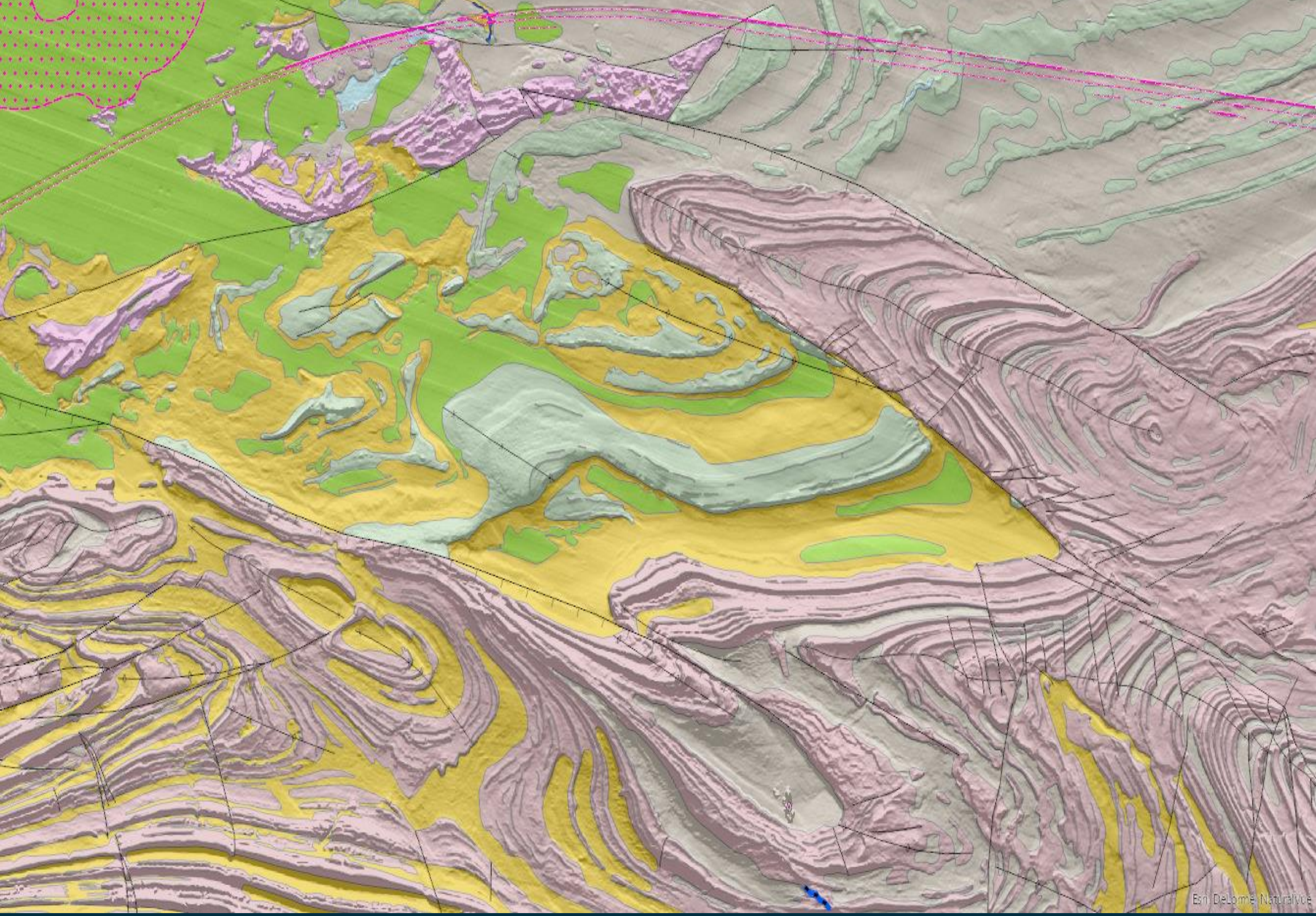

DIGITAL PROGRAMME

User Guide for BGS Seabed Geology 10k: Offshore Yorkshire

Open Report OR/22/063

British Geological Survey

BRITISH GEOLOGICAL SURVEY

DIGITAL PROGRAMME

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User Guide for BGS Seabed Geology 10k: Offshore Yorkshire

British Geological Survey

Keywords

Yorkshire, Seabed Geology, Offshore bedrock, Quaternary sediments, Structural Geology, Geomorphology.

Map

Seabed Geology 10k: Offshore Yorkshire

Front cover

Extract from Seabed Geology 10k: Offshore Yorkshire dataset showing the bedrock geology and superficial deposits. Hillshade image derived from bathymetric data acquired by the MCA © Crown Copyright 2023.

Bibliographical reference

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Foreword

The British Geological Survey (BGS) is a world-leading geological survey, focusing on public-good science for government, and research to understand earth and environmental processes.

We are the UK's premier provider of objective and authoritative geoscientific data, information, and knowledge to help society to:

- use its natural resources responsibly
- manage environmental change
- be resilient to environmental hazards

We provide expert services and impartial advice in all areas of geoscience. As a public sector organisation, we are responsible for advising the UK Government on all aspects of geoscience as well as providing impartial geological advice to industry, academia and the public. Our client base is drawn from the public and private sectors both in the UK and internationally.

The BGS is a component body of the Natural Environment Research Council (NERC), part of UK Research and Innovation (UKRI).

DATA PRODUCTS

The BGS produces a wide range of data products that align to government policy and stakeholder needs. These include baseline geological data, engineering properties and geohazards datasets. These products are developed using in-house scientific and digital expertise, and are based on the outputs of our research programmes and substantial national data holdings.

Our products are supported by stakeholder focus groups, identification of gaps in current knowledge and policy assessments. They help to improve understanding and communication of the impact of geo-environmental properties and hazards in Great Britain, thereby improving society's resilience and enabling people, businesses, and the government to make better-informed decisions.

SEABED GEOLOGY MAP PRODUCTS

The BGS is undertaking a marine mapping programme that provides detailed and accurate characterisation of the Seabed Geology, integrating Substrate Geology, Structural Geology and Seabed Geomorphology. These detailed digital map products are intended as enabling resources to support a diverse range of offshore activities and applications, including scientific research, offshore development, and conservation initiatives. These geological products also provide a new and unique resource to better inform marine spatial planning and management.

The BGS Seabed Geology 10k: Offshore Yorkshire digital map portrays the distribution of the different types of bedrock and sediments that are interpreted to represent the dominant geology within the top 1 m of the seabed, at a scale of 1:10 000. It also includes the distribution of the main seabed morphological and geomorphological features (*e.g.,* sediment waves, moraines) and the principal structural features observed at rockhead (*e.g*., faults, fractures).

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The geological analysis, interpretation, and mapping were carried out at 1:10 000 scale in 2021-22 by Dayton Dove, Jonathan Lee, and Heather Stewart. Important contributions including data compilation, scientific (and technical) advice and review were provided by: Joana Gafeira, Rowan Vernon, Andrew Finlayson, Mary Mowat, and Gareth Carter.

This mapping was based primarily on the high-resolution multibeam echo-sounder (MBES) bathymetry data collected by the Civil Hydrography Programme (CHP) surveys managed by the Maritime and Coastguard Agency (MCA) for the UK Hydrographic Office, as well as data acquired for a candidate Marine Conservation Zone (MCZ) area for the Department for Environment, Food and Rural Affairs (Defra).

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Summary

The BGS Seabed Geology 10k: Offshore Yorkshire digital map comprises three complimentary components: 1) Substrate Geology, showing the distribution of Bedrock and Superficial geological units interpreted to be dominant within the top 1 m below seabed; 2) Structural Geology, delineating the principle structural features such as faults and folds observed at rockhead; and 3) Seabed Geomorphology, classifying the physical morphology and interpreted geomorphic character of the seabed.

This geospatial product is the result of analysing, interpreting, and classifying a number of high-resolution, multibeam echo-sounder (MBES) bathymetry datasets, supported by further data and information, e.g., MBES backscatter, physical samples (*e.g.,* grabs, cores, and boreholes), seismic data, academic and publicly accessible industry literature, and previous BGS mapping (e.g.,1:250k maps).

The bedrock geology comprises Triassic, Jurassic, and Cretaceous sedimentary rocks, with bedrock commonly outcropping in the northern and central parts of the map area. Triassic rocks of the Bacton, Haisborough, and Lias Groups are dominant in the north, whereas Cretaceous Chalk is dominant in the central areas. Extensive folding, fracturing, and faulting is observed at rockhead, indicative of the complex structural evolution of the southern North Sea basin. Superficial deposits comprise several Quaternary deposits, in particular Late Pleistocene subglacial till of the Bolders Bank Formation. Post glacial channel-infill deposits are also common as well as Holocene through modern unconsolidated marine sediments. The Seabed Geomorphology records a range of relict features and active processes, including: 'Bedrock ridges', Late Pleistocene 'Ice-marginal moraines', and active marine sedimentary 'Current-induced bedforms' e.g., 'Sediment Waves'.

The map citation, metadata and overview can be found here:
British Geological Survey (2023): BGS Seabed Geology 10k: Yorkshire version 1.0. (Dataset). https://doi.org/10.5285/4cd1b2e2-1f8f-4f9b-9991-245122e078c0

The information provided in this user guide is intended to provide a quick-start guide to using and understanding this BGS digital product.

1 Introduction

The BGS Seabed Geology 10k: Offshore Yorkshire digital map provides detailed and accurate characterisation of the seabed geology, based on high-quality seabed (e.g., high-resolution bathymetry) and shallow-subsurface data (Figure 1). This product incorporates three complimentary map components, *Substrate Geology*, *Structural Geology,* and *Geomorphology,* each presented at 1:10 000 scale, and provided as discrete layers for viewing within a Geographic Information System (GIS). The *Substrate Geology* shows the distribution of bedrock and unlithified superficial deposits (series of polygons) present at seabed or immediately below the thin veneer of seabed sediments (this can be thought of as the 'one metre principle' described below); The *Structural Geology* represents the structural features observed at rockhead as a polylines layer, and *Geomorphology* consist of points, polylines, and polygons layers to portray the main seabed morphological and geomorphological features.

The geological character of the seabed and shallow sub-surface is important to a range of uses and stakeholders. The BGS fine-scale Seabed Geology maps are intended as enabling resources to support a diverse range of offshore activities and applications including scientific research, resource development (e.g., offshore renewables), conservation efforts, and marine management.

Substrate Geology

This digital map layer shows the dominant geological unit interpreted to be present within the top 1 m below seabed. This general approach is followed in order to characterise the geological substrate present below the frequently thin and potentially ephemeral/mobile seabed sediment (SBS) layer (i.e., consider the offshore SBS as akin to an onshore 'pedogenic soil' layer). At any given location, the mapped geological substrate may comprise either a Bedrock, or Superficial geological unit. The Superficial units may include Quaternary sediment units, thicker deposits of unconsolidated marine sediment, or any other unconsolidated unit (e.g., talus).

Structural Geology

This map layer delineates principle structural features such as faults and folds observed at rockhead. The structural features currently captured on these maps is restricted to significant fractures and fold hinges. Features are only marked as faults as opposed to fractures where bedding is clearly offset.

Seabed Geomorphology

Portraying the Seabed Geomorphology involves describing the morphological character of the seafloor, which integrated with further supporting data and contextual information, potentially enables further detailed interpretation of the environmental origin/evolution, compositional character, and potential mobility/vulnerability of seabed features.

In principle, the Seabed Geomorphology mapping workflow follows the '2-part' approach, which has semi-independent descriptions of 1) Morphology, and 2) Geomorphology (e.g., Dove et al., 2016). Morphological features are those characterised only by the surface (seabed) expression of their physical attributes (i.e., size, shape, configuration, texture); Geomorphological features are defined by the geological process(es) that created that morphology. As such, 'Morphology' provides the fundamental objective physical description of the of the feature(s), whereas 'Geomorphology' also requires an interpretation of the genesis of the feature(s).

An area-specific geological summary is presented in section 3, based on the observations and findings from the Offshore Yorkshire geological analysis, interpretation, and mapping. Attribute information is provided for every record in each layer, with each field of attribution specific to the layer and the characteristic of the feature being described. Attribution may include information as the age of a geological unit, its lithology, links to further resources (such as hyperlinks to BGS webpages) and metadata about the dataset (e.g., the scale, version, release date of the data).

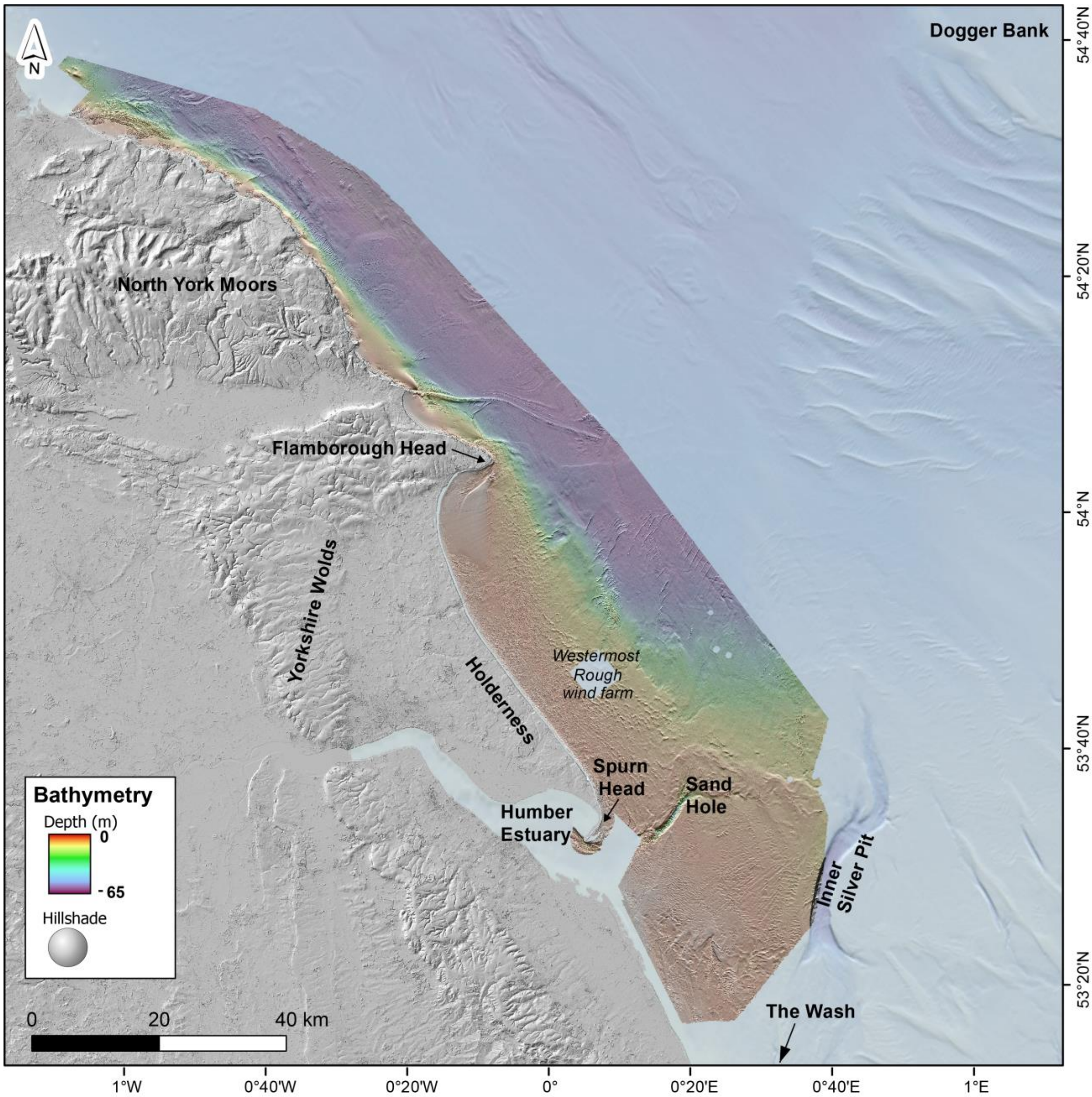

Figure 1 – Location map and bathymetry data within the BGS Seabed Geology 10k: Offshore Yorkshire digital map

This image contains bathymetry data acquired by the MCA and by Defra © Crown Copyright 2022. Terrestrial topography data derived from NEXTMap Britain elevation data from Intermap Technologies

2 Methodology

The information provided in the BGS Seabed Geology 10k: Offshore Yorkshire map has been compiled via a process of geological interpretation and domain analysis, digital capture of seabed topographic features, and data processing and harmonisation.

