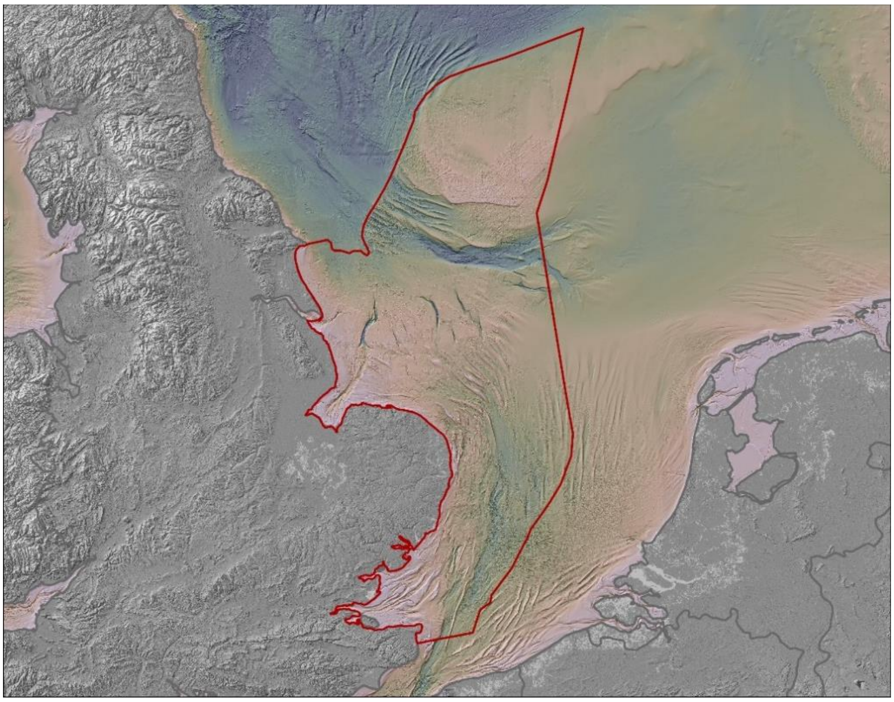
The shallow subsurface geology of the southern North Sea (UK): an updated assessment using data from offshore wind farms

BGS Marine Geoscience

Open report OR/26/005



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Front cover

Southern North Sea showing this report's Area of Interest (offshore bathymetry - EMODnet Bathymetry, 2024. Onshore DEM - SRTM, 2013)

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BRITISH GEOLOGICAL SURVEY

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Foreword

Offshore wind development across the UK Continental Shelf (UKCS) has undergone rapid expansion since the early 2000s, becoming a cornerstone of the UK's energy strategy. As of the time of writing, offshore wind has generated 52.9 TWh of electricity in the past 12 months (The Crown Estate, 2025), enough to supply approximately 14.6 million homes with power for a year. The growth of this sector is underpinned by an increasing volume of high-resolution geophysical, geotechnical and geological data acquired from the marine environment.

This increase in data and reporting across the southern North Sea (SNS) encourages a renewed assessment of the shallow subsurface geology of the area. For this reason, BGS has instigated a compilation of recent observations of the region's shallow geology, based on data and reporting from multiple offshore wind farm (OWF) sites. This report introduces the first integrated chronostratigraphic framework for the region, synthesising open-source geological and palaeo-environmental data from OWF sites. This framework is presented with reference to the existing stratigraphic model as well as recent research advances. The aim is to establish a baseline stratigraphic correlation across OWF developments in the SNS, providing a foundation for future refinement and collaborative research.

This study provides an important first step by delivering an updated assessment of the Quaternary, Pliocene and bedrock sequences of the SNS. We hope this report and dataset will enable a full revision of the regional stratigraphy in the future. However, it is important to acknowledge that the framework relies on limited absolute dating of multiple geological formations for the deeper stratigraphy of many sites and there is a general absence of open access biostratigraphic data available.

This report identifies the following recommendations:

- update and improve the stratigraphic model of the SNS by harmonising and unitising offshore stratigraphy across OWFs
- improve offshore mapping and prediction of detailed lithofacies associations by formation, underpinned by detailed classification codes such as geological setting
- integrate geotechnical data that categorises the subsurface by geological formation and geological setting linked to facies type to create an adaptive geological-geotechnical reference database capable of returning formation-conditioned CPT parameter ranges and probabilistic soil type predictions
- develop an age dating and unified biostratigraphic database to enhance and support a more robust understanding of the subsurface

Together, these improvements would create high-quality datasets that support numerous future offshore applications for future studies across the UKCS. These include the siting and construction of offshore energy infrastructure, sustainable management of marine resources and continued applied research advancement.

Acknowledgements

This study was undertaken as part of the BGS Marine Geoscience programme, supported by NERC National Capability funding. This work is aligned with BGS's strategic priorities to produce maps and models for the 21st century and support a more secure energy transition. The study also received support from the 'Managing the environmental sustainability of the offshore energy transition' (MOET) project, funded by NERC. We would like to acknowledge The Crown Estate and wind farm developers for contributing reports and data to The Crown Estate's Marine Data Exchange.

We would also like to thank Craig Woodward (BGS) for drafting the chronostratigraphic framework and Margaret Stewart (BGS) for valuable discussions.

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Summary

This report presents an integrated assessment of the Quaternary and pre-Quaternary subsurface stratigraphy within the UK sector of the Southern North Sea (SNS), based on interpretations from nineteen offshore wind farm (OWF) sites and three cable landfall locations. The interpretations are derived from publicly available datasets, reports and literature accessed via The Crown Estate's Marine Data Exchange[1] (MDE) and are reported in line with the original investigations. This work aims to support more consistent and accurate geological interpretation across the SNS, facilitating improved offshore assessments and onshore–offshore correlation. The stratigraphic framework also provides a foundation for developing preliminary desk-based ground models and regional research initiatives. In addition to this baseline evidence, the report highlights the value of open-access data and the importance of synthesising multiple multidisciplinary datasets to build a coherent geological framework.

The compiled data spans approximately 400 km in the SNS and includes Holocene, Quaternary, Neogene, Palaeogene and Mesozoic units. Where available, the following information has also been integrated:

- geological formations by site
- references
- absolute dating
- depth to formation boundaries
- lithological descriptions

The landfall sites assessed include:

- Dogger Bank
- Hornsea
- Race Bank
- OWFs:
    - Dudgeon
    - East Anglia ONE and TWO
    - Galloper
    - Greater Gabbar
    - Gunfleet Sands
    - Hornsea Project One and Three
    - Humber Gateway
    - Lincs
    - London Array
    - Norfolk Boreas
    - Norfolk Vanguard West
    - Race Bank
    - Sheringham Shoal
    - Sofia
    - Thanet
    - Triton Knoll
    - Westermost Rough

Data compilation has been structured and is presented as a chronostratigraphic framework , drawing on legacy BGS data (for example, Cameron et al., 1992; Stoker et al., 2011; British Geological Survey, 2024), which is further enhanced by more recent academic, commercial and cross-border research (for example, Fitch et al., 2005; Clark et al., 2022a; Busschers et al., 2025). The results are based on seismic stratigraphy, lithology, chronology and palaeo-environmental context, providing a regional synthesis of the shallow subsurface (less than 100 m below seabed) in the SNS. This work is intended as a baseline dataset for future refinement and collaboration between industry, academia and regulatory bodies, including support for cross-border initiatives.

The BGS stratigraphic framework, developed from the 1970s to the 1990s, was based on the best available data at the time and was delivered through a series of map sheets, offshore regional reports and peer-reviewed research. A core finding of this report is that the SNS offshore stratigraphic nomenclature requires updating to incorporate insights from newly available, high-resolution seismic, borehole and geotechnical datasets, together with advances in understanding of the environmental evolution of the region. While this study does not attempt a full technical validation or revision of geological formations reported from OWF investigations,

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[1] https://www.marinedataexchange.co.uk/

it does propose formation-level interpretations where such information was absent from original available reports. In addition, this work identifies key uncertainties and outlines opportunities for future improvements through a series of recommended initiatives. These include:

- consistently unitising subsurface stratigraphy across OWFs through sesimostratigraphic principles
- multidisciplinary integration of geophysical, geological and geotechnical data
- improving the characterisation of lateral and vertical facies changes relating to variable geological settings within individual formations (underpinned by detailed classification codes)
- strengthening dating and palaeo-environmental strategies

Unravelling these trends will have significant implications for predicting geotechnical properties of individual soil units. In turn, this could improve site-specific efficiencies for optimising ground investigation strategies and identifying units that may contain geohazards or geoengineering constraints.

The work will provide value to a wide range of stakeholders, including those involved in offshore energy (for example, wind; hydrogen storage; carbon capture, utilisation and storage) and marine management and research. It also supports project efficiency, risk reduction and cost savings by enabling a more accurate and consistent characterisation of the seabed and shallow subsurface geology, thus contributing to the UK’s energy transition, net zero ambitions and national marine planning.

1 Introduction

1.1 BACKGROUND

The UK Government has ambitious policy targets for new clean energy capacity, committing to 45 to 50 GW of offshore wind by 2030 (UK Government, 2024). The development of offshore wind farms (OWFs) in the UK began with the installation of two wind turbines (2 MW capacity each) at Blyth, Northumberland, in 2001. Since then, a major expansion in OWFs increased energy capacity to around 14.7 GW in 2025, with several sites now supporting over 100 turbines (The Crown Estate, 2024a).

Figure 1 outlines the current number of OWF sites in the SNS under various phases of development. Many of these datasets are available from fully commissioned sites through The Crown Estate's Marine Data Exchange[1] (MDE). However, with an additional 70 or more OWF projects in various stages, from planning to partial construction, across the UK Continental Shelf (UKCS), data outputs from site characterisation will vastly increase over the next few decades. Integrating these future datasets presents a significant opportunity to collate information that will benefit future seabed management and accelerate renewable energy development.

The size of modern OWF developments (typically 50 to 150 km^2, up to 1500 km^2 in Dogger Bank, the largest OWF project in the UK) results in the availability of near continuous, high-resolution acoustic data (for example, bathymetry and seismic) over large geographical areas. While these large datasets can present data management and workflow challenges, they enable geoscientists to provide detailed interpretations, based on a better understanding of ancient and active processes.

The properties of the seabed and subsurface are largely controlled by geology. Robust geological characterisation is therefore critical for sustainable development in the marine environment, relying on effective evidence-based planning to balance increasing use and demand across numerous sectors (for example, Cotterill et al., 2017a, b; Eaton et al., 2020; Velenturf et al., 2021; OSIG, 2022; Dove et al., 2023; The Crown Estate, 2024b; Petrie et al., 2024; Dakin et al., 2025; Finlayson et al., 2025).

These sectors include (The Crown Estate, 2024a):

- energy (renewables; hydrogen storage; carbon capture, utilisation and storage)
- nature and conservation
- linear assets
- aquaculture
- defence
- tourism and recreation
- maritime transport
- mineral and aggregate resources
- marine management

In the case of offshore wind development, geological knowledge informs decisions throughout the development cycle, from initial stages of strategy development and site identification to review, bidding, site design and engineering considerations (Human Economics, 2025).

Site characterisation associated with OWFs includes the production of geological desk studies, as well as the acquisition, analysis and integration of new geophysical (bathymetry and seismic), geotechnical and borehole data. Using sequence stratigraphy principles (for example, Mitchum et al., 1977), seismic interpretation provides a robust foundation for insights into the geometry and heterogeneity of geological units in the shallow subsurface, forming the basis of a geological ground model. This interpretation provides baseline information on the structural geology, geomorphology, sedimentology and stratigraphy of the subsurface and, when integrated with ground-truthing data, several geological units are proposed. These units are typically linked to sedimentological processes, depositional environments and lithological properties that, importantly, can be associated with specific geological risks such as complex ground conditions that require further engineering considerations.

It is proposed that the term ‘geohazard’ is defined as a dynamic process that impacts offshore development (for example, tsunami; slope instability; seismicity; liquefaction; mobile sediments; shallow gas release) and the term ‘geoengineering constraints’ is proposed to cover existing features that are static in nature but require engineering consideration (Dimmock et al., 2023). Such geoengineering constraints include, but are not limited to:

- geomorphological features
- highly heterogeneous deposits and discontinuities
- over- or under-consolidation of sediments
- organic-rich sediments
- boulders
- overpressurised layers
- rafts
- gravel or cobble beds

One detailed example is the presence of organic-rich sediments that developed in coastal or estuarine environments, freshwater wetlands, swampy conditions or lacustrine settings. Such organic-rich settings, now buried in the subsurface, can be problematic for cable installation due to their fibrous nature, presenting considerable challenges to cable routing. They can also cause increased soil thermal resistivity resulting in the overheating of cables (Johnson et al., 2024; Bellwald et al., in review*;* MacDonald and Stevens, in prep). For a full overview of these challenges related to complex subsurface conditions, the reader is referred to OSIG (2022), Bellwald et al. (in review) and Dakin (2025).

The development of regional screening tools, site-specific integrated ground models and the siting of turbines or cables all require a detailed understanding of the geological history. This is essential not only for identifying geoengineering constraints and potential geohazards, but also for effectively communicating the uncertainty associated with unforeseen ground conditions.

1.2 BGS OFFSHORE STRATIGRAPHY

Site-specific and regional-scale studies, such as those described for OWFs, rely on a preliminary subsurface stratigraphic model to guide and contextualise interpretation. In most cases within UK waters, this function is fulfilled by the BGS stratigraphic framework, established during the 1970s to the 1990s as part of the broader UKCS mapping programme (Cameron et al., 1987; Long et al., 1988; Fannin, 1989; Cameron et al., 1992).

The offshore BGS stratigraphic framework was not developed as a single exercise, but instead resulted from progressive data acquisition, analysis, research, mapping and reporting, including external and international collaboration (Section 2.1). It was organised by formations, representing local-scale units, and groups, representing regional-scale, aggregated units. These were identified seismostratigraphically and described in a consistent manner using litho-, bio- and magnetostratigraphic approaches.

Regular practitioners will be aware that there are inconsistencies, inaccuracies and limitations within the existing BGS stratigraphy, such as boundary matching issues and divergent nomenclature between different mapping areas (Dyson et al., 2026). Many of these issues arise from data quality and density, as outlined in the respective maps and reports. However, some also result from organisational mapping strategies as well as individual mapper bias and methodologies. The publication by Stoker et al. (2011) describes and synthesises the BGS stratigraphy across the mapping areas, reconciles these inconsistencies where possible, and is the most up-to-date official statement on the BGS offshore Quaternary stratigraphy.

