymetry data around Eilean Mòr, Eilean Meadhonach and Eilean Beag with the location of a submarine landslide and two pockmarks identified as part of this study. (b) Submarine landslide as imaged in the 1.0 m resolution reprocessed bathymetry data (note it is also well imaged in the 0.5 m dataset but was not shown here for figure production reasons). (c) Two pockmarks as imaged in the 1.0 m resolution reprocessed bathymetry data. (d) Profile from southwest to northeast across the two pockmarks. For location see dashed line in (c). Multibeam echosounder data were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot.

4.3 AREA 17

Similar to Area 5, the RDMV layers derived from the 0.5 m resolution dataset were used in conjunction with the terrain ruggedness and backscatter intensity layers to interpret the EUNIS sediment classes (Figure 13a-e and 14a).

The dominant sediment class across the entire area is ‘Coarse Sediment’, subdivided into areas of sediment waves and areas of stony habitat. Areas of ‘Coarse Sediment’ waves likely comprise clean sands and gravels with some mud, and may include areas of Flame Shell Beds and Maerl Beds (for example observed during the 2018 Loch Alsh and Inner Sound Benthic camera survey STN_042_S1; O’Dell *et al*., 2021). Closer to the coast, areas of ‘Coarse Sediment’ have been delineated based on the terrain ruggedness layer (0.5 m resolution), and

texture of the bathymetry data (0.5 m resolution). The speckled VRM (terrain ruggedness) response is potentially indicative of a higher proportion of cobbles and/or bedrock beneath a veneer of sediment.

Similar to Area 5, areas of bedrock comprise Torridon Group sandstones, siltstones and mudstones cropping out in the northwest of the study area, which show evidence of being glacially streamlined, taking the form of more blunt streamlined forms rather than classic drumlin and flute morphologies. Immediately adjacent to the coast bedrock crops out with little evidence of glacial modification. Mud rich and more 'Mixed Sediment' sediment classes are interpreted in the southern-most part of Area 17.

4.4 AREA 18

Using the reprocessed 0.5 m resolution bathymetry in conjunction with the terrain ruggedness layer, areas of Jurassic age bedrock were identified as constrained to the coast of the island of Pabay and localised to a broadly east-west oriented line of crag-and-tails in the far south of Area 18 indicating glacial flow to the north (Figures 15a-e and 16). The dominant sediment class was 'Mixed Sediment' as confirmed by video observations. However, the geomorphology indicates numerous east-west trending sediment ridges, interpreted as glacial moraines which extend west outside the Area boundary, clearly identified within the backscatter intensity layer (Figure 15b). Consequently, only limited occurrence of 'Coarse Sediment' boulders and cobbles are mapped. Mud-rich sediments occur between these glacial landforms, although again, the distribution is limited to the very west of the study area. Some 'Coarse Sediment' is suggested to be coincident with the line of crag-and-tails.

The overall distribution of glacial landforms is more limited within Area 18 compared to Area 5. Future survey work combined with analysis of a broader area of HI1567 to the west of Pabay could confirm the composition and extent of the 'Coarse Sediment' features.

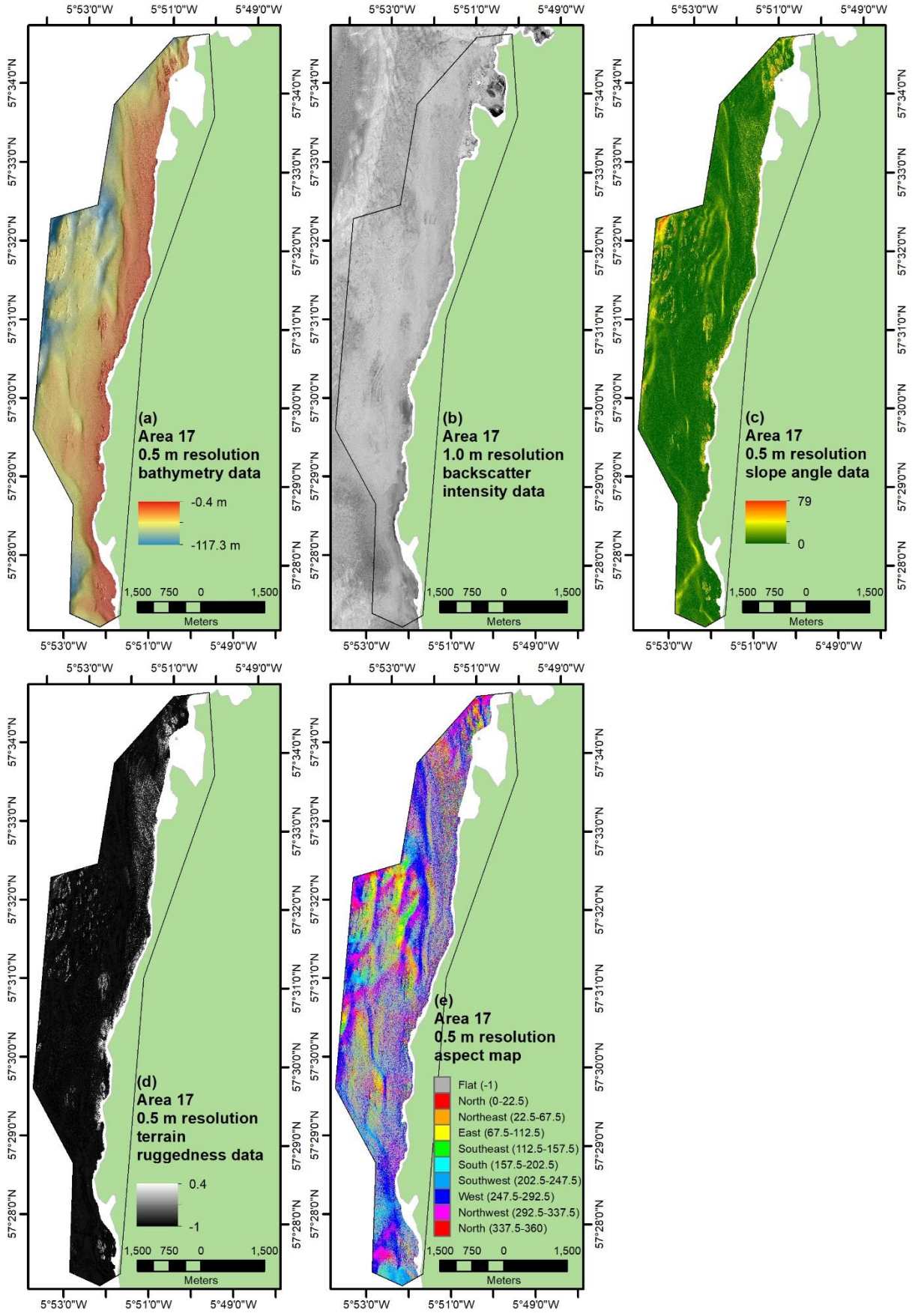


Figure 13 Overview of data and derived layers for Area 17. a) Reprocessed multibeam bathymetry data at 0.5 m x 0.5 m resolution; b) backscatter intensity data as supplied through the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot; c) slope angle derived from the 0.5 m grid; d) terrain ruggedness (VRM), or rugosity, derived from the 0.5 m grid; e) aspect derived from the 0.5 m resolution bathymetry grid.

