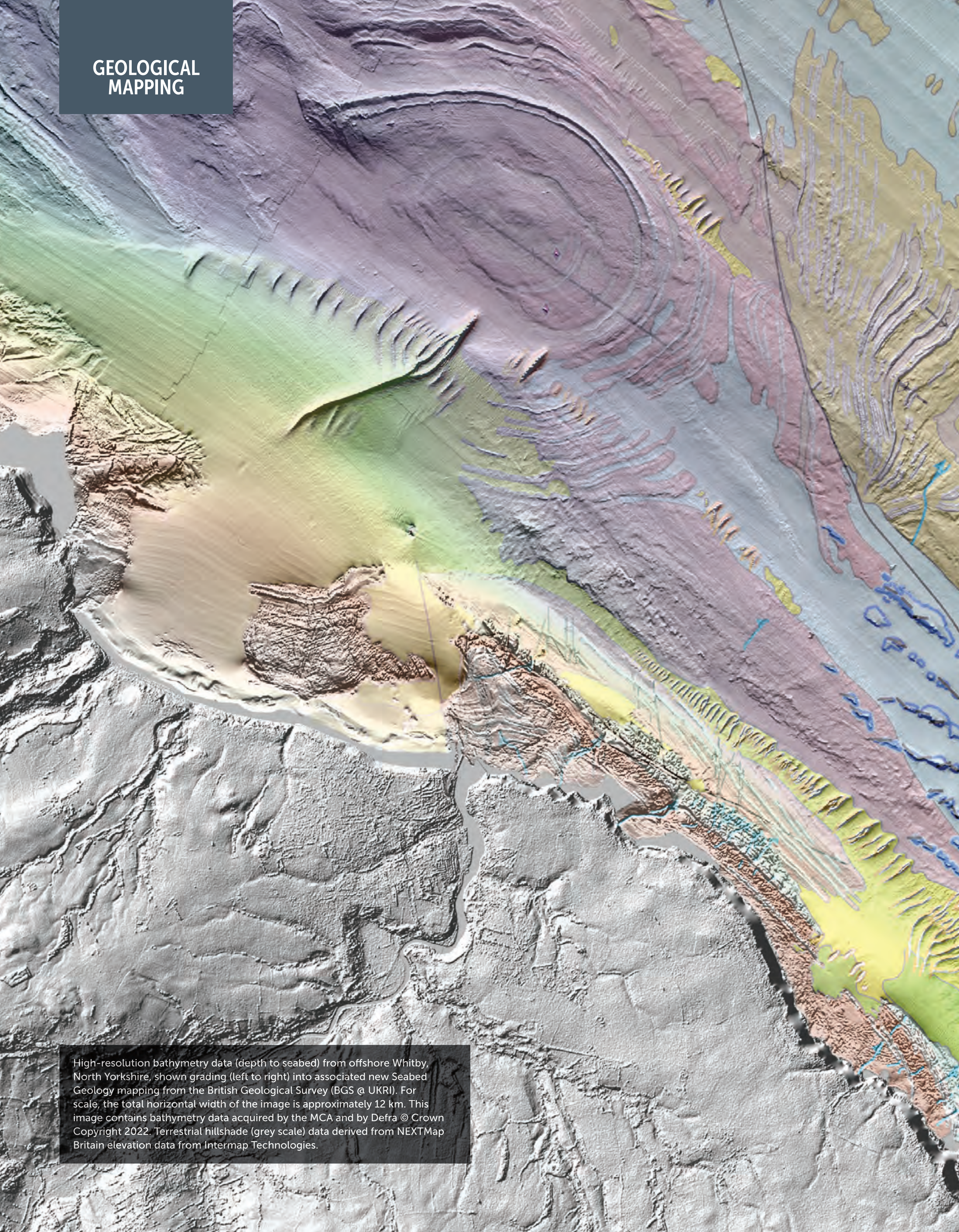
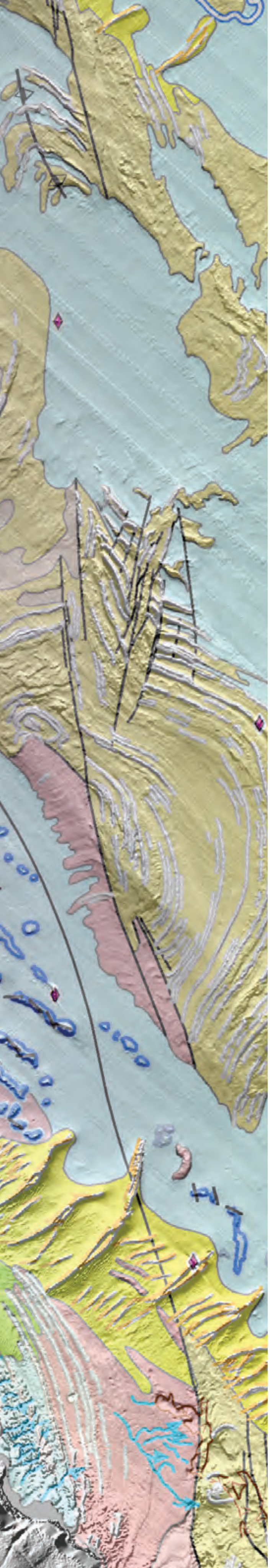


High-resolution bathymetry data (depth to seabed) from offshore Whitby, North Yorkshire, shown grading (left to right) into associated new Seabed Geology mapping from the British Geological Survey (BGS @ UKRI). For scale, the total horizontal width of the image is approximately 12 km. This image contains bathymetry data acquired by the MCA and by Defra © Crown Copyright 2022. Terrestrial hillshade (grey scale) data derived from NEXTMap Britain elevation data from Intermap Technologies.