2.1 SOURCE DATA OVERVIEW

The geological mapping is based primarily on eight contiguous high-resolution multibeam datasets (Figure 2). These include six Hydrographic Instruction (HI) areas (*acquisition dates*) (**HI1358** (Jan-May 2011), **HI1401** (Jan-May 2013), **HI1419** (Sep 2013 - Apr 2014), **HI1472** (*Nov 2015 - Feb 2016*), **HI1473** (*Jan-Apr 2016*), **HI1491** (*Nov-Dec 2016*), & **HI1587** (*Aug-Sep 2020*)) acquired on behalf of the Civil Hydrography Programme (CHP), and one further MBES dataset, **Runswick Bay** (*Feb 2013*), which was acquired as part of the process to establish the area as a Marine Conservation Zone (MCZ). The CHP is managed by the Maritime and Coastguard Agency (MCA) for the UK Hydrographic Office, and the MCZ data are provided by Cefas on behalf of Defra. Both the CHP and MCZ data are made available via Open Government Licence.

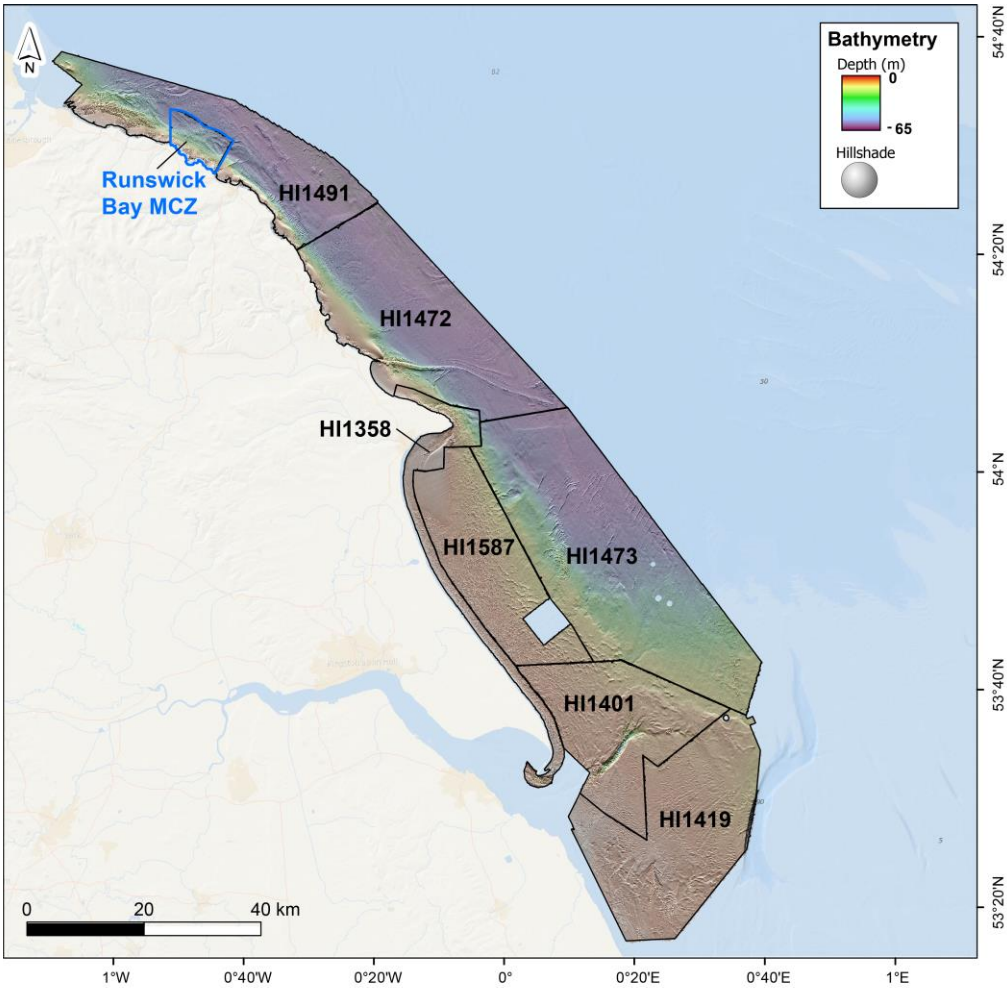

Figure 2 – Location map of the multibeam bathymetry datasets used for the BGS Seabed Geology 10k: Offshore Yorkshire map.
This image contains bathymetry data acquired by the MCA and by Defra © Crown Copyright 2022. Background image from World Ocean Base dataset compiled by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

The individual bathymetry survey datasets were merged to form a single bathymetry surface, with two versions prepared, gridded at 2 m and 4 m horizontal spatial resolution respectively. Mapping was undertaken with the 4 m dataset, with the 2 m version used when mappers wanted to examine features in greater detail, e.g., to confirm feature characteristics and origin.

MBES backscatter, physical samples (*e.g.,* grabs, cores, and boreholes), seismic data, academic publications, previous BGS offshore mapping (e.g.,1:250k maps), and publicly-accessible industry data and reports were also used to inform the geological interpretation (Figure 3). In addition, OS topographic maps, BGS geological maps at 1:50 000 scale and hill shaded Digital Terrain Models (DTMs) for the adjacent onshore areas were also used to ensure that the onshore geological mapping corresponds to that mapped onshore, to facilitate the future development of a “seamless” onshore-offshore geological map for the Yorkshire region.

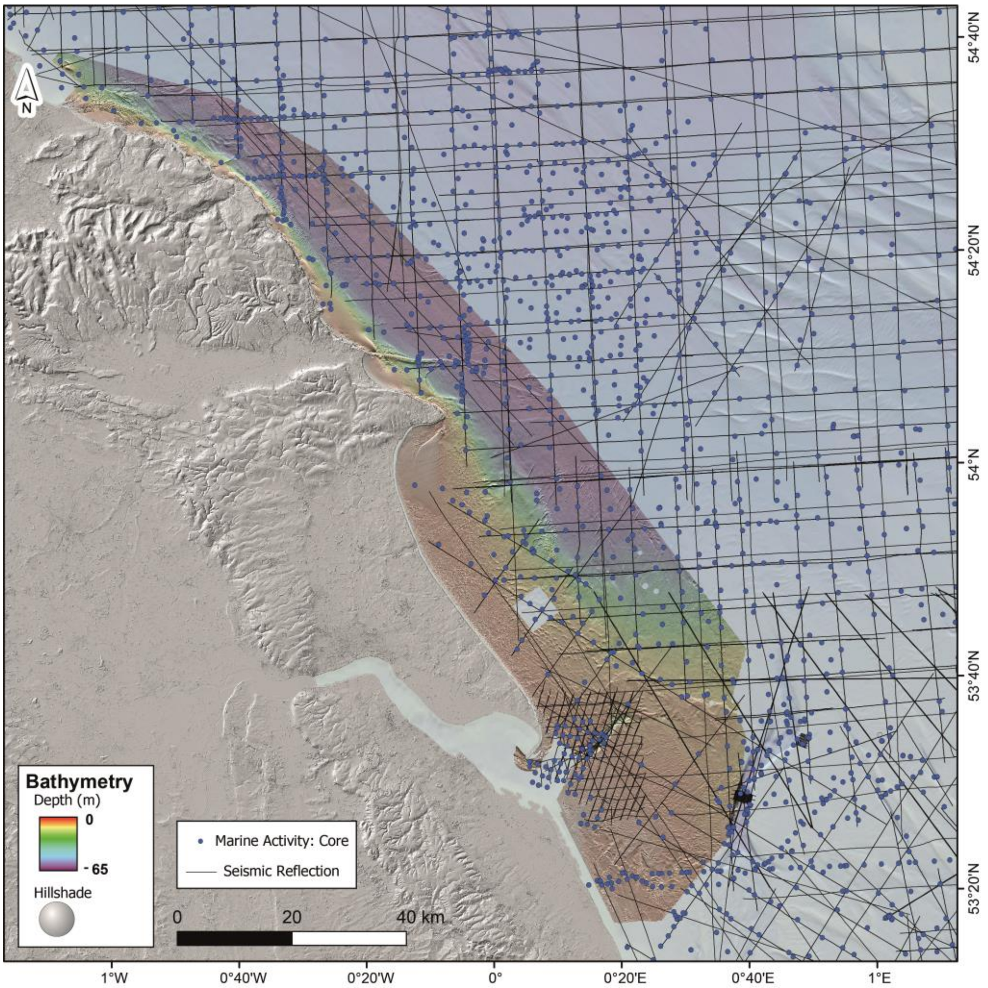

Figure 3 - Location map of BGS seismic reflection data, and sediment cores available to inform Seabed Geology interpretation.

This image contains data acquired by the MCA and by Defra © Crown Copyright 2022. Terrestrial topography data derived from NEXTMap Britain elevation data from Intermap Technologies.

2.2 GEOLOGICAL INTERPRETATION - APPROACH

The geological interpretation of multibeam echo-sounder (MBES) bathymetry is similar to onshore methods of terrain analysis (specifically that which utilises LiDAR), where the surveyor is seeking to identify domains (areas) of similar geology, structural bedrock (where present) lineaments (lines) that either bound the domains, or crosscut, or displace them, and geomorphic features whose morphology provides evidence on both environmental history and shallow sub-surface composition.

From the depth digital terrain model (DTM) provided by the MBES bathymetry, several derived surfaces were created (such as hillshade, slope, and bathymetric position index; Figure 4) (e.g., Lecours et al., 2016). These can be used, for example, to identify changes in the general ‘texture’ of the seabed (finer-grained deposits have smoother seafloor expressions than rough, rocky or cobbly surfaces) or recognise the morphology, orientation and configuration of seabed features at multiple spatial scales. MBES backscatter data are a co-registered dataset acquired simultaneously with the bathymetry data. While bathymetry measures seabed depth, backscatter measures the intensity of the return acoustic signal (Lurton et al., 2015). The backscatter data can therefore be used as a proxy for seabed hardness, and seabed sediment composition (e.g., discriminating between unconsolidated marine sediment).

Importantly, continuous and geographically-extensive MBES bathymetry and backscatter datasets bring enhanced value to existing seabed and shallow sub-surface data (e.g., sediment cores and seismic data), permitting detailed and accurate mapping of the seabed geology. The combination of seabed morphology and acoustic signature coupled with groundtruthing and sub-surface data allows geoscientists to identify areas exhibiting similar rock and deposit characteristics, as well as seabed forms that can imply geological ‘processes’, such as overriding by glacier ice or mobility of sedimentary bedforms.

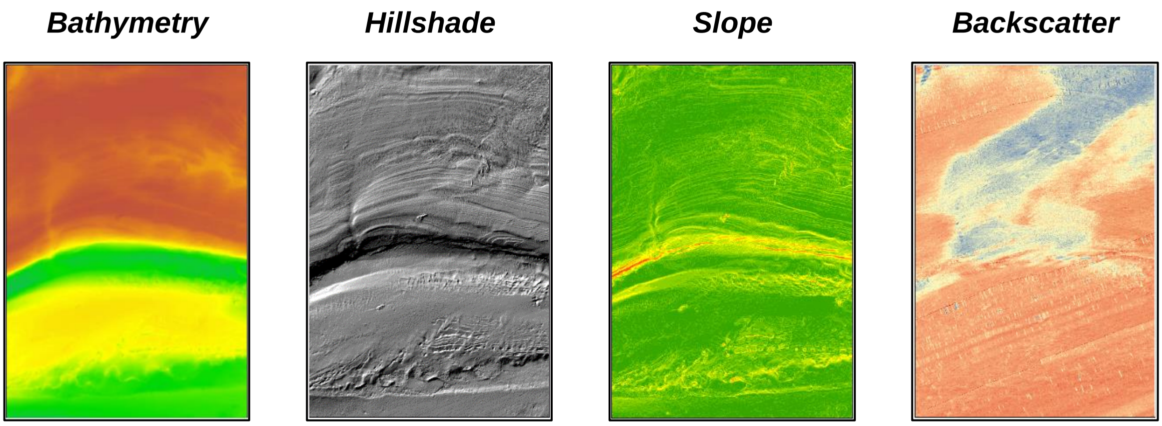

Figure 4 – Extracts of the bathymetry, hillshade, slope and backscatter multibeam data used during the geological interpretation.
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2.3 DIGITAL CAPTURE

The Offshore Yorkshire Seabed Geology map products are presented at a spatial scale of 1:10 000. The geological linework was captured both via manual digitisation, as well as through semi-automated processes to consistently produce linework from the bathymetric surface. The predicted linework was employed (where suitable) to improve mapping accuracy and efficiency, as well as reduce user bias. For the Offshore Yorkshire mapping, predicted linework was primarily used for mapping ridges and ridge crestlines (e.g. sediment wave crestline), as well as using the terrain attributes to guide manual interpretation of larger features to ensure consistency across the mapping area.

The predicted linework was prepared as follows: 1) create terrain attributes that calculate relative bathymetry highs and lows at multiple spatial resolutions, 2) merge derivatives to preserve either maximum (i.e., relative bathymetric high) or minimum value which has the desired effect of extracting the most pronounced morphological forms at seabed, frequently corresponding to discrete geomorphic features 3) unsupervised clustering to segregate groups of shared morphological properties. Where required, linework was extracted from the terrain derivatives (e.g., 'polygon to centreline' to capture ridge crests). While the linework was produced using quantitative methods, all features are classified according to the expert interpretation of the mapping geologist.

Where linework was produced using manual interpretation, features were delineated while viewing the data at scales of 1:5 000 to 1:8 000, for use at the intended presentation scale of 1:10 000. The interpretation was undertaken, and the resulting map is provided using the projected coordinate system EPSG:32631 (WGS 84 / UTM Zone 31N).

2.3.1 Substrate Geology

The Substrate Geology interpretation and digital capture were completed in an ArcGIS™ environment supported by the use of the BGS·SIGMA Desktop application. For the Substrate Geology layer, all map areas covered by either a Bedrock or Superficial unit.

The distribution of bedrock and superficial deposits were mapped as independent layers comprising polygons with geological attribution to describe their stratigraphical age (based on the BGS Lexicon of Named Rock Units), and their lithological composition (as defined in the BGS Rock Classification Scheme) (Figure 5).

One metre principle: For Substrate Geology mapping, the essential aim is to map the dominant geological unit present within the top one metre of the seabed. This approach is taken to avoid mapping the thin veneer of seabed sediment which is akin to the soil layer onshore. The one metre principle of course involves element of interpretation, but importantly also relies on observations in MBES data to guide interpretation/linework.

2.3.1.1 Bedrock Geology

Bedrock is mapped where the geologist can observe characteristic morphologies and features within the bathymetry data, such as bedrock bedding, folding, and fractures. Classification of bedrock units is informed by further supporting data and information which may include boreholes, previous offshore mapping, and adjacent onshore mapping and data.

Bedrock classification is provided to the highest detail possible according to available data and information. In the Offshore Yorkshire map area, bedrock units are mapped to both Group and Formation level depending on local circumstances.

2.3.1.2 Superficial Geology

Superficial deposits include all unlithified deposits, such as Quaternary (unconsolidated or consolidated), modern marine or Holocene marine sediment, mass movement, and bedrock rubble/talus (Stoker et al., 2011). Interpretation of superficial deposits is largely based upon sediment core data, observable changes in seabed texture (bathymetry), seismic and backscatter data where appropriate, as well as previous geological mapping (BGS, commercial, and academic). The Seabed Geomorphology layers may also be used to guide, or even delimit superficial boundaries (e.g., 'area of sediment waves' = province of marine sediment (e.g. MDU-S)). We honour existing boundaries from previous BGS 1:250k mapping where we don't have sufficient justification (e.g., new data and/or information that supersedes previous interpretations) to modify these boundaries. This may be applied in circumstances where suspected/inferred superficial boundaries have no seabed expression.