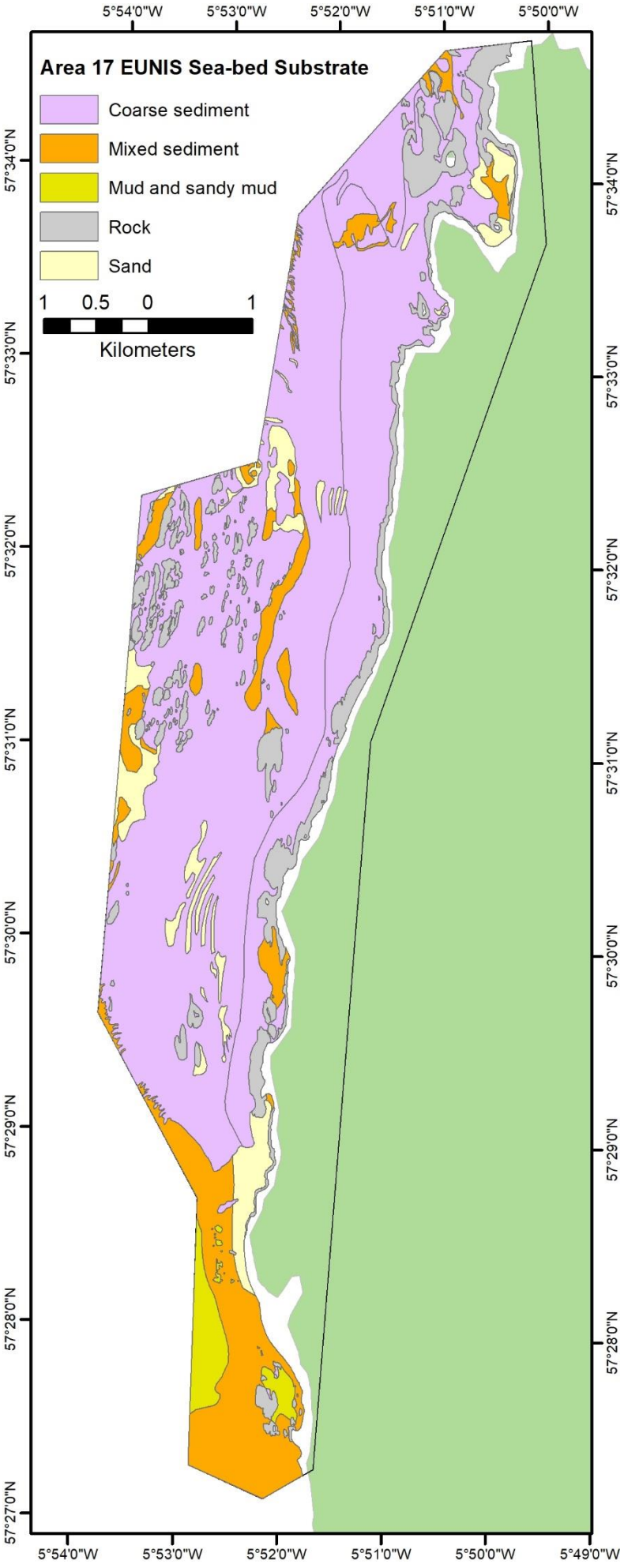


Figure 14 Overview of the sea-bed substrate interpretation in Area 17 undertaken by the BGS for this project using EUNIS sediment classes. This work is undertaken primarily using the 0.5 m resolution bathymetry, derived terrain ruggedness, and 1.0 m resolution backscatter intensity datasets.

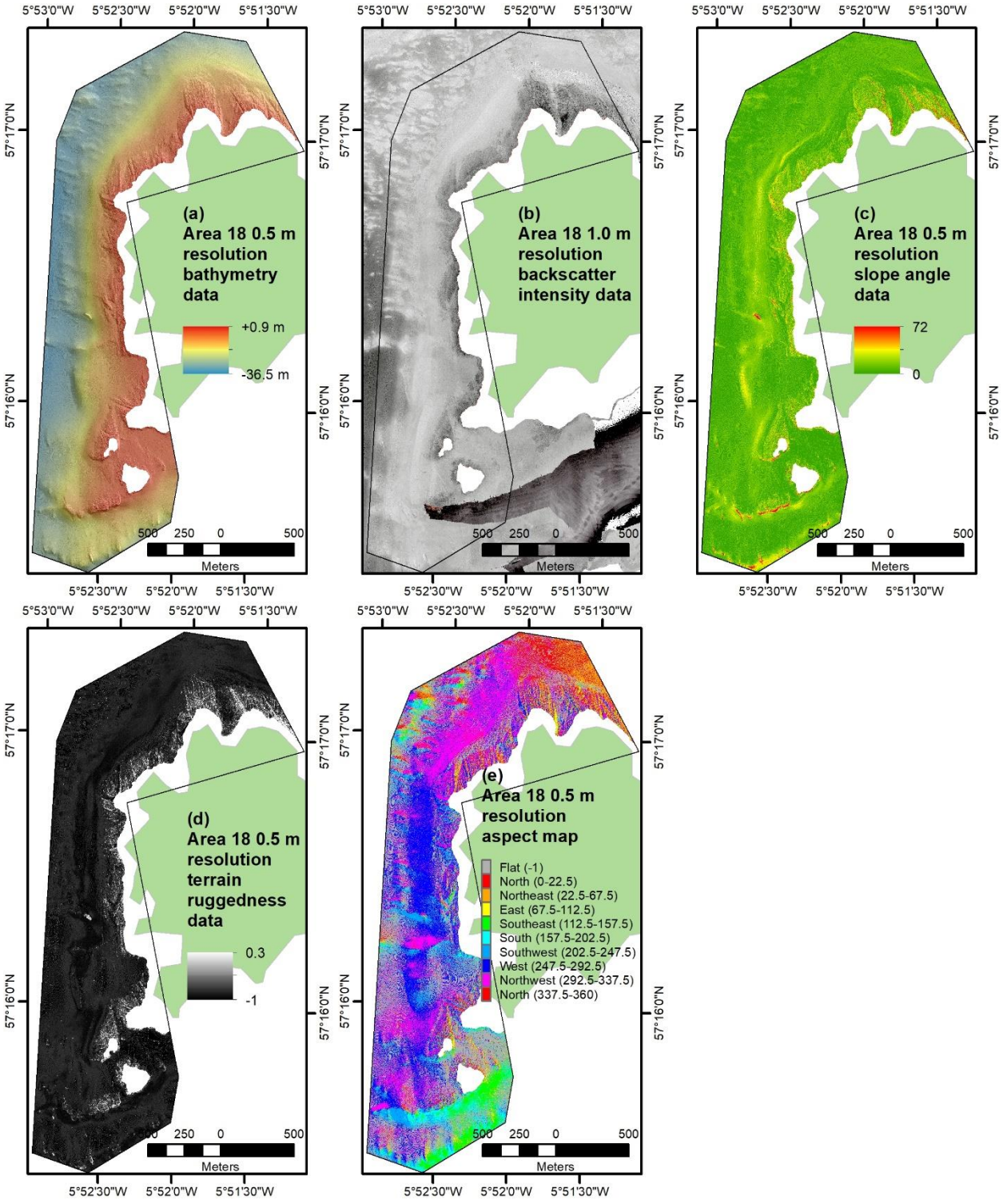


Figure 15 Overview of data and derived layers for Area 18. a) Reprocessed multibeam bathymetry data at 0.5 m x 0.5 m resolution; b) backscatter intensity data as supplied through the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot; c) slope angle derived from the 0.5 m grid; d) terrain ruggedness (VRM), or rugosity, derived from the 0.5 m grid; e) aspect derived from the 0.5 m resolution bathymetry grid.