LAND BELOW SEA: A NEW GENERATION OF SEABED GEOLOGY MAPPING

Spurred on by the increasing availability of high-resolution bathymetry data, as well as growing awareness in the importance of the seabed environment, Dayton Dove and colleagues discuss an initiative to renew mapping of the seabed geology around the UK

THERE IS A RACE ON within the UK's offshore environment. As the transition to renewable energy and net zero gathers pace, initiatives focused on resource development, conservation and climate change, scientific research, and marine management, are all hastening towards their own internal, shared, and at times conflicting objectives (see box 'Importance and competing uses', p 19).

Despite its rapidly accelerating use, the seabed is poorly surveyed globally. Substantial effort and investment are increasingly being directed towards acquiring accurate, high-resolution bathymetry data around the world (Wölfl et al., 2019) (see box 'A coordinated approach', p 20). While bathymetry data alone provide a fundamental metric for many marine studies and applications, geoscientists can add significant value by providing further data, analysis, and knowledge to better characterise the seabed. This may include information on the origin and evolution of seabed features and geological deposits, indicators of environmental change, descriptions of physical and biogeochemical properties, and active seabed dynamics and stability. Here we discuss the British Geological Survey's (BGS) Seabed Geology mapping programme on the UK's continental shelf (www.bgs.ac.uk/datasets/bgs-seabed-geology). This initiative is the first BGS effort to consistently characterise the geology of the UK's seabed in more than 25 years and aims to inform a diverse range of offshore activities and applications.

Mapping approach

The last systematic geological mapping of the UK's continental shelf was undertaken between the 1970s and early 1990s to support oil and gas development. With the need to meet current (and future) decarbonisation and marine science →

challenges, BGS scientists are utilising new high-resolution bathymetry datasets (and other supporting data) to develop fit-for-purpose geospatial products as part of the BGS's strategic role as the UK's national geological survey.

To produce detailed, accurate, digital seabed geological maps, we incorporate both traditional and innovative mapping methods (BGS, 2023). The mapping workflow involves analysis and interpretation of high-resolution multibeam echo-sounder (MBES) bathymetry datasets alongside supporting data and information, (e.g., MBES backscatter, seismic profiles and physical samples such as grabs, cores, and boreholes), academic and publicly accessible industry literature, and previous BGS onshore and offshore mapping. The MBES bathymetry datasets were primarily acquired by the UK Civil Hydrography Programme surveys managed by the Maritime and Coastguard Agency, and delivered in partnership with the UK Hydrographic Office (Fig. 1). These data are uniquely adapted, particularly when integrated with supporting data, to provide extraordinary insights into the often-complex geology and geomorphology of the seabed, as well as active environmental processes (Fig. 2).

Geological linework is captured using both manual digitisation and semi-automated processes (e.g., incorporating machine learning), with the latter employed (where suitable) to improve mapping accuracy and efficiency, as well as to reduce user bias. By applying a consistent approach nationally, the maps are intended to provide a unique resource to inform on the range of pressing issues within the marine environment.

