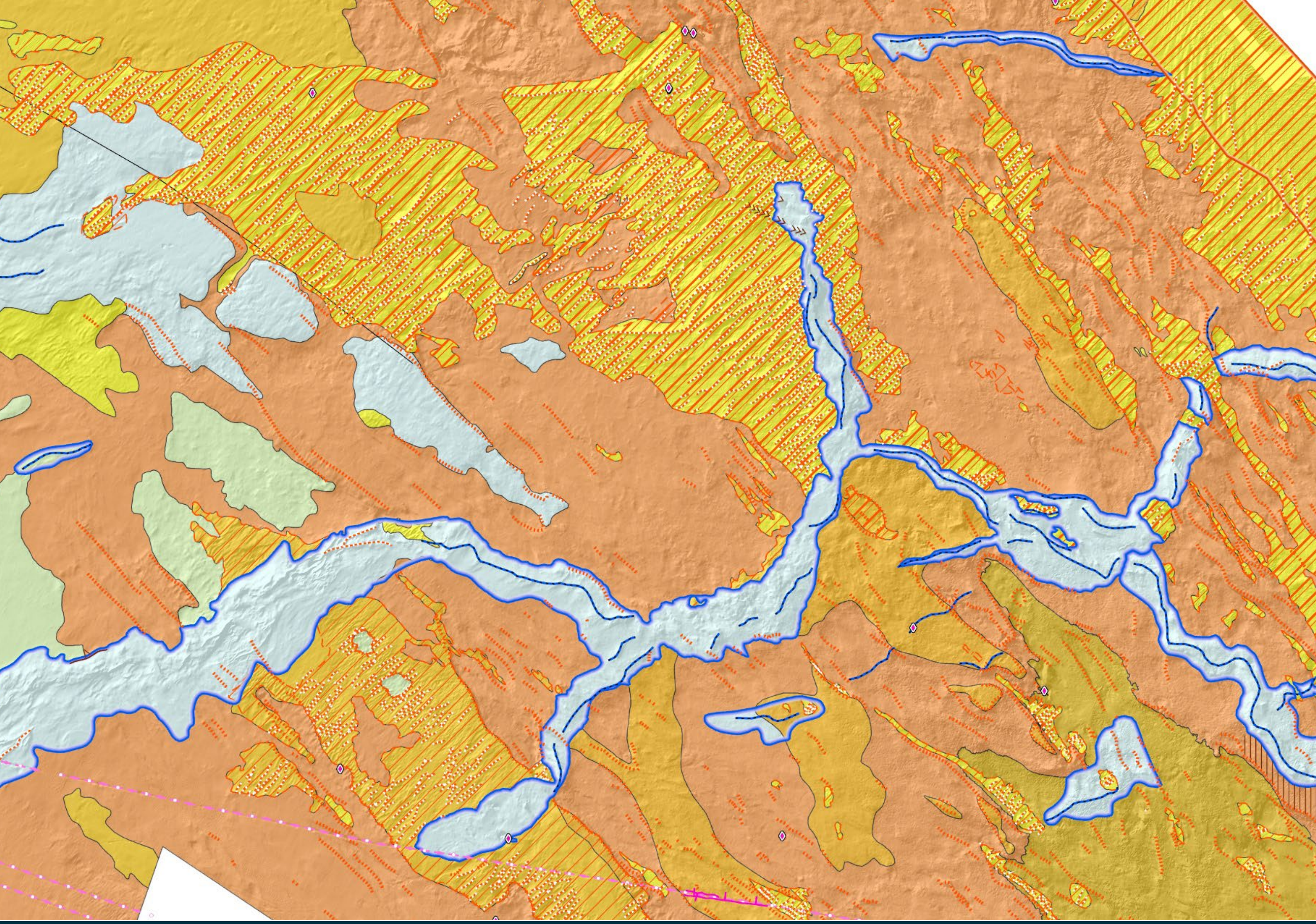

MARINE GEOSCIENCE / INFORMATICS PROGRAMME

User Guide for BGS Seabed Geology: Offshore East Anglia

Open Report OR/24/003

British Geological Survey

BRITISH GEOLOGICAL SURVEY

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Keywords

Northern East Anglia, Seabed Geology, Offshore bedrock, Quaternary sediments, Structural Geology, Geomorphology.

Map

Seabed Geology; Offshore East Anglia

Front cover

Extract from Seabed Geology: Offshore East Anglia dataset showing the bedrock geology and superficial deposits. Hillshade image derived from bathymetric data acquired by the MCA © Crown Copyright 2024.

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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: Offshore East Anglia 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).

Acknowledgements

The geological mapping and interpretation were carried out at 1:10,000 scale between 2021-23 by Jonathan Lee, Dayton Dove and Nicola Dakin; Joana Gafeira undertook the data compilation and helped with the report compilation. Andrew Finlayson undertook the scientific review whilst Emrys Phillips, Margaret Stewart and Jim Rose are thanked for their discussions that have helped shape the map interpretation.

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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The BGS Seabed Geology: Offshore East Anglia digital map comprises three complementary 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 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, shallow seismic data, physical samples (*e.g.,* grab samples, cores, and boreholes), seismic data, academic and publicly accessible industry literature, and previous BGS mapping (e.g.,1:250,000 maps).

The bedrock geology of the mapping area comprises Cretaceous age Chalk Group sedimentary rocks. These rocks crop-out extensively at seabed across the southern and central parts of the mapping area forming an extensive bedrock platform and Europe's largest known offshore chalk reef. This reef has been designated the Cromer Shoal Chalk Beds Marine Conservation Zone (MCZ) owing to the range of unique floral and faunal habitats that it supports. The Chalk Group is covered across the central (partly) and southern parts of the mapping area by natural superficial deposits that accreted during the Quaternary. These include preglacial delta bottom-set (Westkapelle Ground Formation) and delta top-set (Yarmouth Roads Formation); and glacial sediments and landforms that were deposited and formed during at least two separate phases of glaciation that inundated parts of the southern North Sea and adjacent East Anglia during the Middle Pleistocene (Anglian / Elsterian) and Late Pleistocene (Late Devensian / Late Weichselian). Collective geological evidence includes extensive areas of out-cropping subglacial till; the presence of largely concealed and infilled over-deepened (>100 m deep) subglacial tunnel valleys, ice-marginal moraines, and a glacially disrupted chalk surface that includes the development of incised meltwater channels, detached and transported glacitectonic bedrock rafts and megablocks. Post-glacial environments from the Late-Pleistocene – Holocene (prior to marine inundation) included fluvial and estuarine deposition, that together with variable infill of Late Glacial valleys are included within the Botney Cut Formation. Holocene marine transgression flooded the region, with shallow marine sedimentation active through to modern times resulting in the variable cover of unconsolidated marine sediments, as well as the distribution of extensive current-induced bedforms, e.g., sediment banks, sediment waves and fields of mega ripples which are recorded within the Seabed Geomorphology layer.

The map citation, metadata and overview is: British Geological Survey (2024): BGS Seabed Geology: Offshore East Anglia version 1.0. (Dataset).

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

1.1 BACKGROUND

The BGS Seabed Geology: Offshore East Anglia digital map (Figure 1) provides an accurate and detailed characterisation of the seabed geology based on high-resolution bathymetric and shallow sub-surface data that were available at the time of map compilation (2022-2023). The published data product incorporates three viewable digital map themes – *Substrate Geology, Structural Geology* and *Seabed Geomorphology.* The *Substrate Geology* layers show the distribution of bedrock and natural superficial deposits as a series of polygons that occur at seabed or immediately beneath a thin and transient veneer of seabed sediments (see also 'one meter principle). The *Structural Geology* layer shows the distribution of mapped structural geological features (polylines) such as faults and fractures. The *Seabed Geomorphology* layers consists of a range of point, polygon and polyline features that characterise the main seabed morphology and geomorphology.

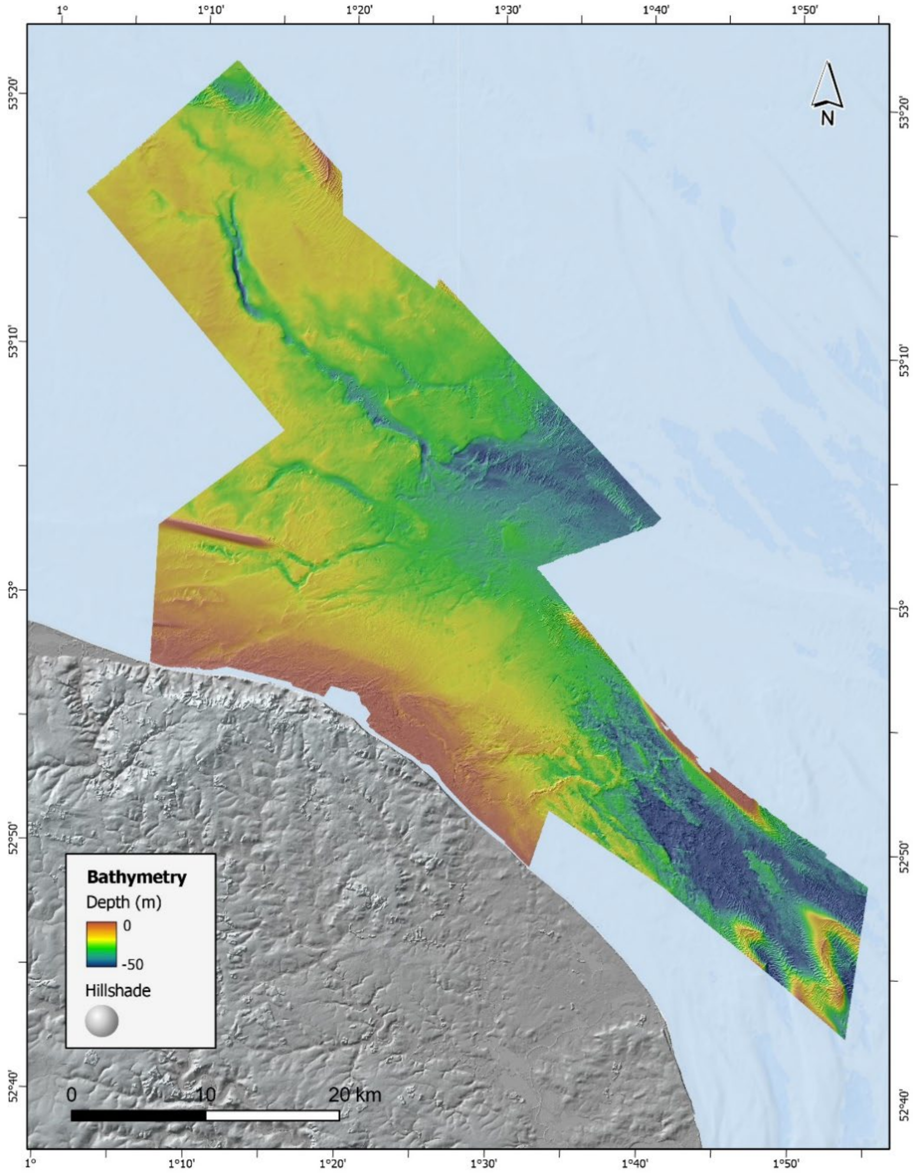

Figure 1. Map showing the location and bathymetry of the BGS Seabed Geology: Offshore East Anglia dataset.