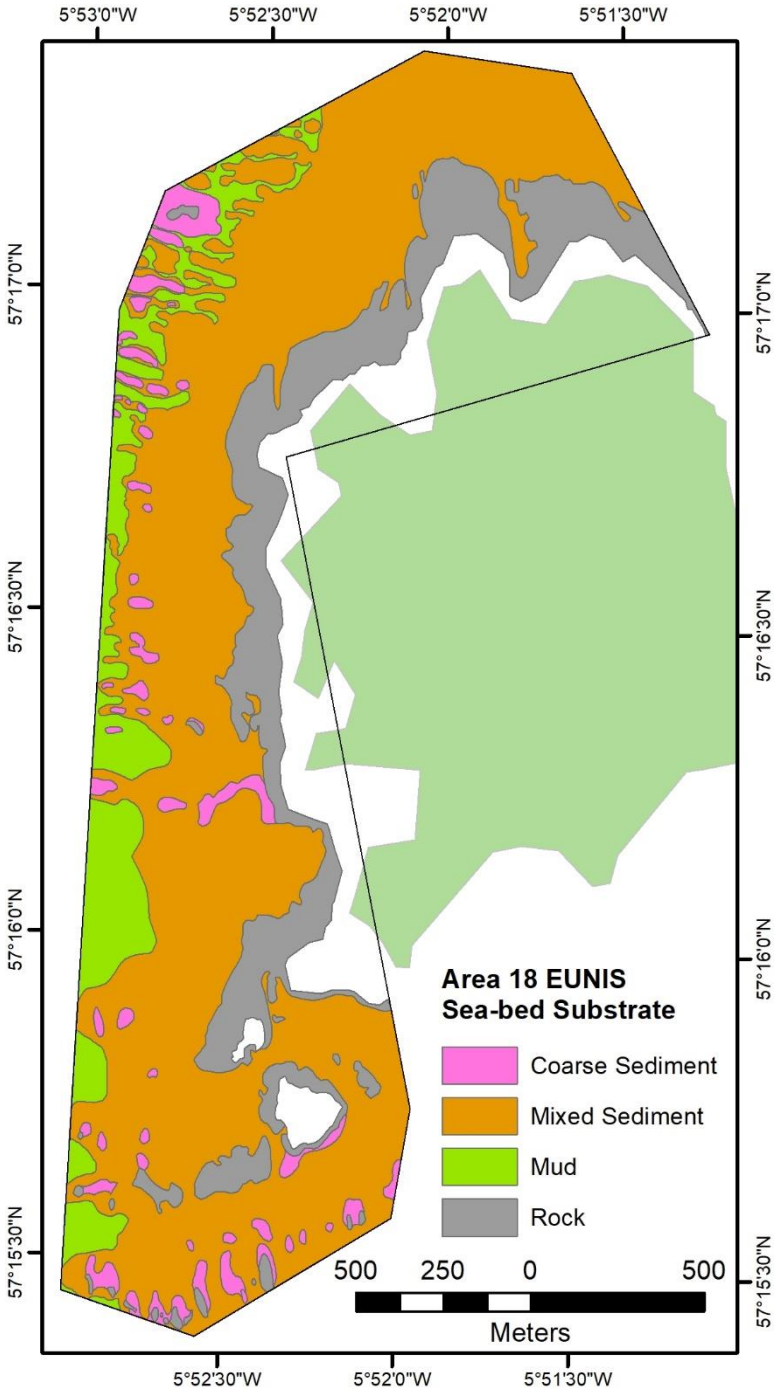


Figure 16 Overview of the sea-bed substrate interpretation in Area 18 undertaken by the BGS for this project using EUNIS sediment classes. This work is undertaken primarily using the 0.5 m resolution bathymetry, derived terrain ruggedness, and 1.0 m resolution backscatter intensity datasets. In particular, crag-and-tail and flutes are clearly identified forming an east-west line in the south of the study area, and the east-end of glacial moraines are depicted by occurrence of 'Coarse Sediment' along the western boundary of the study area.

5 Geodiversity Features within the Red Rocks and Longay Urgent MPA

Located between the mainland and the Isle of Skye, the Red Rocks and Longay MPA (see Figure 1), is located on a large bedrock platform composed of Torridon Group sandstones, siltstones and mudstones of the Aultbea Formation and the Sithean Glac an Ime Member of the Applecross Formation. The wider bedrock platform is divided into two by a deeply incised fjord (reaching a maximum water depth of 247 m) that forms a linear channel oriented roughly NNW-SSE. The Crowlin Islands are located on the eastern half, with the islands of Longay, Sgeir Dhearg, Sgeir Thraid and Pabay located on the western half of the divided bedrock high.

Having been eroded by ice over multiple glacial cycles over the last 500,000 years (Brooks *et al*., 2013), the wider geographic area has a seabed resource composed of a variety of sediment types, ranging from sands, gravels and boulders, to large outcrops of hard bedrock. The Red Rocks and Longay MPA and adjacent western portion of the bedrock platform off NE Scalpay, host a diverse array of glacially modified bedrock (crag-and-tails, rock drumlins, streamlined bedrock) and 'boulder moraine' belts representative of the Quaternary of Scotland geodiversity feature (Figure 17). These are interspersed amongst mixed sediment substrates. The outstanding range of glacial bedforms are of international scientific importance for our understanding of these historic processes and, where other physical conditions are suitable, play a key functional role in the supporting the egg-laying activities of the critically endangered Flapper Skate.

5.1 GEOMORPHOLOGICAL FEATURES - QUATERNARY OF SCOTLAND

At a wider scale the glacially modified bedrock and the boulder moraines that make up the Quaternary of Scotland geodiversity feature help us in reconstructing past ice sheets, telling a story of past global climate change that is useful for future projections of climate change.