For Holocene – modern marine sediments, a simple 6 class system has been adopted with undefined proportions of Gravel, Sand and Mud (Table 1). While bathymetry, backscatter and sediment samples sometimes invite more detailed linework and specific classification (e.g. Folk classes), low density of sediment samples and variable backscatter data quality preclude this approach being applied consistently across this broad mapping area, that incorporates multiple datasets from variable sources.

- Using the Lex code: MDU (Marine Deposits Unconsolidated)
    - E.g., a marine sandy gravel would be mapped 'MDU-XSV', where the 'X' stands for undefined proportions;

V	Gravel
XSV	Sand and Gravel
S	Sand
XSM	Sand and Mud
M	Mud
XVSM	Gravel, Sand and Mud

Table 1. Simplified classification scheme for Marine Deposits Unconsolidated (MDU).

2.3.2 Structural Geology

This layer delineates the principle structural features such as faults, folds, or fractures observed at rockhead within the MBES bathymetry data (Figure 5). Structural lineaments are captured as polylines where observed in the MBES bathymetry data. They are most frequently observed where bedrock is mapped within the Substrate Geology layer, however they are also mapped where superficial deposits are mapped over the bedrock surface. In this later case, independent evidence (e.g., sediment cores) suggests that superficial deposits are at least one metre in thickness, but that the structural lineaments have sufficiently significant morphology as to be apparent through the superficial deposits.

2.3.3 Seabed Geomorphology

Seabed Geomorphology mapping generally follows the 'two-part' mapping approach developed by BGS together with other international marine mapping groups (Geological Survey of Norway, Geological Survey Ireland, Geoscience Australia). A list of 'Geomorphology' features is given within the initial Report (Dove et al., 2016), and updated 'Morphology' terms and glossary definitions are given in Dove et al. (2020).

This approach involves an independent assessment of 'Morphology' and 'Geomorphology', in which the Morphology defines the fundamental physical shape of feature (e.g., 'Bathymetric High > Mound > Streamlined Mound'), and the Geomorphology describes the interpreted origin, or process association of features (e.g., 'Glacial > Subglacial Landform > Streamlined landform > Drumlin. Morphology features are characterised only by the feature's form, i.e., size, shape, configuration, texture, whereas the Geomorphology features are defined by both their form and the environmental and interpreted geomorphological process(es) that created that morphology.

Only seabed features that have discernible morphological expression are mapped, i.e., not features (Figure 6). All features mapped have a Morphology class assigned, whereas the Geomorphology class is only attributed where the mapper feels confident in their interpretation. The attribute fields provided with the digital map are described further in section 4.

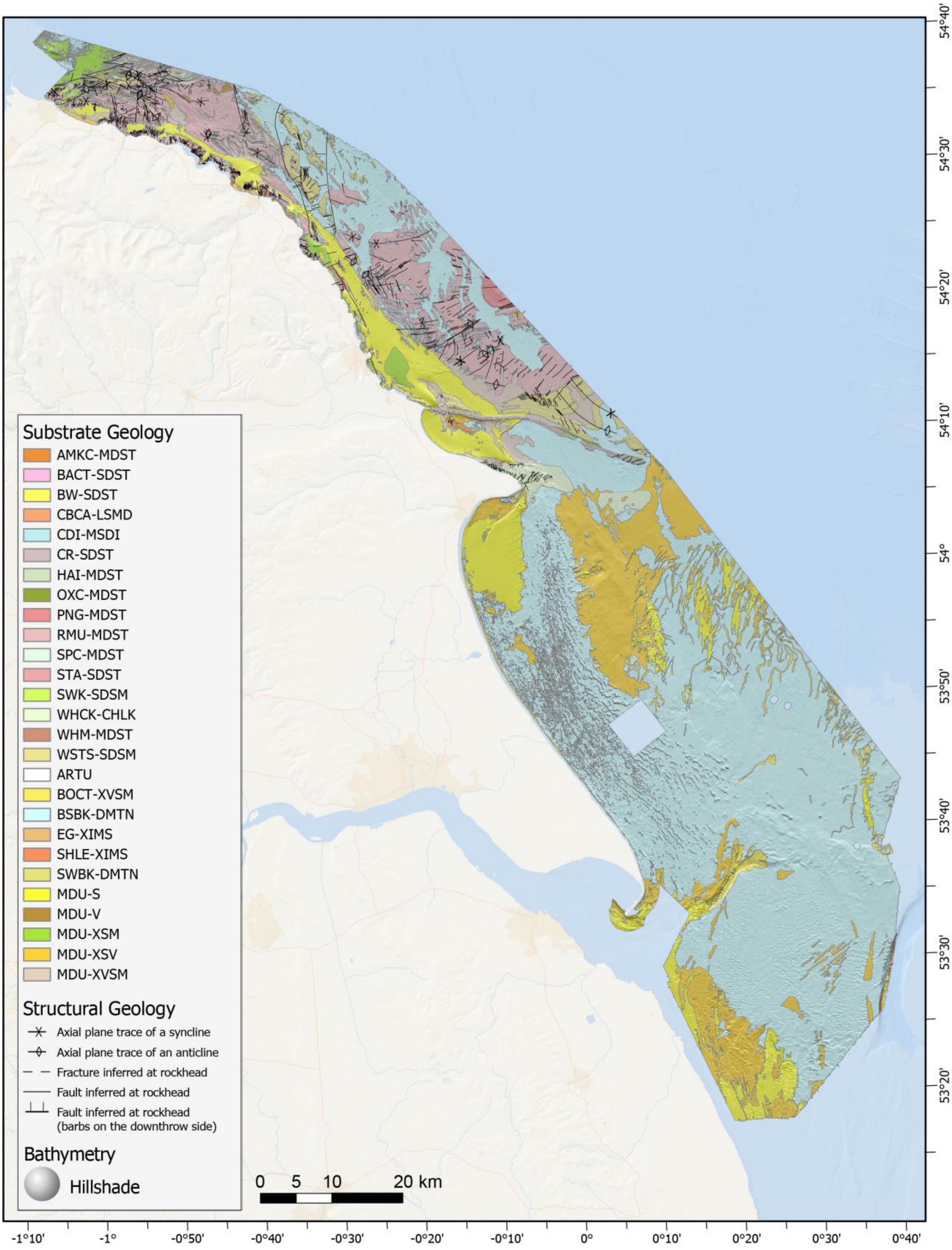

Figure 5 –BGS Seabed Geology 10k: Offshore Yorkshire digital map showing *Substrate Geology* and *Stuctural Geology* layers. Mapping is draped over the hillshade derived from bathymetric data acquired by the MCA © Crown Copyright 2022.

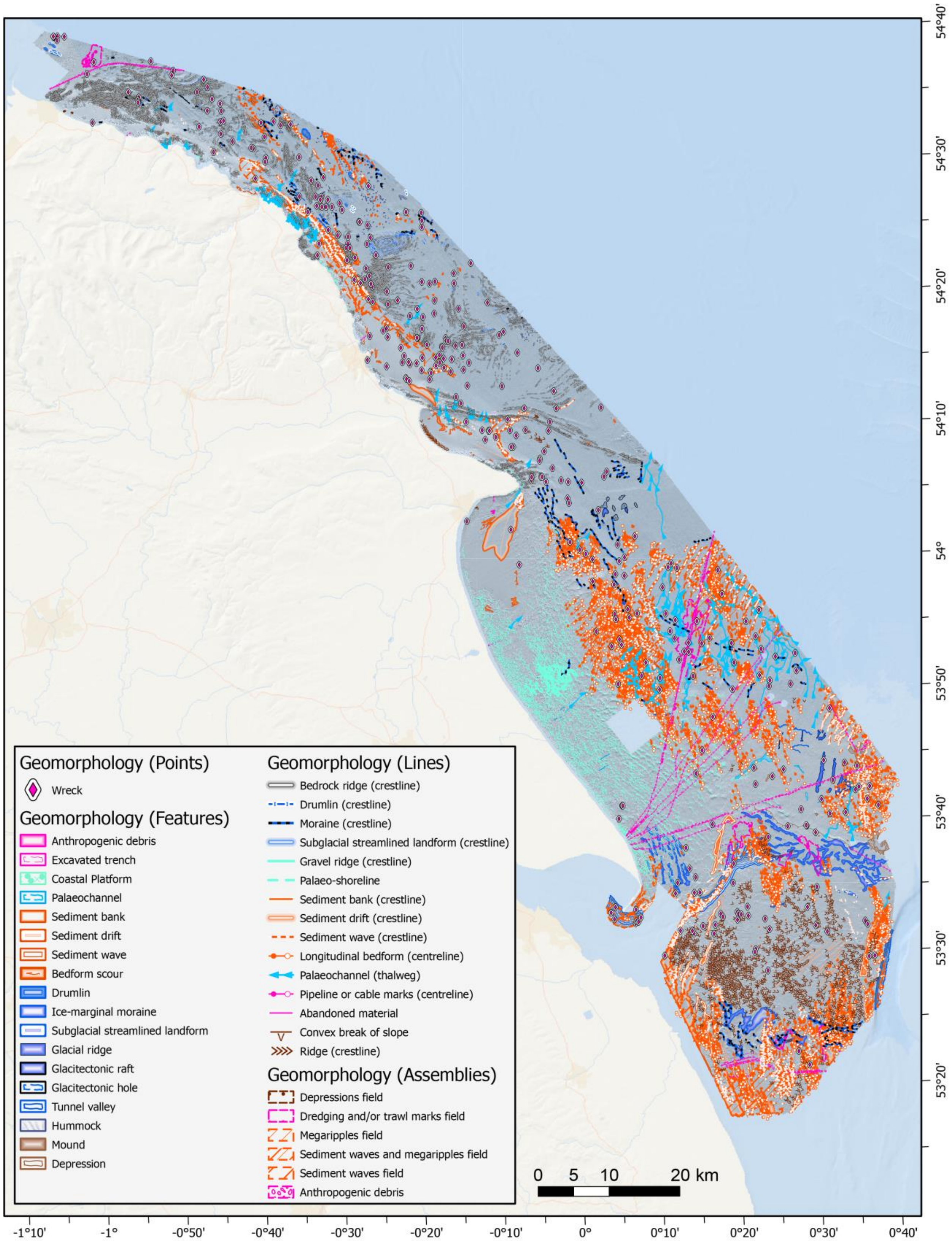

Figure 6 - BGS Seabed Geology 10k: Offshore Yorkshire digital map showing Seabed Geomorphology layer. Mapping is draped over the hillshade derived from bathymetric data acquired by the MCA © Crown Copyright 2022.

2.4 DATASET PROCESSING

During the geological mapping, interpretations were captured in several independent layers within a BGS·SIGMA database. To create the final compilation, the linework of various of BGS SIGMA layers were merged into a single layer. This compilation of linear and polygon features is shown in 7 and example map outputs can be seen in Figures 8-12.

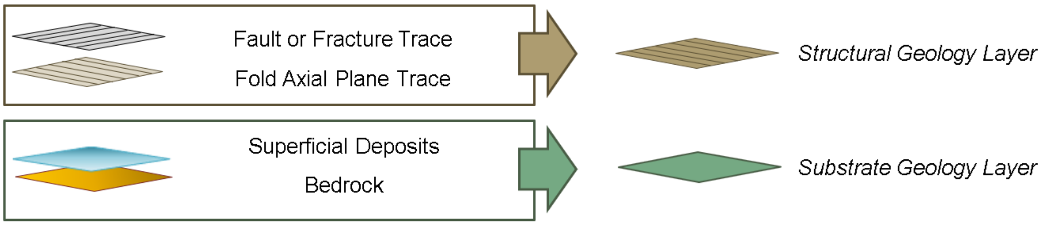

Figure 7 – Schematic representation of the transition from the layers used during the geological mapping and the final layer that comprises BGS Seabed Geology 10k: Yorkshire.

3 Seabed Geology - Summary

This section provides a summary of the scientific findings resulting from geological mapping presented in the BGS Seabed Geology 10k: Offshore Yorkshire map products. The section describes key and characteristic elements mapped, however does not provide a systematic description of all mapped deposits and features, nor an exhaustive discussion of the area's geological and palaeoenvironmental history. Relevant references are provided within.

The map area is within the western sector of the relatively shallow epicontinental North Sea basin (Cameron et al., 1992; Tappin et al., 2011). The map area stretches offshore along the Yorkshire and northern Lincolnshire coastline, extending up to approximately 35 km from the coast. The seabed generally deepens away from the coast towards the east and northeast, reaching a maximum depth of approximately 90 metres within the Inner Silver Pit (Figure 1). The deeps of the Inner Silver Pit and Sand Hole are isolated features however (i.e., subglacial tunnel valleys), and seabed depths more commonly range between 10 m and 55 m across the map area. The far south (i.e., outer Humber) is particularly shallow, with depths predominantly between 5 m and 30 m depth.

The seabed within this large area exhibits a highly variable geological character, with geological units and features preserved from the Carboniferous (bedrock), the Late Pleistocene (e.g., glacial deposits), and into the Holocene, which encompasses modern active processes (e.g., unconsolidated marine sediments, active sediment dynamics). The map area is bordered to the west by bedrock dominated coasts in the northern (e.g., North Yorkshire Moors) and central parts (e.g., Flamborough Head) of the map area (Kent et al., 1980). The southern sector is bordered by the sediment dominated Holderness and northern Lincolnshire coasts. The geological and geomorphic character of the seabed generally follows this trend, i.e., bedrock dominating the seabed character in the north of the map area, with sedimentary deposits and features more prevalent in the south (Figures 5 & 6).

The below sub-sections provide general geological context and summary descriptions of the key elements observed in the Offshore Yorkshire Seabed Geology mapping. A complete listing of mapped units and features may be found in section 4.

3.1 BEDROCK GEOLOGY

Bedrock strata crop-out at seabed across much of the northern and central parts of the map area, although in places bedrock is covered by a thin and discontinuous veneer of superficial deposits and potentially mobile marine sediments. The geometry of bedrock units across the map area is strongly influenced by the longer-term structural evolution of the wider Southern North Sea Basin.

3.1.1 Geological Structure

The map area is situated within the western margins of the southern North Sea Basin, the modern form of the ancient Southern Permian Basin. Formation of the Southern Permian Basin was initiated during the Early Permian due to post-orogenic (Variscan) collapse and subsequent rifting. Since its inception almost 300 million years ago, the basin has undergone multiple phases of rifting, thermal subsidence and localised inversion that have progressively shaped the basin (Grant et al., 2021).

The map area straddles two contrasting structural zones within the basin – the Cleveland Basin in the north and the East Midlands Shelf to the south (BGS, 1996). The East Midlands Shelf, part of the East Midlands Platform, has formed an area of relatively stable crust since the Carboniferous. The northern part of the shelf forms a large 20 km wide rigid block, known as the Market Weighton High, which is believed to be underlain at depth by two large granite batholiths which have given the crust additional rigidity and buoyancy (Bott et al., 1978; Wright, 2022). The Market Weighton High acted as a hinge between the East Midlands Shelf and the Cleveland Basin during the Mesozoic and is associated with the major Mesozoic-age extensional Vale of Pickering - Flamborough Head Fault Zone (Starmer, 1995, 2013; Wright, 2022). Offshore these connect with the northwest-southeast trending Dowsing Fault Zone (Starmer, 1995) located east of the mapping area presented here. The Market Weighton High has exerted a strong influence on sedimentation patterns and regional paleogeography during the Mesozoic causing the thinning of younger strata across the block and the development of a prominent overstep (north- and southwards) of successively older strata by the Chalk Group (Jeans, 1973; Mitchell, 1996).