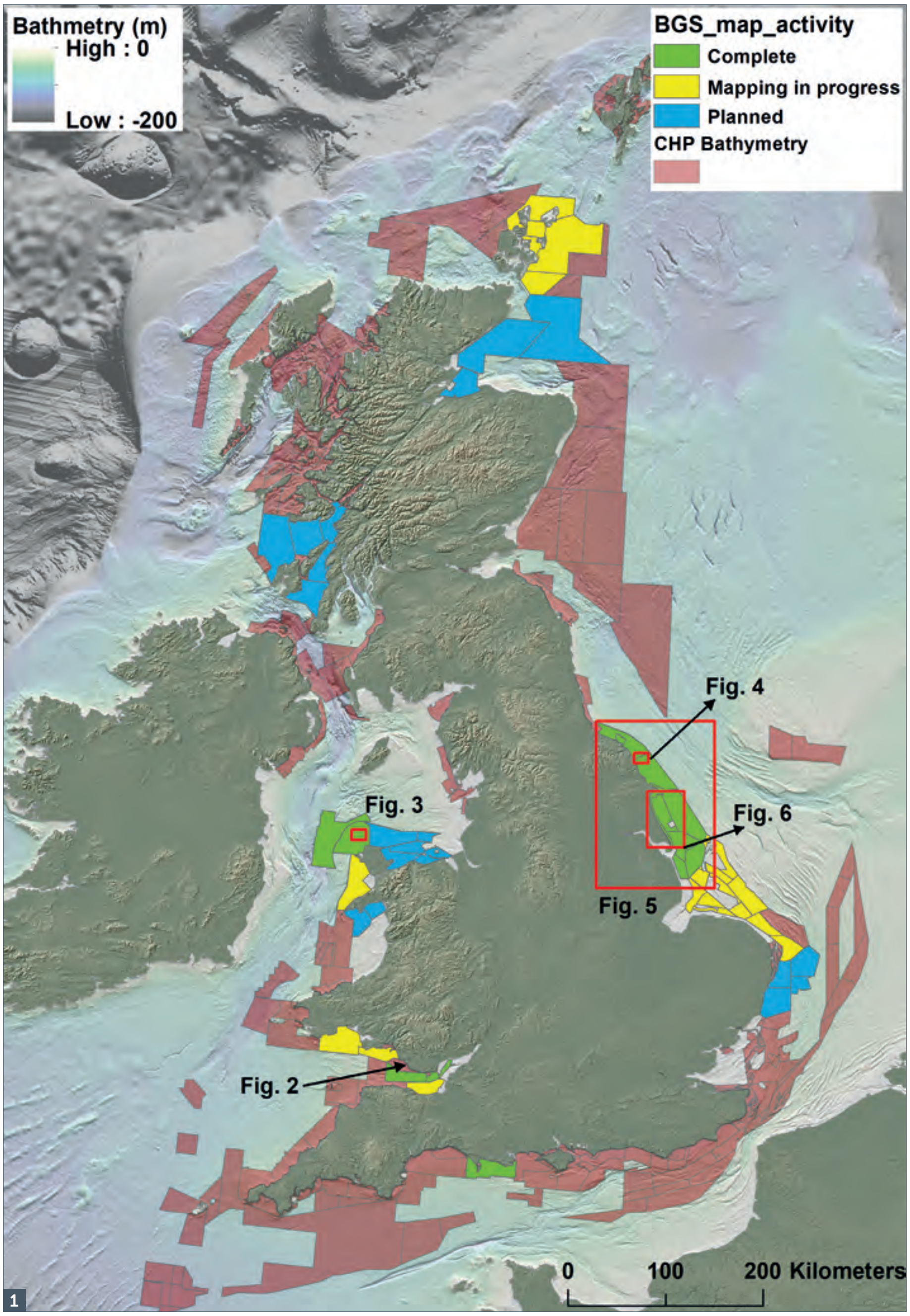


Figure 1: Location map showing BGS Seabed Geology mapping areas, as well as bathymetry survey areas of the UK's Civil Hydrography Programme (CHP). Regional bathymetry sourced from EMODnet Bathymetry (© European Union, available under the CC BY 4.0 licence).

Multi-faceted characterisation

BGS experience in a range of applications has demonstrated that effective, multi-faceted characterisation of the seabed and shallow subsurface requires a good understanding of both the environmental origin and evolution of features and deposits. So, we use the novel integration of three composite layers – seabed geomorphology, substrate geology, and structural geology (Figs. 3-5) – in a combined mapping approach that informs on the environment and age in which geological units originated, compositional properties of the material, and the relative stability (or vulnerability) of deposits and features at or near seabed.

Seabed geomorphology

This layer classifies the physical morphology and interpreted geomorphic →

IMPORTANCE AND COMPETING USES

The seabed is the fundamentally important interface between the water column and the geological subsurface. Around the UK, it records a range of past and active geological and environmental processes that have operated over multiple timescales (Micallef et al., 2018), including tectonism, glaciation and sea-level change, as well as modern hydrodynamics, active sediment transport, and responses to anthropogenic activity. Through playing host to interactions between physical, chemical, and biological processes, the seabed and shallow subsurface have a significant influence on the character and distribution of marine ecosystems, and because of their variable properties, directly impact and constrain many human activities.

In the UK, perhaps most notably there is an urgency to establish new offshore renewable energy capacity to help meet domestic energy demand and enhance energy security, while also progressing towards net-zero targets (The Crown Estate, 2021). In a further attempt to reduce carbon emissions to the atmosphere, burgeoning carbon capture and storage initiatives are employing expertise and technology in the offshore sub-surface. This is set against a backdrop of continued offshore activities, including oil and gas and aggregates extraction, active fisheries, shipping, as well as recreational use.

With increasing use of the marine environment, and growing awareness of the importance of marine ecosystems (Sala et al., 2021), marine scientists are working to better understand natural systems and their interactions with human activities and to translate this knowledge to inform policy. Seeking to effectively balance human activities and conservation requirements, marine planners employ mechanisms such as Marine Protected Areas to help facilitate the UK's vision of 'clean, healthy, safe, productive and biologically diverse seas'.

The familiar issues of coastal change, hazard mitigation, and natural resource assessment will continue to challenge scientists, developers, and managers (not to mention individuals and communities), but increasing attention is now being devoted to relatively new topics such as 'Blue Carbon', with the overarching goal of understanding the marine contribution of carbon storage versus emissions in seabed sediments and coastal wetlands, for example (Legge et al., 2020). Addressing these complex challenges requires effort from across numerous science and engineering disciplines, together with innovative commercial development, community engagement, and effective regulation and policy.