The existing BGS stratigraphy is commonly applied as a standard across maps, papers and reports. It is also provided, although incompletely, within the BGS Lexicon[2], which is a database

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[2] https://webapps.bgs.ac.uk/lexicon/

of geological units in the UK. Here, formation and group names are included as ‘LEX’ codes. While offshore domain LEX codes are primarily based on unit name, the lexicon offers further functionality: for example, within most recent BGS ‘fine-scale’ mapping such as British Geological Survey (2023, 2024), BGS uses two separate LEX codes to define the unit name, as well as characterising associated depositional process or setting. This approach was developed using the two-part morphology and geomorphology classification of Dove et al. (2020) and Nanson et al. (2023).

The BGS Rock Classification Scheme (RCS), which includes the Unlithified Deposit Coding Scheme (UDCS) relevant for Quaternary sediments, is available for classifying and naming geological materials, acting as a corporate standard in support of BGS digital geological maps. The RCS codes are based on observed lithologies, a reason for why it can differ from the BGS Lexicon. The UDCS was developed as a way of coding unlithified deposits (also commonly referred to as superficial deposits, unconsolidated deposits or engineering soils) and is consistent with the civil engineering industry. However, much of this detailed information is currently absent from the offshore BGS Lexicon database, which details:

- lithogenesis (geological setting and origin)
- characteristic associated landforms
- geographical distribution
- thickness
- detailed descriptions of upper and lower boundaries

In addition, there is no seismostratigraphic descriptor for offshore stratigraphy. Geological formations that have not undergone a recent review to include any newly available data, such as that from OWF datasets, are flagged on the BGS Lexicon database as ‘pending upgrade’.

1.3 AIMS OF CHRONOSTRATIGRAPHIC CHART AND REPORT

This study builds upon the recommendations of Stoker et al. (2011), specifically to compile shallow geological data into a regional assessment. This report and accompanying chronostratigraphic chart collate open-access geological datasets available on the MDE and other open-source reports or papers from OWF sites into a regional framework for the SNS. Synthesising information in this way enables a broader stratigraphic perspective, highlighting regional geological conditions that may result in lithological similarities and differences between individual sites.

The subsurface characterisation presented in this report is not exhaustive and does not depict local-scale lithological, structural or geotechnical heterogeneity. Therefore, the information used in this document should be used as a guide and never as a substitution for ground investigation. Instead, the chronostratigraphic framework aims to serve as a preliminary assessment, as we acknowledge that substantial work is required for a comprehensive subsurface evaluation of all OWF developments, including areas in between. However, we hope this geological assessment offers a foundation for future evidence-based decision making by highlighting knowledge gaps that can be addressed through further research and development.

The aim of this report is to assess how the current offshore BGS stratigraphic framework can be improved for modern offshore development challenges. Understanding detailed facies changes, driven by geological settings, can help inform early geotechnical and engineering planning via screening tools for potential geohazards or geoengineering constraints. The results outline how the current chronostratigraphy presented within can be improved with already available datasets (such as sediment mobility reports, seismic data and geotechnical datasets) and new datasets released in the future. This additional detailed assessment of the chronostratigraphy would require completion via future funding opportunities, outlined in the discussion.

1.4 REPORT STRUCTURE

This report is organised into the following sections:

- Section 2 — Geological background: summarises previous research on the geological history of the North Sea
- Section 3 — Methodology**:** details the datasets used and the approach taken to create the chronostratigraphy and outlines the limitations of the study
- Section 4 — Chronostratigraphic framework and stratigraphic assessment: presents the integrated interpretation and key findings of stratigraphy by OWF site
- Section 5 — Discussion: identifies research questions relating to the stratigraphy of the SNS and outlines how improved characterisation of the geology will improve geotechnical and design elements for offshore developments. Highlights uncertainties and opportunities for improvement and recommended future initiatives
- Section 6 — Conclusions

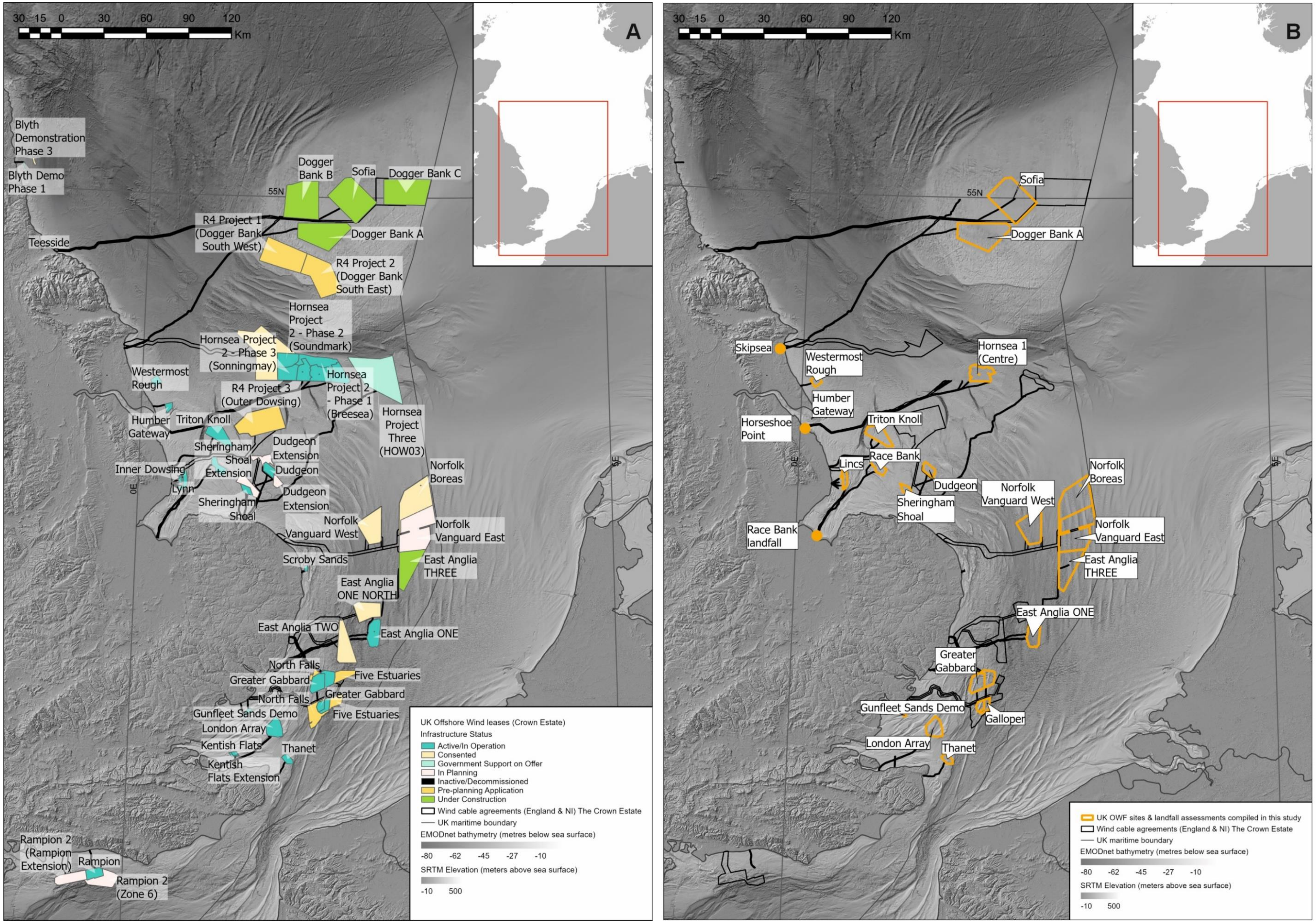

Figure 1 (A) Semi-transparent offshore bathymetry map (EMODnet, 2024) overlain by status of OWF leases and cable route corridors (2025). OWF ground investigation data typically becomes available around 10 years after a site becomes fully operational. Infrastructure status information from The Crown Estate (2025). (B) Offshore bathymetry map (EMODnet, 2024) overlain by OWF leases and cable route corridors (orange dots indicate landfall areas) collated in this study. Onshore digital elevation model (DEM) from SRTM, GTopo30, GEBCO (Tozer et al., 2019). SNS offshore area outline from Charting Progress 2 Reporting Regions (JNCC, 2025). BGS © UKRI 2025.

2 Geological background

The SNS extends from Dogger Bank in the north to the Strait of Dover in the south. It has an average water depth of about 30 m, increasing to a maximum of about 98 m in the Outer Silver Pit (Figure 2). The area has been an important gas-producing basin since the 1960s. More recently, it has been favourable for OWF development due to its shallow bathymetry and proximity to the shore and energy distribution networks.

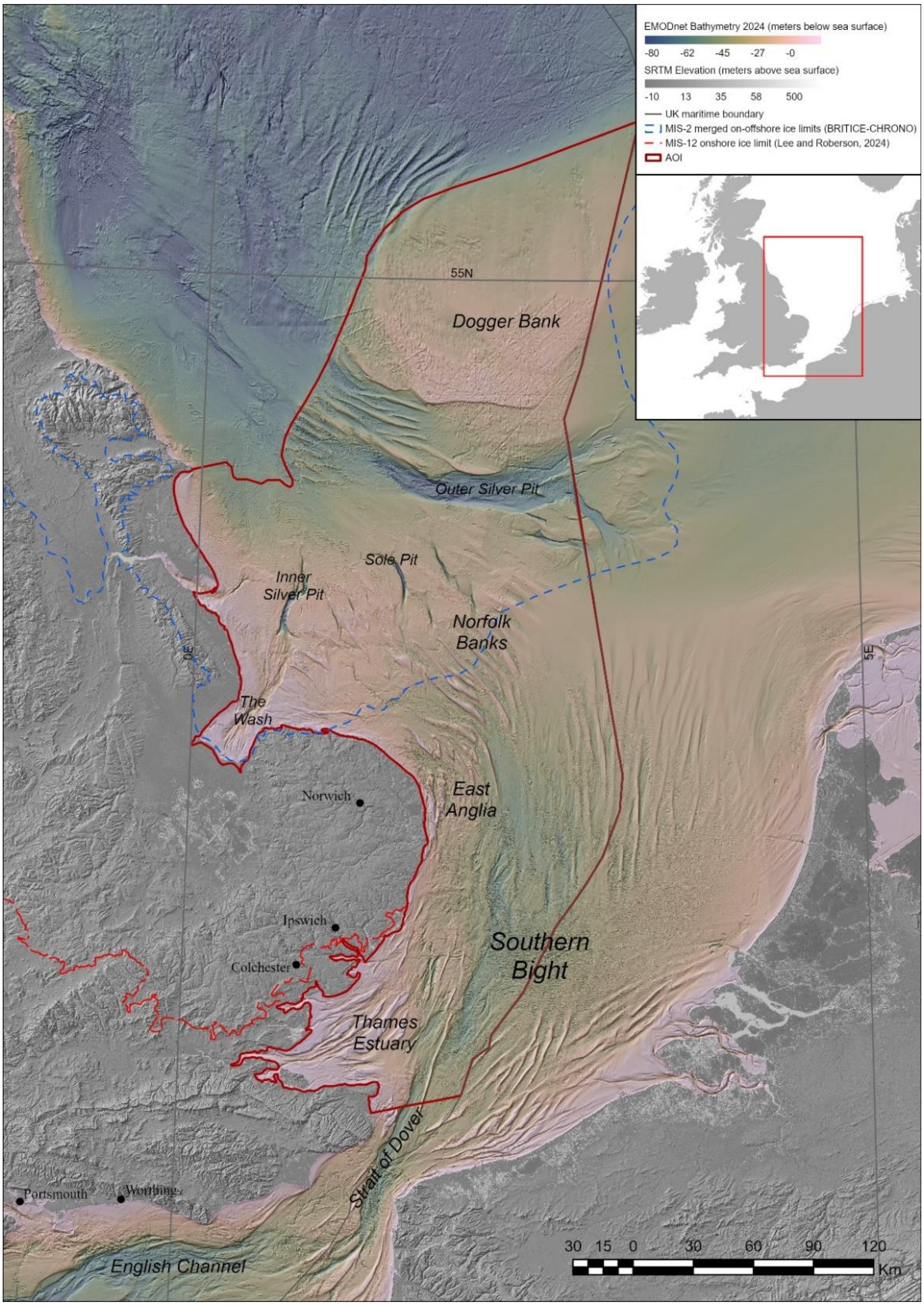

Figure 2 Offshore bathymetry map of the SNS (EMODnet, 2024). Onshore DEM from SRTM, GTopo30, GEBCO (Tozer et al., 2019). MIS 2 ice sheet limit (merged) from Clark et al. (2022b). MIS 12 onshore ice sheet limit from Lee and Roberson (2025). SNS area of interest (AOI) from Charting Progress 2 Reporting Regions (JNCC, 2025). BGS © UKRI 2025.

2.1 HISTORICAL RESEARCH OF THE SOUTHERN NORTH SEA

Here we combine the systematic regional characterisation of the seabed and the shallow subsurface geology of the SNS prior to OWF development and highlight the renewed interest in recent years. Although this timeline focuses on BGS-related activities, key governmental and research outcomes are also indicated.

2.1.1 Late 1960s to 1990s

BGS undertook a regional offshore mapping programme to map the geology of the UK continental shelf (Fannin, 1989). Extensive acquisition of geophysical and borehole data led to the publication of:

- 1:250 000 map sheets: seabed sediments; Quaternary geology; solid geology (for example, British Geological Survey, 1991)
- research publications (for example, Cameron et al., 1987; Long et al., 1988)
- BGS Offshore Regional Reports (Cameron et al., 1992; Johnson et al., 1993; Gatliff et al., 1994, for the southern, northern and central North Sea, respectively)

These datasets have since served as key baseline datasets for all offshore infrastructure development (GeoIndex Offshore[3]). This information was collated and organised into a standardised lithostratigraphic framework (Stoker et al. (2011), summarised in Table 1). Since publication, the 1:250 000 regional-scale maps (excluding seabed sediments - Dove et al., 2025) have not been systematically updated as there have been insufficient data and resources available to develop updated products in a consistent manner.