Relict basinal areas situated to the north (Cleveland Basin) and east (Sole Pit Basin, also known as the Sole Pit Trough) of the East Midlands Shelf were at times major depositional centres during the Mesozoic (e.g., Pharaoh et al., 2010). Whilst the Sole Pit Basin is situated to the east of the map area, the Cleveland Basin occupies much of the northern sector of the mapping area passing onshore to the west. Bounded to the northeast by the Mid-North Sea High, the west by the Pennine High and to the south by the Flamborough and Vale of Pickering fault zones, the Cleveland Basin formed during the Carboniferous and was active during the Permo-Triassic and throughout much of the Jurassic (Powell, 2010; Emery, 2016). Faulting does not generally affect Mesozoic sediments within the Cleveland Basin. However, a narrow (c.5 km) fault zone – the Peak and Hunmanby fault zone, does dissect the offshore area of the Cleveland Basin and the Flamborough Head Fault Zone (Milsom and Rawson, 1986). During the Jurassic, the Cleveland Basin was part of a system of shallow seas and small extensional basins and was connected to the North Sea Basin by the Sole Pit Basin. Movement along several extensional and strike-slip faults acted to deform the basin controlling sedimentation (Powell, 2010).

Multiple phases of uplift and basin inversion, attributed to Alpine crustal compression, affected the Cleveland Basin (and the Sole Pit Basin) during the latest Cretaceous and Paleogene (Corfield et al., 1996). The amount of crustal exhumation of the Cleveland Basin has been estimated to be greater than 2 km resulting in the widespread erosion of any pre-existing cover rocks (Hillis et al., 2008). Alpine-related basin inversion led to the development of a series of structural domes (anticlines) that form a broadly west-east trending arch extending westwards through the North Yorkshire Moors, Whitby and into the area offshore from Scarborough. Here the Scarborough Dome is a prominent seabed feature. The Scarborough Dome is a large anticline which now forms an outlier composed of older Lias Group sediments surrounded by younger Jurassic and Cretaceous strata (outer). Much of the earlier phases of Alpine-related tectonism that affected the map area and broader region are believed to have been variably influenced by deeply-buried salt (Stewart and Coward, 1995; Brennan and Adam, 2022).

3.1.2 Stratigraphy

Bedrock crops-out across much of the seabed within the map area (Figures 5, 8, 9). The bedrock has been mapped and classified based upon seabed texture (Stewart and Coward, 1995), by correlation with onshore sequences and cores (where available). The paucity of core material does limit the level to which the stratigraphy can be interpreted, and the general approach has been to classify to the highest stratigraphic resolution possible. This invariably means that the stratigraphic classification is lower resolution than neighbouring onshore areas where access to exposure enables more detailed stratigraphic classification. A full list of mapped bedrock strata is detailed in section 4. A brief description of the major geological units is outlined below.

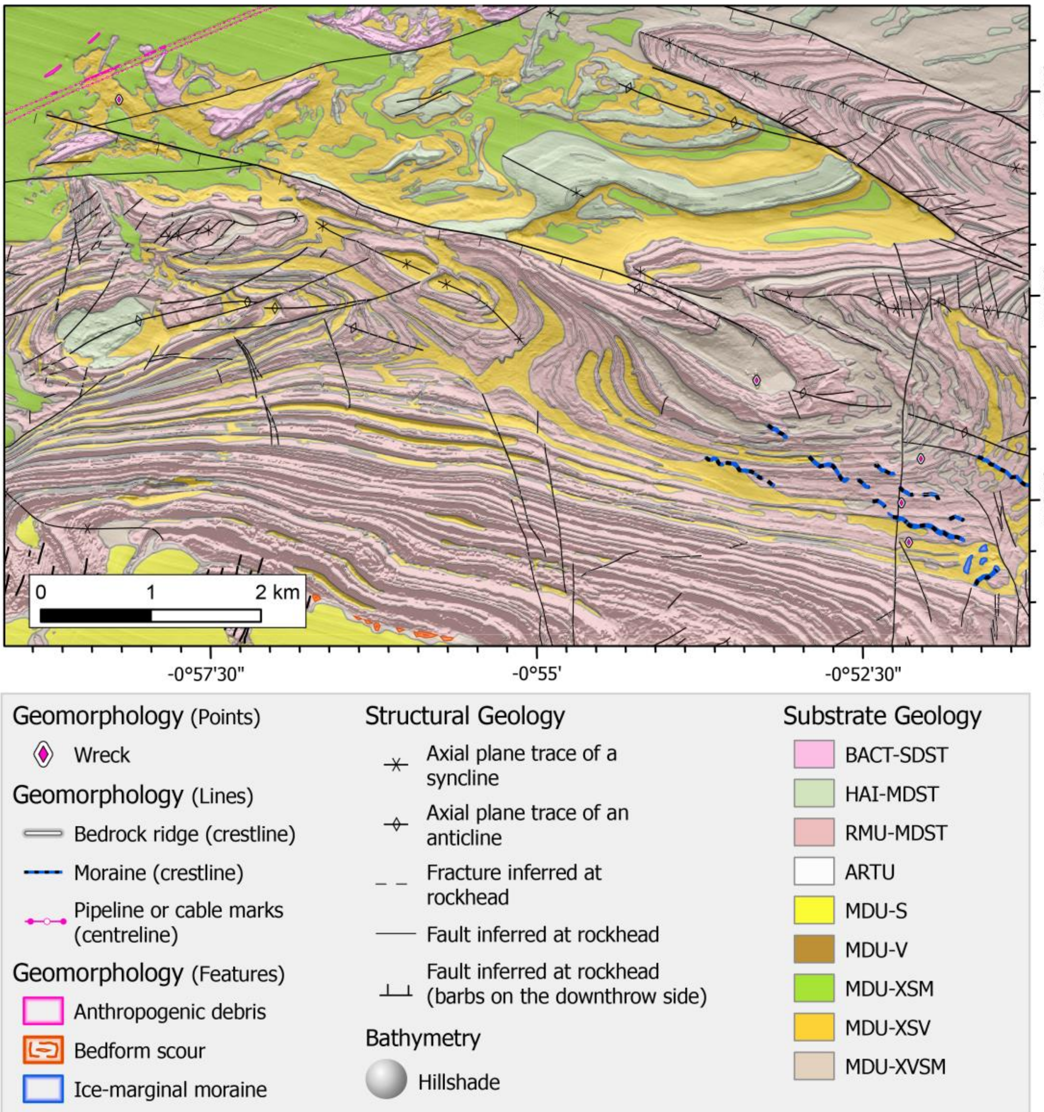

Figure 8 - Extract of the BGS Seabed Geology 10k: Offshore Yorkshire digital map (far north of map area) showing three layers of the dataset (*Substrate Geology*, Seabed *Geomorphology* and *Structural Geology*) draped over the hillshade derived from bathymetric data acquired by the MCA © Crown Copyright 2022.

Note that the legend only shows the features visible in the map extract.

3.1.2.1 TRIASSIC STRATA

Triassic rocks crop-out at seabed within the northern part of the map area within the offshore extension of the Cleveland Basin (Figure 8).

The **Bacton Group (BACT)** is of Early to Mid-Triassic age and comprises predominantly fine-grained sandstones with occasional medium-coarse sandstones and pebble beds. These sediments were eroded from adjacent structural highs – namely the Pennine and Anglo-Brabant massifs (Cameron et al., 1992) – and laid down in predominantly fluvial environments. The unit crops-out at seabed in the northern sector of the map area but occurs at depth elsewhere possibly attaining thicknesses in the order of 200 m offshore from Flamborough and Bridlington. The Bacton Group thickens into the Sole Pit Trough situated to the east of the map area, which was a major depositional centre at the time. The onshore equivalent to the Bacton Group is the Sherwood Sandstone Group.

The **Haisborough Group (HAI)**, of Mid- to Late Triassic age, crops-out at seabed in the northern part of the map area, offshore from Middleborough. It is composed of reddish brown and grey mudstones, often dolomitic with thick beds of halite and anhydrite. The unit is continuous with the onshore Mercia Mudstone Group and thickens markedly at depth towards the east and south.

The **Lias Group** of Late Triassic to Early Jurassic age crops-out extensively at seabed across the northern part of the map area, offshore between Middlesborough and Filey, where it forms the core of the Scarborough Dome (see Jurassic strata for further discussion). The unit is composed of fossiliferous mudstones and argillaceous limestones and thickens southwards through the offshore extension of the Cleveland Basin, attaining thicknesses potentially of up to 200 metres. In the southern part of the map area, the Lias Group occurs at sub-crop, thinning progressively against the northern flanks of the Market Weighton Block (Cameron et al., 1992).

Mapped units within the Lias Group include: **Blea Wyke Sandstone Formation (BW)**; **Cleveland Ironstone Formation (CDI)**; **Redcar Mudstone Formation (RMU)**; **Staithes Sandstone Formation (STA)**; **Whitby Mudstone Formation (WHM)**.

3.1.2.2 JURASSIC STRATA

Jurassic-age rocks possess a relatively limited spatial extent within the map area (Figure 7). They were deposited within the eastern offshore part of the Cleveland Basin (north) thinning southwards against the Market Weighton High forming part a major anticline called the Scarborough Dome (Cameron et al., 1992). Major stratigraphic sub-divisions of the Jurassic strata have been mapped based on their relative relief on the seabed and by broad correlation with their onshore counterparts (where possible). Mapped sub-divisions include, from north to south (oldest to youngest): the West Sole Group, Oxford Clay Formation, Corallian Group, Ravenscar Group and the Ampthill Clay and Kimmeridge Clay formations (undivided). Locally, these rocks may be covered by a thin veneer of till or mobile marine sediment.

The **West Sole Group (WSTS)** has a limited seabed outcrop in the offshore area between Ravenscar and Filey. It forms a narrow arcuate-shaped outcrop composed of interbedded mudstones, sandstones and bioclastic / oolitic limestones that were laid-down within marine, brackish and fluvio-deltaic environments. It occurs on the northern margins of the Cleveland Basin, extending offshore towards the east-southeast and constrained to the south by the Market Weighton structural high (Cameron et al., 1992). The West Sole Group is broadly correlated with the Ravenscar Group (RAG) which crops-out onshore. However, detailed stratigraphic correlations are not possible due to the facies complexity and lack of strong biostratigraphic control.

The West Sole Group is overlain by the **Oxford Clay Formation (OXC)** (Humber Group) within the map area. Like other Jurassic units, the unit exhibits a narrow and arcuate-shaped seabed outcrop and forms a lower area of seabed relief. The Oxford Clay Formation is a marine deposit composed of grey siltstones and mudstones. The overlying **Corallian Group (CR)** (Oxfordian) are typically composed of harder limestones and sandstones that were deposited within a higher energy shallow marine setting. By contrast to mudstone-dominated Jurassic units, the Corallian Group form a relatively upstanding and narrow zone (ridge) of seabed relief. The Corallian Group thins southwards across the Market Weighton High and intercalates with and is replaced by deeper-water mudstones belonging to the Ancholme Group. These include the **Ampthill Clay and Kimmeridge Clay formations** (undifferentiated) (**AMKC**) which are the youngest Jurassic-age units mapped. They are composed of dark brown-grey to black shelly and fissile mudstones and typically form lower (relative) areas of seabed relief.

3.1.2.3 CRETACEOUS STRATA

Cretaceous rocks comprise the uppermost bedrock geology throughout much of the central and southern sectors of the map area (Figure 9). Further to the south, they are increasingly covered by a variably thick veneer of superficial sediments and mobile marine sediments. Cretaceous rocks mapped within the map area include the **Speeton Clay Formation (SPC)** (Lower Cretaceous; Cromer Knoll Group) and the **White Chalk Subgroup (WHCK)** (Late Cretaceous) that forms part of the Northern Province of chalks (Mortimore and James, 2015). The Speeton Clay Formation has a limited and thin outcrop extending offshore from Speeton, North Yorkshire. Composed of fossiliferous marine clays (Lott et al., 1986), the unit forms an area of relatively low seabed relief.

Although not proven, it is anticipated that much of the Chalk bedrock (outcropping at seabed) throughout this offshore area belongs to the Flamborough Chalk Formation, a thick sequence of hard, white, well-bedded, flint-free chalks that contain occasional marl seams. This chalk unit crops-out extensively at seabed around Flamborough Head, where it forms both active and submerged wavecut platforms. The later were likely formed following the early Holocene marine transgression when sea-levels were lower than today. Younger low-density chalk units not seen onshore have also been recognised offshore from Holderness – the Westermost Rough Member (Mortimore and James, 2015), but this could not be verified by the present study.

Offshore from Flamborough Head, the chalk forms a low ridge that extends towards the east-southeast (Figure 9). The overriding of this ridge by ice during the Late Devensian resulted in channel incision as well as localised detachment and transportation down-ice (south) of large blocks of chalk called glacitectonic rafts. Several source holes and corresponding rafts can be clearly imaged within the bathymetry data.

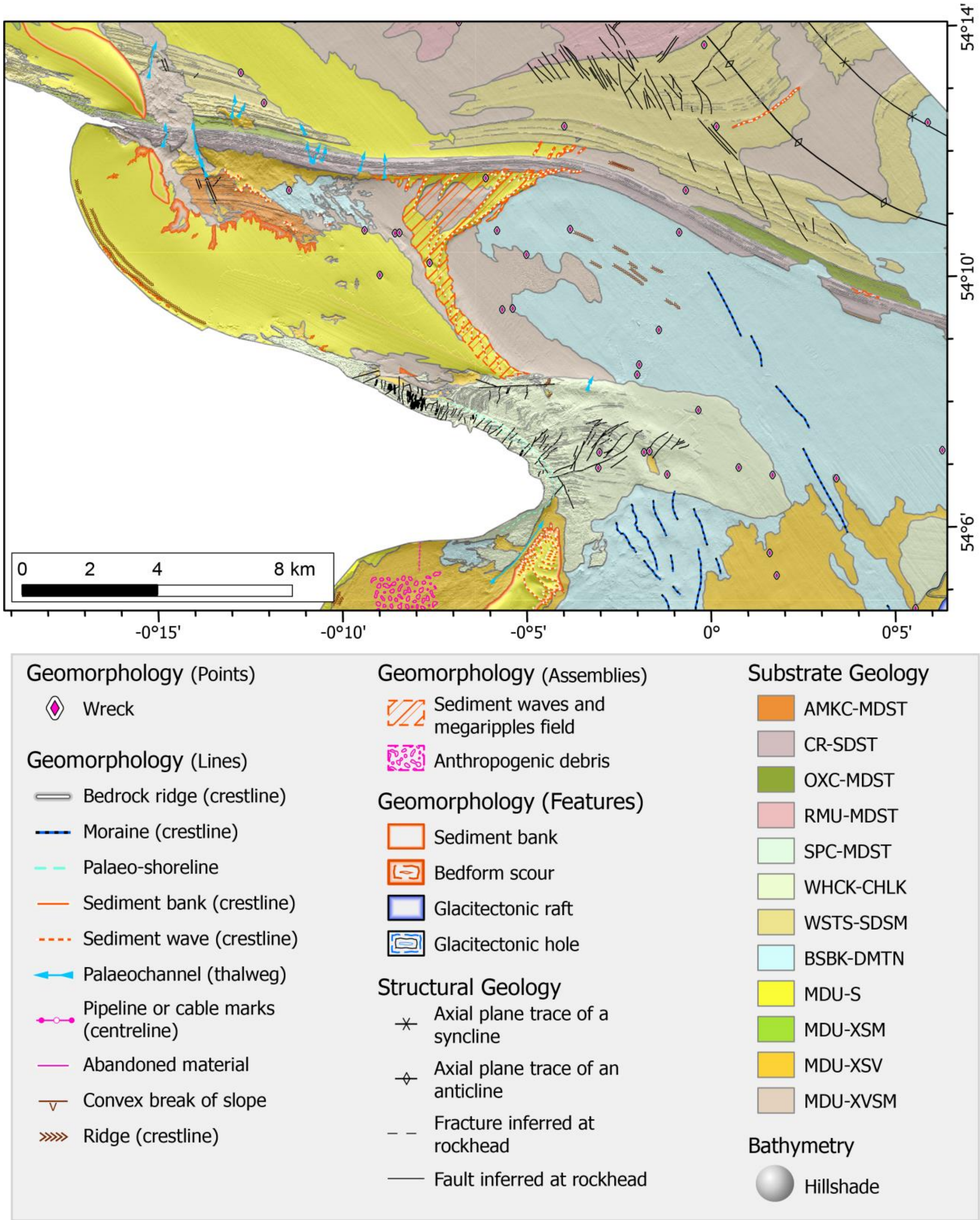

Figure 9- Extract of the BGS Seabed Geology 10k: Offshore Yorkshire digital map (off Flamborough Head) showing three layers of the dataset (*Substrate Geology*, Seabed *Geomorphology* and *Structural Geology*) draped over the hillshade derived from bathymetric data acquired by the MCA © Crown Copyright 2022.