Highlighting its importance, is that each of the challenges and activities described above incorporate considerable interaction with the seabed, and therefore carry significant dependence on the nature and properties of it.

character of the seabed. The science of geomorphology addresses the general configuration of Earth's surface, in this case within a submarine setting, with the purpose of describing the nature and distribution of landforms/bedforms, and their relationship to the underlying geology as well as the overlying (and dynamic) body of water. Such classification can enable the detailed interpretation of the environmental origin and evolution, compositional character, and potential mobility or vulnerability of seabed features.

Our workflow follows a two-part approach, with descriptions of both 'morphology', and 'geomorphology' (Nanson et al., 2023). Morphological features are those characterised only by the surface (seabed) expression of their physical attributes (i.e., size, shape, configuration, texture), whereas geomorphological features are defined by the geological process(es) that are interpreted to have created that morphology.

Substrate geology

This layer reveals the distribution of bedrock and superficial deposits interpreted to be dominant within the top one metre below the seabed. The 'one-metre principle' allows characterisation of the geological substrate present below the frequently thin and potentially ephemeral seabed sediment layer (akin to the onshore soil layer that is generally not shown on BGS maps onshore). The one-metre principle involves an element of interpretation, but importantly also relies on direct observations in the MBES and further supporting data (e.g., cores and seismic data).

Mapping of seabed sediment is common practice and has been well developed and applied towards benthic habitat mapping, but the purpose of substrate mapping here is to capture the seabed and shallow sub-surface geology in new ways. Where active marine sediments are thicker than one metre, the substrate geology mapping will reflect this. Elsewhere, mapping will portray the geological unit that is either present at seabed or sub-cropping the thin seabed sediment veneer.

In using this approach, we are able to capture the shallow geological units that will be encountered by development activities, and describe the units exposed at seabed when the thin seabed sediments are mobilised or removed by current action (e.g., over tidal and storm cycles, or resulting from potential changes in wave energy due to climate change). Mapped substrate geology units include attribution to describe both their stratigraphy, age and lithological composition.

Structural geology

This layer delineates the principle structural features such as faults, folds, or fractures observed at rockhead within the MBES bathymetry data. 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, but also where thin superficial deposits are mapped over the bedrock surface. These elements provide evidence of structural evolution and tectonism, and aid interpretation of rock and engineering properties (e.g., relevant to offshore renewables as well as potential carbon capture and storage development).

Limitations and uncertainties

The mapping approach is in-part empirical and ultimately constrained by data availability and quality, as well as the tacit knowledge of the geoscientist(s).

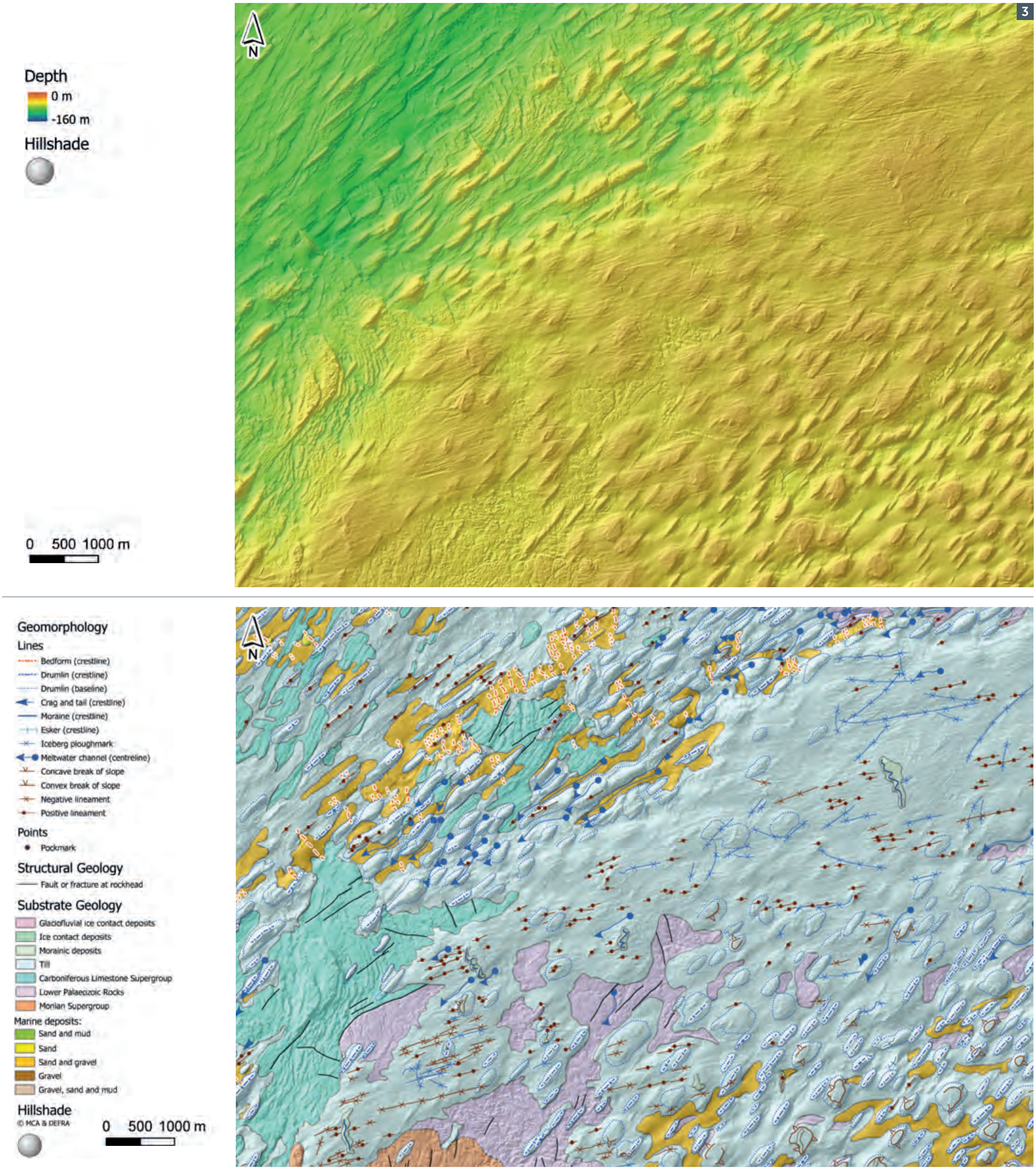
Figure 2: Limestones and shales of Porthkerry Member at Dunraven, adjacent to the Bristol Channel map area (BGS © UKRI). The high-resolution bathymetry imagery enables bedding and structural features like this to be visualised widely across the seabed.