2.1.2 Early 2000s onwards

Numerous research efforts resulting from a mix of academic research (for example, BRITICE-CHRONO) and repurposed oil and gas data, as well as BGS information, significantly improved our understanding of the Quaternary in the SNS (for example, Huuse and Lykke-Andersen, 2000; Fitch et al., 2005; Carr et al., 2006; Graham et al., 2011; Clark et al., 2022a, b; Cotterill et al., 2017a, b; Phillips et al., 2017; Kirkham et al., 2021, 2024; Newton et al., 2024; Hijma et al., 2025). The reader is also referred to the Strategic Environmental Assessments and Regional Environmental Characterisation reports (for example, Limpenny et al., 2011; Tappin et al., 2011), a major UK Government initiative to support sustainable development in the marine environment (UK Government, 2013). An exhaustive literature review is beyond the scope of this report; however, research advances have been made across multiple themes, including:

- interpretation of palaeo-landscapes and archaeology
- dating of peats
- palaeo-icesheet dynamics
- evolution of past sedimentary influx into the North Sea
- characterising the seabed for aggregate extraction

OWF development started early in the 2000s; however, the underlying geological framework that underpins the geotechnical design of foundations typically reports on the stratigraphy provided by BGS, based on seismic data and interpretations from the late 1960s to 1990s.

Table 1 Summary of formations (Cameron et al., 1992; Stoker et al., 2011) with descriptions from OWF data in the SNS, identifying potential geotechnical constraints on infrastructure development. Note: not an exhaustive list of formations present across the North Sea.

Group	UK formation name (BGS LEX Code)	MIS	Geological time name (UK)	Quaternary climate stage	Brief lithology description from OWF reporting, or *Stoker et al. (2011) where missing.*	Depositional environment/ geological setting	In this report?	Typical seismic facies character, if reported	Potential geotechnical constraints per formation	Expected within 50 m of seabed?	Key references beyond Cameron et al. 1992 & Stoker et al. 2011. *(Dutch or German sector references).*
California Glacigenic Group (CALIF)	Southern Bight Formation (SBI)	1	Late Holocene	-	Unconsolidated fine to coarse marine sands.	Marine.	Y	Low amplitude to transparent sheets, with some internal reflections.	Mobile sediments, scour, variable thickness.	Regionally.	Beets et al. (2000); *Rijsdik et al. (2005);* Mellett et al. (2020)
	Elbow Formation (ELW)	1	Early Holocene	Interglacial	Muddy sand, interbedded clay & peat.	Coastal wetland to brackish estuarine shallow water or lagoonal, intertidal, tidal marsh or coastal/shoreface.	Y	Channelised, erosional base, bright amplitudes.	Peats/organic soils & laterally/variable soils, shallow gas, compressible soils/low thermal conductivity, laterally discontinuous soils.	Regionally.	Fitch et al. (2005); Brown et al. (2018); Emery et al. (2019); Gaffney and Fitch et al. (2022); *Gouw and Hijma (2021)*
	Twente Formation (TN)	2	Late Devensian	Late glacial	Wind-blown sands.	Periglacial & aeolian near ice margin.	Y – limited	-	Laterally discontinuous soils.	One possible example.	Bateman and Huissteden (1999)
	Botney Cut Formation (BOCT)	2	Late Devensian	Late glacial (glacial/interglacial)	Variable between sites: Interbedded fine-medium sands with soft-stiff sandy silty clay with gravel (post-glacial fluvial/lacustrine deposits); or soft to stiff muds to sandy/organic channel and basin infill.	Post-glacial. Coastal wetlands deposits: tidal flat, intertidal to open estuarine & fluvial; lacustrine, marine & basinal. Also glacial to post-glacial channel infill.	Y	Channelised, erosional base, laminated (onlapping). Variable channel fills: acoustically transparent, draped with low to high amplitudes.	Vertically & laterally highly heterogenous soils, organic soils & shallow gas.	Regionally.	Fitch et al. (2005); Cotterill et al. (2017a); Emery et al. (2019); Mellett et al. (2020); BGS (2023)

Group	UK formation name (BGS LEX Code)	MIS	Geological time name (UK)	Quaternary climate stage	Brief lithology description from OWF reporting, or *Stoker et al. (2011) where missing.*	Depositional environment/ geological setting	In this report?	Typical seismic facies character, if reported	Potential geotechnical constraints per formation	Expected within 50 m of seabed?	Key references beyond Cameron et al. 1992 & Stoker et al. 2011. *(Dutch or German sector references).*
	Bolders Bank Formation (BSBK)	4(?)–2	Late Devensian (possibly limited early/mid)	Glacial	Firm to stiff silty sandy gravelly clay with occasional sand and gravel layers/ concentrations.	Subglacial/ice marginal.	Y	Transparent, multiple laterally & vertically stacked subunits, including glacial landforms; erosional base.	Overconsolidated till, boulders/rafts, heterogeneous soils, multiple subunits.	Associated with the North Sea lobe of British–Irish ice sheet.	Carr et al. (2006); Davies et al. (2011); Dove et al. (2017); Roberts et al., (2018); Mellett et al. (2020); Clark et al. (2022a), BGS (2023).
	Dogger Bank Formation (DBNK)	4–2	Late Devensian	Glacial	Very heterogenous deposits. Variable clay silt, sand & gravel content. Some organic matter & shell fragments.	Subglacial/ice marginal.	Y	Transparent to thrusted, erosional base.	Overconsolidated, glacioteconised, rafts, boulders, variable geology, hardgrounds, periglacial weathering.	Localised around Dogger Bank.	Cotterill et al. (2017a); Emery et al. (2019); Phillips et al. (2022)
	Brown Bank Formation (BNB)	3–5d	Ipswichian to mid Devensian	Interglacial	Silty sand & sandy silt.	Lagoonal/ intertidal to shallow marine.	Y	Onlapping, multiple units separated by impedance contrast.	Organic material & shallow gas. Multiple subunits (laterally discontinuous). Can be overconsolidated.	Localised towards south of SNS.	Eaton et al. (2020; 2024); Waajen et al. (2024; 2025)
	Eem Formation (EE)	5e	Ipswichian	Interglacial	Shelly sands; can be muddy in places.	Marine.	Y	Low to high amplitude seismic package & continuous reflections.	Laterally discontinuous and/or variable soils.	Localised around Dogger Bank.	Rijsdijk et al. (2005); Cotterill et al. (2017a)
	Cleaverbank Formation (CLBK)	~8–6?	Late Wolstonian	Glacial/interglacial	Laminated clays to fine-grained sand.	Periglacial & aeolian.	N	-	Laterally discontinuous soils.	Unknown: possibly deeper than 50 m towards central North Sea.	Rijsdijk et al. (2005)
	Tea Kettle Hole Formation (TKH)	~10–6?	Late Wolstonian	Glacial/interglacial	Fine-grained sand with organics.	Marine to proglacial.	N	-	Laterally discontinuous soils.	Unknown: possibly deeper than 50 m.	Rijsdijk et al. (2005)

Group	UK formation name (BGS LEX Code)	MIS	Geological time name (UK)	Quaternary climate stage	Brief lithology description from OWF reporting, or *Stoker et al. (2011) where missing.*	Depositional environment/ geological setting	In this report?	Typical seismic facies character, if reported	Potential geotechnical constraints per formation	Expected within 50 m of seabed?	Key references beyond Cameron et al. 1992 & Stoker et al. 2011. *(Dutch or German sector references).*
	Egmond Ground Formation (EG)	11	Hoxnian	Interglacial	Dense sands, locally gravelly, interbedded with silt & clay.	Shallow marine to coastal plain/near shore.	Y	Acoustically transparent to weakly horizontally bedded.	Laterally discontinuous soils, contains gravels/refusal.	Associated with infill of tunnel valleys.	Le et al. (2014); Mellett et al. (2020); Arlott et al. (2023)
	Sand Hole Formation (SHLE)	11	Hoxnian	Glacial/interglacial	Clay-rich sand to sand-rich clay or dense sand.	Coastal or estuarine in cool conditions to restricted shallow marine.	Y	2 units: chaotic & undulating to weak, horizontally bedded reflectors.	Laterally discontinuous soils and subunits with differing properties.	Associated with infill of tunnel valleys.	Scourse et al. (1999); Arlott et al. (2023)
	Swarte Bank Formation (SWBK)	12	Anglian	Glacial	Stiff–very stiff clay with chalk, gravel & flint.	Re-worked glacial deposits, subglacial till, glaciolacustrine to glaciomarine.	Y	Transparent; tends to infill tunnel valleys, erosional base.	Overconsolidated sediments, boulders, variable geology. Low to high plasticity. High clay & silt content. Multiple subunits.	Associated with infill of tunnel valleys.	Davies et al. (2011); Mellett et al. (2020); Lohrberg et al. (2020)
Dunwich Group (DUNW)	Yarmouth Roads Formation (YM)	13 to 62	Early to early-middle Pleistocene	-	Silty sand with occasional shell fragments & clay layers. Can contain plant debris & peat.	Fluvio-deltaic/shallow marine and coastal plain.	Y	Discontinuous reflectors; can be channelised to prograding.	Highly laterally and vertically variable soils, peat lenses/organic matter.	Localised towards south of SNS & East Anglian Coastline.	BGS, 2024; *Deltares* (2017)
Southern North Sea Deltaic Group (SNSG)	Smith's Knoll Formation (SK)	63 to 65	Early Pleistocene	-	Muddy, fine-grained, glauconitic, locally micaceous with minor silty clay or pebbly/shelly sand.	Littoral to marine; pro-delta.	Y	Unstructured: some faint subparallel reflectors.	Contains pebbles/refusal.	No detailed documentation.	-
	Westkapelle Ground Formation (WK)	65 to 103	Late Pliocene? to early Pleistocene	-	Silty clays with fine-grained, glauconitic, bioturbated sands passing up to mud-free sands.	Littoral to marine; pro-delta.	Y	Acoustically unstructured, with faint basal reflector.	Laterally and vertically heterogeneous soils.	Limited detailed documentation.	-

Group	UK formation name (BGS LEX Code)	MIS	Geological time name (UK)	Quaternary climate stage	Brief lithology description from OWF reporting, or *Stoker et al. (2011) where missing.*	Depositional environment/ geological setting	In this report?	Typical seismic facies character, if reported	Potential geotechnical constraints per formation	Expected within 50 m of seabed?	Key references beyond Cameron et al. 1992 & Stoker et al. 2011. *(Dutch or German sector references).*
Crag Group (CRAG)	Red Crag Formation (RCG)	-	Late Pliocene	-	Glauconitic muddy sand.	Marine.	Y	Acoustically unstructured with faint internal reflectors.	Crushable soil?	Limited detailed documentation.	Davies et al. (2019)
Thames Group (THAM)	London Clay Formation (LC) & Wrabness Member (WRAB)	-	Ypresian	-	Stiff becoming hard, olive-brown fissured micaceous clay with gravels/silt pockets. Siltstone beds.	Marine.	Y	Layered, dipping stratigraphy containing multiple faults with faults (<2m offset).	Can be overconsolidated and contain gravels. Occasional weathered upper surface, faults. Periglacial weathering.	In south of SNS. Stratigraphic uncertainty remains between LC and WRAB from OWFs.	-
Lambeth Group (LMBE)	Woolwich Formation (WL)	-	Thanetian to Ypresian	-	Dense to very dense sand gravel with clay layers.	Marine.	Y	-	Contains pebbles/refusal.	In south of SNS. Stratigraphic uncertainty remains between LC and WRAB from OWFs.	-
Montrose Group (MONT)	Thanet Formation (TAB)	-	Thanetian	-	Stiff green clay/sand.	Marine.	Y	-	Could have undergone periglacial weathering.	In south of SNS. Stratigraphic uncertainty remains between LC and WRAB from OWFs.	--

Group	UK formation name (BGS LEX Code)	MIS	Geological time name (UK)	Quaternary climate stage	Brief lithology description from OWF reporting, or *Stoker et al. (2011) where missing.*	Depositional environment/ geological setting	In this report?	Typical seismic facies character, if reported	Potential geotechnical constraints per formation	Expected within 50 m of seabed?	Key references beyond Cameron et al. 1992 & Stoker et al. 2011. *(Dutch or German sector references).*
Chalk Group (CK)	Chalk (multiple formations present as part of Chalk unit)	-	Cretaceous (Upper & Lower)	-	Variable: low to high-density chalk, fractures & flint. Lower Cretaceous can contain hardgrounds.	Marine.	Y	Transparent to well-imaged, well-layered stratigraphy containing multiple faults. Fault-controlled structures.	Variable lateral/vertical geotechnical properties, hardgrounds, periglacial weathering, faults, flint.	Regionally.	Mortimore & James (2015); Mellett et al. (2020); Mortimore (2022)
Ancholme Group (AMG)	Kimmeridge Clay (KC)	-	Jurassic	-	-	Marine.	Y	-	Rock (where not weathered).	Near coastline (The Wash, East Anglia).	-

2.1.3 In 2020

Based on the increased offshore development in the UK and considering newly available data, BGS initiated a renewed programme to map the seabed geology[3] in strategic areas of the UKCS (for example, Dove et al., 2023; British Geological Survey, 2023, 2024). These 1:10 000, fine-scale digital map products (seabed geomorphology, substrate geology and structural geology) are based on high-resolution bathymetry data (down to 1 m spatial resolution) acquired by the UK Civil Hydrography Programme, together with further supporting data and information. The mapping outputs utilise the two-part morphology and geomorphology classification of Dove et al. (2020) and Nanson et al. (2023).

2.1.4 In 2024

BGS and The Crown Estate undertook an assessment of stakeholder requirements for geological data and information of the seabed and shallow subsurface across the UKCS and proposed methods for improving these products (Finlayson et al., 2025). The report aimed to understand stakeholder needs and identified gaps to inform the development of new geological data compilation. The key marine datasets required included:

- likelihood of seabed change
- the potential presence of boulders
- lateral and vertical soil heterogeneity
- improved Quaternary thickness
- interpreted gas or fluid in the shallow subsurface

Much of this information needs an improved understanding and characterisation of Quaternary processes. Additionally, the North Sea was highlighted as a key region where a new generation of geospatial products is essential, as it offers conditions suitable for offshore renewable energy development.

2.2 RECENT GEOLOGICAL HISTORY OF THE SOUTHERN NORTH SEA

The subsurface zone of interest focuses on up to approximately 100 m below the seabed (mbsb), which is the depth commonly considered in OWF development. This zone often includes sediments laid down during the Quaternary Period (the last 2.58 million years (Ma) of Earth's history), although older bedrock stratigraphy is also encountered where the Quaternary layers are thinner (for example, Cameron et al., 1992; Mortimore and James, 2015; Grant et al., 2021; Patruno et al., 2022; Gaitan and Adam, 2023).