This image contains bathymetry data acquired by the MCA and by Cefas © Crown Copyright 2024. . The Background image from World Ocean Base dataset compiled by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

The geological character of the seabed and shallow sub-surface within and adjacent to the northern East Anglia mapping area is important to a wide range of users and stakeholders. For example, two major windfarms – Dudgeon and Sheringham Shoal, occur to the north of the mapping area and offshore-to-onshore cable routes link the windfarms to the National Grid. From a conservation perspective, the Cromer Shoal Chalk Beds are thought to be Europe's largest offshore chalk reef that supports a range of unique habitats and accordingly, this area has been designated a Marine Conservation Zone (MCZ). Significant areas of coastline in north Norfolk bordering the southern edge of the mapping area are also vulnerable to coastal erosion and coastal flooding. This poses a significant risk to homes, businesses, critical infrastructure (e.g. transport and energy) and water resources and this risk is expected to grow under current and future climate change predictions (Fisher *et al*., 2019). The mapping area is also of considerable value to archaeologists, representing an area that prior to being inundated by marine conditions during the early Holocene, was inhabited by Mesolithic hunter-gatherers acting as southerly access route into Doggerland.

The published geological maps provide information on the composition and properties of the seabed, active sediment types and apparent mobility and are intended as enabling resources to support this (and other) diverse range of offshore activities and applications.

1.2 SUBSTRATE GEOLOGY

This digital map layer shows the dominant geological unit interpreted to be present within the top 1 m of the substrate below seabed. This general approach is followed to characterise the geological substrate present below the frequently thin, discontinuous and potentially ephemeral/mobile seabed sediment (SBS) layer (c.f. onshore 'pedogenic soil' layer). At any given location, the mapped geological substrate may comprise either a Bedrock, or natural Superficial geological unit. The Superficial units may include Quaternary sedimentary 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 fractures, faults and folds observed at rockhead. Features are only marked as faults as opposed to fractures where bedding is clearly offset.

1.3 SEABED GEOMORPHOLOGY

Characterising the Seabed Geomorphology involves describing the morphological character of the seafloor. When integrated with other contextual information and supporting data, this information can potentially enable genetic interpretation, enhanced characterisation (by understanding geological processes) and an understanding of the potential mobility/vulnerability of seabed features.

The Seabed Geomorphology mapping workflow adopts a 'two-part' approach, which has semi-independent descriptions of 'morphology' and 'geomorphology' (Nanson et al., 2023). 'Morphological feature(s)' are those characterised only by their seabed expression and physical attributes (i.e., size, shape, configuration, texture) and therefore represent an entirely objective description of the features observed. By comparison, 'geomorphological feature(s)' incorporate varying levels of process and genetic interpretation, based upon their morphological properties and other supporting information.

An area-specific geological summary is presented in Section 3, based on the observations and findings from the Offshore Northern East Anglia 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 such 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).

2 Methodology

The information provided in the BGS Seabed Geology: Offshore East Anglia map has been compiled via a process of manual 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 seven high-resolution multibeam echosounder (MBES) datasets (Figure 2), from two Marine Conservation Zones (MCZ) and five Hydrographic Instruction (HI) areas. Survey names and acquisition dates is listed below:

MCZ Cromer Shoal Chalk Beds Multibeam Survey CSCB_3_2014 (*February-March 2014*);
MCZ Cromer Shoal Chalk Beds Multibeam Survey CSCB_21_2012 *(March-April 2012)*
HI1515 Haisborough Sand to Outer Dowsing Channel Area (*February-April 2018*);
HI1673 Sheringham Shoal (*March-August 2020*);
HI1447 Blakeney Overfalls (*January-February 2014*);
HI1427 The Would North, Centre and South (*September 2014 – January 2015*);
HI1428 Newark Banks to Cross Sands (*April-September 2014*).

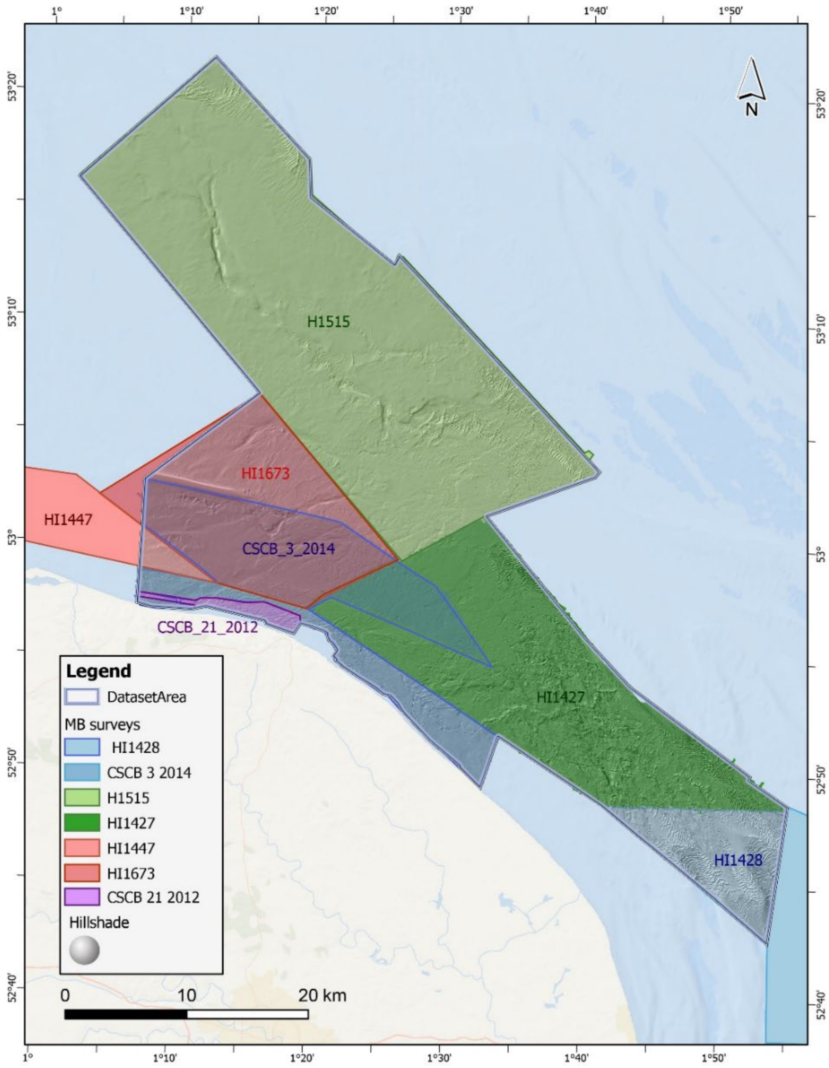

Figure 2. Map showing the MCZ and HI high-resolution multibeam echosounder data used.

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The HI datasets were acquired on behalf of the Civil Hydrography Programme (CHP) which is managed by the Maritime and Coastguard Agency (MCA) for the UK Hydrographic Office. The MCZ datasets were acquired on behalf of the Centre for Environment, Fisheries and Aquaculture Science (Cefas) for the Department for Environment, Food and Rural Affairs (Defra). The MBES data are available via an Open Government Licence.

The individual bathymetry survey datasets were merged to form a single bathymetry surface, gridded at 4 m horizontal spatial resolution. MBES backscatter, physical samples (*e.g.,* grab samples, cores, and boreholes), shallow seismic data, previous BGS offshore mapping (British Geological Survey, 1991), publicly accessible industry reports and data, and knowledge of geology exposed in adjacent onshore coastal sections were used to underpin the geological interpretation.

2.2 GEOLOGICAL INTERPRETATION - APPROACH

The geological interpretation of multibeam echo-sounder bathymetry is akin to onshore methods of geological mapping using Digital Elevation Models (DEMs) and terrain analysis, where the geologist identifies domains (areas) of different geology based upon their shape, texture, morphological expression within the seabed and cross-cutting relationships.

From the digital surface model (DSM) provided by the MBES bathymetry, several derived surfaces were created (such as hillshade, slope, and bathymetric position index; Figure 3) (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 such as discriminating between a hard substrate (e.g., chalk, till) and a substrate dominated by unconsolidated marine sediments such as sand.

Importantly, continuous and 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 ground-truthing, and sub-surface data allows geologists to identify areas that exhibit similar geological properties, as well as seabed forms that can imply geological 'processes', such as overriding by glacier ice or mobility of sedimentary bedforms.