A COORDINATED APPROACH

The UK Centre for Seabed Mapping (UK CSM; www.admiralty.co.uk/uk-centre-for-seabed-mapping) was launched in June 2022 and is administered by the UK Hydrographic Office. Composed of numerous public and government organisations, including the BGS, the UK CSM aims to establish a collaborative and unified approach to the collection and management of, as well as access to, seabed mapping data.

The UK CSM supports the UK Government's commitment to the UN Ocean Decade (oceandecade.org) and The Nippon Foundation-General Bathymetric Chart of the Oceans Seabed2030 Project (seabed2030.org), which aims to accurately map the global seafloor by 2030.

Figure 3: Example high-resolution bathymetry data (top panel) and resulting Seabed Geology (bottom panel) from offshore Anglesey (BGS @ UKRI). This image contains bathymetry data acquired by the MCA © Crown Copyright 2022, available under the Open Government Licence v3.0.



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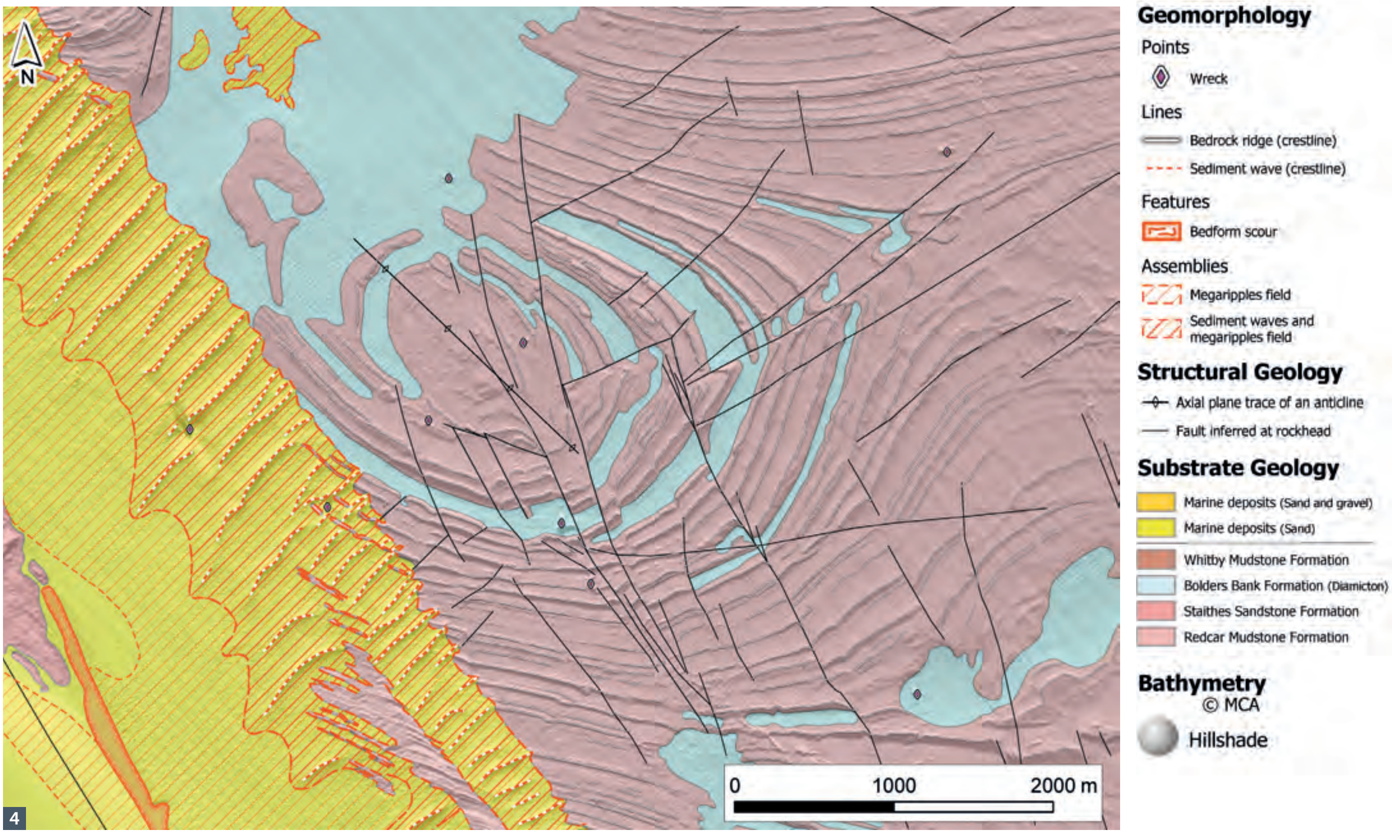