Note that the legend only shows the features visible in the map extract.

3.1.3 Seabed Geomorphology Features - Bedrock

The seabed is often rugose in bedrock dominated areas, with the rock often fractured and faulted as observed in the bathymetry data (Figure 8).

Bedrock Ridges (e.g., 'homoclinal ridges') are common features where bedrock is mapped at seabed, associated with upstanding relatively resistant strata. These ridges are often asymmetric in cross section (i.e., associated dip and scarp slopes) with variable plan-form orientation (e.g., linear, sinuous, circular, disjointed), and together form complex stratal patterns indicative of the structural evolution of the region (e.g., significant folding and faulting). The Bedrock ridges are prominent seabed features with vertical relief commonly 1-2 metres, though some are less distinct, which may result from different rock properties and/or variable erosional (e.g., subglacial) histories. While primarily reflecting bedding, some of the mapped bedrock ridges related to upstanding ridges associated with fault development.

The Bedrock ridges are mapped as ridge crestlines, and were mapped using semi-automated processes, manually selecting from linework that was produced based on calculated morphometric layers of relative bathymetric highs.

In several locations, *Palaeoshorelines* (Coastal features) are observed, relating to subtle and discontinuous, though apparent marine terraces); *Palaeochannels (*Fluvial features*)* are also observed eroded into the bedrock, and recorded at seabed.

3.2 QUATERNARY GLACIAL DEPOSITS, LATE PLEISTOCENE/ EARLY HOLOCENE TERRESTRIAL TO MARINE TRANSITION, AND ACTIVE SEDIMENT DYNAMICS

This sector of the southern North Sea is generally accepted to have hosted at least two major periods of glaciation during the Middle and Late Pleistocene, the Anglian (Marine Isotope Stage (MIS) 12; ~480 kya), and the Devensian (MIS 5d-2; ~115-11.7 kya) (Cameron et al., 1992; Graham et al., 2011; Lee et al., 2012; Cohen et al., 2014; Clark et al., 2022). The Wolstonian Glaciation (MIS10-6; ~375-130 kya) has also been inferred to have extended over this region (e.g., Evans et al., 2019), however, to date no offshore sediments within this region have been attributed to this glaciation. Both the Anglian and Devensian glaciations are associated with extensive tunnel valley incision (e.g., Van der Vegt et al., 2012), however within this mapping area, Anglian tunnel valleys (and associated sediment units) are almost entirely buried beneath younger sediments. As such, both the glacial deposits (i.e., **Bolders Bank Formation**) and geomorphological features observed at seabed within the map area are attributed to the Devensian glaciation, and primarily the Late Devensian (Figure 5).

It is important to note that global sea levels were up to ~120 m lower during the Late Devensian glaciation relative to modern times due to water being locked-up as ice volume (Spratt and Lisiecki, 2016). Due to the shallow bathymetry of the southern North Sea, even small changes in global sea-level significantly impacted palaeogeography across the basin. The region was therefore emergent throughout the Late Devensian and part of the early Holocene until sea-levels rose and the continental shelf was submerged.

Following deglaciation from the region by 17,000 years ago (Evans et al., 2021), terrestrial conditions prevailed until approximately 8,000 years ago with fluvial and coastal conditions occurring in the present offshore area. Fluvial, lagoonal, and estuarine deposits are preserved from this time interval, including peat and channel-fill deposits, e.g., **Botney Cut Formation** offshore, and are of significant archaeological interest (e.g., Gaffney et al., 2007; Waller and Kirby, 2021).

From the initial Holocene marine transgression around 11,000 to 7,000 years ago (Sturt et al., 2013; Brown et al., 2018) through to modern times, this shallow subtidal region of the southern North Sea has been exposed to a high-energy wave and tidal conditions (e.g., Hashemi et al., 2015; Huthnance et al., 2016). This complex hydrodynamic environment, together with variable sources of sediment supply (e.g., river discharge, coastal erosion, and winnowing of underlying glacial deposits), results in the distribution of relatively coarse unconsolidated seabed sediments, as well as a complex configuration of current-induced (and potentially mobile) sediment bedforms, such as sediment banks, sediment waves, and longitudinal forms (Cameron et al., 1992; Stanev et al., 2009; Tappin et al., 2011; Pye and Blott, 2015).

3.2.1 Substrate Geology - Superficial deposits

Swarte Bank Formation (SWBK) - There is limited exposure of the SWBK (Anglian glacial unit) on the flanks of the Inner Silver Pit (described within Geomorphology section below). Elsewhere within the map area, the SWBK is expected to sub-crop at depth beneath younger Quaternary deposits (BGS, 1991).

Deposits from the SWBK infill large subglacial valleys incised during a major ice advance during Anglian times. These deposits comprise variable infill lithologies associated with a number of seismostratigraphic sub-units, ranging from stiff to hard sub-glacial tills, glacifluvial sand lenses, glaciolacustrine muds, and marine clay with foraminiferal assemblages (e.g., Cameron et al., 1992; Mellett et al., 2013).

Egmond Ground Formation (EG) and **Sand Hole Formation (SHLE)** – Similar to the SWBK described above, the EG and SHLE are interpreted to have outcrops limited to within the Inner Silver Pit (BGS, 1991). Both EG and SHLE units are thought to be interglacial deposits of predominantly marine origin (e.g., Scourse et al., 1998). The EG typically comprises well-sorted, fine-medium grained dense silty marine sand with common shell fragments and organic sand, silt, and clay laminae. The EG may also incorporate fine gravel or organic laminations/inclusions (Cameron et al., 1992; Mellett et al., 2013). The SHLE unit comprise later interglacial deposits composed of lower silty clays (cold climate taxa) and more temperate silty sands and clays (Scourse et al., 1998).

Bolders Bank Formation (BSBK) - The most extensive superficial unit within the map area is the BSBK. In this sector of the North Sea, the Late Devensian ice sheet functioned as an ice lobe termed the 'North Sea Lobe' that extended southwards across the map area and deposits associated with this lobe are ascribed to the BSBK till succession (BGS, 1991; Cameron et al., 1992; Davies et al., 2011; Roberts et al., 2019) (Figure 5). Dove et al. (2017) demonstrated that the BSBK is a composite unit composed of overlapping glacial till sheets/wedges that were deposited during successive advances of an oscillating ice margin (associated with the 'North Sea lobe'). This interpretation suggests that buried terminal moraines and associated glacitectonism (e.g., folding and faulting) within the BSBK are likely to be present, and also predicts thin sand/gravel layers separate the multiple till units (i.e., outwash deposited between sub-glacial episodes). The BSBK is the offshore equivalent of glacial tills that crop-out onshore within eastern Lincolnshire and Yorkshire (Catt, 2007; Boston et al., 2010; Sutherland et al., 2020).

Within the map area, BSBK is expected to typically be between 5-15 m in thickness. BSBK deposits are generally expected to be thicker to the south where submarginal processes concentrated deposition at/near ice margins compared to thin and discontinuous deposits expected in the north of the map area, where BSBK is mapped more sparsely overlying bedrock. The BSBK formation is a reddish-brown to grey coloured matrix-supported diamicton, that exhibits a sandy clay matrix texture and contains numerous bedrock clasts ranging from pebble to boulder size.

Botney Cut Formation (BOCT) – Deposits from the BOCT infill glacial and post-glacial channels within this sector of the North Sea (BGS, 1991; Cameron et al., 1992; Brown et al., 2018) (Figure 10). BOCT is known to incorporate several subunits indicating multiple phases of channel infill (e.g., Mellett et al., 2020). These sub-units may include (younger to older): unconsolidated marine sand-rich deposits, organic-rich laminated (silty sands & clays) fluvial/estuarine/lagoonal deposits (including peats), glacimarine and/or glacilacustrine mud-rich deposits, glacifluvial sand-rich deposits, and re-worked glacial tills. From regional seismic surveys and industry studies, the smaller (presumably fluvial) channels tend to comprise the younger estuarine/lagoonal deposits, whereas larger (presumably glacial) channels may also comprise older glacial sediments. The younger estuarine/lagoonal deposits may be attributable to the Elbow Formation (Stoker et al., 2011) as encountered elsewhere within the southern North Sea (Cotterill et al., 2017), however there are not sufficient data to consistently discriminate the BOCT from the Elbow Formation within the map area.

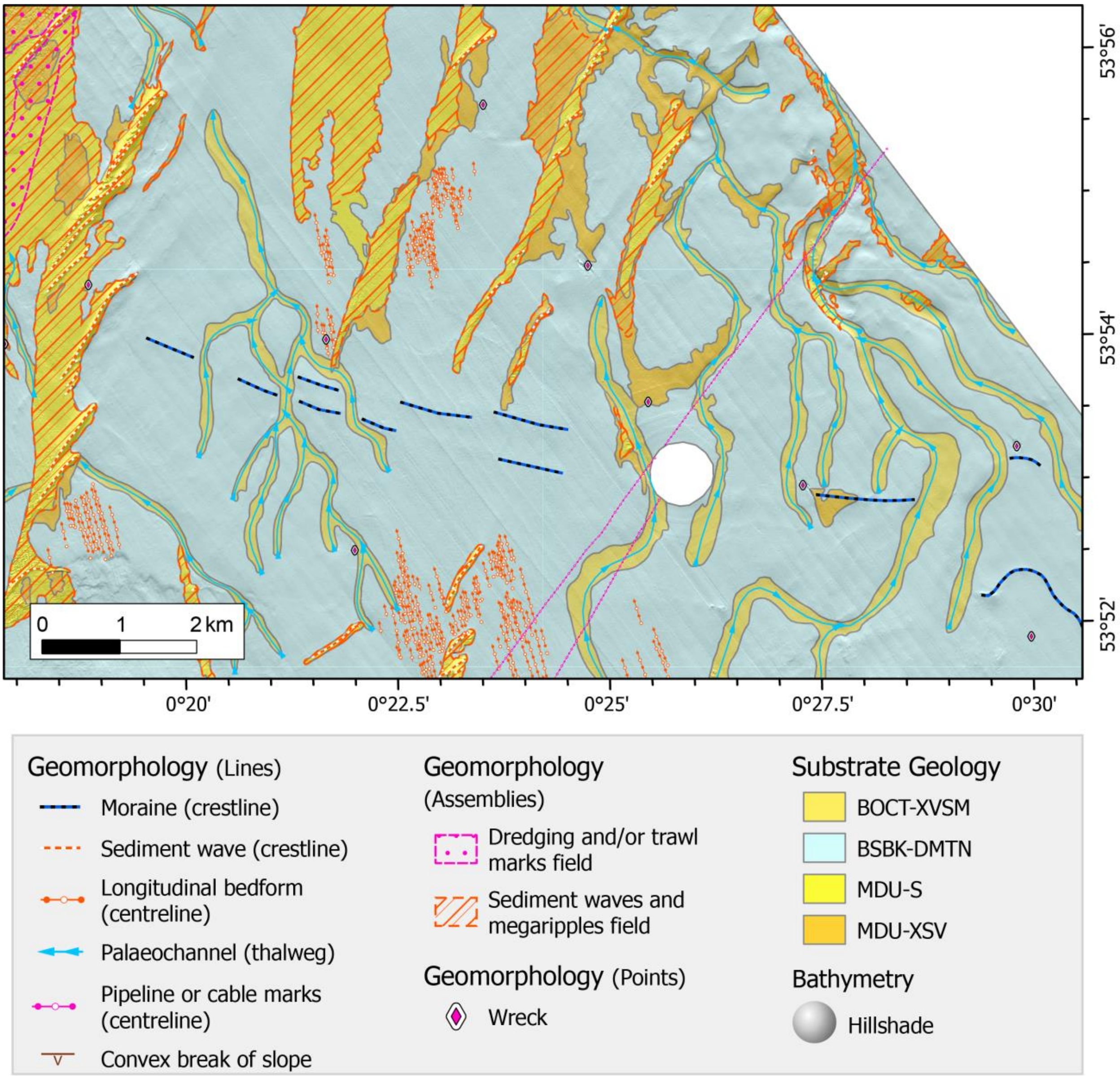

Figure 10 – Paleochannel network (BOCT infill) incised into glacial deposits (BSBK). Extract of the BGS Seabed Geology 10k: Offshore Yorkshire digital map showing three layers of the

dataset (*Substrate Geology* and *Seabed Geomorphology*) draped over the hillshade derived from bathymetric data acquired by the MCA © Crown Copyright 2022. *Note that the legend only shows the features visible in the map extract.*

The BOCT is mapped within the map area where palaeo-channels (i.e., relict fluvial, and potentially glaciofluvial channels) are apparent at seabed, as previous projects within the region have demonstrated these channels comprise a BOCT infill (e.g., Tappin et al., 2011).

One limitation of the Superficial Geology layer at present is the inability to identify boundaries between Quaternary superficial units (potentially below a veneer of seabed sediments) where there is no apparent seabed expression (e.g., texture, morphology). Existing cores indicate the dominant superficial units, but smaller features (e.g., buried channels) are potentially not captured. In this area, we expect BOCT deposits are significantly more common than currently mapped. Higher numbers and density of BOCT channels/deposits are known from previous research and industry developments in the region, but often exhibit no surface expression (e.g., Gardline, 2011; Fugro, 2012, Mellet et al., 2020). However, as sub-bottom data are not available across the region in sufficient density, an accurate and consistent representation of shallow buried BOCT channels across the entire map area cannot yet be undertaken.

Marine Deposits Unconsolidated (MDU)

Within the map area there are five separate classes of MDU deposits mapped (S, V, XSV, XSM, XSVM; Table 1; Figure 5). The map area is characterised by complex hydrodynamic conditions operating over tidal, storm, and seasonal cycles (Huthnance et al., 2016). Multiple variables affect the distribution, composition, and stability of marine sediments, including: regional physiography and finer-scale geomorphology, tidal current vectors and amplitudes, wave environment, sediment supply (e.g. River Humber, Holderness coastal erosion) and suspended particulate matter (SPM); and the erosion of underlying substrate (e.g. BSBK till) (Kenyon and Cooper, 2005; Stanev et al., 2009; Tappin et al., 2011; Pye and Blott, 2015).

The shallow water depths (and associated energetic hydrodynamic environment), particularly in the south, results in generally coarse MDU sediment fractions. In the north of the map area, MDU sediments are commonly observed within relative depressions atop the bedrock surface. There are significant accumulations of MDU north and south of Flamborough Head along the coast (Figure 9). Central and southern areas exhibit significant MDU accumulations associated with current-induced bedforms (e.g., *Sediment Waves* and *Megaripples*). In the far south along the Lincolnshire coast, thicker accumulations of MDU are associated with sediment delivery from the Humber and sediment flux in and out of the Wash (Kenyon and Cooper, 2005).

MDU sediments are mapped according to the following criteria (one or multiple): sediment cores suggest thickness >1 m of unconsolidated marine (e.g., 'shelly') sediment, area of current-induced bedform(s), seabed morphology (e.g., smooth seabed; infill of depressions) to extrapolate between core samples (or in the absence of cores); seismic data indicative of >1 m sediment thicknesses. Sediment composition is classified according to available sediment samples, backscatter data (variable quality), seabed geomorphology, and previous mapping results. Areas of current-induced bedforms are generally assigned MDU-S. The Gravel (Coastal) ridges are classified MDU-V (includes cobbles/gravel) according to direct observations from geophysical and seabed videography (Gardline, 2011; EMU, 2011).