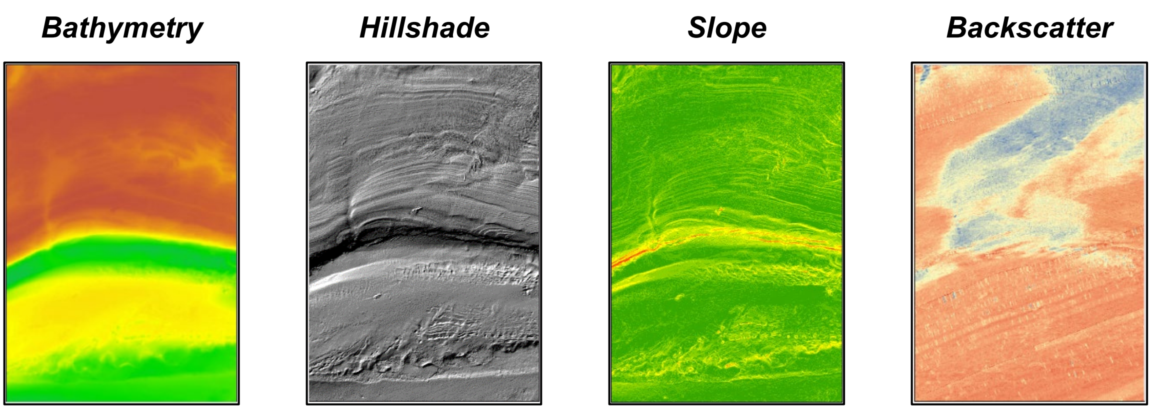

Figure 3. Extracts of bathymetry, hillshade, slope and backscatter multibeam data used to support the geological interpretation.

This image contains data acquired by the MCA © Crown Copyright 2024.

2.3 DIGITAL CAPTURE

The geological linework was captured both via manual digitisation, as well as by semi-automated processes to produce consistent linework for certain specific seabed features. This semi-automated linework was employed, where appropriate, to enhance mapping accuracy and efficiency, as well as reduce geologist bias. Semi-automated linework was primarily used for mapping ridges and 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 semi-automated linework was prepared using the following workflow: (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 the seabed, frequently corresponding to discrete geomorphic features; (3) unsupervised clustering to segregate groups of shared morphological properties; and (4) manual checking of semi-automated linework. 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 interpretation of the geologist.

Where linework was produced using manual interpretation, features were mapped while viewing the data between 1:5,000 to 1:8,000 scales, for use at a scale of between 1:10,000 to 1:50,000. This scale varies depending on the layers and is generally higher for the Seabed Geomorphology layers. 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

Mapping of the substrate geology and its interpretation was undertaken digitally using ArcGIS™ supported by the BGS·SIGMA Desktop toolkit. For the Substrate Geology layer, all map areas are covered by either a Bedrock or Superficial unit.

The mapped bedrock and superficial deposits were captured as independent polygon layers with their geological attribution underpinned by underpinning stratigraphic frameworks for the UK Continental Shelf, and standard stratigraphic, chronostratigraphic and litho-genetic dictionaries (e.g., the BGS Lexicon of Named Rock Units and the BGS Rock Classification Scheme). A one-metre principle was applied to mapping the dominant geological unit within the top one metre beneath seabed. This interpretative approach was utilised to avoid mapping thin, discontinuous veneers of seabed sediment where the fabric of the underlying geology (bedrock or superficial) was visible. Where this fabric was not visible, seabed sediment was mapped as the dominant mappable unit within the top one metre.

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 variably includes boreholes, previous offshore mapping, and adjacent onshore mapping and data.

2.3.1.2 Superficial Geology

Superficial deposits include all unlithified deposits, which incorporate all Pliocene to Quaternary age sediments including Holocene and modern marine sediment sediments, and mass movement deposits. The mapping interpretation of superficial sediments is based on core data, changes in seabed texture observed within the bathymetry, shallow seismic and backscatter data as well as previous offshore and onshore geological mapping. 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)).

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), the low density of sediment samples and variable backscatter data quality preclude this approach from 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;

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

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

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.

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 (e.g., Geological Survey of Norway, Geological Survey Ireland, Geoscience Australia, Dove *et al.*, 2016). Lists and definitions of 'Geomorphology' features are provided within the updated classification framework (Nanson et al., 2023), and 'Morphology' terms and glossary definitions are provided by Dove *et al.* (2020).

This two-tiered approach involves an independent assessment of 'Morphology' and 'Geomorphology'. The Morphology defines the fundamental geometry of the feature on the seabed (e.g., 'Bathymetric High > Mound > Streamlined Mound'), whereas the Geomorphology describes the interpreted origin, or process association of features (e.g., 'Glacial > Subglacial Landform > Streamlined landform > Drumlin). Only seabed features that have a discernible morphological expression have been mapped. All features mapped have a Morphology class assigned, whereas the Geomorphology class is only attributed where the geologist has been able to justify their interpretation. The Seabed Geomorphology includes both observed natural and anthropogenic features.

Collectively, the Seabed Geomorphology has been grouped into four feature categories: points, lines, units (polygons) and assemblies (polygons). The attribute fields provided within the digital map are described further in Section 4.

3 Seabed Geology - Summary

3.1 OVERVIEW

This section of the report provides a summary of the geological findings resulting from the mapping presented in the BGS Seabed Geology: Offshore East Anglia digital map. The section describes key and characteristic elements mapped as well as providing a general contextual backdrop. However, the report does not provide a systematic description of all mapped deposits and features, nor an exhaustive discussion of the area's geological and palaeoenvironmental history. Instead, readers are directed to the literature referenced within this section of the report for further information.

The mapping area is situated within the western sector of the relatively shallow epicontinental North Sea basin (Cameron *et al*., 1992; Tappin *et al*., 2011) stretching around the coastline of north and northeast Norfolk between Weybourne and Winterton-on-Sea and extending offshore between 15 and 45 km. The seabed geology of the mapping area was previously mapped at 1:250,000 scale with the resulting geological map published in the early 1990s (British Geological Survey, 1991). Between Happisburgh and Winterton-on-Sea, a zone 5 to 7 km wide parallel to the coastline has not been mapped due to the absence of modern, high resolution bathymetric data. The depth of the seabed generally deepens away from the coastline towards the north, northeast and east reaching a maximum observed depth of approximately 50 m in the east of the mapping area. Water depths across the Cromer Shoal chalk reef which occurs offshore from the modern coastline between Weybourne and Overstrand are typically 6-10 m. To the north and east of this chalk reef, the bedrock is buried beneath a veneer of natural superficial sediments which increase in thickness towards the northeast and east.

The sub-sections below provide a general geological context and summary descriptions of the key elements observed in the area covered by this dataset. A complete listing of mapped units and features may be found in Section 4.

3.2 BEDROCK GEOLOGY

Bedrock strata crop-out at seabed across much of the northern and central parts of the mapping area, although in places bedrock is covered by a thin and discontinuous veneer of superficial deposits and potentially mobile marine sediments (Figure 4). The geometry of bedrock across the map area is strongly influenced by the longer-term and more recent (neotectonic) structural evolution of the Southern North Sea Basin.

Bedrock crops-out extensively at seabed within the western and central parts of the mapping area forming a prominent offshore reef – Cromer Shoal, between Weybourne and Overstrand that extends farther offshore. The bedrock has been mapped and classified based upon seabed texture (Stewart and Coward, 1995), offshore cores (where available), and by correlation with onshore sequences.

The bedrock geology has been classified across the entire offshore mapping area as the Cretaceous age Chalk Group. Onshore Norfolk, the Chalk Group dips and gets younger towards the east and is defined as (oldest-youngest respectively): Cenomanian to Lower Campanian-aged Chalk (BGS onshore GeoIndex; Pearce et al., 2020). The Trunch Borehole, located near to the north Norfolk coast, contains ages from palynological events throughout the Cenomanian to Early Campanian and is a key referencing sequence (Pearce et al., 2020).

Such stratigraphic subdivisions within the Chalk Group in the nearshore area have not been mapped as part of this study due to the paucity of suitable core or borehole data and thus, the stratigraphy of the Chalk offshore from north Norfolk continues to remain enigmatic. From previous studies, it has been demonstrated that chalk within north Norfolk and the adjacent offshore area forms part of the 'Transitional Province', reflecting the progressive northwards evolution of chalk lithologies and stratigraphy between the Southern (southern England) and Northern chalk provinces (Yorkshire and Lincolnshire). Mortimore and James (2015) have suggested that the transitional chalks in the offshore mapping area possess a much closer affinity to chalks within the Chiltern Hills and west Norfolk than the Northern chalks that occur in Lincolnshire, Yorkshire and the adjoining offshore area.