The geological character of the shallow subsurface records variable environmental processes from associated geological settings that have operated over multiple time scales, from tidal, storm and seasonal cycles through to millennial-scale and tectonic events. Quaternary glacial/interglacial cycles have had a dominant influence on the region, where multiple dynamic glacial periods and relative sea-level changes have resulted in a complex but increasingly well-constrained geological history (Cameron et al., 1992; Stanev et al., 2009; Sturt et al., 2013; Cohen et al., 2014; Phillips et al., 2017; Lamb et al., 2018; Clark et al., 2022a, b; Bradley et al., 2023). The different geological formations and bedrock lithologies have unique geotechnical properties impacting infrastructure siting and foundation design.

Here we outline the relevant pre-Quaternary stratigraphy and the subsequent glacial and interglacial cycles that form the principal building blocks of the Quaternary stratigraphy. Note that this report predominantly uses UK terminology for glacial and interglacial stages. For reference to equivalent north-west European stages, please refer to the accompanying chronostratigraphic chart.

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[3] https://www.bgs.ac.uk/datasets/bgs-seabed-geology/

2.2.1 Pre-Quaternary processes

The uppermost pre-Quaternary strata in the SNS are dominated by Mesozoic and Cenozoic rocks (Cameron et al., 1992; Kuhlmann et al., 2006; Mortimore and James, 2015; Grant et al., 2021; Patruno et al., 2022). These predominantly include the Cretaceous-aged Chalk Group, forming an acoustic boundary in geophysical data, and younger Palaeogene and Neogene strata that record the development of marine and deltaic environments within the SNS.

The Palaeogene and Neogene record of the SNS is discontinuous and is punctuated by numerous regionally extensive, angular unconformities. These unconformities reflect the longer-term tectonic history of the SNS during the Cenozoic and its control on basin architecture, accommodation space and, ultimately, regional palaeo-geography. The Cenozoic tectonic history of the SNS is highly complex, incorporating:

- multiple phases of Alpine-related crustal compression that acted to drive crustal uplift and exhumation across the basin
- re-activation of relict faults and inversion of former basins
- widespread development of salt tectonics within Zechstein Group salts

Uplift has been punctuated by phases of thermal subsidence within the centre of the SNS basin, which initiated the accumulation of thick sedimentary sequences.

Since the end of the Miocene, the basin's tectonic history has transitioned to a weakly compressional tectonic stress regime, with climate-driven erosional isostasy causing accelerated subsidence across the centre of the basin and uplift in marginal areas (Westaway, 2017; Lee et al., 2020). The Cenozoic tectonic history of the SNS therefore plays a critical role in regulating basin architecture, sediment accommodation space and the distribution of Quaternary deposits across the basin (Lamb et al., 2018).

2.2.2 Glacial stage processes

The cyclical growth and decay of mid-latitude ice sheets and the resulting global sea-level changes that occurred during the Quaternary have significantly influenced the palaeo-environments of the SNS. Glacial periods are generally correlated with even-numbered Marine isotope stage (MIS) intervals (such as MIS 2, 6, 12 and 16) where global ice volume increased. During these periods, shallow epicontinental basins such as the North Sea were highly susceptible to environmental changes associated with lowering of the global sea level by up to 120 m below present day (Brooks et al., 2011; Dutton et al., 2015; Bradley et al., 2023). Periglacial processes were able to affect exposed mid-latitude continental shelves during these low sea-level stands, such as in the SNS.

The first known and most extensive glaciation to affect the UK SNS is generally considered to be the Anglian (around 478 to 424 thousand years ago (ka)), associated with MIS 12 (Graham et al., 2011; Lee et al., 2012). At that time, ice sheets advanced southwards covering much of East Anglia and large parts of the SNS (Figure 2). The Anglian phase is widely considered to be equivalent to the Elsterian glaciation within north-west Europe, although there is growing awareness that some geological features of what have historically been attributed to the Elsterian may correspond to older phases of glaciation (Lee et al., 2012; Lohrberg et al., 2022).

There is a large amount of uncertainty regarding potential phase(s) of glaciation in the Wolstonian glaciation(s) (Late Saalian or Moreton stadial, around 374 to 130 ka) associated with MIS stages 10, 8 and 6 (for example, Lee et al., 2012; Gibson et al., 2024). Later glacial episodes occurred between about 123 and 11.7 ka (MIS 5d, 4 and 2), of which the late Devensian (MIS 2) British–Irish ice sheet is the most well understood (for example, Carr et al., 2006; Hughes et al., 2016; Clark et al., 2022a; Scourse, 2024).

Within each of these glacial periods, ice masses were not static, but rather highly dynamic with changing ice extents, shifting ice divides and multiple advance and re-advance phases (for example, Clark et al., 2022a, b). These changing glacial environments included subglacial, ice-marginal and proglacial land systems (for example, Benn and Evans, 2014), resulting in a highly complex stratigraphy.

The sediments associated with such environments are highly variable and can contain numerous engineering constraints or geohazards. These include, but are not limited to:

- tunnel valleys and meltwater channels
- coarse lag deposits
- exposed bedrock
- glaciotectonised sediments
- overconsolidated diamictons
- fine-grained soft sediments
- boulders
- frequent high lithological and structural soil heterogeneity

All of these affect ground conditions and engineering solutions (for example, Cotterill et al., 2017a, b; Lohrberg et al, 2020; Coughlan et al., 2020; Velenturf et al., 2021; Dakin et al., 2025).

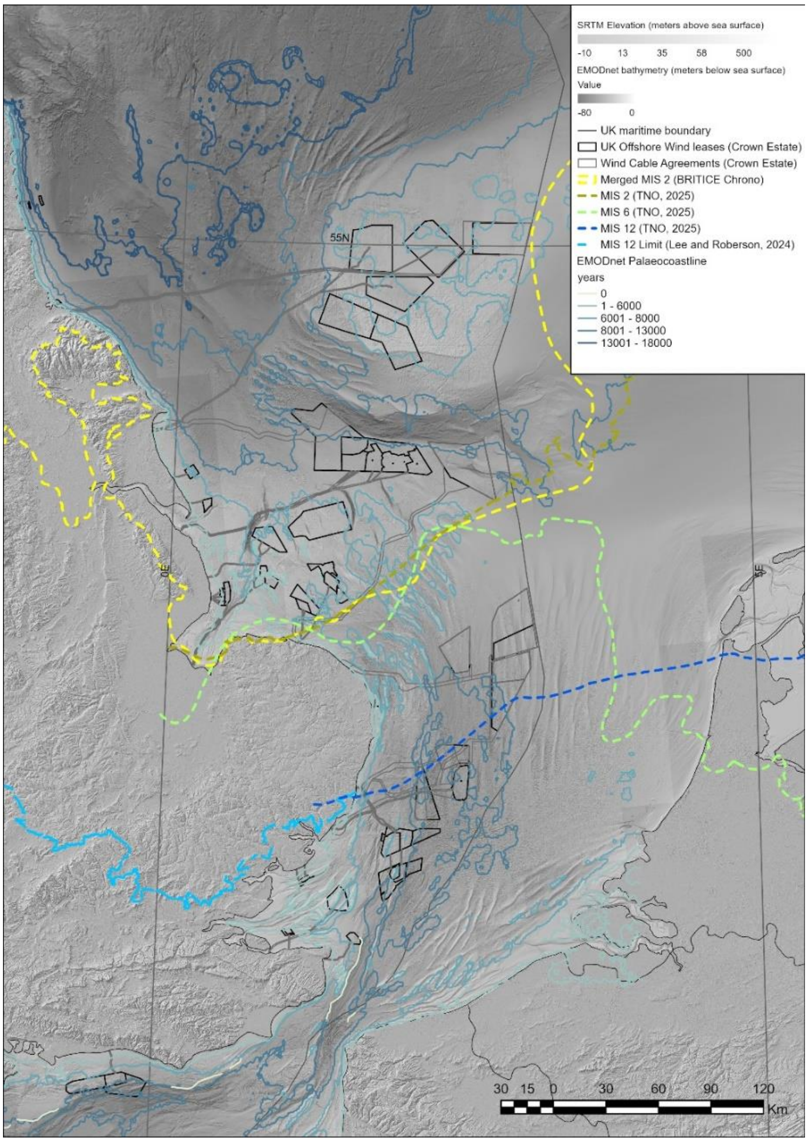

Figure 3 Image of interpreted ice limits from multiple sources (Clark et al., 2022b; Lee and Roberson, 2025; Busschers et al, 2025). Palaeo-coastline data from EMODnet Geology (original reference Brooks et al., 2011). Onshore DEM from SRTM, GTopo30, GEBCO (Tozer et al., 2019). Bathymetry data from EMODnet (2024). BGS © UKRI 2025.

2.2.3 Interglacial stage processes

Here we use the term ‘interglacial’ to define a temperate period with a warm climatic optimum and elevated global sea levels (Kukla et al., 2002; Pillans and Gibbard, 2012). Such intervals are represented by odd-numbered MIS intervals, for example (oldest to youngest):

- Hoxnian (MIS 11)
- ‘Wolstonian’ temperate stages (MIS 9; 7)
- Ipswichian (MIS 5e)
- Holocene (MIS 1)

These interglacial periods feature the deposition of sediments relating to terrestrial (that is, fluvial), coastal or marine processes (Scourse et al., 1999; Waajen et al., 2024, 2025).

In the SNS, the transition from glacial to interglacial periods often resulted in a rapid change from terrestrial to marine settings, where low-lying coastal plains were susceptible to dramatic depositional changes relating to the rising sea levels (Brown et al., 2018; Eaton et al., 2020, 2024). Deposits from these phases can include coarse lags from fluvial environments, highly compressible peats or organic matter in lowland coastal areas, or interbedded and laterally heterogenous clays and sands from shallow-marine settings (Fitch et al., 2005; Gaffney et al., 2007; Sturt et al., 2013; Brown et al., 2018). Full marine incursion led to similar environments as observed today in the North Sea, with the deposition of marine sands and gravels influenced by the hydrodynamic environment (tidal and wave energy), terrigenous sediment input and biogeochemical processes operating at the seabed (for example, Stanev et al., 2009).

Interglacial stages have historically received less research attention than glacial stages in the North Sea. However, there is increasing awareness of interglacials’ importance for understanding the environmental response to climate change, human migration and considerations for offshore site assessment due to the deposition of organic sediments. Palaeo-coastlines have been reconstructed from 18 000 years to the present day (Brooks et al., 2011), providing a record of sea-level change (Figure 3). They serve as a valuable indicator for how coastlines evolved during past interglacial and glacial periods.

3 Methodology

This section details the datasets extracted from open-source reports and describes the process used to integrate them into the chronostratigraphic framework. Limitations of the compiled results are provided, which inform the future recommendations provided in this report.

Geological data was sourced from OWF sites within the area of interest (AOI) (Figure 2) via the MDE, which hosts around 25 years' worth of site data and reports that have completed their licensing agreements. Other open-source reports and academic papers were also utilised; a comprehensive list is provided in the references.

These cable landfall areas are included as part of this assessment:

- Dogger Bank
- Hornsea
- Race Bank

These OWFs are also included:

- Dogger Bank A
- Dudgeon
- East Anglia ONE
- East Anglia TWO
- Galloper
- Greater Gabbard
- Gunfleet Sands
- Hornsea Project One
- Hornsea Three
- Humber Gateway
- Lincs
- London Array
- Norfolk Boreas
- Norfolk Vanguard and Norfolk Vanguard West
- Race Bank
- Sheringham Shoal
- Sofia
- Thanet
- Triton Knoll
- Westermost Rough

3.1 DATASETS AND DEVELOPMENT OF STRATIGRAPHIC FRAMEWORK

The geological formations present at each site were compiled from technical reports, along with key stratigraphic data for each formation. The reports covered multiple science themes, including:

- archaeology
- environment or habitat assessments
- geology
- geophysics
- geotechnics
- palaeo-environment

When extracting the information from the reports, the exact wording was retained and no further interpretation of the data was undertaken. A tabulated summary of these results is shown in Table 1, with the basal depth ranges of formations summarised in Table 2**2**. For further information of the reports utilised per site, please refer to Appendix 1.

For each formation, the following stratigraphic information, where available, was extracted and compiled into this synthesis. The reader is also directed to where information can be found in this report. Any remaining uncertainties or where interpretation was required per formation are also indicated.

- MIS: Stoker et al. (2011). Queries and tentative boundaries are shown where uncertainty remains (Table 1 summary and chronostratigraphic chart)
- Geological time: Stoker et al. (2011)

- Quaternary climate stage: Table 1. Quaternary units grouped as ‘glacial’, ‘interglacial’ or ‘glacial/interglacial’, indicating transitional units during a deglacial period
- Lithological descriptions: Table 1 (summary) and Section 4.1
- Depositional environment: Table 1 (summary) and Section 4.1 Interpretation of the Botney Cut and Elbow formations are occasionally provided, as limited information is provided in the reports
- Seismic facies character: Table 1 (summary) and Section 4.1
- Potential geotechnical constraints: Table 1 (summary) — inferred from knowledge of sedimentological processes, depositional environments and lithological properties and linked with geohazards and geoengineering constraints from Bellwald et al. (in review)
- Expected within 50 m of seabed: Table 1 — inferred from spatial descriptions from OWF reporting. Chronostratigraphic chart indicates ‘TD’ (total depth) of deepest borehole penetration
- Key references: distributed within report, Appendix 1 and references
- Range of formation depths (below seabed): Table 2 (summary)
- Absolute chronological data: Section 4.1, Appendix 2, Table 3 and chronostratigraphic chart
- Top bedrock (where applicable): Table 1, Table 2, Section 4.1 and chronostratigraphic chart

Absolute chronological data for certain formations was available from eight sites (Table 3; full details in Appendix 2). This includes radiocarbon dates from OWFs at:

- Dogger Bank A
- Dudgeon
- Norfolk Boreas
- Norfolk Vanguard
- Race Bank
- Sofia

Optically stimulated luminescence (OSL) data was also available for the Norfolk Boreas and Norfolk Vanguard OWFs.

Radiocarbon dating constrains the age of stratigraphy up to approximately 50 ka (Wood, 2015). In this study, formations older than 11.7 ka are assigned to MIS 2 (late Weichselian) and ages less than 11.7 ka are assigned to MIS 1 (the Elbow and Southern Bight formations, comprising Holocene channels and marine sediments, respectively). The MIS 1 to MIS 2 boundary marks a major palaeo-climatic transition from glacial to interglacial conditions and differentiates deposition of the Botney Cut and Elbow formations, outlined in sections 4.1.19 and 4.1.20.