3.2.2 Seabed Geomorphology Features

Geomorphic features are below organised according to the environment in which they (primarily) originated, i.e., Glacial, Fluvial, Coastal, Marine, and Anthropogenic. Further post-formational modification and/or superimposition of other features is common for many features (e.g., current-induced bedforms superimposed on glacial landforms).

3.2.2.1 Glacial Features

Glaciation has a significant capacity to modify the Earth's surface and glacial features are frequently well preserved (as morphological features) at seabed within formerly glaciated regions (e.g., Dowdeswell et al., 2016). All glacial geomorphic features within the map area are thought to be associated with the Late Devensian glaciation of the British and Irish Ice Sheet (BIIS).

Ice-marginal Moraines:

Ice-marginal moraines are positive-relief feature of variable morphology, but commonly an irregular ridge, formed by the deposition, extrusion, and/or deformation of sediment around the edge of a glacier. Ice-marginal moraines demarcate the margins of former ice masses (Benn and Evans, 2014). Due to the complex processes of moraine formation, they commonly comprise variable sediment composition, including coarse sediment fractions (up to boulders).

Moraines are mapped in a number of locations throughout the map area, e.g., Figure (10). In the south of the map area, they delineate arcuate margins. Here the moraines are relatively low-relief features, and significantly modified/eroded by later marine processes. These moraines are known to be associated with the broad, overlapping till wedges of the BSBK (Dove et al., 2017). In the central region (off Flamborough Head) many of the moraines are oriented approximately NNW-SSE (also delineating a broad arcuate margin), likely indicative of a significant though transient stillstand margin of the 'North Sea Lobe'. From this position, research suggests that the ice lobe retreated northwards from offshore northeast England and southeast Scotland, with multiple bedrock highs forming pinning points which, in conjunction with variation in relative water depth (e.g., as sea-level increased), resulted in episodic rates of retreat (Roberts et al., 2019; Evans et al., 2021). To the north the moraines are typically small, fragmentary features, potentially resulting from either later marine erosion or thinner and less active ice.

Tunnel Valleys:

Tunnel Valleys are large subglacial valleys typically with abrupt start and end points, steep sides and relatively flat floors. They are commonly U-shaped in cross-section, distinctively concave-up or undulating in longitudinal profile and lacking a constant down-valley increase in depth with uneven thalwegs, and shallower sills or thresholds. They are generally thought to form sub-glacially through erosion by over-pressurized meltwater, commonly at, or near the former ice-margin.

The Inner Silver Pit and Sand Hole are both interpreted as subglacial Tunnel Valleys related to a former still-stand position of the former Late Devensian 'North Sea Lobe' (Tappin et al., 2011; Dove et al., 2017) (Figure 1). Within this sector of the southern North Sea, the formation and position of Tunnel Valleys have a clear genetic relationship with former ice margins and associated till wedges and moraines (Dove et al., 2017). The Tunnel Valleys are incised perpendicularly to the lobate/arcuate ice margins, with the southern margins of the valleys coincident with the respective till wedge/moraines.

Drumlins:

Drumlins are a type of streamlined subglacial landform indicative of fast-flowing and persistent ice-sheet flow. They are manifest in the mapping area as comparatively smooth and elongated mounds or hills (commonly oval-shaped) with a core of bedrock and / or glacigenic sediment, oriented parallel to the former ice-flow direction. Typically, the steep blunter end faces the up-ice direction and the gentler sloping, pointed end faces the down-ice direction (Benn and Evans, 2014).

There are se*veral Drumlins mapped in the northern part of the map area, though they are not as common, prominent, or well preserved as within other regions of the UK Continental Shelf (BGS, 2022).*

Glacitectonic Raft (and Hole):

Glacitectonic Rafts are slabs of bedrock and/or unconsolidated bedrock that have been detached and transported down-ice by glacier ice. Areas of rafted bedrock occur offshore from Flamborough Head, and several detached blocks and corresponding holes (source) can be observed adjacent to a minor bedrock ridge. Within the Offshore Yorkshire mapping area, rafts appear to be only associated with areas of Chalk bedrock.

3.2.2.2 Fluvial features

Palaeochannel:

Palaeochannels are relict fluvial and/or coastal channels indicative of former subaerial or potentially intertidal drainage conduits. Palaeochannels may be apparent at seabed as channels and mapped as geomorphic features, or buried by sediment with no surface expression (not possible to map by geomorphology alone).

Several Palaeochannels are mapped as morphological channels within the Offshore Yorkshire map area indicative of former drainage networks, likely from the Late Pleistocene (post-glacial) and early Holocene (Figure 10). Many further buried Palaeochannels are expected (but not currently mapped) within the map area, however there is insufficient sub-surface data to map these in consistent detail.

3.2.2.3 Coastal features

Palaeoshoreline:

Palaeoshorelines are relict shorelines, indicated by preserved coastal landforms, e.g., escarpments associated with Shore platforms. Palaeoshorelines are observed and mapped as Break-in-slope morphological features in several locations within the Offshore Yorkshire map area, both in bedrock (e.g., offshore Flambourgh Head) and eroded into **Bolders Bank Fm.** subglacial till (Figure 9).

Gravel ridge

Numerous narrow, high-relief ridges have been observed and mapped in the southern sector of the map area, predominantly off the Holderness coast (Figure 11). These ridges may be linear to convolute/zigzag in plan-view, and are commonly part of longer ridge chains. The ridges, and ridge chains are commonly coast ~parallel (at least nearshore), and exhibit regular ridge-spacing suggestive of a cyclic formation process. Videography and samples from offshore developments indicates the ridges are comprised by gravel, cobbles, and boulders (classified on Superficial deposits map as ‘Gravel’, MDU-V) (Gardline, 2011; EMU, 2011). The ridges are typically asymmetric (steep side facing coast), which may result from either origin or post-formational processes. The coarse material forming the ridges (gravel-boulders) is expected to be drawn from the underlying **Bolders Bank Formation**. Repeat surveys (bathymetry) do not indicate any discernible ridge mobility/migration.

These ridges have here been classified as Gravel ridges, and are tentatively ascribed a Coastal origin. To date BGS scientists have not identified analogous features regionally or globally, and as such interpretations remain uncertain. Alternative hypotheses considered include Glacial (i.e., Ice-marginal moraine) and Marine (i.e., storm-induced ridges). An Ice-marginal moraine origin has merit with respect to ridge morphology (high-relief), composition, and orientation. However shallow seismic data show that the Gravel ridges sit atop post-glacial **Botney Cut Formation** channel infill, which would preclude a glacial origin. Also, such high-relief/rugose ridge morphology seems unlikely to have persisted through marine transgression in this shallow environment. The Marine storm-ridge hypothesis is also currently ruled out as no mobility is observed between repeat overlapping surveys.

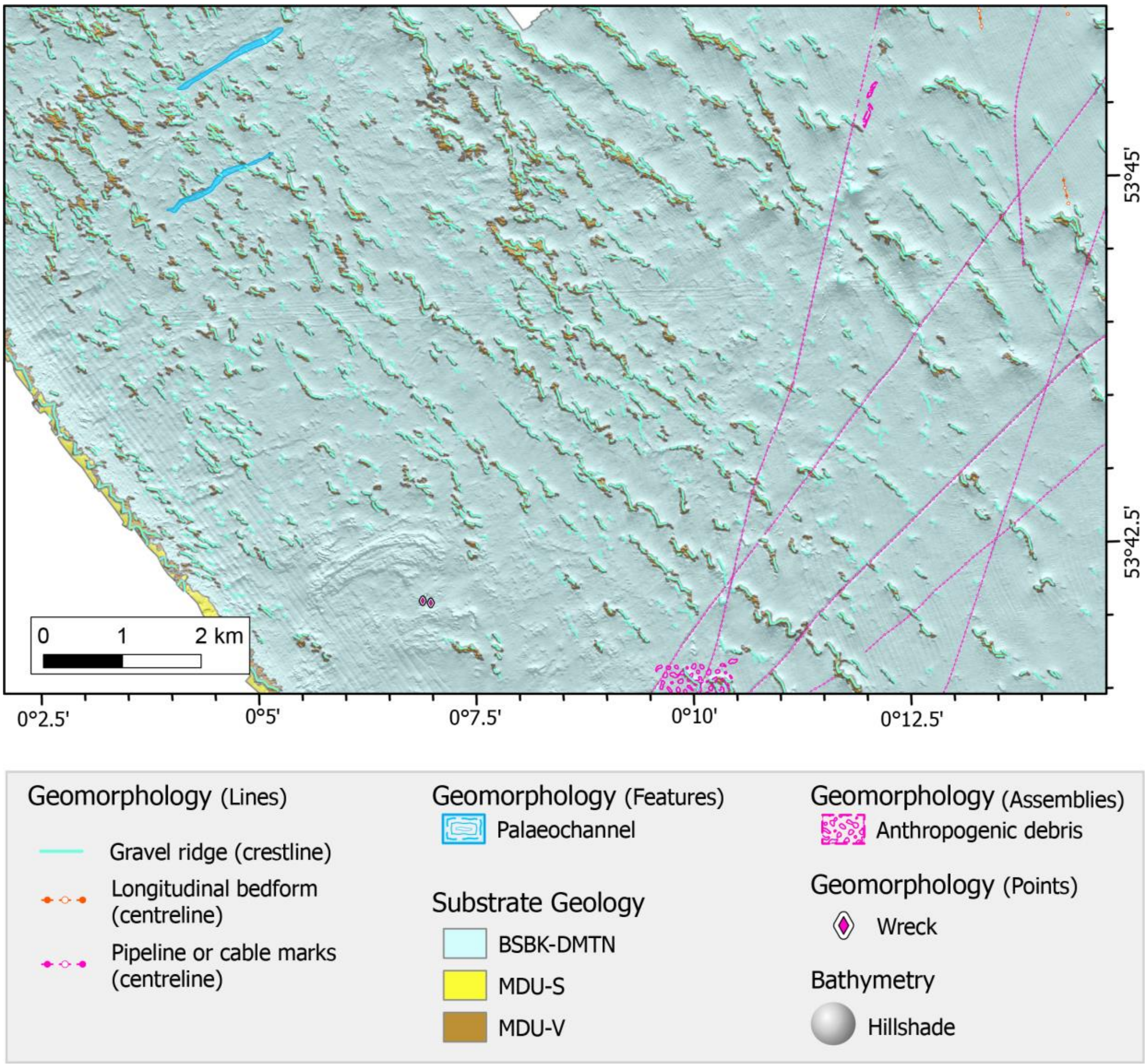

Figure 11 – Gravel ridges off Holderness coast. Extract of the BGS Seabed Geology 10k: Offshore Yorkshire digital map showing three layers of the dataset (*Substrate Geology* and *Seabed Geomorphology*) draped over the hillshade derived from bathymetric data acquired by the MCA © Crown Copyright 2022.
Note that the legend only shows the features visible in the map extract.

Further work is required to better understand these features, but a Coastal origin is the current preferred hypothesis for the Gravel ridges. This is consistent with the coast-parallel nature of the ridges and ridge chains, as well as the rugose ridge morphology. Two potential Coastal models are considered viable: 1) ridges formed in the subtidal surf zone, or 2) ridges formed as a result of cliff collapse. The surf-zone model would have involved the reworking of till substrate to form the ridges within the high-energy subtidal surf zone. This is supported by the observation of gravel/boulder ‘skerries’ observed at spring neap tides along Holderness (Scott, 1976). The cliff-collapse model would involve ridge formation from mass-movement, with slide deposits accumulating at the base of the cliffs behind the beach (e.g., similar to the modern geomorphic setting along Holderness). The cliff collapse model is consistent with ridge morphology (plan-view), but it is not clear whether these ridges could be preserved through drowning during sea level rise. In either Coastal model, the Gravel ridges and ridge chains demarcate and record the relative position of former coastlines, as relative sea levels progressively rose during the Holocene.

These Gravel ridges may be related to the numerous lower relief, and wider *Ridges (Morphology only)* mapped to the south and east of the Sand Hole. The Gravel ridge may also have a relationship with ‘Ords’ (landform assemblage of till platform and upper shoreface bars) that have been described along the Holderness Coast (Pringle, 1986), however we note the Gravel ridges are not ‘Ords’ themselves, as they are of distinct morphology, composition, and mobility.

3.2.2.4 Marine features

A range of current induced bedforms are mapped across the map area, including: *Sediment Banks, Sediment Waves, Megaripples, Sediment Drifts*, and longitudinal *Current-Induced Bedforms (Undifferentiated) (*Figure 12*).* There are also fields of *Sediment Waves, Megaripples,* and combined *Sediment waves and Megaripples,* in which polygons delimit an area of numerous features. All mapped current-induced bedforms were formed in a submarine environment, following marine transgession shelf seas during global sea level rise (Sturt et al., 2011). The region’s large *Sediment Banks* may have initially formed earlier in the Holocene, as higher tidal energy environments (required for sediment bank formation) have been modelled for the early Holocene (Dyer and Huntley, 1999; Ward et al., 2016).

All current-induced bedforms are potentially mobile, but the smaller current-induced landforms in particular (i.e., sediment waves, megaripples, ribbons) are interpreted to be active features maintained by the modern hydrodynamic environment. While the size, shape, orientation, and configuration of bedforms provide a first-order indication of flow amplitude and direction, the precise vectors and degree of mobility cannot be quantified by geomorphology alone, i.e., repeat surveys, and/or sediment-transport modelling are required (Van Landeghem et al., 2012; Coughlan et al., 2021).

Sediment bank:

Sediment banks are positive relief features formed by the interaction between current instabilities (commonly generating cyclonic flows) and unconsolidated sediment at the seabed. Sediment banks are the largest occurring current-induced bedforms within a submarine setting, whose formation relies on sufficiently strong current flows and sediment supply. The morphology, orientation, and potential mobility of sediment banks depends on local hydrodynamic and physiographic conditions, e.g., open-shelf banks are elongated, and aligned obliquely to flow. Some modern sediment banks on continental shelves are thought to be moribund features, initially created during lower relative sea level periods when tidal regimes were more energetic, and now maintained or modified by present-day hydrodynamics (Stride, 1982; Dyer and Huntly, 1999; Kenyon and Cooper, 2005).

Sediment banks are observed near the coast in the central and southern sectors of the map area. The features observed within the map area are not as prominent as the larger Norfolk Banks observed farther east, and here are lower-relief, and have more diffuse boundaries.