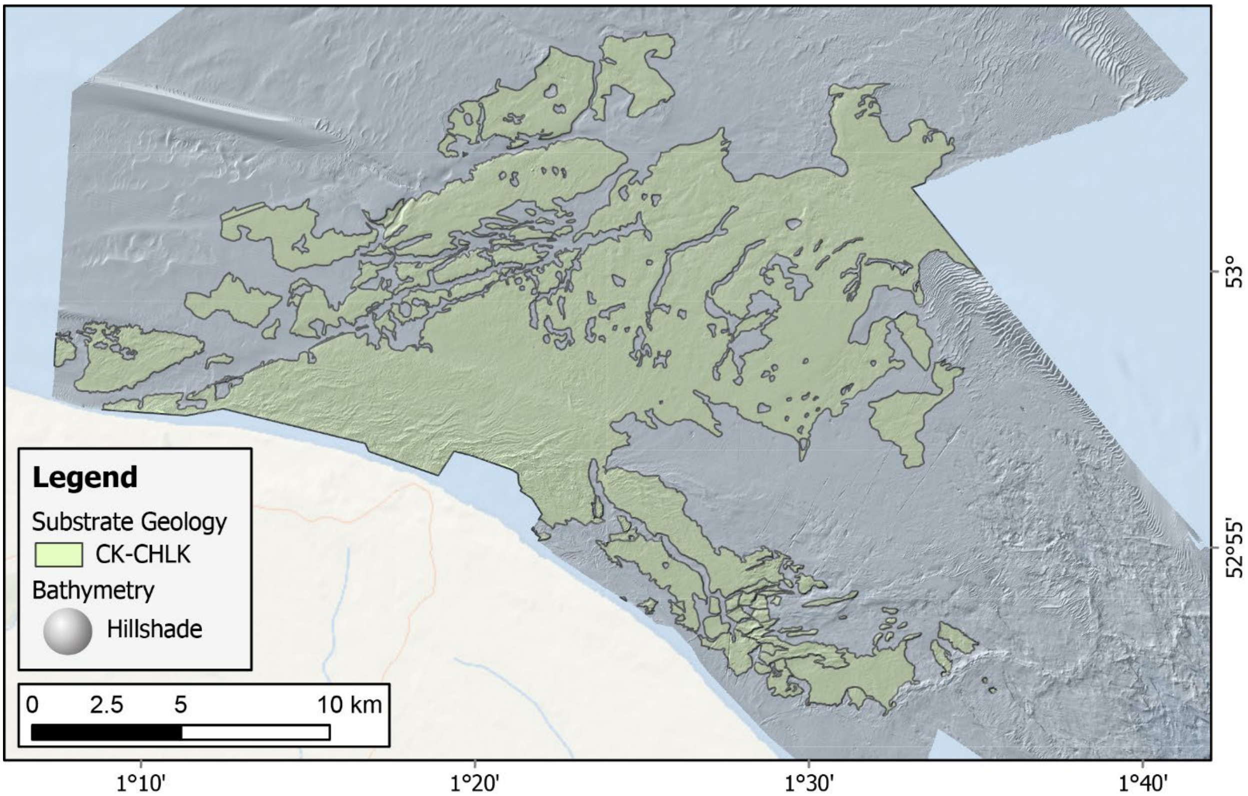

Figure 4. Extract of the BGS Seabed Geology: Offshore East Anglia, showing the mapped distribution of bedrock geology occurring at seabed within the dataset area draped over the hillshade derived from bathymetric data acquired by the MCA and Cefas © Crown Copyright 2024.

Chalk strata crop-out discontinuously onshore within coastal cliffs (where they are overlain by superficial deposits) and the beach foreshore at low tide between Weybourne and Overstrand. Onshore, Chalk strata strike broadly north-south and dip gently eastwards (<1°). However, the geometry of the chalk appears to change offshore and the primary bedrock structural fabric observed in the MBES appears to be orientated WSW to ENE.

3.3 SUPERFICIAL GEOLOGY

Superficial geology outcrops extensively at seabed within the survey area with two prominent domains of contrasting age separated by chalk reef – older preglacial and glacial deposits (Early to early Middle Pleistocene) in the south and much younger glacial and non-glacial (Late Pleistocene to Holocene) in the north (Figure 5). The geometry and distribution of the superficial deposits reflect the complex history of environmental change that has affected the mapping area and broader Southern North Sea region during the Pliocene and Quaternary. Patterns of environmental change are driven by longer-term neotectonic marginal uplift and basinal subsidence (Westaway, 2017; Lee *et al*., 2020) and the enhanced influence of global climate change (Lee *et al*., 2018). Owing to the shallow bathymetry of the SNS, cyclic changes in climate and sea-level have had a profound impact on palaeogeography and sedimentation patterns across the basin and especially within marginal areas like the current mapping area.

The geology of the SNS during the Early and early Middle Pleistocene (c.2.6 – 0.48 Ma) is dominated by the progressive shallowing and infilling of the basin caused by the progradation of large river-fed deltas emanating from the Baltic, central Europe (eastern side of the basin) and the UK (western side of the basin) (Cameron et al., 1992). Within the deeper southern and eastern parts of the mapping area, this is reflected by older deltaic (**Westkapelle Ground**

Formation) and younger 'non-marine' fluvial and estuarine sediments (**Yarmouth Roads Formation**) that progressively onlap the bedrock succession. This sequence reflects the increased ability of large river systems that drained adjacent eastern and central England (the Bytham and Kesgrave Thames rivers) at transporting coarse bedload through their catchments; the accretion of an eastwards-prograding coastal delta (sediment wedge), reduced accommodation space and fluctuating global sea-levels (Rose, 2009; Stoker *et al.*, 2011; Lee *et al.*, 2018).

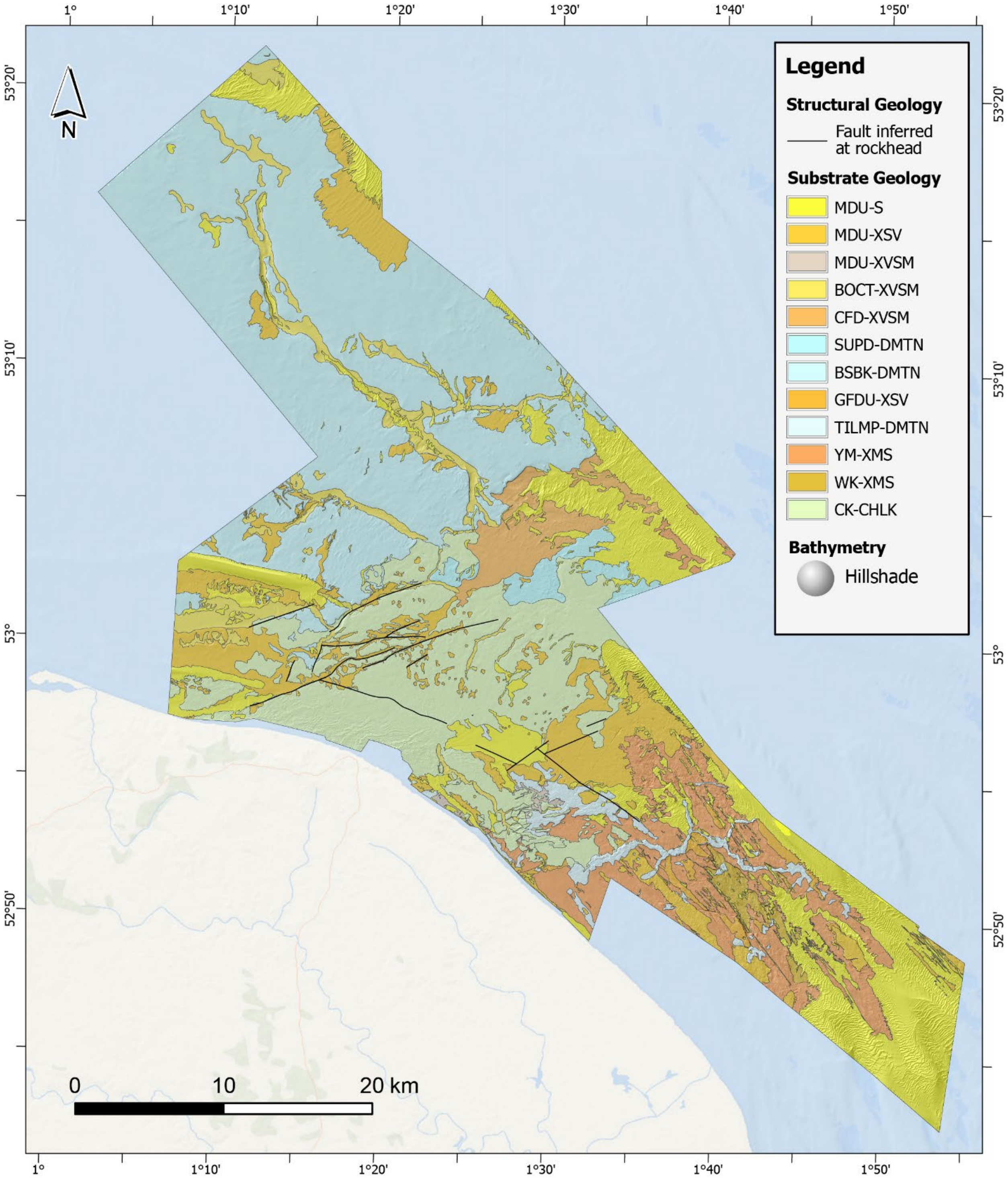

Figure 5. The Substrate Geology layer of the BGS Seabed Geology: Offshore East Anglia, showing the mapped distribution of superficial deposits within the dataset area.

Mapping is draped over the hillshade derived from bathymetric data acquired by the MCA and Cefas © Crown Copyright 2024. The Background image from World Ocean Base dataset compiled by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

Evidence for two separate phases of Middle and Late Pleistocene glaciation is recognised within the mapping area. The first corresponds to the Elsterian Glaciation (Anglian Glaciation; Marine Isotope Stage 12; c.0.48 – 0.43 Ma) of the late Middle Pleistocene, and the second, the Late Weichselian (Late Devensian Glaciation; Marine Isotope Stage 2; c.0.028 – 0.016 Ma). Whilst intervening Saalian glacial episodes have been recognised within the Norwegian, Danish, Dutch and German sectors of the North Sea, no tills relating to this glaciation have yet been recognised within the British sector.