OSL data was reported from the Brown Bank Formation in Norfolk Boreas and Norfolk Vanguard OWFs. This dating technique can be used to date sediments up to 400 ka (for example, Pawley et al., 2010), although it is more commonly applied in sediments up to 100 ka. In this study, OSL dating of the Brown Bank Formation indicates deposition during the early Devensian, prior to the last glaciation in the North Sea.

The chronostratigraphic chart distils all these datasets into a visual format, showing both the spatial and temporal relationships of the subsurface stratigraphy. The simplified stratigraphic architecture highlights regional geometric relationships, such as the presence or absence of geological formations or time-gaps associated with unconformities and hiatuses. These features are interpreted through seismic stratigraphic principles, offering insights into the sedimentary evolution through time on the vertical axis. From this study, there are no amendments to the Cameron et al. (1992) and Stoker et al. (2011) geological framework.

Table 2 Summary of geological formations reported at OWFs. Basal depth ranges (in metres) summarised where available, apart from Chalk Group ('top Chalk'). Where numbers are given, these are the ranges in depths to bases of formations. x: penetrated at site and interpreted as present; o = inferred as present (not proven but suggested, for example, by seismic character; ?: tentative/uncertain interpretation. Numbers in parentheses refer to those presented in the accompanying map of the chart are ordered numerically along the cross-section.

Formation	Race Bank cable route (1)	Horseshoe Point – cable route (2)	Withow Gap cable route (3)	Westermost Rough (4)	Humber Gateway (5)	Lincs (6)	Race Bank (7) (m below lowest astronomical tide)	Triton Knoll (8) (mbsb)	Dudgeon (9)	Sheringham Shoal (10) (m from soil design profiles)	Greater Gabbard (11)	Galloper (12)	Gunfleet Sands (13)	London Array (14)	Thanet (15) (m Core Depth)	East Anglia TWO (16)	East Anglia ONE (17)	Norfolk Vanguard (18)	Norfolk Boreas (19)	Hornsea (20)	Dogger Bank A (21)	Sophia (22)
'Holocene alluvium'	x	x																				
'Holocene alluvial sands'	x																					
Southern Bight Formation (SBI)				0–12	?	x	10.4–33.8	6 (mobile sand)	x	0.6–2.4	x	x	x	x	17.56–24.03 m	x	x	x	0.5 >4 m	0.2–8.6 m	x	x
Elbow Formation (ELW)			?				?		?		?		?		?	**?**0.8–11.7 mbsb	x		?			
Twente Formation (TN)							?											?	?			
Botney Cut Formation (BOCT)	?			2–32	?			x (not mapped but present)	x	6.5	?		?		?18.58–38.57	?0.8–11.7mbsb	x			13.4 m	x	x
Bolders Bank Formation (BSBK)	x	x	x	10–32	?	x	13.4–40.7	10–16 up to 36	x	0–13										4.3–13.4 mbsb		
Dogger Bank Formation (DBNK)																					x	x

Formation	Race Bank cable route (1)	Horseshoe Point – cable route (2)	Withow Gap cable route (3)	Westermost Rough (4)	Humber Gateway (5)	Lincs (6)	Race Bank (7) (m below lowest astronomical tide)	Triton Knoll (8) (mbsb)	Dudgeon (9)	Sheringham Shoal (10) (m from soil design profiles)	Greater Gabbard (11)	Galloper (12)	Gunfleet Sands (13)	London Array (14)	Thanet (15) (m Core Depth)	East Anglia TWO (16)	East Anglia ONE (17)	Norfolk Vanguard (18)	Norfolk Boreas (19)	Hornsea (20)	Dogger Bank A (21)	Sophia (22)
Brown Bank Formation (BNB) – Upper and Lower																x	x	x	x			
Eem Formation (EE)																				x	x	x
Tea Kettle Hole Formation (TKH)																					o	
Cleaverbank Formation (CLBK)																					o	
Egmond Ground Formation (EG)	?						21–31.8	Average 16–21 m. Minimum 2; maximum 32	x	13–15										?	o	
Sand Hole Formation (SHLE)							26.2–51.3	14–64														
Swarte Bank Formation (SWBK)							22.1–77.1	x	x	13–50										x		
Lowestoft till (LTIL)	x																					
‘Lower Till'	x																					
Yarmouth Roads Formation (YM)																x	x	5–20	x	x	o	

Formation	Race Bank cable route (1)	Horseshoe Point – cable route (2)	Withow Gap cable route (3)	Westermost Rough (4)	Humber Gateway (5)	Lincs (6)	Race Bank (7) (m below lowest astronomical tide)	Triton Knoll (8) (mbsb)	Dudgeon (9)	Sheringham Shoal (10) (m from soil design profiles)	Greater Gabbard (11)	Galloper (12)	Gunfleet Sands (13)	London Array (14)	Thanet (15) (m Core Depth)	East Anglia TWO (16)	East Anglia ONE (17)	Norfolk Vanguard (18)	Norfolk Boreas (19)	Hornsea (20)	Dogger Bank A (21)	Sophia (22)
Smith's Knoll Formation (SK)																?o	?o					
Westkapelle Ground Formation (WK)																o	o					
Red Crag Formation (RCG)																o	o					
London Clay Formation (LC)											x	x	x	0–25								
Harwich Member (HWH) – now Wrabness Member (WRAB)													?									
Woolwich Formation (WL)													x		x							
Thanet Formation (TAB)											x		x		x							
Chalk Group (CK) - top				6–38	22.5–25.8	7–10.5	32–91.6	15–135	14–23	15.6–44.1	110–160		35–49 & >100		18.3–72.3							
Kimmeridge Clay Formation (KC)	42–51.3																					

Table 3 Absolute dating summary of possible formations within MIS 2 and 1 from sites in AOI. All dates given as range cal. yr BP. See Appendix 2 for all sample data. Formations are interpreted from the dates for the purpose of this study. P: sample from peat/organic material; Sh: sample from shell; SF: sample from stem fragment; Ph: sample from *Phragmites australis* (leaf); Bs: sample from bulk sediment; Bu: sample from bud scale; Se: sample from seed; n/a: data not available; ?: tentative result.

Possible formation	Race Bank cable route	Horseshoe Point (Hornsea cable route)	Race Bank OWF	Dudgeon OWF	Norfolk Boreas OWF	Norfolk Vanguard OWF	Dogger Bank A OWF	Sofia
‘Holocene alluvium’	?250–400 Sh							
‘Holocene alluvial sands’								
Southern Bight	?4040–3820 Sh		5960–5760 Sh				7240–6980 n/a	
Elbow		8010–7860 Ph 10180–9890 Bs	8990–8660 SF 9020–8780 Ph	8105–7931 Sh 8996–8760 Sh 8978–8718 Sh 9108–8447 Sh 10 513–9305 Bs	9901–9564 Bu 9884–9542 Se	10 208–9911 Se 10 226–9918 Se 10 416–10 199 Se ?10 169–9744 Se	10 750–10 580 n/a	
Botney Cut					117 07–11 264 Bs 12 895–12 685 Se	?12091-11707 Se ?13781-13556 Se		13 810–13 480 n/a 14 890–14 010 n/a
Brown Bank					69.8 ± 7.7 OSL 83.2 ± 9.5 OSL	57.2 ± 6.4 OSL 69.5 ± 7.7 OSL		

Note that technical validation of the stratigraphy provided from OWF reports is beyond the scope of this study, resulting in a key limitation as outlined in Section 3.1.1. Formations are coloured according to their BGS LEX code. However, tentative interpretations, such as assigning the Bolders Bank and Dogger Bank formations as part of MIS 4 or inferring units solely from seismic facies by OWF site (for example, the Eem to Swarte Bank formations at Dogger Bank), are shown as transparent (pale) layers to indicate their uncertainty. The deepest penetration of each borehole or CPT data is indicated by 'TD' (total depth), showing the lowest stratigraphic level confirmed by ground-truthing data.

To ensure graphic visibility of stratigraphy, the vertical axis uses a non-linear scale divided into five discrete intervals:

- Holocene: present day to 11.7 ka
- Pleistocene: 11.7 to 533 ka
- Pliocene: 1.6 to 2.5 Ma
- Cenozoic: 51 to 56.5 Ma
- Mesozoic: 66 to 201.3 Ma

The horizontal axis of the chronostratigraphic framework is arranged by OWF site, progressing from present-day coastal areas outward into deeper waters of the northern section of the SNS.

The numbers shown after each site named in this report refer to those presented in the accompanying map of the chart and are ordered from 1 to 22 along the cross-section shown in the map. There are multiple ways of visualising the order of the OWF sites; however, the method presented attempts to group the data by spatial distribution of geological formations. This enables a high-level screening assessment to identify which geological formations may occur between sites.

3.1.1 Data limitations

The intention of this study was to obtain a standardised suite of subsurface data from geological reports, detailing geological formations, facies variations and associated depth ranges. However, compiling a comprehensive geological overview was difficult due to the incomplete open-source documentation of geological data. There was particularly limited access to geological ground-modelling reports. Where geological ground-model reports were unavailable via the MDE, supplementary information on geological formations was sourced from alternative datasets in geotechnical and archaeological reports.

It should be noted that these sources may not represent the final or officially validated stratigraphic interpretation of the subsurface stratigraphy. All geological information has been sourced directly from these reports and has not been cross-checked with the original seismic datasets. Additionally, biostratigraphic data is sparse, making it difficult to compare geological settings between sites, therefore restricting a more robust regional assessment.

It is important to acknowledge that OWF site interpretation is shaped by the scope and objectives of the original investigations. As such, updating the stratigraphy or identifying new formations lies beyond the remit of contractual work, which in some cases may limit the completeness of the chronostratigraphic framework presented in this report. Additionally, the level of detail reported varies by site. While some formations may be present, they may not be reported if they are below the foundation zone (60 to 100 mbsb) or if they are not deemed geotechnically significant. For these reasons, the findings in this report may not fully capture the detailed subsurface geology at every site. To reflect this, the framework is designed as a *working* chronostratigraphy, signalling to the end user that this framework is not considered final, but a step toward integrating multidisciplinary datasets into a more robust regional model.

4 Chronostratigraphic framework and stratigraphic assessment

The chronostratigraphic framework presents the results of this study, collating information from 22 sites (Table 2 and presented in the chronostratigraphic chart). The OWF sites use nomenclature exclusively from the existing BGS offshore stratigraphy; however, exceptions occur at some landfall cable routes as there are alluvial deposits and onshore till sequences that are not correlated to the offshore environment.

The resulting framework illustrates our current understanding of the subsurface stratigraphy of the SNS, simplified using colours from the BGS LEX code, which can be improved upon later. Multiple regional and formation-specific trends are observed, as summarised in Section 4.2. Cited references can be used for more detailed work on respective geological units and evolution of the region.

Each formation and associated facies has geotechnical implications that should be considered for foundation and infrastructure design of wind turbines. A comprehensive list of geological features that can impact the geospatial location of foundations are outlined in Bellwald et al. (in review) and Dakin (2025). The geological history (non-glacial, post-glacial and glacial), morphology, geomorphology, source and geological setting also influence the geotechnical properties of sediments and require assessment on a site-by-site basis. These broad geotechnical constraints per formation are outlined in Table 1.

4.1 SUBSURFACE STRATIGRAPHY WITHIN OFFSHORE WINDFARMS

This section provides an overview of the geological formations interpreted as present within the region, with key geological characteristics summarised per OWF site. Stratigraphy is described from oldest to youngest, starting with the oldest Jurassic-aged bedrock, moving through to the youngest Holocene and modern marine sediments. Where a synthesis of data is required, a subsection titled ‘Synthesis and outstanding uncertainties’ is included for that geological unit. These subsections indicate potential research targets, which are further addressed in sections 4.2 and 5.

4.1.1 Kimmeridge Clay Formation (Jurassic)

Jurassic-aged bedrock has only been identified at the landfall zone of the Race Bank (1) cable route within The Wash. At this site, the bedrock is interpreted as weathered Kimmeridge Clay Formation and is generally encountered as stiff to very stiff, very dark grey to black mudstone weathered to clay and containing ammonites, pyrite nodules and cementstones (less than 50 mm) (Fugro, 2015).

4.1.2 Chalk Group (Cretaceous)

Cretaceous Chalk Group subcrops many of the OWFs in the SNS (the numbers shown after each site refer to those presented in the accompanying map of the chart and are ordered from 1 to 22 along the cross-section shown in the map):

- Dudgeon (9)
- Humber Gateway (5)
- Galloper (12)
- Greater Gabbard (11)
- Gunfleet Sands (13)
- Lincs (6)
- London Array (15)
- Race Bank (7)
- Sheringham Shoal (10)
- Thanet (15)
- Triton Knoll (8)

- Westermost Rough (4)

Chalk is below the depth of interest (likely to be present based on seismic but not penetrated) in:

- Dogger Bank A (21)
- Hornsea (20)
- Sophia (22)
- cable route sites (2 and 3)

Identified Chalk Group characteristics are listed by OWF:

- Dudgeon (9): chalk is present within the upper 100 mbsb varies from early to late Cretaceous (indicated from belemnites), resulting in high lithological and geotechnical variability across the site. The lower stratigraphy (Holywell Nodular Chalk Formation (including the Plenus Marls Member and Melbourn Rock Member), New Pit Chalk Formation and parts of the Burnham Chalk Formation) can comprise high to very high density chalk layers (ChalkRock, 2015a; Mellet et al., 2020), which is a marked lithological and geotechnical difference to the low-density stratigraphy observed in other OWFs. Contrasting lithologies, such as the Plenus Marls Member, create seismic markers used to map seismic data across the site (Mortimore, 2021). Fault-controlled anticlinal and synclinal structures suggest syndepositional growth during the Cretaceous
- Gunfleet Sands (13): the Chalk Group is described as ‘relatively uniform’, containing flint gravel up to 60 cm in thickness (BH16, 22, 26, 28) (RPS Hydrosearch, 2004)
- Humber Gateway (5): remoulded Chalk Group, which contained lumps of intact chalk (25.8 to 37 cm), becoming rubbly to blocky, medium-hard with no visible joint: interpreted as more ‘unweathered’ deeper in the borehole (UXO-5 at 37 to 40.8 m)
- Race Bank (7): the Chalk Group is extremely weak and very weak, low to medium density, creamish white to white, with occasional marl lenses and seams and rare flints, sponges and *Zoophycos* (Gardline, 2015a). The ‘top Chalk’ horizon is noted as difficult to interpret on geophysical data at depth, possibly related to a highly eroded or weathered upper unit, which grades to a more structured rock
- Sheringham Shoal (10): the Chalk Group is very weak to weak, low to medium density and rare flints are encountered. The upper 10 to 15 m are classified as grade Dc/Dm with a grade B5 classification assigned at greater depth (Lord et al., 2002; Gardline, 2008)
- Thanet (15): the Chalk Group is not fully penetrated by boreholes; however, it is recorded between 7.4 to 50.35 mbsb and crops out at the seabed towards the shore. It is described as white and has a veneer of grey marl, interpreted as weathering (Wessex Archaeology, 2006a)
- Triton Knoll (8): the Chalk Group is interpreted as late Cretaceous (late Campanian to early Maastrichtian) and is low density with intervals of medium density (ChalkRock, 2015b). Most fractures are closed to tight, indicating grade A chalk (Lord et al., 2002). Steeply inclined (dipping around 70°) joints feature in all chalk cored sections, with subhorizontal fractures always present and some continuous vertical fractures present in boreholes (ChalkRock, 2015b). Most fractures are mineralised and polished or striated with calcite and clay from slickensides. There are occasional sheet flints
- Westermost Rough (4): the Chalk Group is interpreted as late Cretaceous (possibly Rowe Formation), represented by low-amplitude parallel reflectors that dip to the north across much of the site, forming a syncline in the north of the area (Maritime Archaeology, 2013)

4.1.2.1 SYNTHESIS AND OUTSTANDING UNCERTAINTIES:

As the Chalk Group forms the bedrock beneath many OWFs, detailed assessments have provided new insights (Mortimore and James, 2015), helping to extend and refine the offshore Chalk Group within this framework. However, many of these assessments are yet to be synthesised, regionally mapped or published.