The Red Rocks and Longay MPA, lies within the catchment of the Minch palaeo-ice stream that drained the NW sector of the Pleistocene British-Irish Ice Sheet over several glacial cycles. Bedrock landforms produced by glacial erosion are an important vestige for understanding glacial processes but have received relatively little attention compared to their soft-bed counterparts, and subtle differences in bedrock bedform morphology are regarded as valuable indicators of former sub-glacial processes. This assemblage of geodiversity interests in and around the Red Rocks MPA form evidence of intense subglacial erosion by powerful fast-flowing ice, providing comprehensive information regarding palaeo ice-flow dynamics. In a broader context, the isolated bedrock high on which the MPA is located represents a marked increase in bed strength creating a "sticky spot" during overall retreat of the ice steam into the Inner Sound around 16.5-16 calendar ka BP (Bradwell *et al*., 2019, 2021). Observed 'boulder moraine' belt deposits within and adjacent to the MPA represent a retreat stage (or local readvance) of the last British-Irish Ice Sheet. To the best of our knowledge, this is the first time 'boulder moraine' belts have been observed in such detail offshore Scotland.

5.2 FEATURE SENSITIVITY AND RESISTANCE - QUATERNARY OF SCOTLAND

The components of the geodiversity feature were formed during repeated glaciations over at least the last 500,000 years (Brooks *et al.,* 2013). They are entirely natural in origin and are not considered to have been modified by human activity. Given its static and relict status, these glacial features have few active functions.

The structure of the Quaternary of Scotland feature is considered not sensitive where the landforms are in bedrock. 'Boulder moraine' deposits described onshore in the Northwest Highlands of Scotland (e.g. Small *et al*., 2012; Bradwell *et al*., 2021; Ballantyne and Bradwell, 2021; Bradwell and Ballantyne, 2021) suggest that disturbance of these deposits since deposition is unlikely. However, even though these boulder deposits are considered to have high resistance to degradation, note that the processes which formed the geodiversity feature no longer exist and therefore these features have no recovery potential if disturbed.

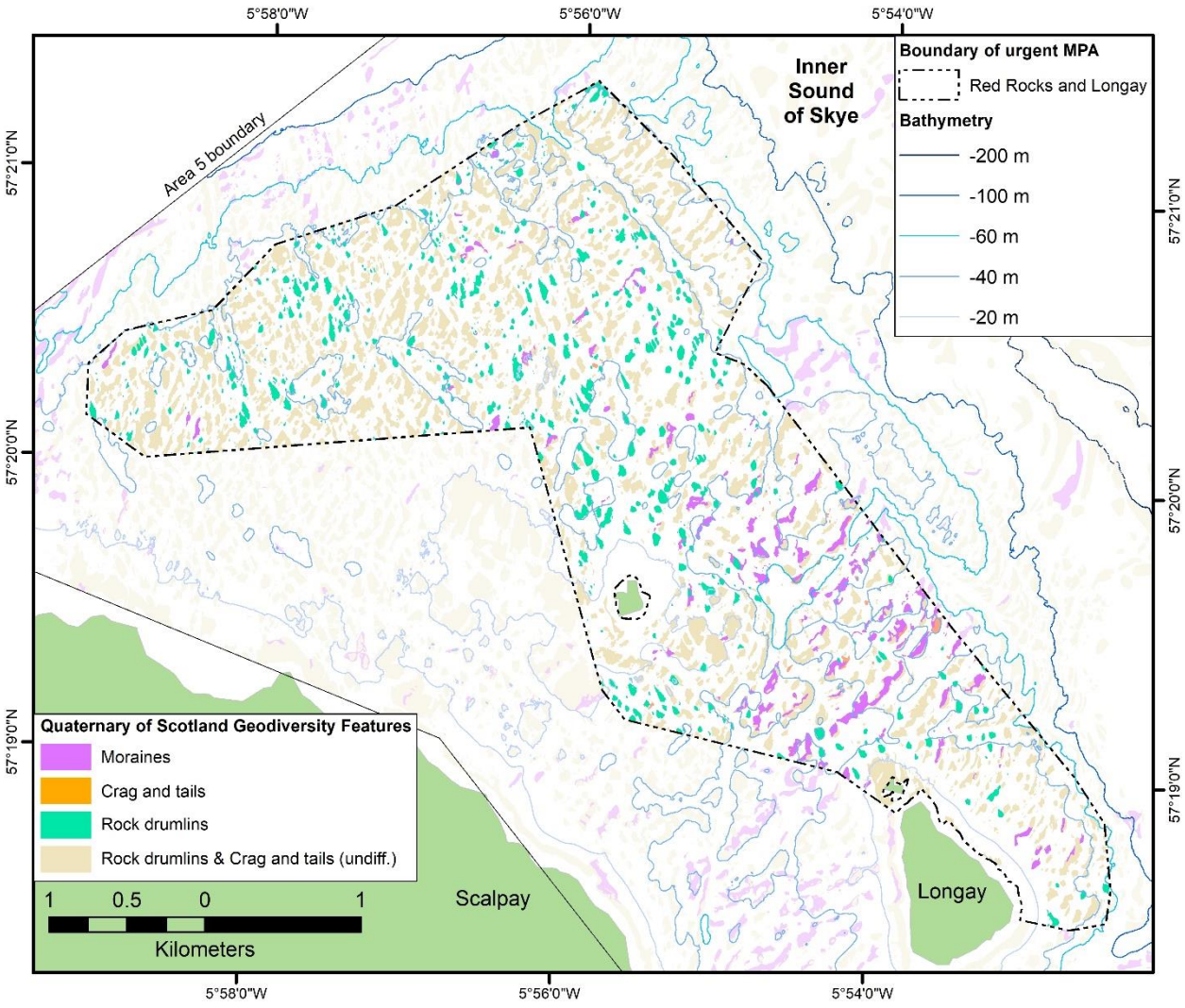


Figure 17 Overview of the known distribution of Quaternary of Scotland geodiversity features interpreted by the BGS within the Red Rocks and Longay urgent MPA (bold colours), and the wider bedrock platform offshore NE Scalpay (semi-transparent colours).