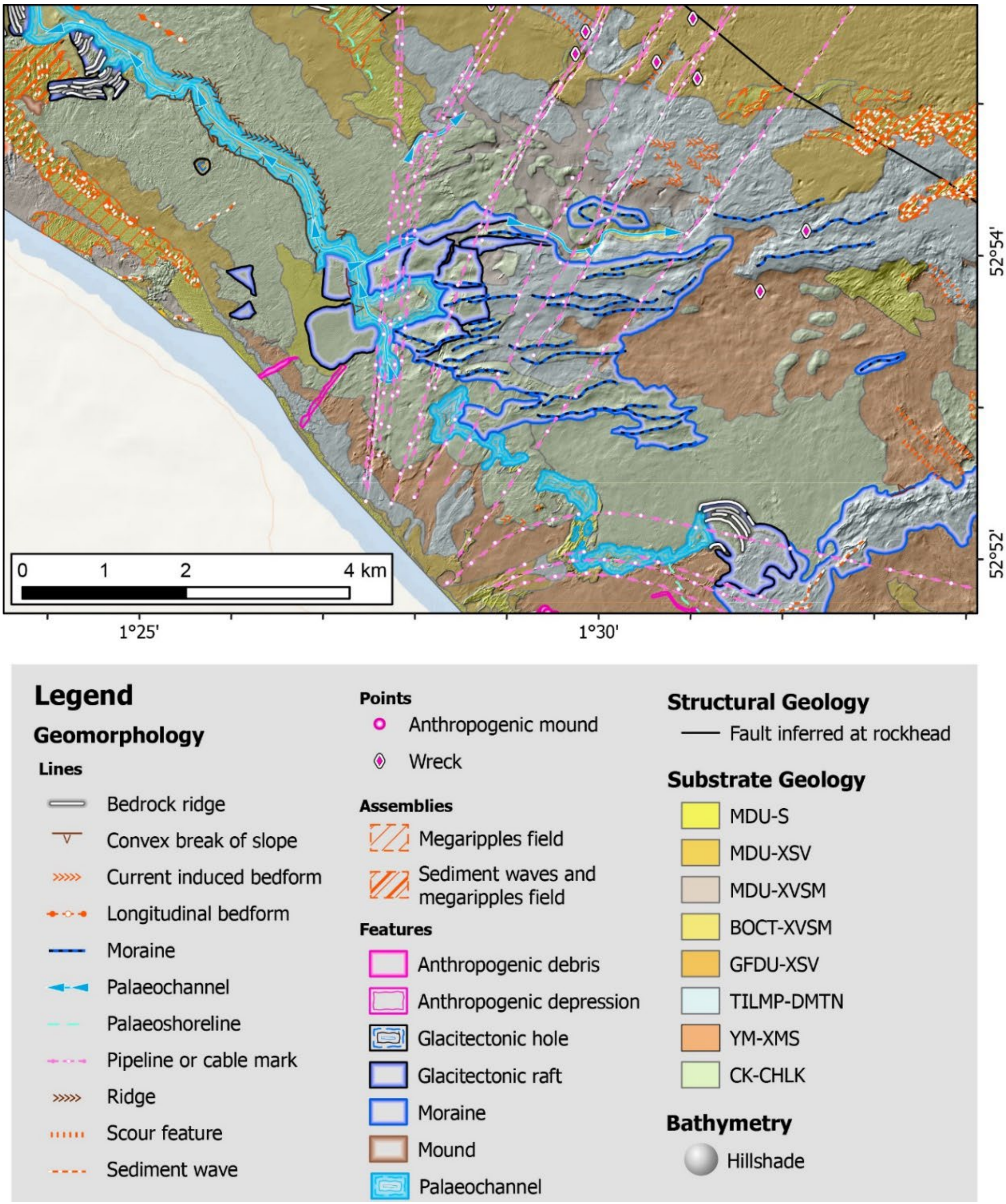

Figure 6. Extract of the layer of Substrate Geology of the BGS Seabed Geology: Offshore East Anglia digital map showing the mapped geology and a range of glacial landforms including glacitectonic rafts, scoured channels and moraines.

Mapping is draped over the hillshade derived from bathymetric data acquired by the MCA and Cefas © Crown Copyright 2024. The Background image from World Ocean Base dataset compiled by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

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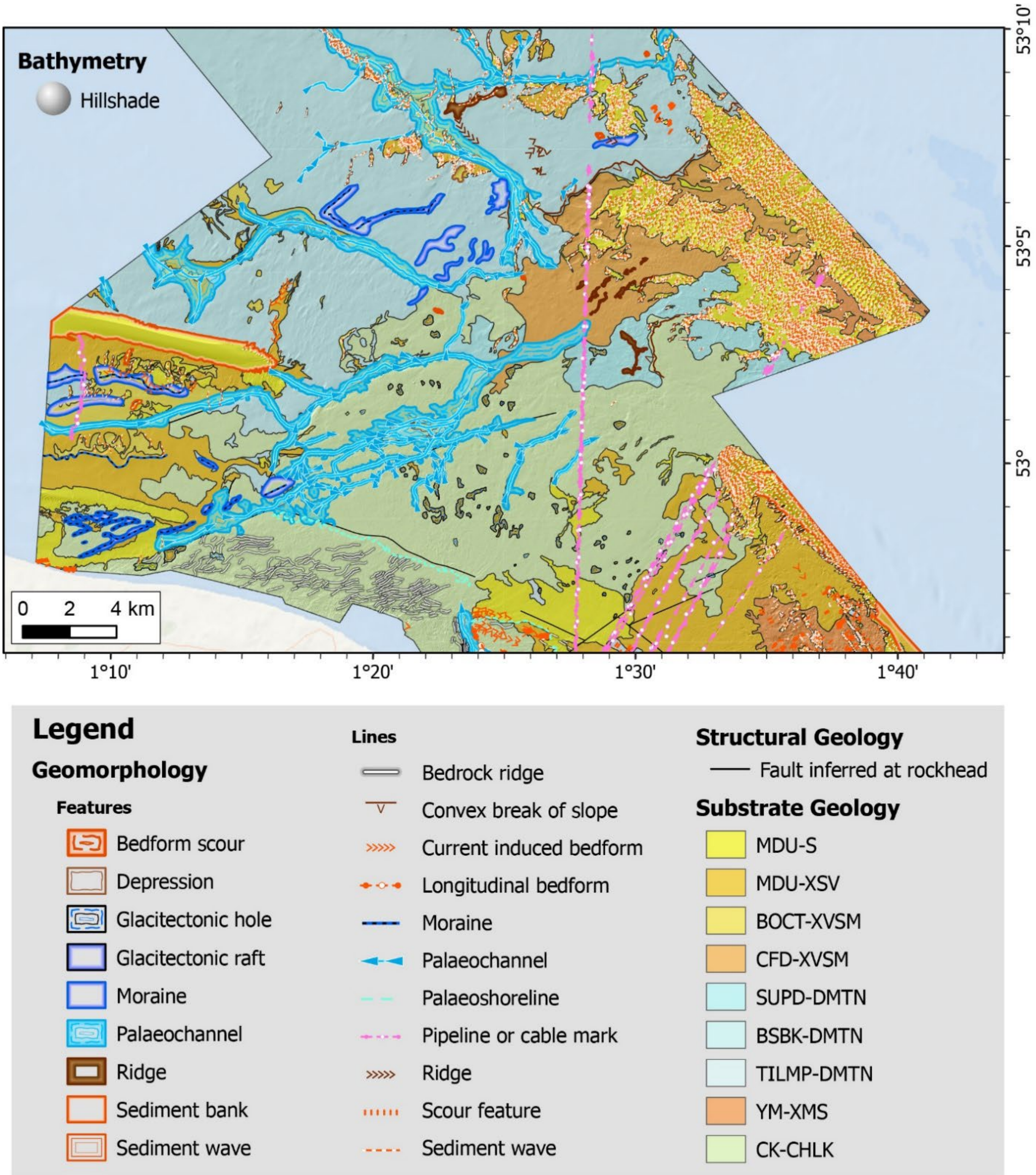

Figure 7. Extract of the layer of Substrate Geology of the BGS Seabed Geology: Offshore East Anglia digital map, showing the distribution of the Late Weichselian Bolders Bank Formation till sheet (BSBK-DMTN) and morainic landforms.

Mapping is draped over the hillshade derived from bathymetric data acquired by the MCA and Cefas © Crown Copyright 2024. The Background image from World Ocean Base dataset compiled by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

Indicative evidence for the Elsterian Glaciation is present within the mapping area. A major tunnel valley was incised to depths of more than -100 m offshore from Cromer extending to the northeast beneath the Dudgeon windfarm area but is largely infilled and concealed by more recent sediments and has minimal geomorphic expression within the seabed. Glacial landforms mapped in the study area related to the Elsterian Glaciation include meltwater channels, ice marginal moraines, imbricate thrust stacks of glacitectonic chalk rafts and glacitectonic hill-hole pairs (Figure 6). To the south of these landforms, occasional and discontinuous bodies of Middle Pleistocene till and glaciofluvial sand and gravel are interpreted to crop-out at seabed within the interfluve areas between extensive northwest-southeast trending scour features. These bodies of till and glaciofluvial sand and gravel are considered to have originally formed laterally persistent sheets that have been heavily dissected and eroded by scouring.

Evidence for the Late Devensian glaciation corresponds to the widely mapped occurrence of subglacial till (**Bolders Bank Formation**) at seabed, morainic landforms, and the development of numerous small meltwater channels (Figure 7). This map area includes what is interpreted to be the southern known extent of MIS 2 glaciation (i.e., the southern limit of Bolders Bank Fm) (e.g., Dove et al., 2017). The occurrence of other glaciations within the mapping area and adjacent northern East Anglia remains controversial. Currently, there is some potential evidence (albeit not mappable) for an intervening late Middle Pleistocene glaciation during MIS 6 that impinged on northwest Norfolk and the Fen Basin (Evans *et al*., 2019).

The Southern North Sea region remained emergent during the Late Devensian glaciation with deglaciation of the region occurring by about 17 ka (Evans *et al*., 2021). Despite rising post-glacial sea-levels, the area remained largely emergent until the early Holocene (c. 8 ka) when the entire continental shelf was drowned (Sturt et al., 2013). Fluvial and coastal conditions prevailed during this emergent interval with fluvial, lagoonal, and estuarine deposits (**Botney Cut Formation**) accumulating within low-relief areas of the post-glacial landscape. This now drowned offshore area is of high archaeological significance because it extends northwards into Doggerland an area of elevated relief during the Late Glacial and early Holocene, that captures the story of Mesolithic hunter-gatherers and how they adapted to rising sea-levels and changing climates (Gaffney *et al*., 2007; Brown et al., 2011; Emery et al., 2020; Waller and Kirby, 2021).Since the Holocene marine transgression (c.11-7 ka) and through to present times, this shallow subtidal region has been exposed to high-energy wave and tidal currents (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; Limpenny et al., 2011; Pye and Blott, 2015).