OWFs that encounter Lower Cretaceous chalk (such as Dudgeon) versus Upper Cretaceous chalk (such as Triton Knoll or Sheringham Shoal) exhibit significant lithological and geotechnical differences (for example, ChalkRock, 2014a, b). Where Upper Cretaceous chalk is identified, it typically exhibits very weak to weak properties, denoted by 'Dm' (matrix-dominated) of the CIRIA classification, meaning that it is expected to exhibit cohesive behaviour in engineering terms. However, high to very high density layers are identified in Dudgeon, where Lower Cretaceous chalk is present within the foundation zone.

Chalk age influences several primary and secondary characteristics, including the presence of flint and flint morphology, porosity, compaction, tectonics, faulting and diagenesis (Mortimore et al., 2001; Mortimore, 2012; Mortimore and James, 2015), and is likely a critical factor for the geotechnical variations observed between these sites. Another factor that can affect chalk density is periglacial weathering, occurring due to repeated freeze/thaw cycles that result in the degradation of soils and bedrock, such as from glacial cycles during the Quaternary (Johnson et al., 2023). 'Top Chalk' horizons, including both Upper and Lower Cretaceous, are often described as 'weathered', 'structureless' or 'degraded', becoming more structured beyond these zones (for example, Maritime Archaeology, 2013; Dong Energy, 2015). Former glaciated terrain (Figure 2) and extended permafrost zones are more likely to exhibit such degraded soils.

4.1.3 Thanet Formation (Thanetian)

At Thanet (15), Paleocene sediments belonging to the Thanet and Woolwich formations could not be distinguished either in lithology (composition and grain size) or shallow seismic data due to their close lithological similarities; however, both units are described as stiff, green sand and clay in cores BH2A, BH3, BH5 and BH6 (Wessex Archaeology, 2006a).

In Gunfleet Sands (13), the Thanet Formation is interpreted as stiff to very stiff clay (RPS Hydrosearch, 2004). Boreholes identify the clay as fissured and friable, with geophysical data in the northern part of the site showing small-scale faults and folds.

4.1.4 Woolwich Formation (Thanetian to Ypresian)

The Woolwich Formation is tentatively assigned in Gunfleet Sands (13) in the north-east of the site; however, there is uncertainty whether this is part of the Wrabness Member (formerly the Harwich Member), Section 4.1.5. This unit is characterised as dense to very dense sand gravel with clay layers (RPS Hydrosearch, 2004).

4.1.5 Wrabness Member (Ypresian)

Sediments of the Wrabness Member (formerly the Harwich Member) are characterised as dense to very dense sand and gravels with clay layers in Gunfleet Sands (13) (RPS Hydrosearch, 2004). Borehole-28 logged 1.6 m of well-cemented sandstone and other geotechnical samples identified hard, calcareous sandstones or siltstones. The sandstone bed has also been tentatively ascribed as part of the Harwich Stone Band, therefore stratigraphic uncertainty remains.

4.1.6 London Clay Formation (Ypresian)

The London Clay Formation is only identified in the south of the AOI, including in the Greater Gabbard (11), Gunfleet Sands (13) and London Array (14) developments, where it comprises multiple units. It is predominantly fissured, olive-brown, micaceous clay containing occasional gravels of weathered siltstone and moderately weak siltstone beds. Minor constituents include pyritised algal tubes and soft to firm carbonate nodules within the uppermost 0.5 m. Deeper units comprise a stiffer soil (Marine Geosystem, 2006). In London Array, soil strengths range between 50 to 126 kPa (Gardline, 2005). In Gunfleet Sands, this unit is observed to have multiple small-scale faults (throws less than 2 m) and the clay is fissured (RPS Hydrosearch, 2004).

4.1.7 Red Crag Formation (late Pliocene to early Pleistocene)

Previous work indicates that the Red Crag Formation comprises glauconitic marine sands (Cameron et al., 1992). Available OWF reports do not indicate that this unit is confirmed from coring. However, in East Anglia ONE and TWO (16, 17), the Red Crag Formation is suggested as present either directly below the seabed or beneath modern marine sediments, based on seismic character. The seismic data shows this unit as acoustically unstructured with some parallel internal reflectors (Wessex Archaeology, 2018a, b).

4.1.8 Westkapelle Ground Formation (MIS 103 to 63) (Pliocene/Pleistocene transition)

The Westkapelle Ground Formation is part of the Southern North Sea Deltaic Group and is interpreted in northern parts of East Anglia ONE and TWO (16, 17). In East Anglia TWO, it is interpreted to the north of the site as forming a blanket deposit overlying the Red Crag Formation. Its suggested presence is based on seismic character, which shows the unit as acoustically unstructured with a faint basal reflector. It is interpreted as deltaic silts, clays and sands (Wessex Archaeology, 2018a, b). There is no sedimentological information on this unit.

4.1.9 Smith’s Knoll Formation (MIS 65 to 63) (early Pleistocene)

The Smith’s Knoll Formation is part of the Southern North Sea Deltaic Group and is interpreted in the East Anglia ONE and TWO OWFs. Its suggested presence is largely based on seismic data, which shows this unit as acoustically unstructured with some faint subparallel reflectors (Wessex Archaeology, 2018a, b). There are no borehole descriptions on this formation. This unit is also interpreted as pro-delta.

4.1.10 Yarmouth Roads Formation (MIS 62 to 13) (early to early-middle Pleistocene)

The Yarmouth Roads Formation is interpreted as a delta-top deposit with fluvial, estuarine and shallow-marine components. It is extensive throughout the SNS (Cameron et al., 1992).

This unit is identified and penetrated in OWFs located in the central-eastern sector of the AOI; however, regional mapping also shows it crops out at the seabed along the northern East Anglian shoreline (British Geological Survey, 2024). This unit is identified in the East Anglia ONE and TWO OWFs, located directly below the seabed in places, and is interpreted as representing deltaic or beach deposits (Wessex Archaeology, 2018a, b).

This formation comprises yellow, coarse, silty sands and clays with occasional gravel. Seismic characteristics show layered subparallel internal reflectors, along with a well-defined regional erosion surface at its upper boundary (Wessex Archaeology, 2018a). In Norfolk Vanguard West, this unit occurs some 5 to 40 mbsb and is characterised in seismic data by subhorizontal, high-amplitude reflectors. It is interpreted as a fluvially dominated delta-top environment, comprising peat and saltmarsh deposits (Eaton et al., 2020).

4.1.10.1 SYNTHESIS AND OUTSTANDING UNCERTAINTIES

The Yarmouth Roads Formation is difficult to characterise due to limited penetrations in the UK sector, due to either the formation lying at greater (more than 100 m) depths below the seabed or detailed results from OWFs in the UK sector not being published. Where reported, seismic data shows it as laterally and vertically heterogeneous in nature resulting from a complex deltaic to shallow-marine depositional environment, likely including coastal plain environments. This unit is well characterised from OWFs in the Dutch sector, where it is located within 20 to 40 mbsb. Here, the Yarmouth Roads Formation consists of a heterogeneous channel system comprising sands and local silty clays. Additionally, this formation can contain organic soil units including peats, both reworked and in situ (Deltares, 2017).

4.1.11 Swarte Bank Formation (MIS 12) (Anglian)

The Swarte Bank Formation is interpreted as an associated tunnel valley infill, formed during the Anglian glaciation (for example, Praeg, 2003; Lohrberg et al., 2020). Identified in Race Bank (1) nearshore cable route and Race Bank OWF (7) as well as the Triton Knoll (8), Dudgeon (9), Sheringham Shoal (10) and Hornsea OWFs (20), Swarte Bank Formation sediments typically comprise a combination of unsorted, grey, stiff to very stiff, sandy gravelly clays with clasts of chalk, flint and gravels and can contain interbeds, often at subhorizontal angles (Wessex Archaeology, 2010a; Dong Energy, 2015; Gardline 2015a). The carbonate content of this unit can be relatively high (29 per cent); however, this may be attributed to the presence of chalk gravel, as observed at Sheringham Shoal (SCIRA, 2007).

Three distinct subunits are described as part of the Swarte Bank Formation in Race Bank (7). The lower unit is an unsorted deposit of grey, gravelly, sandy clay containing inclusions of chalk, occasional flints, red sandstone and black mudstone gravels. This unit becomes paler with depth, possibly relating to a higher degree of white chalk erosion (forming the bedrock at this site), interpreted as a re-deposited till (Wessex Archaeology, 2010a, b). The middle unit is described as grey laminated clay, often laminated with sand and silt, interpreted as glaciolacustrine deposits. Finally, the upper unit comprises brown, shelly sands and gravels, interpreted as glaciolacustrine or glaciofluvial deposits.

In Dogger Bank, seismic facies are described as variable fills of deep channel forms, generally acoustically transparent to low-amplitude chaotic fills (RWE, 2024a). In Triton Knoll, the Swarte Bank Formation is observed to generally infill large channels cut into the underlying Chalk Group, up to 135 mbsb, which may overspill the channel shoulders to form a thin unit beneath the Sand Hole Formation. In Sheringham Shoal, the unit is described as firm to hard, slightly sandy, gravelly clay, with a proven thickness between 1.45 m and 48.26m and a low to high plasticity (SCIRA, 2007).

4.1.11.1 SYNTHESIS AND OUTSTANDING UNCERTAINTIES

Glacial periods are characterised by highly dynamic environments, which experience oscillating ice-sheet margins and multiple stages of erosion, transportation and (re)deposition of geological material (for example, Benn and Evans, 2014; Clark et al., 2022a ,b; Ely et al., 2024). The sedimentary infill of tunnel valleys can record successive phases of ice sheet advance and retreat, preserving a range of geological units deposited from subglacial, proglacial and transition into interglacial marine environments. Such complex infills within tunnel valley sequences are documented in many sites and are increasingly being documented from borehole records and cone penetration test (CPT) data across the much of the North Sea.

In the UK, the basal units of tunnel valleys commonly comprise overconsolidated tills and, where the channels are sufficiently large, upper sequences may grade into basinal sand and mud-dominated sequences associated with the transition towards glaciomarine and glaciolacustrine conditions (for example, Stewart et al., 2012; Moreau and Huuse, 2014). This accommodation space also hosts later marine deposits (for example, the Sand Hole and Egmond Ground formations) that may be (incorrectly) incorporated as part of the Swarte Bank Formation if sequences are juxtaposed. This problem is identified by Wessex Archaeology (2010a), outlining that the composition of the upper unit (gravelly sand containing variable shell content) is almost identical to composition to the Egmond Ground Formation. This evolution between different depositional environments results in significant variability in sediment and geotechnical properties, emphasising the importance of accurate analysis and mapping.

4.1.12 Sand Hole Formation (MIS 11) (late Anglian to earliest Hoxnian)

The Sand Hole Formation has been interpreted to represent the early rising sea levels following the preceding Anglian glaciation and infills the antecedent topography, such as tunnel valleys, created by the previous glaciation. The lithology is dominated by laminated clay containing a diverse assemblage of shallow marine foraminifera and is typically limited to a small area of the North Sea centred on the Silver Pit (Cameron et al., 1992; Stoker et al., 2011).

Interpreted in Triton Knoll (8) and Race Bank (7) (Wessex Archaeology, 2010b; Gardline, 2015a; Dong Energy, 2015), Sand Hole Formation sediments are described as ‘sandy silt/clay, dark brown in colour and very uniform with marine shells and organic material along with a thinly laminated structure’ (Dong Energy, 2015). In Race Bank, these sediments are limited to the north of the site and are described as a ‘grey clay, laminated with sand and silt deposited as a shallow marine to lagoon deposit’ (Wessex Archaeology, 2010b). It is also recognised at Race

Bank that the middle glaciolacustrine unit, interpreted as part of the Swarte Bank Formation sequence (Section 4.1.11), is identical in character to the Sand Hole Formation, which can make distinctions problematic where these two formations are potentially vertically juxtaposed.

In Triton Knoll, sediments of the Sand Hole Formation are geotechnically split into two broad units, differing from publicly available literature (Arlott et al., 2023). Here, the formation was observed as laterally and vertically variable, comprising medium to very dense sand and very high strength clay with varying thickness. The upper unit ('Unit B') was subdivided into sand- and clay-dominated units ('Unit B – sand' and 'Unit B – clay'). A summary of the best estimate derived geotechnical sand and clay-dominated soil parameters for 'Unit B' includes:

- cone resistance: 45 / 5 MPa
- sleeve friction: 0.54 / 0.25 MPa
- friction ration: 1.2 / 1.5 per cent

The lower unit ('Unit C') was identified as a clean, very high strength clay with occasional beds of sand. A summary of the best estimate derived geotechnical sand and soil parameters for Unit C includes:

- cone resistance: 4 MPa
- sleeve friction: 0.07 MPa
- friction ration: 1.7 per cent

The geophysical characteristics of the lower unit show multiple undulating, incising and cross-bedded reflectors that, in some cases, may reflect filled channels. Others are interpreted as buried dune features, indicating a complicated depositional environment (Arlott et al., 2023).