6 Conclusions

- The higher resolution multibeam bathymetry dataset (0.5 x 0.5 m grid) added a significant amount of value to the project when mapping indicators of bedrock and small-scale glacial moraines across all three areas of interest, particularly Area 5.
- Correlation between visual observations from client supplied video transects and mapped glacial moraines suggests these deposits comprise predominantly boulders and cobbles with lesser amount of gravel and sand- and/or mud-grade sediment (Figure 11). These 'Coarse Sediment' features, or 'boulder moraines' may provide particularly favourable Flapper Skate egg habitat where other physical parameters are suitable (e.g. water depth, water flow, silt levels etc.). Observations from NatureScot-led remote video sampling in 2021 on a small number of mapped moraines within and adjacent to the Red Rocks and Longay MPA appear to support this hypothesis (NatureScot, *pers comm*.).
- Derived layers of terrain ruggedness (0.5 m resolution) and backscatter intensity (1 m resolution) were essential to differentiate boundaries between substrate classes in sediment dominated areas (Areas 17 and 18). Backscatter intensity data across Areas 17 and 18 were useful to differentiate between areas of 'Coarse Sediment', 'Mixed Sediment', and more sand or mud rich sediment classes. However, across the bedrock platforms which dominate Area 5, the backscatter response was similar for both areas of 'Coarse Sediment', 'Mixed Sediment' and bedrock. Therefore, the RDMV products combined with visual confirmation using the 0.5 m resolution bathymetry raster were used to delineate areas of bedrock outcrop.
- The resultant sea-bed substrate interpretations across the three defined areas of interest represent a step-change in the level of detail compared to the seabed texture sheets supplied as part of the original CHP surveys (see Appendix 1). This was particularly apparent in Area 5.
- The corresponding increase in time necessary to interpret the detailed 0.5 m resolution datasets, compared to the 2 m and 4 m resolution datasets on which the CHP seabed texture sheets are based, should be realistically budgeted in any future project utilising such high-resolution data. Area 5 encompasses the Red Rocks and Longay urgent MPA (as amended in December 2021), one of the key drivers for the current analysis project.
- A single submarine landslide was identified during the course of this project, in Area 5, located approximately 300 m west of Eilean Beag (Figure 12). The headwall is ~105 m wide and the feature is ~250 m in length.
- Two large pockmarks were identified in Area 5, approximately 600 m south of Eilean Mòr. The two features are around 200 m in diameter each, extending from 122 m water depth on their flanks to a maximum of 133.5 m water depth (Figure 12).
- Validating the mapping layers has been limited due to sparse availability of physical seabed samples. Figure 6 shows the distribution of sediment samples across the broader study area with only ten samples located within the three defined areas of interest. Although these sediment samples give a good indication of seabed sediment distribution across the area, a detailed sampling campaign should be considered in the future. A more structured analysis of existing video transect data could be considered in any future study in addition to a review of new video samples collected by NatureScot and Marine Scotland in the three study areas in 2021.
- Glacial landforms identified during this study indicate the bedrock platform where the Red Rocks and Longay urgent MPA is situated comprises an outstanding range of geodiversity features ('Quaternary of Scotland') that are of international scientific importance for our understanding of past glacial and interglacial cycles (Figure 17). The geodiversity interests in this area are intrinsically linked to the Flapper Skate 'biodiversity' conservation interests of the MPA.

Appendix 1 Comparison between Sea-bed Substrate Interpretations

AREA 5

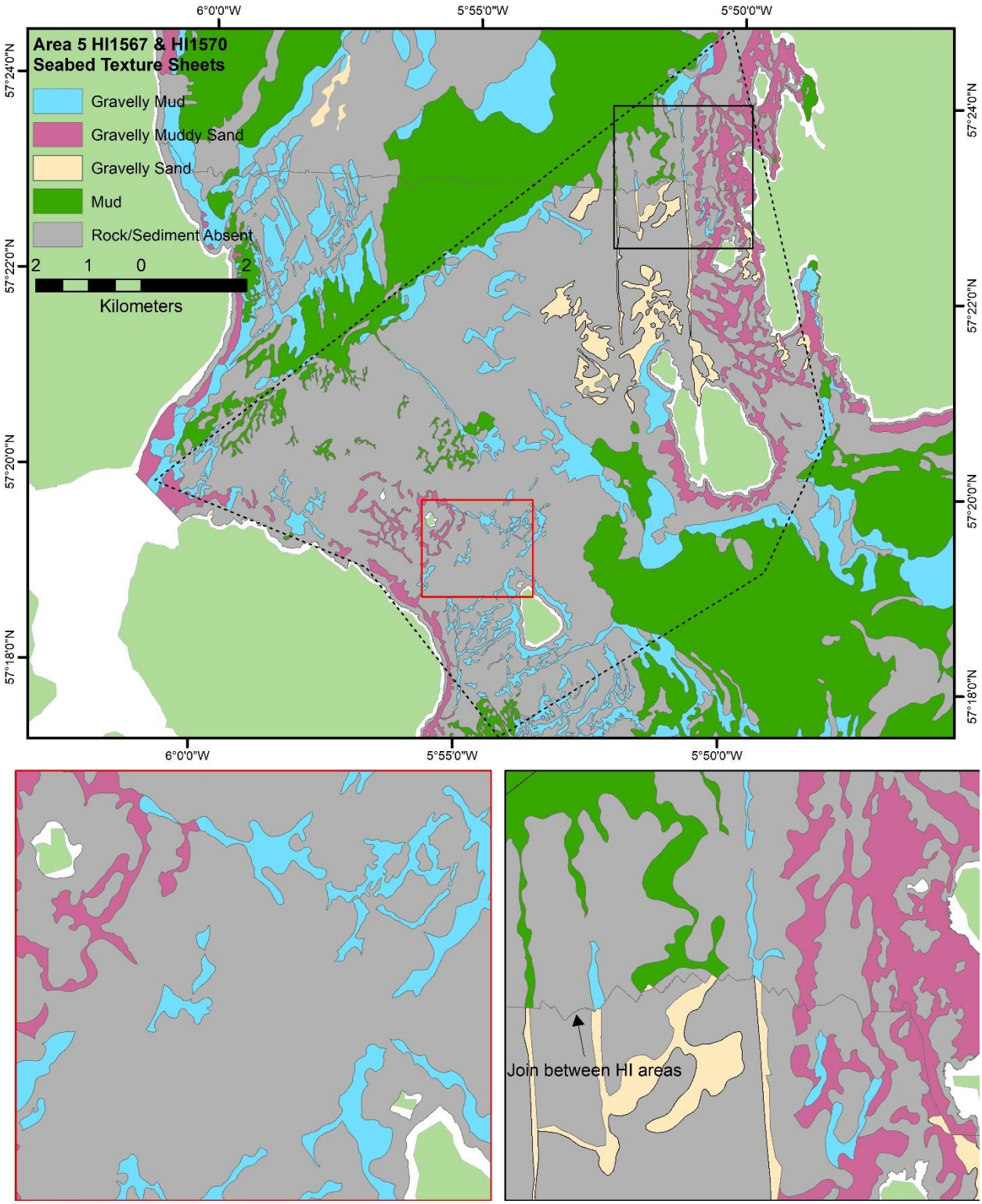


Figure 18 Overview of the sea-bed texture sheets published as part of the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot. The coloured boxes indicate the location of the two inset maps. These interpretations were undertaken using a coarser resolution of data. Generally, the major faults are

depicted by gravel-, sand- and mud-rich sediments, the detail of when rock is present/absent is lost and no glacial deposits are identifiable.