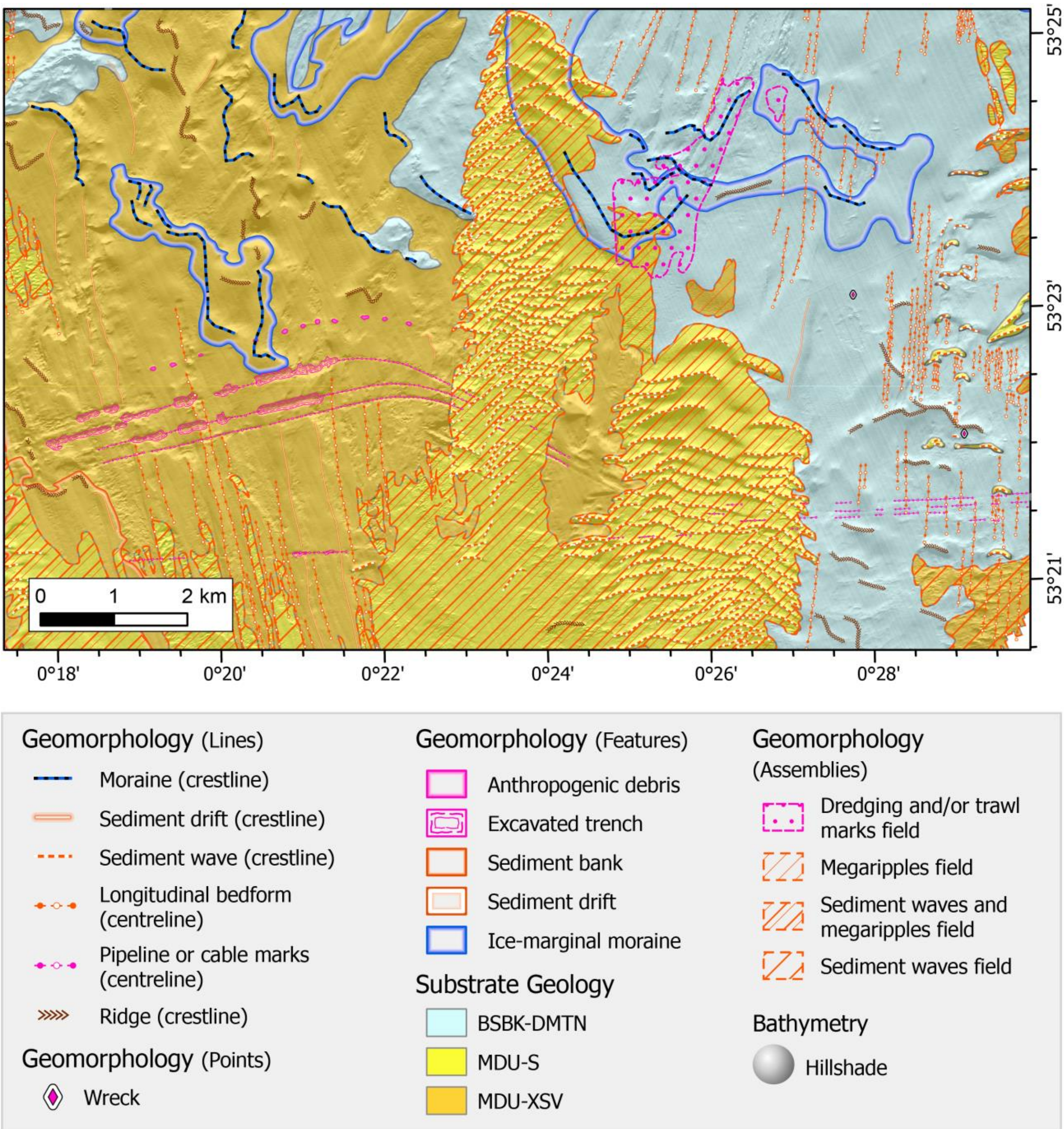

Figure 12 – Marine deposits (MDU) and current-induced bedforms over glacial deposits (BSBK). Extract of the BGS Seabed Geology 10k: Offshore Yorkshire digital map showing three layers of the dataset (*Substrate Geology* and *Seabed Geomorphology*) draped over the hillshade derived from bathymetric data acquired by the MCA © Crown Copyright 2022.
Note that the legend only shows the features visible in the map extract.

<u>*Sediment waves*</u>:

Sediment waves are positive-relief features, formed by the interaction between turbulent hydrodynamic flow and unconsolidated sediment at the seabed. Sediment waves commonly exhibit a smooth wave/dune morphology (though can be super-imposed by megaripples), commonly linear to sinusoidal, and oriented approximately transverse to the dominant hydrodynamic flow direction. Where asymmetric in cross-section, the steeper ‘lee’ slope indicates the down-flow side of the sediment wave, whereas the shallower ‘stoss’ slope indicates the up-flow side. Sediment waves may occur individually or within a rhythmic assemblage of numerous waves. The morphology, size, and spacing (i.e., wavelength) of sediment waves is a function of hydrodynamic regime (e.g., flow strength and consistency), sediment properties (e.g., composition), and sediment availability. Sediment waves are ubiquitous features on continental shelves and slopes, and are alternatively referred to as ‘sand waves’ or ‘marine dunes’. (Belderson et al., 1982; Ashley, 1990; Damen et al., 2018; Duran and Guillen, 2018).

Sediment waves are observed across the map area (e.g., Figures 5, 12). In the northern sector they are concentrated, and oriented approximately perpendicularly to the coast. They exhibit variable relief (particularly in the South) and are mapped individually as well as within fields of multiple features. They frequently co-occur with other current-induced bedforms, and are a prominent feature within the bathymetric deep of the Sand Hole. The Sediment Wave crestlines were mapped using semi-automated processes, manually selecting from linework that was produced based on calculated morphometric layers of relative bathymetric highs.

Megaripples occur as an assemblage of rhythmic sediment waves comprising unconsolidated sediment formed under oscillatory hydrodynamic flow. Megaripples are commonly mixed-relief bedforms with linear-to-lingoidal wave crests separated by intervening troughs.   Mega ripples may co-occur with larger, longer wavelength sediment waves, either occurring between sediment waves or superimposed obliquely on sediment-wave slopes. Megaripples may alternatively be termed small 3D marine dunes (Ashley 1990; Paschier and Keinhans, 2005).

Megaripples are observed across the map area, typically co-occurring with Sediment Waves.

Longitudinal *Current-induced bedforms (Undifferentiated*):

Longitudinal Current-induced bedforms are observed in the central and southern parts of the map area. These are elongated, typically highly linear features anticipated to be aligned subparallel to parallel with dominant hydrodynamic flow vectors. These latitudinal forms are commonly oriented ~perpendicularly to the flow-transverse Sediment Waves and Megaripples. Longitudinal bedforms include ‘sand ribbons’ and ‘furrows’, however within this map area we prefer the more generic classification because the bedforms variably exhibit positive and/or negative bathymetric relief. These longitudinal bedforms exhibit complex configurations in places (e.g., radiating pattern east of the Inner Silver Pit) that warrant further investigation.

3.2.2.5 Anthropogenic

Anthropogenic features are mapped where they have a clear bathymetric expression, and/or impact the immediately surrounding seabed morphology (e.g., scour), e.g., Figure (12). These features are mapped here to provide an indication of the interaction between anthropogenic features and natural seabed processes.

These Seabed Geology maps should not be used as an official geospatial source for location data of any anthropogenic features.

Wreck

Numerous Wrecks are mapped as point features within the map area. Wrecks are only mapped where either the wreck or surrounding seabed (e.g. scour) has a clear morphological expression.

Pipeline or cable mark

Pipeline or cable features are commonly observed as lineament features impacting the seabed morphology, linking offshore infrastructure (e.g., offshore wind farms).

Excavated Trench

In several locations within the map area, the seabed has been significantly excavated for cable and/or pipeline installation. Where observed, these areas are mapped here as polygon features.

Area of Dredging and/or trawl scars

In several locations within the map area, the seabed has been significantly impacted by dredging (aggregate extraction) or trawling (fisheries), modifying the morphology of the seabed. These features are not mapped individually, but as Areas of Dredging and/or trawl scars.

4 Technical Information

4.1 SCALE

This dataset is produced for use at 1:10 000 scale. The multibeam data was used with spatial resolution of 4 m, but due to the nominal scale of the dataset the minimum mappable feature size is in principle 10 m x 10 m.

4.2 COVERAGE

The BGS Seabed Geology 10k: Offshore Yorkshire map covers an area of approximately 4510 km^2 off the east coast of Yorkshire (and northern Lincolnshire), extending from near the town of Redcar in the north, to the just below the Humber Estuary in the south (Figures 1,13).

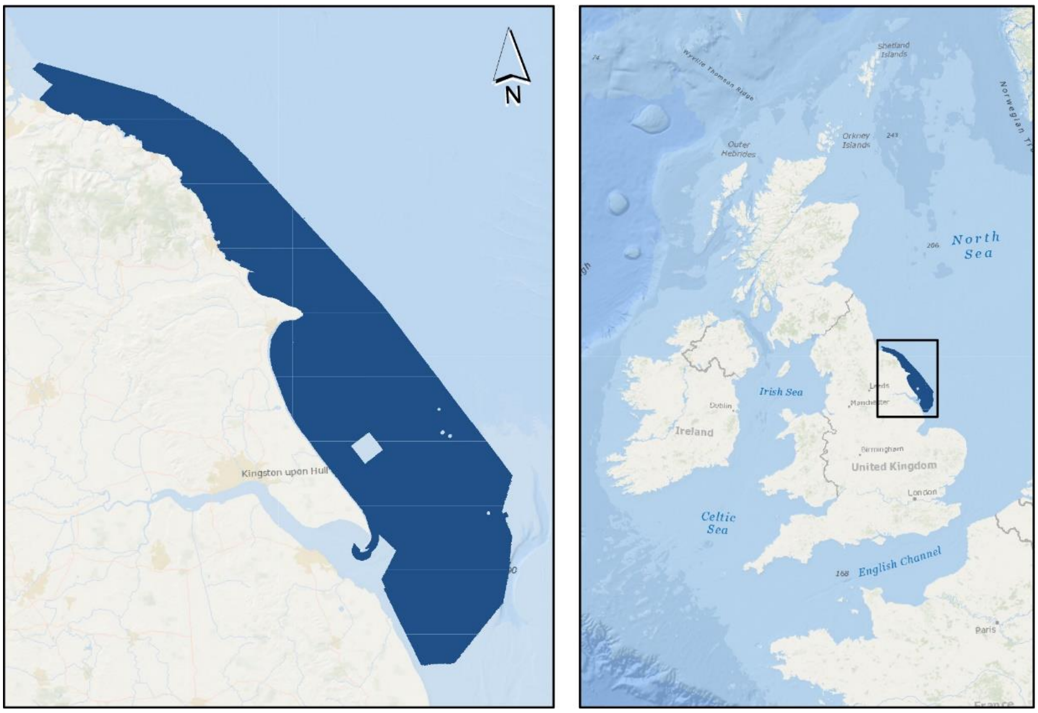

Figure 13 - Coverage of BGS Seabed Geology 10k: Yorkshire shown in dark blue. Background image from World Ocean Base dataset compiled by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

4.3 ATTRIBUTE DESCRIPTION

Each geological theme (map layer) in BGS Seabed Geology 10k: Offshore Yorkshire contains a series of attribute fields. Attribution is specific to the layers, for example, bedrock objects are attributed with lithostratigraphy, chronostratigraphy or lithodemic class, whereas the *Structural Geology* layer with features such as fractures is not. Table 2, Table 3 and Table 4 describe the attribute fields in each layer. Note the following abbreviations are used as attribute values: N/A - Not applicable and N/D - Not defined.

Table 2 - Names and their descriptions of the attribute table fields of the polygonal features on *Substrate Geology* layer of the BGS Seabed Geology 10k: Yorkshire.

Field name	Description
BGS_ID	Unique ID for each polygon
BGSTYPE	The BGS Geology theme: e.g. BEDROCK, SUPERFICIAL
LEX_RCS	The two-part code, LEX & RCS, used to label the geological units in BGS Geology data: e.g. PNG-MDST
LEX_RCS_D	Description of the two-part code above giving the name and the lithology of the unit: e.g. Penarth Group-Mudstone
LEX	Lexicon (or LEX) code. First part of the LEX_RCS label. Up to 5 characters (mostly letters). An abbreviation of the rock unit or deposit as listed in the BGS Lexicon of Named Rock Units: e.g. LI
LEX_D	Description of the Lexicon code above giving the name of the unit: e.g. LIAS GROUP is the full name of the unit coded as LI
RCS	The RCS code (or an abbreviation for the string of RCS codes given in full in RCS_X)
RCS_X	RCS codes. An alternative code abbreviation (or a string of such codes joined by + signs with square brackets used for subordinate types), each up to 6 characters, for the type of rock or lithology as based on the hierarchical BGS Rock Classification Scheme (RCS): e.g. MDST + LMST
RCS_D	Description of the RCS code(s) above giving the lithology of the unit: e.g. MUDSTONE and LIMESTONE
RANK	Rank of the unit in the lithostratigraphical or lithodemic hierarchy: e.g. GROUP
PARENT_DESC	Name of the ‘parent’ unit of greater rank, where applicable: e.g. Blue Lias Formation
MB_EQ_D	Name at member level, where applicable.
FM_EQ_D	Name at formation level, where applicable
SUBGP_EQ_D	Name at subgroup level, where applicable
GP_EQ_D	Name at group level, where applicable
SUPGP_EQ_D	Name at supergroup level, where applicable
MAX_TIME_D	Maximum or oldest age of the unit, to the most accurate time (or geochronological) division possible: e.g. ALBIAN
MIN_TIME_D	Minimum or youngest age of unit, to the most accurate time (or geochronological) division possible: e.g. APTIAN
MAX_AGE	Maximum age. Name of the age of maximum geochronological time applicable: e.g. RYAZANIAN
MAX_EPOCH	Maximum epoch. Name of the epoch of maximum geochronological time applicable: e.g. CARADOC

MAX_PERIOD	Maximum period. Name of the period of maximum geochronological time applicable: e.g. CARBONIFEROUS
MAX_ERA	Maximum era. Name of the era of maximum geochronological time applicable: e.g. PALAEOZOIC
MAX_EON	Maximum eon. Name of the eon of maximum geochronological time applicable: e.g. PROTEROZOIC
MIN_AGE	Minimum age. Name of the age of minimum geochronological time applicable: e.g. BARREMIAN
MIN_EPOCH	Minimum epoch. Name of the epoch of minimum geochronological time applicable: e.g. ASHGILL
MIN_PERIOD	Minimum period. Name of the period of minimum geochronological time applicable: e.g. PERMIAN
MIN_ERA	Minimum era. Name of the era of minimum geochronological time applicable: e.g. MESOZOIC
MIN_EON	Minimum eon. Name of the eon of minimum geochronological time applicable: e.g. PHANEROZOIC
LEX_WEB	The LEX_WEB link provides a direct hyperlink to the definition of the particular geological unit in the BGS Lexicon of Named Rock Units: e.g. http://www.bgs.ac.uk/Lexicon/lexicon.cfm?pub=PNG
RCS_WEB	The RCS_WEB link provides a direct hyperlink to the definition of the particular type of rock or lithology as based on the BGS Rock Classification Scheme (RCS): e.g. https://webapps.bgs.ac.uk/bgsrcs/rcs_details.cfm?code=MDST
BGSREF	BGS reference colour for the polygon based on the LEX_ROCK code pair. The default printing colour defined as a 3-digit number:
RED	The equivalent red channel colour of the intended colour
GREEN	The equivalent green channel colour of the intended colour
BLUE	The equivalent blue channel colour of the intended colour
HEX	The equivalent HEXadecimal value of the intended colour
NOM_SCALE	Nominal scale used to prepare the digital data: e.g. 10000. Also gives an indication of scale-dependant accuracy
DATASET	Official name of the dataset
VERSION	Version of the digital data. The version number is changed when a new dataset is released following major changes
RELEASED	Date released

Table 3 - Names and their descriptions of the attribute table fields of the linear features on *Structural Geology* layer of the BGS Seabed Geology 10k: Yorkshire.

Field name	Description
BGS_ID	Unique ID for each polyline
BGSTYPE	The BGS Geology theme, it can be FAULT or FOLD AXIS
FEATURE_D	Description of the geological feature e.g. Axial plane trace of an anticline
NOM_SCALE	Nominal scale used to prepare the digital data: e.g. 10000. Also gives an indication of scale-dependant accuracy

DATASET	Official name of the dataset
VERSION	Version of the digital data. The version number is changed when a new dataset is released following major changes
RELEASED	Date of dataset release

Table 4 – List of names and description of the fields in the can be found in the different *Geomorphology* layers of the BGS Seabed Geology 10k: Yorkshire.