4.1.13 Egmond Ground Formation (MIS 11) (Hoxnian)

The Egmond Ground Formation belongs to the Hoxnian interglacial, interpreted as representing fully open-marine conditions following deposition of the Sand Hole Formation. Its lithology is described as variable, containing locally gravelly sands interbedded with silt and clay, and is defined on seismics by a persistent tabular geometry (Cameron et al., 1992).

The formation is characterised in the Race Bank (7), Triton Knoll (8), Dudgeon and Sheringham Shoal (9, 10) and Dogger Bank (21) OWFs. Where present, it is described as a 'dense to very dense, and locally gravelly sand' (Triton Knoll) (Gardline, 2015a; Arlott et al., 2023). In Race Bank (7), it is identified in 24 boreholes and is described as a 'sporadic and lithologically variable deposit comprising grey-brown fine to medium dense to very dense sand with local gravelly sands interbedded with silt and clay and contains marine shells and shell fragments' (Dong Energy, 2015) and is 16 m thick (Wessex Archaeology, 2015a).

In Triton Knoll, the geophysical response shows the Egmond Ground Formation as acoustically transparent to weakly horizontally bedded, with characteristics relatively consistent across the whole of the site. A summary of the best estimate derived geotechnical soil parameters includes:

- cone resistance: about 45 MPa
- sleeve friction: 0.54 MPa
- friction ration: 1.2 per cent

The Egmond Ground Formation is interpreted as being deposited in a coastal plain setting at Triton Knoll, where the site was likely covered by a shallow sea in a high-energy environment (Arlott et al., 2023). In Dogger Bank, Egmond Ground Formation sediments are described as part of the infill of the tunnel valley complex; the seismic facies are characterised as variable fills of deep channel forms, which are generally acoustically transparent to low amplitude to chaotic (RWE, 2024a).

Across the Dogger Bank zone, the deepest samples assessed for geoarchaeological investigation are from borehole BH1282 between 37.62 and 38.1 mbsb. The foraminifera (*Haynesina orbiculare*) from these levels indicate a cold, shallow marine, near-shore environment typical of a transitional temperate to cold Pleistocene stage (Wessex Archaeology, 2014a), likely indicating Hoxnian-aged sediments. Note that the original biostratigraphy reports are not openly available as part of this assessment.

In Sheringham Shoal, the sediments are described as fine dense to very dense, occasionally silty sand, documented to be 1.7 to 5.7 m thick, with an average of 4.1 m (SCIRA, 2007).

4.1.14 Eem Formation (MIS 5e) (Ipswichian)

The Eem Formation dates to the Ipswichian interglacial period and has been interpreted as representing a marine inundation prior to the Weichselian glacial. Previous research describes the formation as consisting of up to 20 m of shelly sands, passing westwards into muddy sands and muds of an intertidal environment (Cameron et al. 1992; Limpenny et al., 2011). The East Coast Regional Environmental Characterisation (REC) study interprets the Eem Formation deposits as isolated, discontinuous patches that sit unconformably above the Yarmouth Roads Formation, located in the northernmost part of the REC study area (north of about 52°33′N) (Limpenny et al., 2011).

There is limited detailed information on the Eem Formation from OWF data available in the AOI; however, it is interpreted as present in Hornsea (20) (McDermott et al., 2011; RPS, 2018) and Sophia (22) (Wessex Archaeology, 2014a). In Sophia, geoarchaeological samples were collected that indicate a post-temperate, boreal forest. Recovered pollen flora are dominated by *Pinus* (pine), *Betula* (birch) and *Picea* (spruce), similar to late Ipswichian/early Devensian (MIS 5e/5d) environments (Wessex Archaeology, 2014a; note that the original biostratigraphy reports are not openly available as part of this assessment). Additionally, in Dogger Bank (21), seismic facies attributed to the Eem Formation are described as high amplitude, medium frequency, continuous, parallel reflections with channel forms incised into the unit (RWE, 2024a).

4.1.14.1 SYNTHESIS AND OUTSTANDING UNCERTAINTIES: SAND HOLE, EGMOND GROUND AND EEM FORMATIONS

These units are grouped as they represent interglacial periods and can form stacked, vertically juxtaposed units comprising clay, silt and sand.

The presence of dinoflagellate cysts, benthonic and planktonic foraminifera and calcareous nanoplankton were originally used to differentiate these deposits. However, Stoker et al. (2011) provides no further palaeo-environmental detail of these formations in the SNS due to limited new datasets at the time. On a site-by-site basis and because these interglacial units can be lithologically similar (Wessex Archaeology, 2010b), differentiation between the stratigraphic units deposited around 300 ka apart relies on the interpretation of microfossil, macrofossil and pollen assemblages.

OWF datasets indicate that the Sand Hole and Egmond Ground formations (both commonly attributed to MIS 11) were deposited within and adjacent to antecedent depocentres created by the erosion and infill of underlying Anglian tunnel valleys. In contrast, the Eem Formation (MIS 5e) is interpreted from seismic data as being more laterally extensive within the boundary of OWF sites, with occurrences predominately identified toward the northern part of the AOI.

Where interpreted, the inferred environmental settings of the Egmond Ground Formation differ from the ‘fully marine conditions’ described by Cameron et al. (1992). Access to detailed biostratigraphy reporting remains restricted; however, the Wessex Archaeology (2014a) report discusses broad biostratigraphic trends. Results from Dogger Bank and Sophia suggest more nuanced depositional environments than previously recognised, indicating near shore and coastal plain conditions rather than exclusively fully marine settings in MIS 11 (Egmond Ground Formation). The summarised biostratigraphic results provided in Wessex Archaeology (2014a) also highlight differences between colder depositional conditions associated with the Sand Hole and Egmond Ground formations versus pollen assemblages relating to warmer climates in the Eem Formation.

Future investigations should use biostratigraphy where vertically juxtaposed sand- and clay-dominated units are identified within candidate areas within the SNS. This has important implications, as it may influence the final stratigraphic framework adopted in future studies. In Triton Knoll (8), new observations enabled the Sand Hole Formation to be to be subdivided into three subunits (Unit B-sand, Unit B-clay and Unit C) (for example, Arlott et al., 2023). This is the first time this unit has published results that highlight the importance of interpreting seismic facies and depositional environments that directly affect geotechnical results that may have geoengineering implications.

4.1.15 Brown Bank Formation (MIS 5d to 4) (Ipswichian to early middle Devensian)

The Brown Bank Formation is interpreted as having been deposited during early Devensian sea-level fall in an interglacial marginal marine environment (Stoker et al., 2011).

This unit is identified in OWF sites located close to the international UK/Dutch border:

- East Anglia ONE and TWO (16, 17)
- Norfolk Vanguard (18)
- Norfolk Boreas (19)
- Hornsea (20)

In Norfolk Vanguard and Norfolk Boreas, the Brown Bank Formation is divided into two units, Upper and Lower. The Upper Brown Bank unit consists of clayey silts and sands, whereas the Lower Brown Bank unit contains coarser-grained sands, locally containing frequent shell fragments (Wessex Archaeology, 2018c, d; Eaton et al., 2020). Geophysical data from Norfolk Boreas show that the Lower Brown Bank unit accumulated within topographically controlled depressions. These depressions display a low-relief basal reflector and an infill that appears either acoustically transparent or well layered. Seismic data also reveal several dune features, although their origin - submarine or terrestrial - remains uncertain. The Upper Brown Bank unit forms a blanket deposit across much of the region. It appears either acoustically transparent or represented by sub-horizontal layered reflectors. This unit contains numerous internal erosion surfaces, organic matter, occasional fluid-escape structures and zones of acoustic blanking (Wessex archaeology, 2018e; Wessex Archaeology, 2019a). Additionally, iron minerals were observed in samples VC047 and VC016 in Norfolk Boreas, possibly indicating weathering or near-surface ground waters due to intermittent periods of drying out relating to subaerial exposure (Wessex Archaeology, 2019a).

In Norfolk Boreas, the Brown Bank Formation contains a diverse assemblage of marine and outer estuarine macrofossils (for example, marine molluscs) and foraminifera (for example, miliolids, *Ammonia batavu* and *Elphidium williamsoni*), with diatoms not preserved in the sedimentary succession. The microfauna suggest deposition in a marine embayment to outer estuarine conditions that were deposited in a subarctic climate (Wessex Archaeology, 2019a).

The formation is also observed as two discrete units in East Anglia ONE. The lower unit largely infills hollows or channels and has a distinct, occasionally undulating reflector and internal acoustically transparent to subhorizontal seismic reflectors. Like the Norfolk sites, the upper unit is observed as a blanket deposit, characterised as having numerous faint, subparallel internal reflectors. Additionally, the Brown Bank Formation sediments in East Anglia TWO are interpreted as two distinct units with geomorphological ‘dune features’ at the base. The dune features have acoustically chaotic fill with some internal dipping reflectors (Wessex Archaeology, 2018a, b). The Brown Bank Formation is interpreted above the underlying Red Crag and Yarmouth Roads formations, where it is observed to have an undulating base and numerous subparallel, internal reflectors.

4.1.15.1 OPTICALLY STIMULATED LUMINESCENCE DATING

The Brown Bank Formation has been dated using OSL methods in Norfolk Vanguard, Vanguard West and Norfolk Boreas OWFs. However, not all dates were accepted because of data scatter in the sample distribution. The accepted age estimates are (Figure 4 and Table 3):

- Norfolk Vanguard West: Vibrocore 085 (VC085) — 69.5 ± 7.7 ka (4.6 to 4.8 mbsb) and 57.2 ± 6.4 ka (5.1 to 5.3 mbsb) = MIS 4 (Wessex Archaeology, 2019a)

- Norfolk Vanguard: VC074 — 82.4 ± 8.5 ka (5 to 5.36 mbsb) spanning MIS 5a (Wessex Archaeology, 2019a)
- Norfolk Boreas: VC016 — 83.2 ± 9.5 ka (1.7 to 2 mbsb) and 69.8 ± 7.7 ka (2.65 to 3 mbsb) = MIS 5a and 4 (Wessex Archaeology, 2019a).Absent diatoms but presence of foraminifera and ostracods indicate outer estuarine and marine conditions with biostratigraphy placing deposition between MIS 5e and MIS 3 in a cool climate
- Norfolk Boreas: VC047 — 60.5 ± 5.8 ka (2.55 to 3.0 mbsb) and 78.9 ± 8.3 (3.7 to 4 mbsb (age estimates accepted with caveats – see Appendix 2)

4.1.15.2 SYNTHESIS AND OUTSTANDING UNCERTAINTIES

Ultra high resolution seismic data from OWF sites shows increasingly detailed information that was not captured in the early BGS studies (for example, Cameron et al., 1992). In the UK sector, seismic, geotechnical and core data collected from the Norfolk and East Anglia ONE and TWO sites show at least two distinct units associated with the Brown Bank Formation, with East Anglia ONE and Norfolk Boreas also identifying possible dune geomorphologies near the base of the unit (Wessex Archaeology, 2018a, 2019a; Eaton et al., 2020, 2024).

Research from the Dutch sector also shows this formation as complex, with at least four distinct units and other sub-units characterised. Additionally, the Brown Bank Formation in the Dutch sector is identified as containing organic-rich sediment samples (Waajen et al., 2024; 2025). These architectural and sedimentological complexities may include changes of sediment input and potential periods of drying out and exposure around 72 ka (Waajen et al., 2025). These observations are supported in the Norfolk Vanguard and Norfolk Boreas sites where internal erosion surfaces, possible organic-rich layers and the presence of iron minerals are identified in core that may indicate periods of exposure (Wessex Archaeology, 2019a).

Understanding the complexity of the Brown Bank Formation across international borders is important, as it forms a distinct unit near the eastern part of the UK sector. The number of variable lithological units across relatively short distances between the UK and Dutch sectors suggests that deposition during the early Devensian is more complex than previously understood, relating to an interplay of variable climate conditions, coastal regression and Rhine delta progradation (as outlined in Waajen et al., 2025). Horizontally heterogeneous sediments, the occurrence of shallow gas anomalies and organic material also present considerations for engineering assessments.

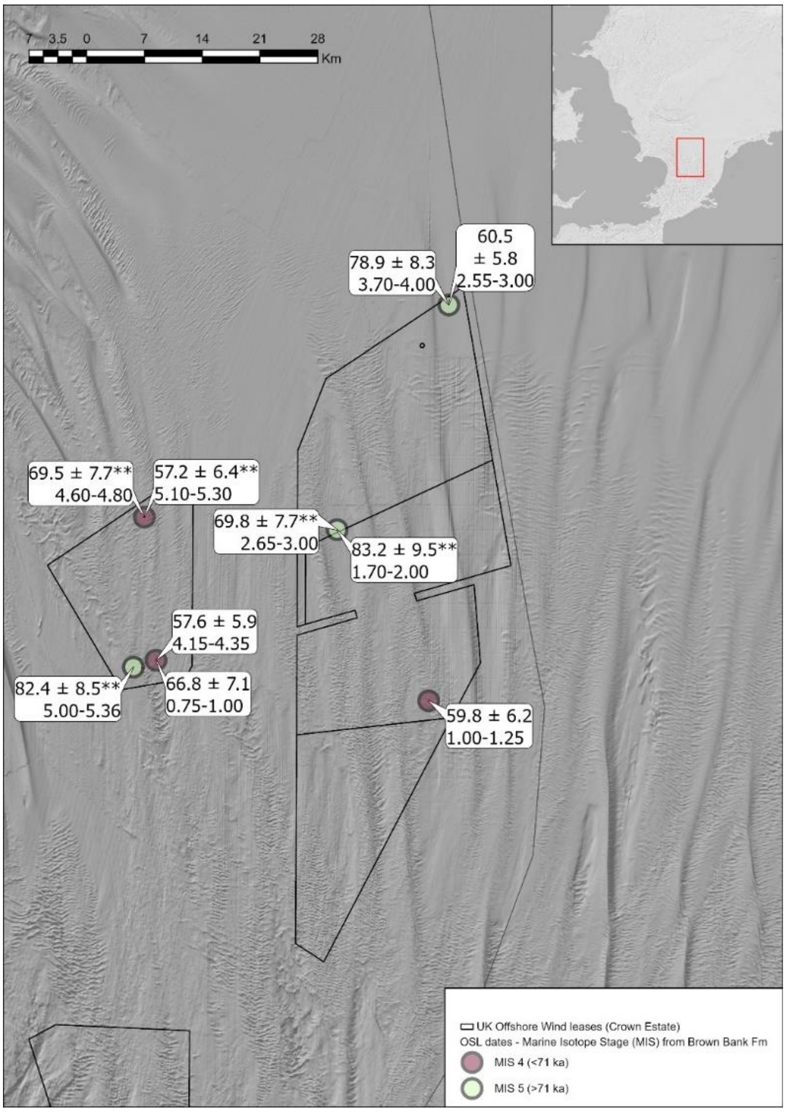

Figure 4 All OSL dates sampled from the Brown Bank Formation across the Norfolk Vanguard and Boreas sites (accepted dates indicated by **). Labels show age in ka ± degree of uncertainty, followed by the depth of sample below seabed (in metres). Onshore DEM from SRTM, GTopo30, GEBCO (Tozer et al., 2019). Bathymetry data from EMODnet 2024. BGS © UKRI 2025.