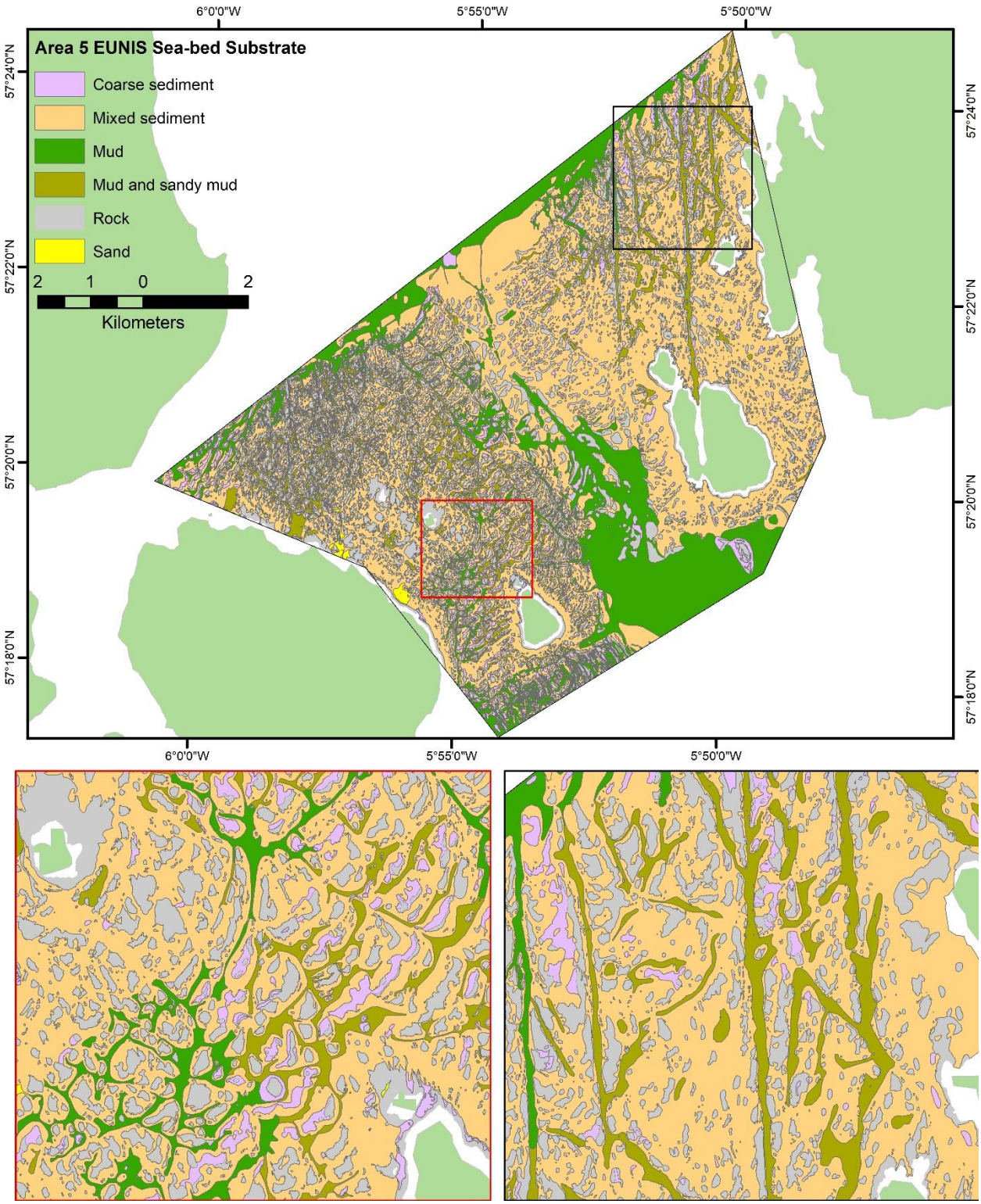


Figure 19 Overview of the sea-bed substrate interpretation in Area 5 undertaken by the BGS for this project using EUNIS sediment classes. This work is undertaken primarily using the 0.5 m resolution bathymetry data. The coloured boxes indicate the location of the two inset maps. The red inset map shows examples of crag-and-tails and rock drumlins preserved on the platform around northern Longay and Sgeir Dhearg, with mud-rich sediments infilling depressions caused by faults. The pink 'Coarse Sediments indicate presence of glacial moraines preserved on the topographic highs. The black inset map shows the prevalent structural fabric of the Torridon Group bedrock units, depicted by the fault network forming topographic lows now infilled with mud-rich sediment.

AREA 17

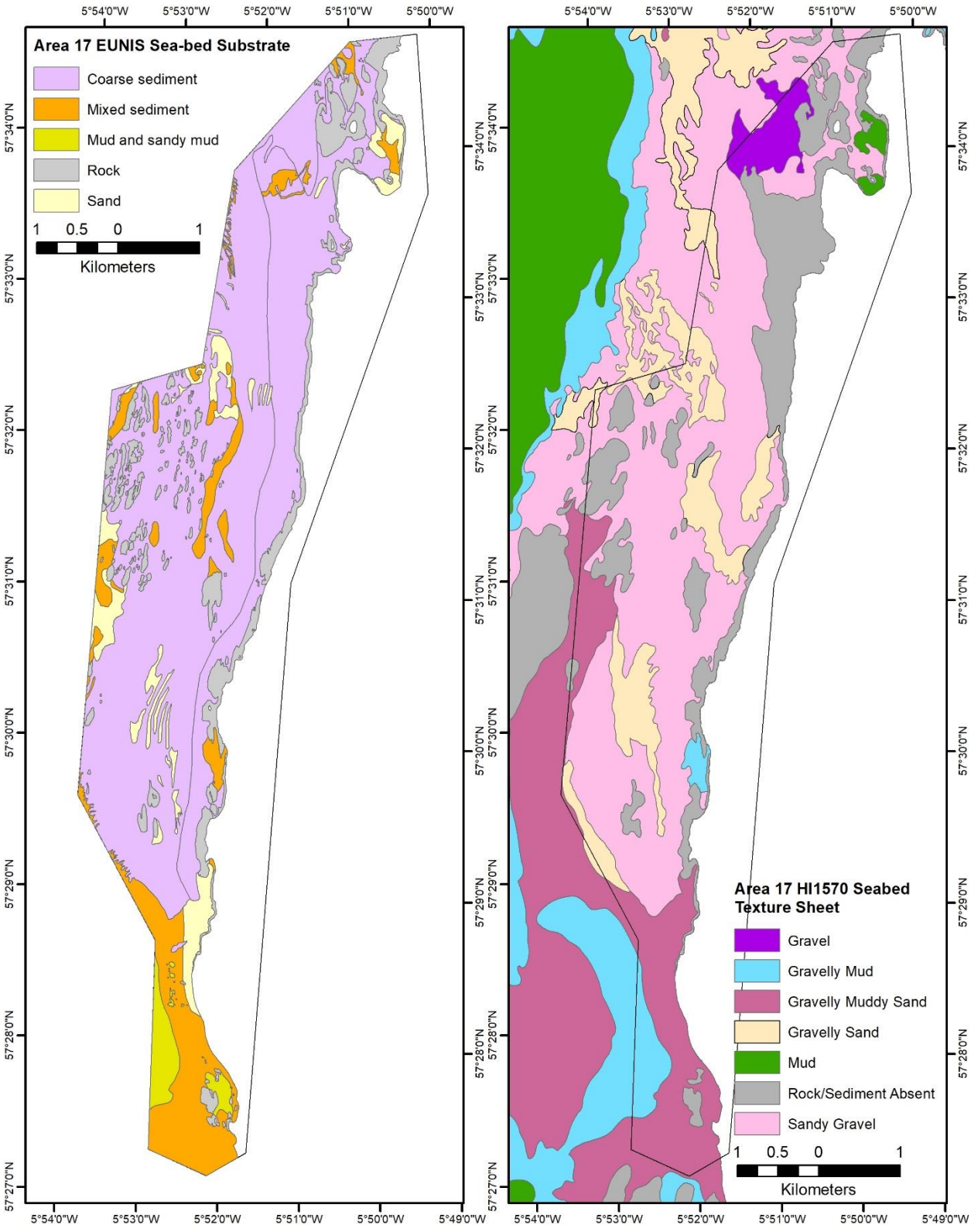


Figure 20 *Left* Overview of the sea-bed substrate interpretation in Area 17 undertaken for this project using EUNIS sediment classes. This work is undertaken primarily using the 0.5 m resolution bathymetry, derived terrain ruggedness, and 1.0 m resolution backscatter intensity datasets. *Right* Overview of the sea-bed texture sheets published as part of the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot. The CHP interpretations were undertaken using a coarser resolution of data. Overall there is a general correlation between the two interpretations.