Figure 4: Example of detailed seabed geology mapping from offshore Yorkshire, showing marine and glacial deposits overlying highly deformed bedrock strata (BGS @ UKRI). This image contains bathymetry data acquired by the MCA © Crown Copyright 2022, available under the Open Government Licence v3.0.

Interpretations carry a level of uncertainty relating to the accuracy and precision of the linework and its attribution. All mapping is undertaken using the best data, information, and scientific understanding available at the time of map compilation and the map's 'date stamp' is an important means of validating this uncertainty.

Specific limitations generally result from insufficient density and/or quality of subsurface data. For example, we are typically not able to identify intricate, fine-scale boundaries between Quaternary superficial units (potentially below a veneer of seabed sediments) where there is no apparent seabed expression (e.g., texture, composition, morphology). Existing cores and regional seismic data indicate the dominant superficial units and general trends, but smaller-scale features like buried channels are potentially not captured.

Within the offshore Yorkshire area for example (Fig. 5), we expect that channel deposits are significantly more common than currently mapped. Site-specific academic and industry surveys in the region have demonstrated that post-glacial channel deposits are not only found where a channel feature is (at least partially) apparent at seabed; there are also buried channel deposits with no surface expression. Unfortunately, sub-bottom data (e.g., shallow seismic) are not available across the region in sufficient density to permit consistent representation of such features (BGS, 2023). BGS welcomes feedback on the efficacy and limitations of the map products.

Novel scientific findings

In addition to providing important baseline datasets, the analysis and mapping process also leads to interesting new findings, and the potential for genuine discovery.

For example, within the western sector of the relatively shallow epicontinental North Sea basin, the Offshore Yorkshire map area extends approximately 35 km from the coast. The seabed here exhibits a highly variable geological character, including bedrock from the Carboniferous through Cretaceous (frequently exhibiting complex structural histories), glacial deposits and landforms from the Late Pleistocene, post-glacial fluvial and lagoonal networks that were formed prior to the flooding of the North Sea ('Doggerland'), and unconsolidated marine deposits from Holocene through modern times. (Figs. 4, 5; BGS, 2023).

One assemblage of features worth highlighting is the numerous, narrow high-relief ridges observed offshore from the actively eroding Holderness Coast

SEABED GEOLOGY MAPS

The maps are available and free to view (via ArcGIS) at www.bgs.ac.uk/map-viewers/geoindex-offshore/ (under the fine-scale maps section).

Map areas are selected according to multiple criteria including: data availability, areas of significant development, conservation or management interest, and research drivers.

- Currently available: Bristol Channel, Anglesey, and Offshore Yorkshire (www.bgs.ac.uk/datasets/bgs-seabed-geology).
- Planned further releases in 2023/2024: offshore East Anglia, offshore Orkney, and further areas within the Bristol Channel.

(Fig. 6). The ridges are linear to convolute or zigzag in plan-view, and commonly form longer ridge chains. They run approximately parallel to the coast and exhibit regular ridge-spacing suggestive of a cyclic formation process.

Videography and samples from offshore developments indicate that the ridges are comprised of gravel, cobbles, and boulders, with the coarse material derived from underlying glacial deposits. The ridges are typically asymmetric (steep side facing coast), resulting either from their origin or post-formational processes, and repeat bathymetric surveys do not indicate any discernible ridge mobility or migration.

Currently classified at 'gravel ridges', we haven't identified any obvious regional or global analogues to date. Although we consider alternative glacial (e.g., ice-marginal moraines) and marine (storm-induced ridges) hypotheses, we tentatively ascribe a coastal origin, in which the ridges formed either in the subtidal surf zone or as a result of coastal cliff collapse.

In either (coastal) case, the ridges would demarcate and record the position of former coastlines, as relative sea levels progressively rose during the Holocene. If so, this provides a fascinating opportunity to investigate the rate and style of coastal retreat in an area of significant national concern.