3.3.1 Substrate Geology - Superficial deposits

Westkapelle Ground Formation (WK) – Westkapelle Ground Formation has been previously mapped using shallow seismic data in the southern part of the mapping area (British Geological Survey, 1991) and its extent has been refined here where data is available. It has been interpreted to form a narrow coast-parallel zone of outcrop as well as cropping-out locally within bathymetric lows where overlying cover has been removed by scouring. Seismically, the unit is characterised by sub-parallel eastwards dipping bedding reflectors interpreted as a delta bottomsets.

Yarmouth Roads Formation (YM) – The Yarmouth Roads crops-out extensively in the southern and eastern part of the mapping area forming a wedge-shaped seismic body that overlaps the WK, thickening eastwards offshore. Seismically, the unit is characterised by broadly sub-parallel, horizontal reflectors interpreted as delta topsets. The upper boundary of the YM with overlying Holocene marine deposits is diffuse and gradational.

Swarte Bank Formation (SWBK) – There is no exposure of the SWBK interpreted within the mapping area, although it is expected to be present within large buried (e.g., below BSBK) subglacial tunnel valleys that occurs beneath Dudgeon. SWBK deposits elsewhere are defined by a variable and complex series of infill lithologies associated with several seismostratigraphic sub-units, including stiff to hard subglacial tills, glacifluvial sand lenses, glaciolacustrine muds, and marine clay with foraminiferal assemblages (e.g., Cameron *et al.*, 1992; Mellett *et al.*, 2013).

Till, Middle Pleistocene (TILMP) – TILMP has an extensive outcrop within the mapping area and occurs in two different bathymetric associations. Firstly, in the area extending offshore from Overstrand and Bacton, TILMP is interpreted to crop-out in areas of seabed associated with the development of W-E trending moraine ridges. The composition of TILMP is unknown but based on its association with the moraine ridges is likely to highly heterogeneous and may include masses of stiff to hard subglacial till, sand and gravel and thrust blocks of chalk bedrock. The second bathymetric association of TILMP occurs to the south of these moraine ridges, cropping out discontinuously within the flanks of the scoured seabed relief. The relatively smooth concavo-convex form of these ridges implies that TILMP is relatively thin (several metres thickness) and uniform in lithology. Based upon the known mapped extent of till units onshore, it is possible that this till unit is equivalent to either the Corton or Lowestoft Till members (c.f. Lee *et al.*, 2017).

Glaciofluvial deposits (GFDU) – sands and gravels of probable glacial origin that locally crop-out above (and occasionally below) TILLMP, forming discontinuous caps to several scoured ridges.

Bolders Bank Formation (BSBK) – The BSBK is the most extensive superficial unit cropping-out at seabed across much of the northern and western parts of the mapping area. The unit is composed of a reddish-brown to grey matrix-supported diamicton with a sandy clay matrix texture and numerous pebble to boulder sized clasts of chalk, flint, sandstone, mudstone and far-travelled crystalline erratic lithologies derived from northern and eastern UK. The unit is between 1-15 m thickness, thinning southwards towards its feather edge aligned broadly east-northeast to west-southwest across the mapping area. Along its southern feather edge, the unit is patchy and discontinuous, forming localised bedrock smears or interbedded with ice-marginal sands and gravels and muds. The BSBK is the offshore equivalent to the Holkham Till Member which crops-out discontinuously along the northern north Norfolk coast between Hunstanton and Salthouse (Moorlock *et al.*, 2008). It was deposited by the 'North Sea Lobe' of the Late Devensian British-Irish Ice sheet that extended south and southeastwards across the mapping area (Cameron *et al.*, 1992; Davies *et al.*, 2011; Roberts *et al.*, 2019). Dove *et al.* (2017) demonstrated that the BSBK is a composite unit composed of multiple overlapping till sheets/wedges that were deposited during successive advances of an oscillating ice margin.

Superficial Deposits (SUPD) – a thin and discontinuous unit overlying chalk bedrock that crop-outs along the southeastern edge of the BSBK till sheet comprising patchy diamicton, sand and gravel and clay. The genesis of this unit is unclear, but it is possible that it represents an assemblage of ice-marginal to proglacial glacigenic sediment.

Channel-Fill Deposits (CFD) – CFD crops-out within the northeastern sector of the mapping area, forming the upper infill to a deeply incised west-southwest to east-northeast trending channel/valley. This incised feature may be of glacial (i.e., tunnel valley or proglacial meltwater channel) or fluvial (i.e., emergent period prior to marine transgression) origin. Based on similar infilled incised channels/valleys elsewhere in the southern North Sea, valley infill may include marine sands and clays, fluvial/lacustrine deposits, and/or Botney Cut Formation (Cameron *et al.*, 1992; Tappin *et al.*, 2011).

Botney Cut Formation (BOCT) – Deposits from the BOCT infill glacial and post-glacial channels within this sector of the North Sea (Cameron *et al.*, 1992; Brown *et al.*, 2018). 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.

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 four separate classes of MDU deposits mapped (S, XSV, XSM, XSVM). 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. local rivers, E. Anglia 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;Limpenny et al., 2011; Pye and Blott, 2015; Almehmadi, 2022).

MDU deposits are distributed intermittently throughout the map area, with relatively coarser fractions (MDU-XSV) concentrated in the central sector atop the shallow Chalk platform as well as infilling shallow depressions and channels. Finer fractions (MDU-S) are commonly associated with current-induced bedforms (e.g., sediment waves and banks), and are the dominant substrate type in the far south of the map area.

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.

3.4 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).

3.4.1.1 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 either the Elsterian (Anglian) glaciation or the Late Weichselian (Devensian) glaciation of the Last 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 and temporary still-stand positions of former ice masses (Benn and Evans, 2014). Due to the complex processes of moraine formation and materials that they are formed from, they are typically heterogeneous in composition containing a range of coarse sediment fractions (up to boulders) and imbricate stacks of glacitectonic rafts.

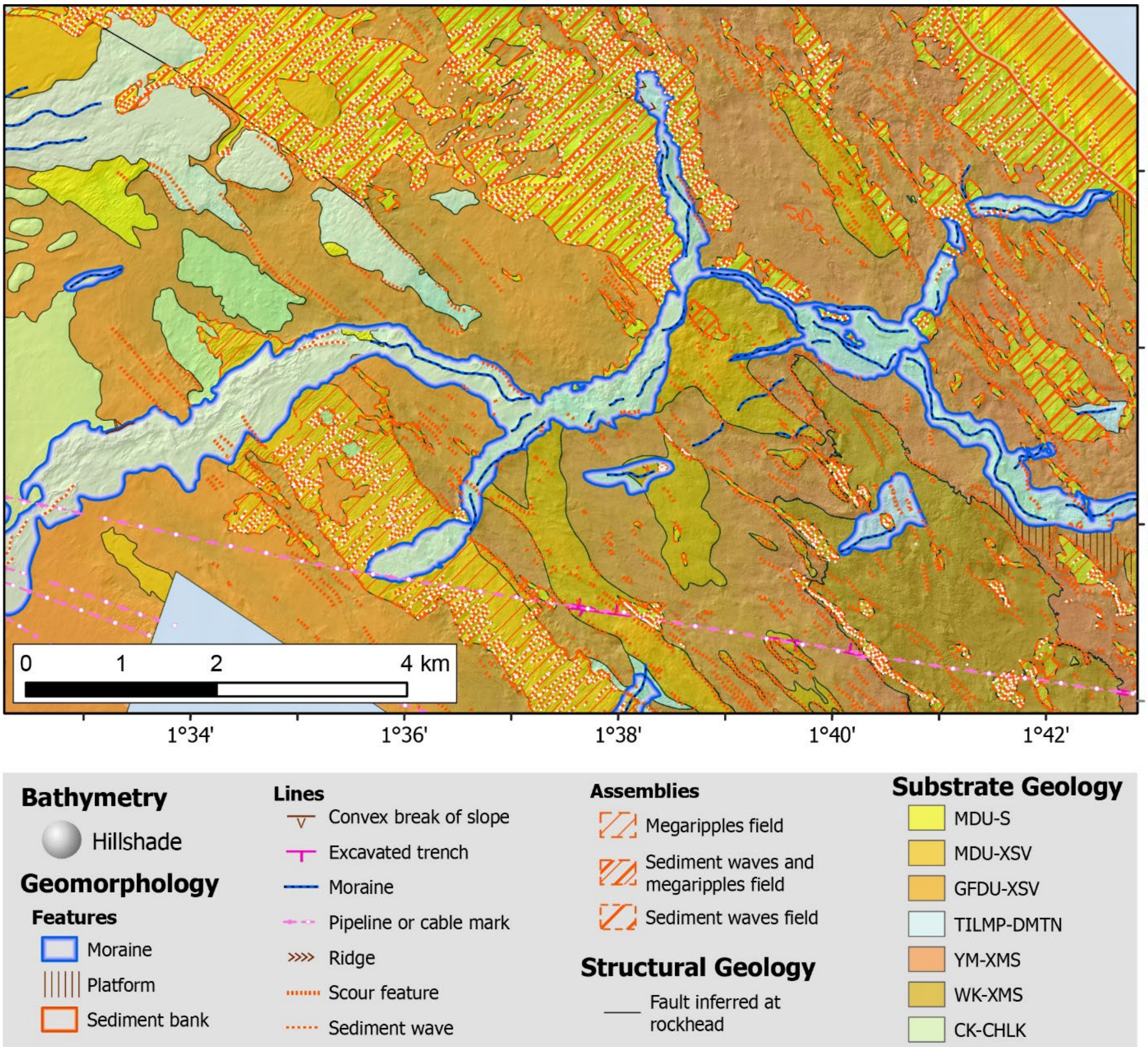

Figure 8. Hybrid geological and morphological map showing the mapped substrate geology a mapped offshore moraine feature possibly of late Middle Pleistocene age.

Mapping is draped over the hillshade derived from bathymetric data acquired by the MCA and Cefas © Crown Copyright 2024.