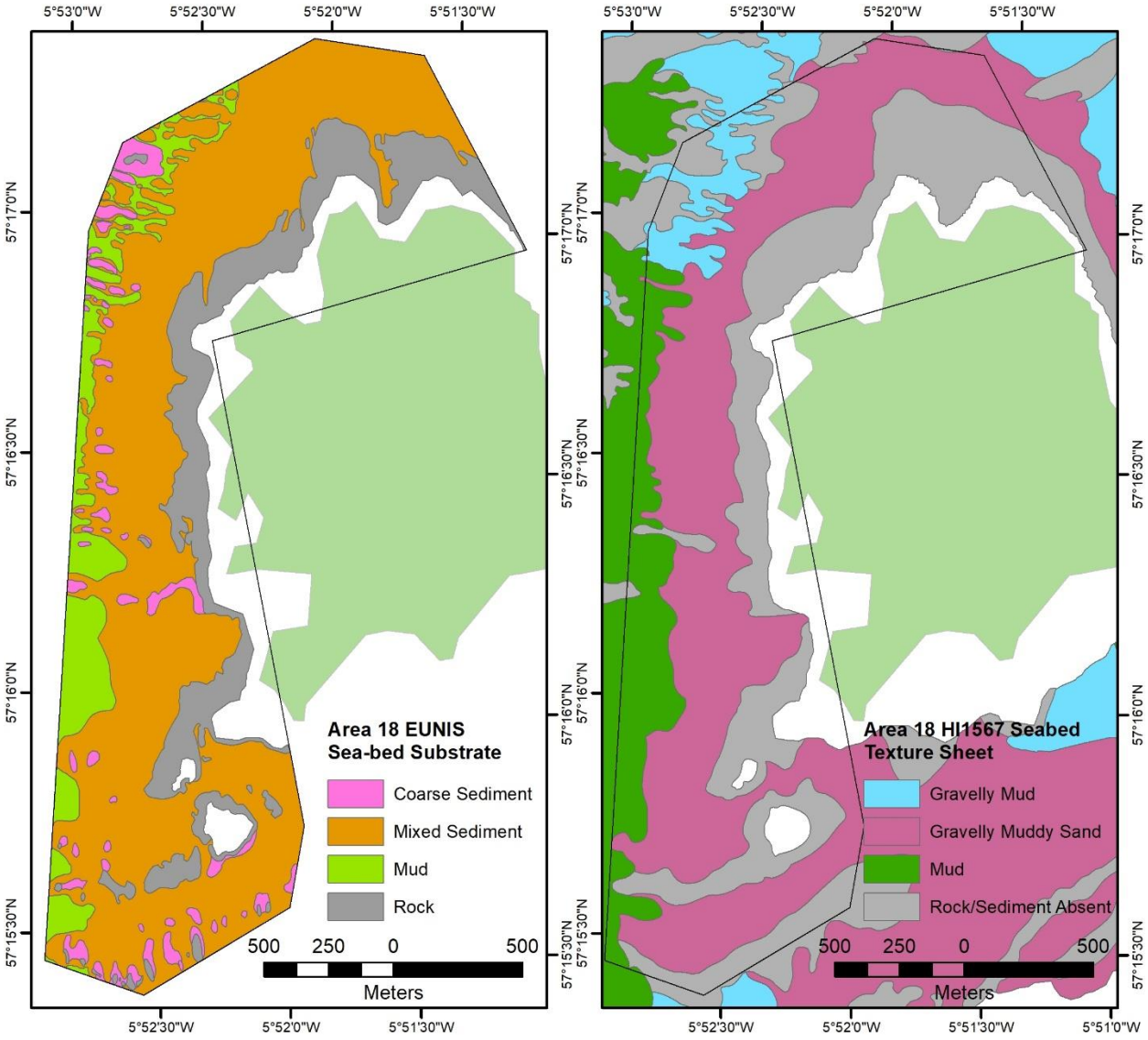


Figure 21 *Left* Overview of the sea-bed substrate interpretation in Area 18 undertaken for this project using EUNIS sediment classes. This work is undertaken primarily using the 0.5 m resolution bathymetry, derived terrain ruggedness, and 1.0 m resolution backscatter intensity datasets. *Right* Overview of the sea-bed texture sheets published as part of the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency (MCA) and made available to the BGS through an agreement with the MCA via NatureScot. The CHP interpretations were undertaken using a coarser resolution of data. Overall there is a general correlation between the two interpretations although glacial deposits such as the moraine landforms are underrepresented in the CHP sea-bed texture sheet.

Appendix 2 Deliverables

The following folders and files have been delivered to NatureScot:

On the Nature Scotland HDD with the video/habitat data (Seagate PN: 2N1AP3-570).
CHP_NatureScot_Delivery_From_BGS

This folder contains two sub-folders:

- **GIS**
  - Comprises 4 ArcGIS (v 10.7.1) .mxd files **All_Study_Areas**, **Area_5**, **Area_17** and **Area_18**;
  - **Local_Coastline.shp**
  - .lyr files that can be dropped into any ArcGIS project and linked to the folder structure contained in this folder:
    - **Area 5 1m rasters (ALL).lyr** – *all 1m x 1m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
    - **Area 5 50 cm Aspect.lyr** – *0.5m x 0.5m rasters of aspect.*
    - **Area 5 50 cm Bathymetry.lyr** – *all 0.5m x 0.5m rasters of bathymetry and hillshade.*
    - **Area 5 50 cm Slope.lyr** – *all 0.5m x 0.5m rasters of slope.*
    - **Area 5 50 cm VRM Rugosity.lyr** – *0.5m x 0.5m rasters of rugosity (VRM).*
    - **Area 5 EUNIS Interpretation.lyr** – *the BGS interpretation of EUNIS seafloor substrate.*
    - **Area 17 1m rasters (ALL).lyr** – *all 1m x 1m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
    - **Area 17 50 cm rasters (ALL).lyr** – *all 0.5m x 0.5m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
    - **Area 17 EUNIS Interpretation.lyr** – *the BGS interpretation of EUNIS seafloor substrate.*
    - **Area 18 1m rasters (ALL).lyr** – *all 1m x 1m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
    - **Area 18 50 cm rasters (ALL).lyr** – *all 0.5m x 0.5m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
    - **Area 18 EUNIS Interpretation.lyr** – *the BGS interpretation of EUNIS seafloor substrate.*
  - **Area 5 folder** containing the following 8 folders:
    - **1 m Bathy** – *all 1m x 1m rasters of bathymetry and hillshade.*
    - **1 m BathyDerivedLayers** – *all 1m x 1m rasters of slope, rugosity (VRM) and aspect.*
    - **50cm_Aspect** – *0.5m x 0.5m rasters of aspect over the 3 Area 5 tiles.*
    - **50cm_Bathy_50cm_part_1** – *0.5m x 0.5m rasters of bathymetry and hillshade over Area 5 tile 1.*
    - **50cm_Bathy_50cm_part_2** – *0.5m x 0.5m rasters of bathymetry and hillshade over Area 5 tile 2.*
    - **50cm_Bathy_50cm_part_3** – *0.5m x 0.5m rasters of bathymetry and hillshade over Area 5 tile 3.*
    - **50cm_Slope** – *all 0.5m x 0.5m rasters of slope over the 3 Area 5 tiles.*
    - **50cm_VRM_Rugosity** – *all 0.5m x 0.5m rasters of rugosity (VRM) over the 3 Area 5 tiles.*
  - **Area 17 folder** containing the following 2 folders:
    - **1 m** – *all 1m x 1m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
    - **50 cm** – *all 0.5m x 0.5m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
  - **Area 18 folder** containing the following 2 folders:
    - **1 m** – *all 1m x 1m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*