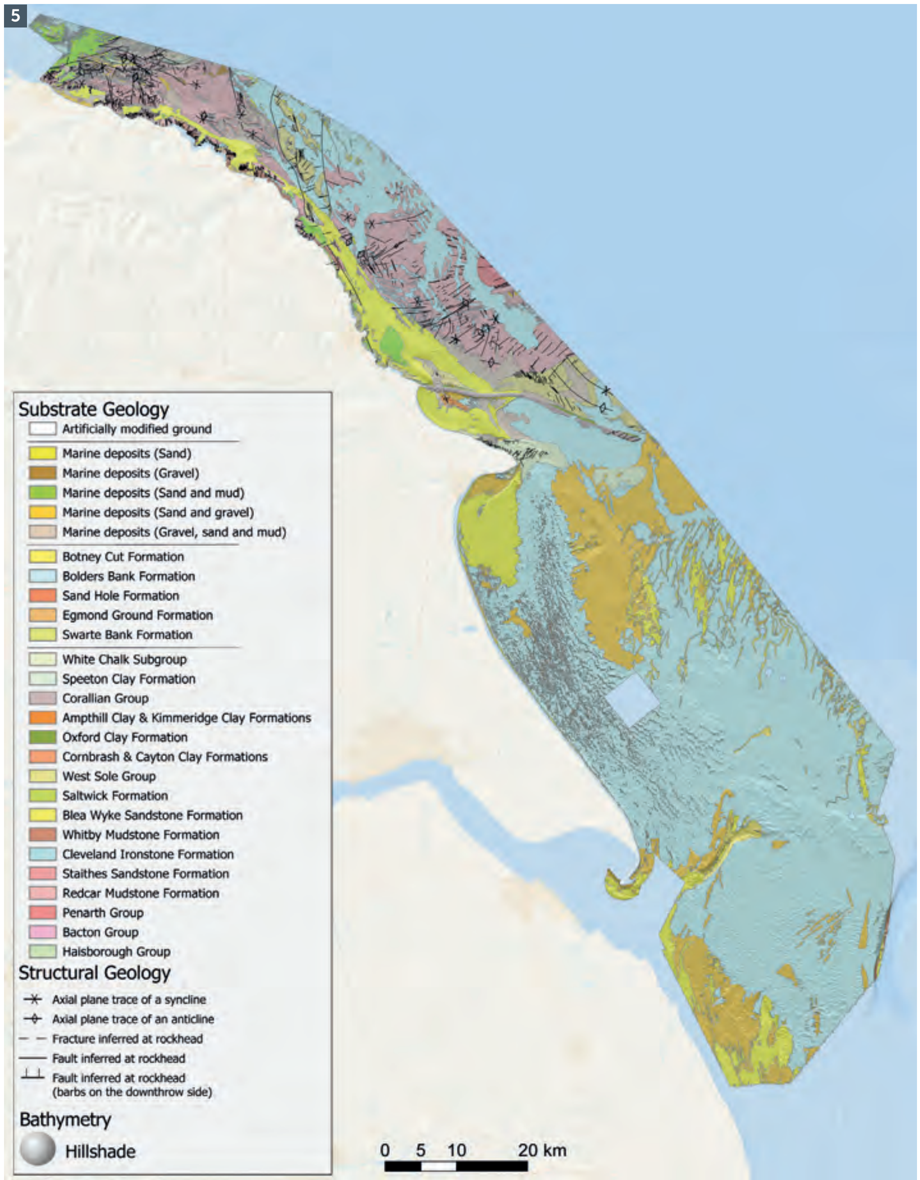


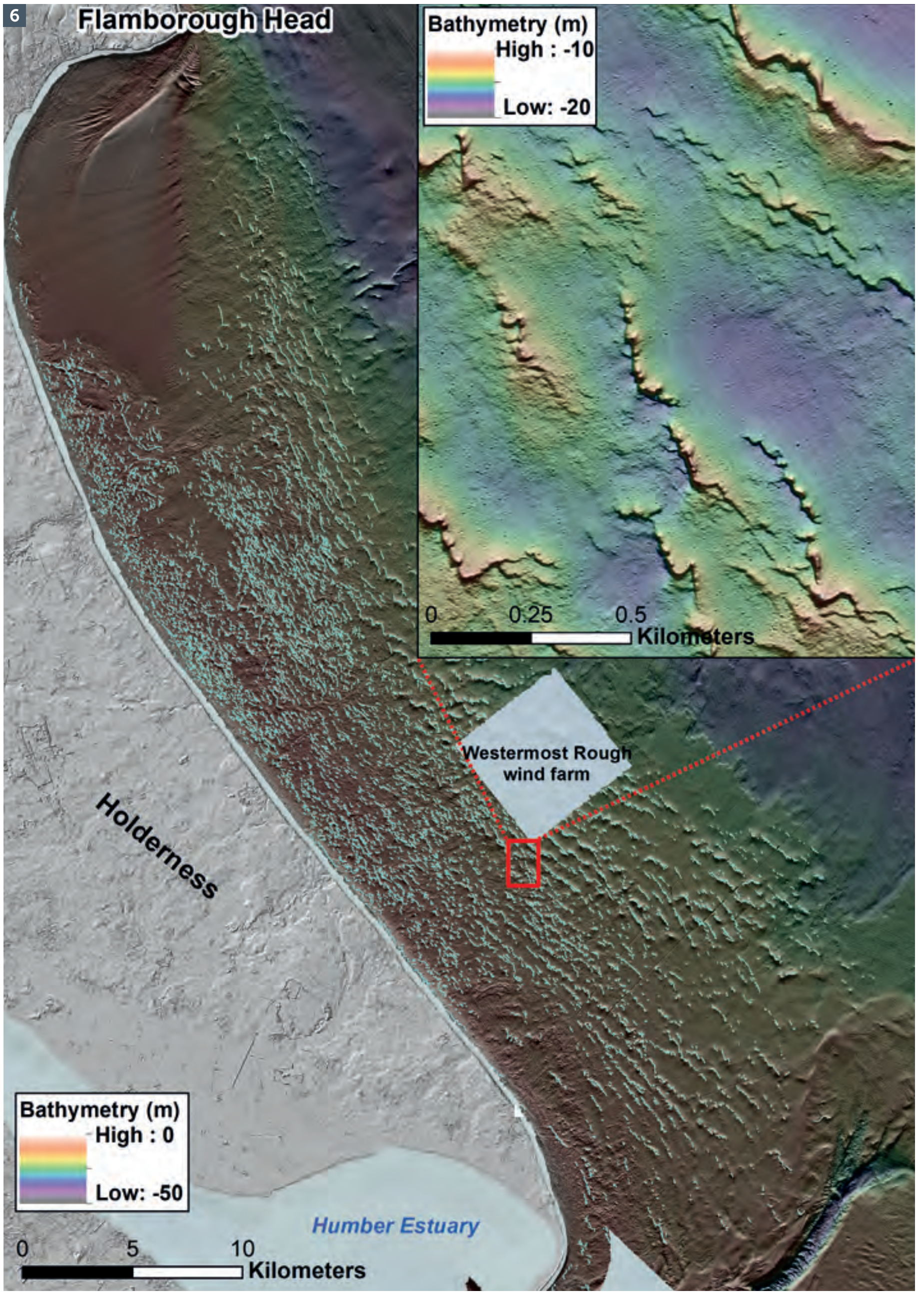
Figure 5: Substrate and Structural Geology of the entire Offshore Yorkshire mapping area. Bedrock generally dominant at seabed in the north of the map area, giving way to glacial, fluvial/lagoonal, and marine sediments in the south (BGS @ UKRI). This image contains bathymetry data acquired by the MCA © Crown Copyright 2022, available under the Open Government Licence v3.0.

A unique resource

There are numerous other challenges that seabed mapping can help address in the future around the UK offshore. Issues ranging from siting of new offshore infrastructure as well as decommissioning of existing structures, and potential impacts on marine ecosystems; identifying constraints on potential offshore CCS developments; understanding potential impacts of aggregate extraction and fisheries; helping to guide investigations of our submerged archaeology; and informing better models of coastal change and resilience.

Our hope is that our seabed geology mapping will inform and encourage more targeted academic and industry investigations to examine environmental, engineering, and possible hazard-related implications of our geologically complex →

Figure 6: Example figure showing only mapped 'Gravel ridges' (Seabed Geomorphology) offshore from Holderness. Inset panel shows closer view of ridge morphology. These 'Gravel ridges' potentially record progressive coastal retreat. This image contains bathymetry data acquired by the MCA © Crown Copyright 2022, available under the Open Government Licence v3.0. Terrestrial topography data derived from NEXTMap Britain elevation data from Intermap Technologies.



seabed environment. Future decisions on how the UK offshore environment is used, particularly in the context of our transition to renewable energy and net zero, will require accurate, reliable, and interoperable data, and it seems clear that geological information and expertise concerning the seabed will play an important role.