Moraines have been mapped in several locations within the mapping area but broadly form two mappable zones. In the north and northwest of the mapping area, several linear bands of low-relief arcuate morainic ridges have been mapped aligned broadly WSW to ENE. These moraines are of Late Weichselian age and are associated with broad, overlapping till wedges of BSBK which they are superimposed upon (Dove *et al*., 2017). These moraines formed at the margins of the 'North Sea Lobe' of the Last British-Irish Ice Sheet, from ice derived in central and eastern Scotland that extended southwards over the floor of the North Sea which was dry at the time of glaciation. The moraines mapped within the study area record the southern-most known offshore extent of this ice lobe (Dove *et al*., 2017) and can be linked to other ice-marginal features onshore in north and northwest Norfolk (Roberts *et al*., 2019; Evans *et al*., 2019, 2021). The northwards succession of these Late Weichselian morainic ridges is interpreted to represent the stepwise retreat of the ice margin during 'active retreat'.

Moraine ridges have also been mapped farther to the south, forming a broad group of low-moderate relief arcuate landforms that extend offshore from Mundesley and Paston (Figure 8). These morainic ridges are interpreted to be significantly older (Elsterian), representing the heavily eroded offshore remnants of an ice margin and successive phases of ice marginal retreat associated with a southward expansion of the British-based ice into the North Sea (Lee *et al*., 2017). They are anticipated to be variably composed of till and / or thrust-stacked glacitectonic rafts and broadly trend west-southwest to east-northeast.

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. However, in many cases, they have been subsequently utilised and modified by post glacial drainage and marine scouring.

There are no conspicuous tunnel valleys exposed within across the seafloor within the mapping area. However, a major tunnel valley in excess of 100 m deep occurs beneath the Dudgeon Windfarm to the north-northeast of Cromer. Trending southwest-northeast the valley is typically infilled by Channel-Fill Deposits passing westwards into Botney Cut Formation.

Glacitectonic Holes and Rafts:

Glacitectonic Rafts are slabs of bedrock and/or unconsolidated sediment that have been detached and transported down-ice by glacier ice. *Glacitectonic Holes*, by contrast, correspond to the areas of substrate where the rafts have been derived from. Both occur extensively within the central parts of the survey area offshore from Sheringham, Cromer and Mundesley with rafts occurring either individually, as clusters, or forming imbricate thrust stacks and forming morainic landforms.

Scour feature (break of slope):

Scour features occur extensively across the central and southern parts of the mapping area and correspond to areas where the superficial geology (glacial and preglacial sediments) has been subjected to significant scouring. They are mapped as lines that correspond to northwest-southeast trending breaks (concave to convex) breaks of slope. The precise origin of the scours remains unclear; however, the cross-cutting relationship of these features to other seabed features suggests that they postdate the deposition of the Middle Pleistocene till but originally predate the development of the Elsterian-age moraines. One possibility is that scouring was caused by glacial meltwater activity (e.g. an outburst flood), with the relief modified by Late Pleistocene environmental dynamics and potentially amplified by more recent (Holocene) scouring by energetic tidal currents.

3.4.1.2 Fluvial / glaciofluvial features

Palaeochannels:

Palaeochannels are relict glacial, fluvial and/or coastal channels indicative of former subglacial and/or subaerial or potentially intertidal drainage conduits. Many palaeochannels are polyphase and appear to have been active several times since their generation, sometimes with opposing directions of drainage. 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). Numerous distinctive palaeochannels occur within the northern and central parts of the mapping area. This includes a major linear to slightly sinuous channel that extends south-southeast to north-northwest adjacent to the Dudgeon and Sheringham Shoal windfarms that is variably infilled by Botney Cut Formation and / or marine sand. It is tentatively interpreted as a subaerial drainage channel. Further to the south, a shallow, broadly trellis shaped palaeochannel network is incised into the chalk bedrock extending west-southwest to east-northeast offshore from Sheringham. These channels are infilled by marine sand and gravel and appear to be incised along joint or fracture sets within the chalk bedrock.

3.4.1.3 Coastal features

<u>Palaeoshoreline</u>

Several linear concave-convex slope breaks are evident within the MBES bathymetry, 4-5 km offshore and reflect subtle steps of upto 2.5 m in the elevation of the bedrock surface. These are tentatively interpreted to represent an earlier Holocene shoreline.

3.4.1.4 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).* 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 transgression shelf seas during the global Holocene sea-level rise (Sturt *et al*., 2013). The region's large *Sediment Banks* may have initially formed earlier in the Holocene, as higher tidal energy environments (required for sediment bank formation) are predicted 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).

<u>Sediment banks:</u>

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, Horillo-Carabello and Reeve, 2008).

Several sediment banks have been observed and mapped within the mapping area. The banks are regionally part of the Norfolk Banks system (e.g., Cooper et al., 2008). In the far north of the mapping area, the mapping captures the southwestern portion of Cromer Knoll. Approximately 10.5 km to the north of the north Norfolk coast, Sheringham Shoal is a large west-east trending sediment bank. Further to the southeast, located approximately 13 km offshore from Bacton, and oriented northwest-southeast, is the western flank of Haisborough Sands. Offshore from Winterton-on-Sea (8 km), and in the far south of the mapping area is an additional sequence of sediment banks including the northern components of Middle Cross Sand and the Newarp Banks. These, together with Haisborough Sands, form part of the 'Haisborough, Hammond and Winterton' Special Area of Conservation (SAC). Located farther offshore, and trending north-northeast beyond the limit of the mapping area are the Northern Norfolk Sandbanks. This series of banks comprises 10 sub-parallel linear sediment banks and correspond to the largest offshore group of linear sediment banks in UK waters. They are designated a Marine Protection Area (MPA) and a further SAC.

Sediment waves:

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 the 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, Nanson et al., 2023).

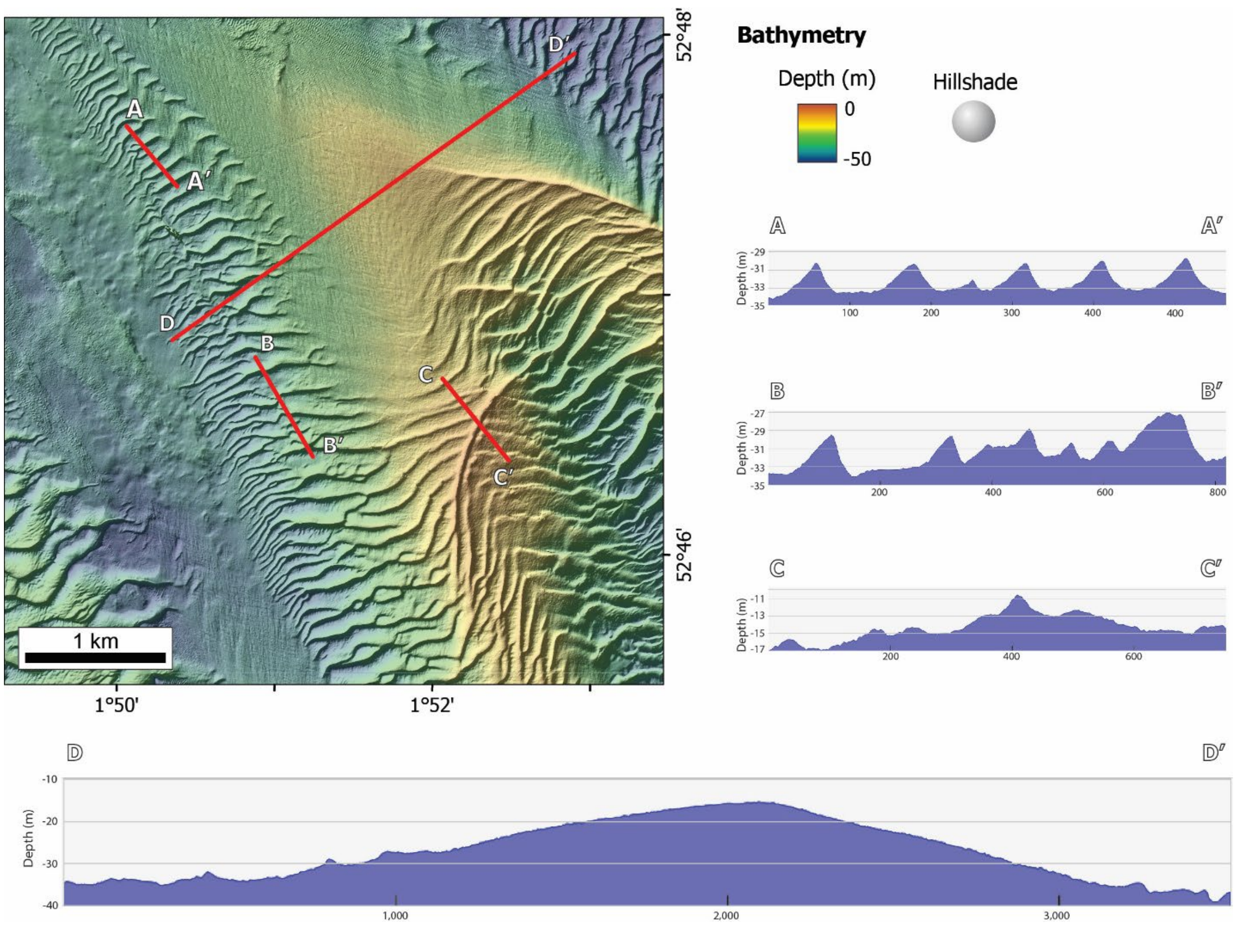

Figure 9. A morphologically distinct area of seabed with well-developed sediment waves superimposed upon a larger sediment bank. Cross-profiles demonstrate the asymmetrical morphology of the sediment waves, some of which are up to 7m height.