        - **50 cm** – *all 0.5m x 0.5m rasters of bathymetry, hillshade, slope, rugosity (VRM) and aspect.*
    - **Report_Figures**
        - Contains the figures from the report produced by the BGS (CR/21/080)

The following data is on the NatureScot Seagate Backup Plus Hub (SN: NA9RB2GY)

Two folders:

- **HI1567**
    - Comprises the original folders from the Civil Hydrography Programme.
- **NatureScotland**
    - **HI1567**
        - 3 folders containing reprocessed data: **1m_Product, 50cm_Product**, and **Other.**
    - **1m_Product**
        - **CSAR folder** – CARIS format for the reprocessed 1m x 1m resolution fourteen sub-tiles of HI1567.
        - **ESRI folder** – reprocessed 1m x 1m resolution fourteen sub-tiles of HI1567 bathymetry in .asc ESRI ArcGIS format,.
            - **Derived_Layers** folder – derived layers of aspect (files ending "_a"), slope (files ending "_s") and hillshade (files ending "_hs").
        - **GEOTIFF folder** – reprocessed 1m x 1m resolution fourteen sub-tiles of HI1567 bathymetry in .tiff/.tfw georeferenced geotiff format.
        - **XYZ folder** – reprocessed 1m x 1m resolution fourteen sub-tiles of HI1567 bathymetry in .xyz format.
    - **50cm_Product**
        - **CSAR folder** – CARIS format for the reprocessed 0.5m x 0.5m resolution thirty sub-tiles of HI1567.
        - **ESRI folder** – reprocessed 0.5m x 0.5m resolution thirty sub-tiles of HI1567 bathymetry in .asc ESRI ArcGIS format.
            - **Derived_Layers folder** – reprocessed .5m x 0.5m resolution thirty sub-tiles of slope (slp-), aspect (asp-) and hillshade (hs-).
        - **GEOTIFF folder** – reprocessed 0.5m x 0.5m resolution thirty sub-tiles of HI1567 bathymetry in .tiff/.tfw georeferenced geotiff format.
        - **XYZ folder** – reprocessed 0.5m x 0.5m resolution thirty sub-tiles of HI1567 bathymetry in .xyz format.
    - **Other**
        - Experiment to reprocess the data to 25cm x 25cm resolution bathymetry. These data were not used in any interpretation and does not cover the whole HI area. Do not use.

The following data is on the NatureScot Seagate Backup Plus Hub (SN: NA9RB2VX)

Three folders:

- **HI1570**
    - Comprises the original folders from the Civil Hydrography Programme.
- **HI15880**
    - Comprises the original folders from the Civil Hydrography Programme.
- **NatureScotland**
    - **HI1570**
        - 2 folders containing reprocessed data: **1m_Product, 50cm_Product**, and **Other.**

- **1m**
  - **ESRI folder** – reprocessed 1m x 1m resolution eight sub-tiles of HI1570 bathymetry in .asc ESRI ArcGIS format.
    - **Derived_Layers** folder – derived layers of aspect (files ending "_a"), slope (files ending "_s") and hillshade (files ending "_hs").
  - **GEOTIFF folder** – reprocessed 1m x 1m resolution eight sub-tiles of HI1570 bathymetry in .tiff/.tfw georeferenced geotiff format.
  - **XYZ folder** – reprocessed 1m x 1m resolution eight sub-tiles of HI1570 bathymetry in .xyz format.
- **50cm**
  - **ESRI folder** – reprocessed 0.5m x 0.5m resolution twenty-six sub-tiles of HI1570 bathymetry in .asc ESRI ArcGIS format.
    - **Derived_Layers** folder – derived layers of aspect (files ending "_a"), slope (files ending "_s"), hillshade (files ending "_hs"), and rugosity (files ending "_vrm").
  - **GEOTIFF folder** – reprocessed 0.5m x 0.5m resolution twenty-six sub-tiles of HI1570 bathymetry in .tiff/.tfw georeferenced geotiff format.
  - **XYZ folder** – reprocessed 0.5m x 0.5m resolution twenty-six sub-tiles of HI1570 bathymetry in .xyz format.
- **SNH_AOIs**
  - Comprises 3 folders with the shapefiles of each study area (5, 17 and 18), and initial 1m x 1m resolution reprocessed bathymetry files created as part of this study. For comprehensive set of all reprocessed products created as part of this project see **CHP_NatureScot_Delivery_From_BGS.**

Note all hillshade files are created at 45° azimuth and 25° altitude.

All Rugosity (VRM) files are created using a neighbourhood cell size of 3.

All processed bathymetry, their respective derived layers, and EUNIS interpretation files are in WGS 1984 UTM Zone 30N projection.

Glossary

Backscatter Intensity 'Backscatter' is computed by measuring the amount of sound that is reflected by the sea floor and received by the multibeam echosounder sonar. It is used as a proxy to derive information on the 'hardness' of the sea floor and is used to differentiate between different types of sea floor, such as hard rock or soft sediment.

BGS British Geological Survey.

CHP Civil Hydrography Programme.

Drumlin An elongated hill formed sub-glacially with the 'point' pointing in the direction of ice flow. Rock and sediment versions can be formed. There is much active debate on the exact genesis of these features.

MCA Maritime and Coastguard Agency.

Moraine A moraine is an accumulation of unconsolidated debris (sediment and/or rock), sometimes referred to as glacial till or diamicton that has been transported and subsequently deposited by a glacier or ice sheet. Moraines occur in both currently and formerly glaciated regions, and may consist of a range of grain-sizes from boulders, down to gravel and sand, and predominantly fine-grained materials such as clay.

UKHO United Kingdom Hydrographic Office.

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

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