Field name	Description
BGS_ID	Unique ID for each polyline
BGSTYPE	Geological theme, it can be MORPHOLOGICAL or GEOMORPHOLOGICAL
FEATURE_D	Description of seabed feature type: e.g. Bedform (Crestline)
MORPH_FEAT	Description of the feature according to its morphologic type, regardless of the geological process: e.g. Crestline of a ridge
MORPH_TYP	Type of morphology: e.g. Lineament
ASSOC_REL	Type of relief of associated relief: e.g. Bathymetric high
MORPH_ATTR	Additional information relative the morphological characteristics of the seabed feature described: e.g. Narrow, Low-relief
ORIG_ENV	The geological setting contemporaneous of the development of the seabed feature or the dominant geological process associated to the formation of the geomorphological feature: e.g. Marine, Glacial
FEATURE_C	Type of class of geomorphological features according to the geological process that formed the feature, when known e.g. Current-induced bedform
NOM_SCALE	Nominal scale used to prepare the digital data: e.g. 10000. Also gives an indication of scale-dependant accuracy
DATASET	Official name of the dataset
VERSION	Version of the digital data. The version number is changed when a new dataset is released following major changes
RELEASED	Date of dataset release

4.4 DATA FORMAT

The BGS Seabed Geology 10k: Yorkshire data are in vector format and comprise six geospatial data layers: one *Substrate Geology* layer (comprised of polygons), one *Structural Geology* layer (comprised of polylines) and four *Geomorphology* layer (one comprised of polylgons, one comprised of polylines and one comprised of points).

They are released in ESRI shapefile format. Other vector formats are available on request. More specialised formats may be available but may incur additional processing costs. Please email BGS Enquiries (enquiries@bgs.ac.uk) to request further information.

4.5 DATASET HISTORY

The BGS Seabed Geology 10k: Offshore Yorkshire digital map was created in 2023. This is the first release of the dataset.

4.6 DISPLAYING THE DATA

It is recommended that the *Substrate Geology* layer should be displayed based on the "LEX_RCS" field in the attribute table (Table 5) whereas, the *Structural Geology* layer and *Geomorphology* layers should be displayed based on "FEATURE_D" (Tables 6 to 10). The "LEX_RCS" field provides an abbreviation of the rock or deposit unit as listed in the BGS Lexicon of Named Rock Units and the type of rock (lithology) or sediment according to the hierarchical BGS Rock Classification Scheme. The "FEATURE_D" field provides a description of the geological feature delineated. The *Structural Geology* and the *Geomorphology* layers should display above the *Seabed Substrate* layer, to allow the best visualisation and clarity of the map objects.

Table 5 – Colour symbology intended for the *Substrate Geology* layer based on field "LEX_RCS".

LEX-RCS	RED	GREEN	BLUE	HEX	
AMKC-MDST	237	117	0	#ED7500	
BACT-SDST	255	176	224	#FFB0E0	
BW-SDST	255	255	54	#FFFF36	
CBCA-LSMD	255	148	84	#FF9454	
CDI-MSDI	176	237	237	#B0EDED	
CR-SDST	201	176	176	#C9B0B0	
HAI-MDST	201	224	176	#C9E0B0	
OXC-MDST	117	148	0	#759400	
PNG-MDST	237	117	117	#ED7575	
RMU-MDST	237	176	176	#EDB0B0	
SPC-MDST	224	255	224	#E0FFE0	
STA-SDST	237	148	148	#ED9494	
SWK-SDSM	201	255	54	#C9FF36	
WHCK-CHLK	237	255	201	#EDFFC9	
WHM-MDST	201	117	84	#C97554	
WSTS-SDSM	237	224	117	#EDE075	
ARTU	255	255	255	#FFFFFF	
BOCT-XVSM	255	237	54	#FFED36	
BSBK-DMTN	201	255	255	#C9FFFF	
EG-XIMS	237	176	84	#EDB054	
SHLE-XIMS	255	117	54	#FF7536	
SWBK-DMTN	224	224	84	#E0E054	
MDU-S	255	255	0	#FFFF00	
MDU-V	176	117	0	#B07500	
MDU-XSM	148	224	0	#94E000	
MDU-XSV	255	201	0	#FFC900	
MDU-XVSM	224	201	176	#E0C9B0	

Table 6 - Symbology intended for the *Structural Geology* layer based on field “FEATURE_D”.

FEATURE_D	Symbol
Axial plane trace of a syncline	
Axial plane trace of an anticline	
Fracture inferred at rockhead	
Fault inferred at rockhead	
Fault inferred at rockhead (barbs on the downthrow side)	

Table 7 - Symbology intended for the *Geomorphology (lines)* layer based on field “FEATURE_D”.

FEATURE_D	Symbol
Bedrock ridge (crestline)	
Drumlin (crestline)	
Moraine (crestline)	
Subglacial streamlined landform (crestline)	
Gravel ridge (crestline)	
Palaeo-shoreline	
Sediment bank (crestline)	
Sediment drift (crestline)	
Sediment wave (crestline)	
Longitudinal bedform (centreline)	
Palaeochannel (thalweg)	
Abandoned material	
Pipeline or cable marks	
Convex break of slope	
Ridge (crestline)	

Table 8 – Symbology intended for the *Geomorphology features (polygons)* layer based on field "FEATURE_D".

FEATURE_D	Symbol
Anthropogenic debris	
Excavated trench	
Coastal Platform	
Palaeochannel	
Sediment bank	
Sediment drift	
Sediment wave	
Bedform scour	
Drumlin	
Ice-marginal moraine	
Subglacial streamlined landform	
Glacial ridge	
Glacitectonic raft	
Glacitectonic hole	
Tunnel valley	
Hummock	
Mound	
Depression	

Table 9 – Symbology intended for the *Geomorphologyassembly (polygons)* layer based on field "FEATURE_D".

FEATURE_D	Symbol
Anthropogenic debris	
Depressions field	
Dredging and/or trawl marks field	
Megaripples field	
Sediment waves and megaripples field	
Sediment waves field	

Table 10 – Symbology intended for the *Geomorphology (points)* layer based on field "FEATURE_D".

FEATURE_D	Symbol
Wreck	

5 Limitations

5.1 DATA CONTENT

The BGS Seabed Geology 10k: Offshore Yorkshire portrays the distribution of the different types of bedrock and unconsolidated superficial deposits and also includes the distribution of the main seabed morphological features and structural features observed at rockhead. Some features, such as bedforms crests will be identified by only a subset of selective, representative digitisation. The mapping, description and classification of the seabed geology are based upon the interpretations and evidence available at the time.

5.2 SCALE

This digital map at 1:10 000 scale is generalised and the geological interpretation should be used only as a guide to the geology at a local level, not as a site-specific geological plan based on detailed site investigations. Do not over-enlarge the data; for example, do not use 1:10 000 nominal scale data at 1:5 000 working scale.

5.3 ACCURACY/UNCERTAINTY

Linework provided within this digital map has been interpreted from multibeam bathymetry data, with a grid cell size of 4 m, and a working scale of 1:10 000. It is not possible to provide a consistent level of accuracy for all objects in a geological map. For example, a sharp geological boundary will be captured with greater accuracy (and precision), than a conceptual, gradational boundary.

The Seabed Geomorphology layer inherently supports finer-scale mapping that the substrate mapping as linework and boundaries are based only on seabed morphology (i.e. high-resolution bathymetry). There is greater uncertainty with the Substrate Geology layer, as while boundaries and classification are informed by the high-resolution bathymetry and backscatter data, interpretation is also based on discontinuous sub-surface and further seabed data with lower, and sometimes disparate sample density (e.g., sediment cores, seismic data).

This is even more marked on geological maps of the seabed, based on the remote geophysical data and limited ground-truthing data. Marine in situ measurement techniques (e.g. grabs, cores and underwater video footage) reveal detailed information of the seabed substrate and provide, in general, an accurate representation of the local seabed. However, the seabed sampling that underpins this dataset was principally collected at a reconnaissance level and, therefore, the data could be several kilometres apart and may not always be sufficient to represent the sediment heterogeneity. Backscatter and texture analyse of the bathymetric data also indicate the boundaries between sediment types. However, it will depend heavily on the relationship between the different seabed substrates being mapped. For example, a sharp boundary separating two contrasting sediments types is likely to be more accurately mapped, with greater certainty than a diffuse or gradational boundary between two similar seabed substrates (e.g. sand and sand and gravel).

In addition, the user of this digital map should also be aware that it should be considered a "snapshot in time" of a transitory reality due to the high mobility of certain sedimentary deposits. Within the most dynamic areas, the spatial distribution of these deposits may change dramatically over time due to the local hydrodynamic regime, plus the seafloor may have been subjected to a range of anthropogenic disturbances (e.g. dredging of sediments).

5.4 DISCLAIMER

The use of any information provided by the British Geological Survey ('BGS') is at your own risk. Neither BGS nor the Natural Environment Research Council (NERC) or UK Research and Innovation (UKRI) gives any warranty, condition or representation as to the quality, accuracy or completeness of the information or its suitability for any use or purpose. All implied conditions relating to the quality or suitability of the information, and all liabilities arising from the supply of the information (including any liability arising in negligence) are excluded to the fullest extent permitted by law. No advice or information given by BGS, NERC, UKRI or their respective employees or authorised agents shall create a warranty, condition or representation as to the quality, accuracy or completeness of the information or its suitability for any use or purpose.

6 Frequently asked questions

Q: What does this map show?

A: The BGS Seabed Geology 10k: Offshore Yorkshire digital map products comprise three complimentary components: 1) Substrate Geology, showing the distribution of Bedrock and Superficial geological units interpreted to be present within the top 1 m below seabed; 2) Structural Geology, delineating the principle structural features such as faults and folds observed at rockhead; and 3) Seabed Geomorphology, classifying the physical morphology and interpreted geomorphic character of the seabed.

Q: What are the different colours on the map for?

A: The different colours are to show the different rock units and types of seabed substrate, as listed in the BGS Lexicon of Named Rock Units.

Q: How accurate is this map?

A: The geological interpretation that was undertaken to create this map was done to be viewed at a scale of 1:10 000 scale. Users should be aware that geological maps are a compilation of inferred features. It is not possible to provide a consistent level of accuracy for all objects in a geological map. Further details about the accuracy of this dataset are provided in the 'Limitations' section of this report.

Q: How often will this map be updated?

A: As more multibeam datasets became available in the area, future versions of this dataset are likely to expand its geographic coverage. However, dates for new version releases are, as yet, undetermined. BGS will contact licence holders with information on future releases of this dataset once they become available.

Q: Where can I get digital data?

A: This digital map is licenced from BGS, subject to certain standard terms and conditions. However, an increasing number are available for view or download. Many products also offer sample data downloads and user guides to help you decide if the data is suitable for you.

Q: In what formats can these data be provided?

A: This is available in a range of GIS formats, including ArcGIS (.shp), ArcInfo Coverages and MapInfo (.tab). More specialised formats may be available but may incur additional processing costs. Please email BGS Enquiries (enquiries@bgs.ac.uk) to request further information.

Q: I don't have a GIS. Can I still view the data?

A: Yes! Our Offshore Map Viewer is a good place to start. It is an online data and GIS service that covers a very wide range of marine geoscience research.

Q: Can I use this map as part of a commercial application?

A: Please refer to the licencing terms supplied alongside the dataset. For further queries regarding the licencing terms of our products, please contact digitaldata@bgs.ac.uk.

Q: I think the geology map might be wrong. What can I do?

A: We make every effort to ensure that our mapping reflects our best understanding of the geology of Anglesey. Sometimes our interpretations need to be revised as new evidence (such as new multibeam data) are obtained and simple errors sometimes get through our quality assurance procedures. We are currently working on a web service to improve notifications of errors that have been found and corrected; we hope to make this available soon. If you think you have spotted a problem with our datasets please let us know.

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Glossary

Jargon	Explanation
ArcGIS	Geographic Information System (GIS) software for working with maps and geographic information maintained by the Environmental Systems Research Institute (ESRI).
Attribute	Named property of an entity. Descriptive information about features or elements of a database. For a database feature like census tract, attributes might include many demographic facts including total population, average income, and age. In statistical parlance, an attribute is a variable, whereas the database feature represents an observation of the variable.
Backscatter data	Data that was acquired with a sonar system capable of measuring the intensity of the return acoustic signal (echo) reflected by the seafloor. The intensity of the return signal results from a complex combination of acoustic and geophysical processes, accounting for both transmitting and recording electronics of the sonar and intricate physical phenomenon occurring both in the water column and at the seafloor. New methods of analysing backscatter data have increased its potential for seabed characterisation.
Bathymetry	The measurement of the water depth in oceans, seas, or lakes over an area of seabed. In other words, bathymetry is the underwater equivalent to topography.
Bedrock	The main mass of rocks forming the earth, laid down prior to 2.588 million years ago. Present everywhere, whether exposed at the surface in rocky outcrops or concealed beneath superficial deposits, artificial ground or water. Formerly called solid.
Epoch	Geological unit of time during which a rock series is deposited. It is a subdivision of a geological period.
ESRI	Environmental Systems Research Institute (ESRI) is an international supplier of Geographic Information System (GIS) software, web GIS and geodatabase management applications.
Geophysical data	Data that has been acquired by recording and analysing measurements of the Earth's physical properties, such as electrical, gravity, magnetic, radioactivity and seismic properties.
Geospatial data	Data that has a geographical component to it. This means that the records in a dataset have locational information directly linked to them, such as geographic data in the form of coordinates, address, city, or postcode.

Lexicon	Vocabulary defining rock names, the BGS Lexicon of Named Rock Units database provides BGS definitions of terms that appear on our maps and in our publications. https://www.bgs.ac.uk/lexicon/home.html
Lithological units	A rock identifiable by its general characteristics of appearance colour, texture and composition defined by the distinctive and dominant, easily mapped and recognizable petrographical or lithological features that characterize it.
Lithology	Rocks maybe defined in terms of their general characteristics of appearance: colour, texture and composition. Some lithologies may require a microscopical or chemical analysis for the latter to be fully determined.
Lithostratigraphy	Age and lithology. Many rocks are deposited in layers or strata and the sequence of these strata can be correlated from place to place. These sequences of different rock types are used to establish the changing geological conditions or the geological history of the area over time. The description, definition and naming of these layered or stratified rock sequences is termed lithostratigraphy (rock stratigraphy). Lithostratigraphy is fundamental to most geological studies. Rock units are described using their gross compositional or lithological characteristics and named according to their perceived rank (order) in a formal hierarchy. The main lithostratigraphical ranks in this hierarchy are Bed (lowest)>Member,>Formation>Subgroup>Group>Supergroup (highest). The units are usually named after a geographical locality, typically the place where exposures were first described.
Multibeam echosounder (MBES) data	Data that was acquired with a multibeam echosounder. This type of sonar system emits sound waves in a fan shape. Multibeam systems acquire both bathymetry (depth) and backscatter (intensity) data. The amount of time taken for the sound waves to bounce off the seabed and return to a receiver is used to determine water depth. Whereas, the return intensity (i.e. how much of a transmitted acoustic signal is bounced back) reflects the nature of the seabed and can be used to determine the composition, relative hardness, and texture of the seafloor.
Polygon	Polygons are a representation of areas. A polygon is defined as a closed line or perimeter completely enclosing a contiguous space and is made up of one or more links.
Scale	The relation between the dimensions of features on a map and the geographic objects they represent on the Earth, commonly expressed as a fraction or a ratio. A map scale of 1/100,000 or 1:100,000 means that one unit of measure on the map equals 100,000 on the earth.

Sedimentary	Rocks that originated from the broken up, or dissolved and re-precipitated, particles of other rocks. Examples include claystone, mudstone, siltstone, shale, sandstone, limestone and conglomerate. Sedimentary rocks cover more than two-thirds of the Earth's surface. They are formed from the weathering and erosion products of rock material, which have been transported (usually by water or wind), redeposited and later lithified.
Sediments	Mud, sand, gravel, boulders, bioclastic material (shells, plants), and other matter carried and deposited by water, wind, or ice.
Shapefile	The shapefile format is a geospatial vector data format for geographic information system software. It is developed and regulated by ESRI as a mostly open specification for data interoperability among ESRI and other GIS software products.
Superficial	The youngest geological deposits formed during the most recent period of geological time, the Quaternary. They range in age from about 2.6 million years ago to the present.
Vector	A representation of the spatial extent of geographic features using geometric elements (such as point, curve, and surface) in a coordinate space.