Sediment waves occur widely within the mapping area either individually or coexisting with other current-induced bedforms such as megaripples (*Sediment waves and megaripples)* or sediment banks. Individual sediment waves typically exhibit a variable relief with examples occurring offshore from 5 km offshore from Weybourne, and extensively (with sediment banks) offshore from Sea Palling, Waxham and Winterton-on-Sea. Sediment waves and megaripples are also common, occurring 3 and 9.5 km offshore from Weybourne – in the case of the later, possibly superimposed upon a moraine. Sediment waves and megaripples occur more extensively in the vicinity of Dudgeon Windfarm and approximately 9 km offshore from Walcott. 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. Sediment wave orientation in the central and southern sectors of the map area suggest that dominant current flows are approximately coast-parallel.

Megaripples:

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-linguoidal 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, but also as fields of variable spatial extent.

3.4.1.5 Anthropogenic

Anthropogenic features are mapped where they have a clear bathymetric expression, and/or impact the immediately surrounding seabed morphology (e.g., Bedform scour, Excavated trench). 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 to onshore infrastructure (e.g., offshore wind farms, gas fields).

Excavated trench:

Trenches that have been excavated for offshore infrastructure include drainage outfalls, pipelines and cables.

Anthropogenic debris:

Areas of placed anthropogenic debris.

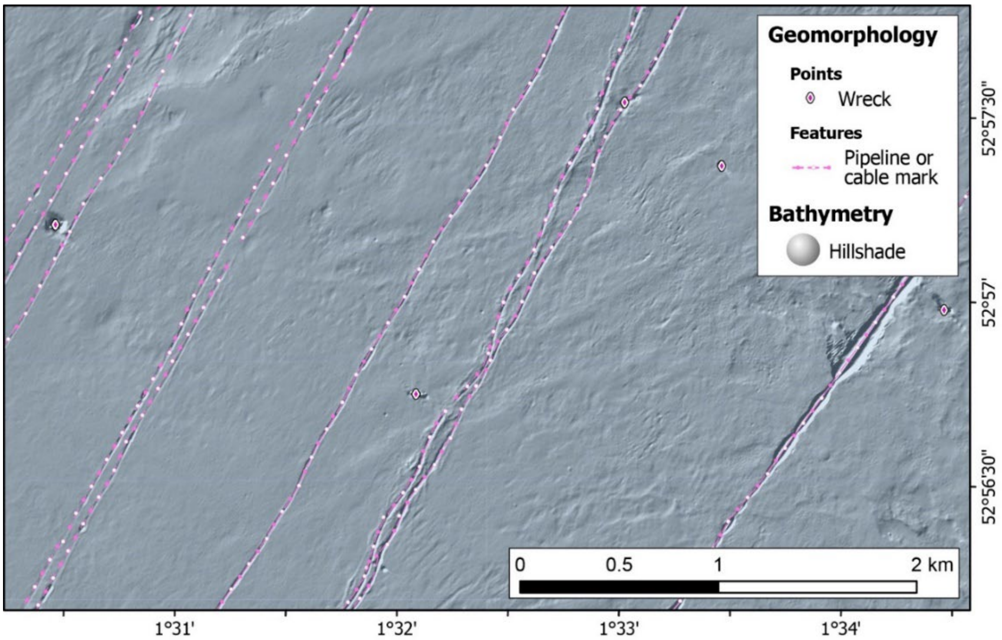

Figure 10. An area of mapped seabed which has been modified by anthropogenic activity including the location of wrecks and pipeline or cable mark features.

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4 Technical Information

4.1 SCALE

This dataset is produced for use at a scale between 1:10,000 to 1:50,000. The multibeam data was used with a 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: Offshore East Anglia map covers an area of approximately 1,445 km^2 off the north and east coast of Norfolk, extending in the nearshore around the coastline from Weybourne in the north, to near Winterton-on-Sea in the southeast (Figure 11).

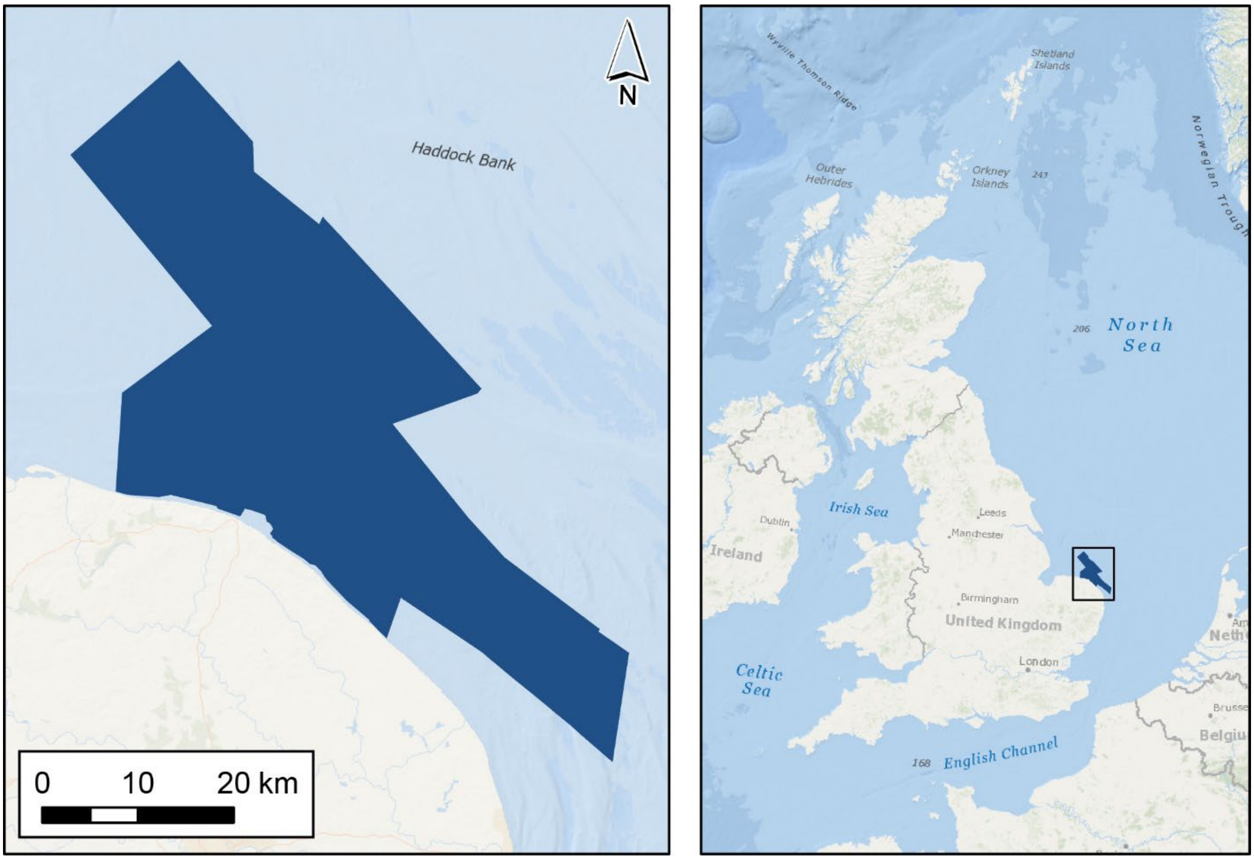

Figure 11. Coverage of BGS Seabed Geology =: Offshore East Anglia shown in dark blue. Background image from World Ocean Base dataset compiled by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

4.3 ATTRIBUTE DESCRIPTION

Each geological theme (map layer) in BGS Seabed Geology: Offshore East Anglia 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: Offshore East Anglia.

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: Offshore East Anglia.

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 that can be found in the different Geomorphology layers of the BGS Seabed Geology: Offshore East Anglia.

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: Offshore East Anglia 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* layers (two comprised of polygons, 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: Offshore East Anglia digital map was created in 2024. 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	LOOKS LIKE
MDU-S	255	255	0	#FFFF00	
MDU-XSV	255	201	0	#FFC900	
MDU-XVSM	224	201	176	#E0C9B0	
BOCT-XVSM	255	237	54	#FFED36	
CFD-XVSM	255	176	54	#FFB036	
SUPD-DMTN	176	255	255	#B0FFFF	
BSBK-DMTN	201	255	255	#C9FFFF	
GFDU-XSV	255	176	0	#FFB000	
TILL-DMTN	0	12	0	#E0FFFF	
YM-XMS	255	148	54	#FF9436	
WK-XMS	224	176	0	#E0B000	
CK-CHLK	224	255	176	#E0FFB0	

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

FEATURE_D	Symbol
Fault inferred at rockhead	

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

FEATURE_D	Symbol
Bedrock ridge (crestline)	
Current induced bedform (crestline)	
Excavated trench (break of slope)	
Longitudinal bedform (centreline)	
Moraine (crestline)	
Palaeochannel (thalweg)	
Palaeoshoreline	
Pipeline or cable mark (centreline)	
Scour feature (break of slope)	
Sediment wave (crestline)	
Slide lateral scarp	
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	
Anthropogenic depression	
Bedform Scour	
Depression	
Glacitectonic hole	
Glacitectonic raft	
Moraine	
Mound	
Palaeochannel	
Platform	
Ridge	
Sediment bank	
Sediment wave	
Slide (surface)	

Table 9. Symbology intended for the Geomorphology assembly (polygons) layer based on field "FEATURE_D".

FEATURE_D	Symbol
Megaripples field	
Sediment waves and megaripples field	
Sediment waves field	
Reef field	

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

FEATURE_D	Symbol
Anthropogenic Mound	
Anthropogenic Depression	
Depression	
Wreck	

5 Limitations

5.1 DATA CONTENT

The BGS Seabed Geology: Offshore East Anglia 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 is published at 1:10,000 scale and is viewable at between 1:10,000 and 1:50,000 scale. 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. It is recommended that users do not over-enlarge the data; for example, do not use 1:10,000 nominal scale data at 1:50,000 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 mapped at scales between 1:5,000 to 1:8,000. 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 sediment 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: Offshore East Anglia 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 maximum scale of 1:10,000 scale. Users should be aware that geological maps are a compilation of inferred and interpreted 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 (digitaldata@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 northern East Anglia. 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.

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.

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

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