The new BGS Seabed Geology maps will contribute to this effort, serving to support a diverse range of offshore activities and applications, including stimulating new scientific research, informing offshore development and conservation initiatives, and providing a new and unique resource for marine managers who are working to balance multiple demands on a busy seabed.

Acknowledgements
We thank BGS colleagues (past and present) who have worked to better understand, progress, and promote the mapping of the seabed and shallow geology. Specifically, we thank Prof. Emrys Phillips (Quaternary and Glacial Geologist), Heather Stewart (Marine Geoscientist), and Hannah Pole (Communications and Media Manager) for important contributions to the mapping programme and this article. We also extend thanks to the Maritime and Coastguard Agency (MCA) and UK Hydrographic Office (UKHO) for providing the fundamental bathymetry data that enables this work, and for driving forward initiatives like the new UK Centre for Seabed Mapping. This work was supported by the BGS via NERC national capability.

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FURTHER READING
A full list of further reading is available at geoscientist.online.

- British Geological Survey (2023) Open Report OR/22/063 (Unpublished).
- Legge, O. et al. (2020) Front. Mar. Sci. 7.
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- Nanson, et al. (2023) Open Report. Zenodo; doi.org/10.5281/zenodo.7804019.
- Sala, E. et al. (2021) Nature 592, 397-402.
- The Crown Estate (2021) Offshore Wind Report.
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Data sources
- BGS maps and data: www.bgs.ac.uk/map-viewers/geoindex-offshore/
- Publicly available bathymetry (Admiralty Marine Data Portal): https://data.admiralty.co.uk/portal/apps/sites/#/marine-data-portal/pages/seabed-mapping-services