4.1.16 Dogger Bank Formation (MIS 3 to 2) (late Devensian)

Dogger Bank sits at the north of the AOI, forming a prominent positive bathymetric high on the present-day sea floor (Figure 2). It is considered to have been an emergent feature during the late Devensian and early Holocene (Fitch et al., 2005), leading to a unique geological history that differs from the other OWF sites further to the south.

The Dogger Bank Formation is restricted to Dogger Bank OWF (21) and is generally linked to ice-marginal processes during confluence of the British–Irish and Fennoscandian ice sheets in the SNS, between approximately 30 to 20 ka BP (Cotterill et al., 2017a; Roberts et al., 2018; Phillips et al., 2022; Clark et al., 2022a, b). It is composed of deposits resulting from several depositional cycles, including clay till, sandy glacial outwash and glaciofluvial channel deposits. This cyclic deposition is likely to have been controlled by repeated oscillation of the late Weichselian ice front, a process that has also resulted in repeated compression and associated glaciotectonic deformation of the sediments (Cotterill et al., 2017a, b). Gradual and continuous relative sea-level rise after the last glacial maximum eventually inundated Dogger Bank around 8 ka BP (RWE, 2024a).

4.1.17 Bolders Bank Formation (MIS 4 to 2) (late Devensian)

The Bolders Bank Formation is interpreted as a till related to the expansion and decay of ice sheets during the late and possibly middle Devensian (Cameron et al., 1992; Davies et al., 2011; Dove et al., 2017). It forms an extensive blanket of glacial till that is present across much of the SNS and is approximately coeval with the Dogger Bank Formation.

The formation is identified in many OWF site reports, including:

- Dogger Bank (21)
- Dudgeon (9)
- Hornsea (20)
- Humber Gateway (5)
- Lincs (6)
- Race Bank (7)
- Sheringham Shoal (10)
- Triton Knoll (8)
- Westermost Rough (4)

However, it is not identified in sites further east or south, such as the Norfolk and Thames Estuary sites. This is because the North Sea ice lobe did not extend this far south or east (Dove et al. 2017).

In seismic data, the Bolders Bank Formation's basal horizon is subhorizontal; however, frequent channels occur at the base, with the largest channel trending north-north-east to south-south-west (for example, Triton Knoll (Gardline, 2015a)). In core, Bolders Bank Formation sediments are described as very stiff to hard, slightly sandy, slightly gravelly clays with beds of sand (for example, Triton Knoll (Gardline 2015a)). In Race Bank, this unit is observed either at the seabed or beneath a thin veneer of sediment and comprises brown, poorly sorted, sandy, gravelly clay with numerous (generally chalk) inclusions (Wessex Archaeology, 2010b).

In Dogger Bank, seismic facies are described as chaotic, discontinuous reflections with varying amplitude in thick sheets or mounds with irregular top-unit topography (RWE, 2024a). Some sites report subunits of the Bolders Bank Formation with an 'upper even deposit of lodgement till represented by moderate amplitude subparallel reflectors and a lower uneven deposit of ablation till' (Westermost Rough (Maritime Archaeology, 2013)).

In Sheringham Shoal, this unit is around 6.42 to 9.06 m thick and forms a blanket deposit over the site about 8 mbsb. It has low to intermediate plasticity and has a relatively high clay and silt content (SCIRA, 2007).

In Hornsea, a blanket deposit of uniform greyish-brown till (about 10 to 15 m thick) is present, appearing structureless on seismic data. At this site, shear strengths reported vary between 50 to 130 kPa; however, values up to 500 kPa are also reported (McDermott et al., 2011).

Descriptions of the Bolders Bank Formation show the presence of multiple subunits that, if located close to the palaeo-ice margin, can form broad, arcuate till wedges comprising glacial till (for example, Dove et al., 2017), which may relate to different glacial cycles during the Devensian. It is also possible that lower members could be as old as MIS 5d, as explained in Section 4.1.17.1 and tentatively indicated in the accompanying chronostratigraphic chart.

4.1.17.1 SYNTHESIS AND OUTSTANDING UNCERTAINTIES

The Bolders Bank Formation was deposited within subglacial and submarginal environments associated with the southern extent of the North Sea lobe of the British–Irish ice sheet during the late Devensian. Glacial diamictons like the Bolders Bank Formation can present ground investigation challenges due to their degree of overconsolidation, soil heterogeneity, potential boulder content and erosion of the underlying substrate.

The approximate upper boundary of the Bolders Bank Formation can be constrained via dating from the ice-sheet margins indicating retreat from the SNS by about 18 ka (Evans et al., 2021). Radiocarbon dating of organic soils within the overlying channel sequences (for example, Upper

Botney Cut and Elbow formations) gives dates of around 14 to 8 ka. The lower boundary of the Bolders Bank Formation can be constrained by OSL dating in the preceding Brown Bank Formation (around 57 ka). However, the geological record between about 57 to 18 Ka (MIS 5d to 2) is poorly constrained. As identified on seismic data, the Bolders Bank Formation contains multiple subunits (for example, Dove et al., 2017; Roberts et al., 2018), but tying these subunits to the MIS framework is challenging. Seismic and core data from OWF data may be used to target datable material (for example, outwash sediment within proglacial channels), which could help tie these units chronostratigraphically. Further targeted sedimentological and seismostratigraphic research on the distinct Bolders Bank Formation subunits will provide insight on ice-sheet dynamics and dramatically changing depositional environments within the region, with clear implications for offshore engineering.

4.1.18 Twente Formation (MIS 2) (late Devensian)

The Twente Formation is interpreted as an aeolian sand deposited in a periglacial, terrestrial environment (Cameron et al., 1992; Stoker et al., 2011).

This unit was originally tentatively interpreted in the Norfolk Vanguard (18) site as a 1 m-thick sand unit. However, particle size analysis suggested the sand was coarser grained and more well-rounded than expected for a windblown deposit; it could therefore be more indicative of a water-lain deposit, possibly within a palaeo-channel or floodplain (Wessex Archaeology, 2018d). This uncertainty of formation presence is highlighted by a question mark on the chronostratigraphic chart.

In other sites, such as Norfolk Boreas, this unit was not identified in either the shallow geophysical data or the geotechnical logs; it was therefore not mapped in areas where the original BGS interpretation (1984) suggested a possible extent (Wessex Archaeology, 2018e).

4.1.18.1 SYNTHESIS AND OUTSTANDING UNCERTAINTIES

The poor preservation potential of the periglacial wind-blown Twente Formation has resulted in insufficient evidence to prove the presence or absence of this unit within the UK sector, especially without access to detailed sedimentological or palaeontological analysis. Further work would be needed to assess the presence and significance of this unit in the subsurface.

4.1.19 Botney Cut Formation (MIS 2 into earliest MIS 1)

The Botney Cut Formation represents a key depositional unit in the final phases of the Weichselian glacial interval. Cameron et al. (1992) describes the formation as channels less than 100 m deep and 8 m wide containing at least two members: a lower diamicton and an upper, soft to stiff, laminated mud, interpreted as originating from glaciomarine to glaciolacustrine deposition. Stoker et al. (2011) offers a more simplified definition referring to '…channels infilled by diamictons of the Botney Cut'. Note that the 'Synthesis and outstanding uncertainties' for this formation is included as part the Elbow Formation in Section 4.1.20.

From late MIS 2 into MIS 1, radiocarbon dating techniques can be used to determine the age of organic material, such as plant remains or peat (for example, Blaauw and Christen, 2005). The following sites provide dates from organic samples, allowing the Botney Cut Formation (over 11.7 ka) to be assigned (Figure 5):

- Norfolk Vanguard West (18): six samples were taken from three vibrocores representing up to 4000 years of peat development (Wessex Archaeology, 2018d). The dates range from (oldest to youngest):
    - 13 781 to 9911 cal. yr BP (VC076)
    - 12 091 to 11 707 and 10 169 to 9744 cal. yr BP (VC085), to 10 208 to 9 911 cal. yr BP (VC076)
    - sample VC076 (13 871 cal. yr BP) suggest the oldest basal peats began to accumulate around the close of the late Devensian period (MIS 2)
    - the upper peats (less than 11 700 years) continued to develop in the earliest Holocene (MIS 1), indicating deposition as part of the Elbow Formation

    - it is noted that some uncertainty remains regarding the reliability of the radiocarbon dates from vibrocore VC085, which should therefore be treated with caution, particularly where there is an inversion of ages between two samples in one core
- Sofia (22): radiocarbon dating of peat, sandy peat and organic clay yielded ages between 12 900 and 13 480 cal. yr BP (MIS 2). Plants sampled from kettle holes were dated 14 890 to 14 010 cal. yr BP during the Windermere/Bølling-Allerød Interstadial (Wessex Archaeology, 2013; RWE, 2024a). The younger peats contained evidence for birch, pine, alder, elm and willow, indicating the establishment of woodlands and suggesting an extensive terrestrial plain covering a large area of the SNS between south-east England and the European mainland (for example, Fitch et al. 2005)

In Westermost Rough (4), Triton Knoll (8), Dudgeon (9), Greater Gabbard (11), Thanet (15) and East Anglia ONE and TWO (16, 17), Hornsea Project One and Three (20), and Dogger Bank (21), channel systems lack organic-rich units (or do not have publicly available information). The following sites are provisionally attributed to the Botney Cut Formation, although no age-dating data is currently available to validate this stratigraphic assignment. Samples lacking organic remains may suggest reworking of late glacial sediments or deposition in a cooler climate (for example, Brown et al., 2018).

The seismic character of the interpreted Botney Cut Formation for the following sites include:

- Westermost Rough (4): parallel, low-amplitude reflectors form steep, north-north-east to south-south-west channels that incise up to 38 m in the south-west of the site
- Triton Knoll (8)**:** the Botney Cut Formation is mentioned as being present; however, the base is not always mapped or identified as its own unit and it is occasionally combined with the underlying Bolders Bank Formation. This unit is also primarily identified via seismostratigraphy, therefore it is possible that what is reported as the Botney Cut Formation may be Elbow or possibly even Bolders Bank channels
- Dudgeon (9)**:** research (for example, Brown et al., 2018; British Geological Survey, 2023) suggests that the Botney Cut Formation should be redefined to encompass multiple channel subunits that include mixed glacial to post-glacial infill. Each subunit reflects a distinct depositional environment and facies, resulting in unique geotechnical properties
- Greater Gabbard (11): similarly, reports identify numerous stacked, relict channel features that vary in terms of sediment, magnitude and orientation. Lower gravelly sand and sandy gravels are described as part of the 'Pleistocene Fluvial Terrace' deposits (Marine Geosystem, 2006)
- Thanet (15): the archaeological assessment identified numerous channels within the upper 13 mbsb. Ranging from 300 × 10 m (width × depth) to 795 × 11.5 m, the channels are interpreted as fluvial channels from the late Devensian. However, they were not assigned a formation (Wessex Archaeology, 2006a)
- OWF reports such as East Anglia ONE and TWO (16, 17) identify several north-north-west to south-south-east channel features to the south of the AOI. They are typically found as simple cut/fill channels up to 11.2 mbsb. The channels are interpreted as having been deposited in a terrestrial setting during low sea level (Wessex Archaeology. 2018a, b)
- Hornsea Project One and Three (20): infill channels interpreted as Botney Cut Formation cut down into the underlying deposits (typically Bolders Bank Formation) (McDermott et al., 2011; RPS, 2018). In Hornsea Project One, this unit is divided into a lower, structureless unit of poorly sorted, gravelly, coarse sands and an upper, parallel-bedded, soft and slightly sandy mud, interpreted as being deposited in a glaciolacustrine environment. Indications of acoustic blanking in seismic data may also indicate the presence of gas (McDermott et al., 2011)
- Dogger Bank A (21): the Botney Cut Formation is interpreted as a sequence of thinly laminated, grey clays containing laminae of silt and fine sand, interbedded with a layer of well-sorted sands and occasional gravel (Cotterill et al., 2017a). Other areas contain organic-rich and bioclastic detritus; these are interpreted as lacustrine deposits. Seismic

facies of the Botney Cut Formation are described as variable fills of channel forms, acoustically transparent, draped with low to high amplitudes (RWE, 2024a)

4.1.20 Elbow Formation (MIS 1)

The Elbow Formation was deposited during the Holocene, as relative sea level rose within the North Sea (for example, Sturt et al., 2013). Mud-rich units were deposited within channels and local depressions, commonly including organic-rich layers (including peats) in shallow-water intertidal or low-coastal environments (Cameron et al. 1992; Stoker et al. 2011; Brown et al., 2018; Waller and Kirby, 2021).

Based on the presence of age dating from peat and wetland environmental indicators, the Elbow Formation (less than 11.7 ka) is interpreted at:

- Boreas (18, 19)
- Dogger Bank (21)
- Dudgeon (9)
- Horseshoe Point (2)
- Norfolk Vanguard
- Race Bank (7)
- Withow Gap (3)

(For example, Wessex Archaeology, 2010a; Royal Haskoning DHV, 2019.). Extensive peat deposits (~85 km^2) occur across Norfolk Boreas and Norfolk Vanguard, forming a substantial buried peatland alongside peat-infilled and peat-fringed palaeochannels. During the transition from MIS 2 to MIS 1, freshwater fluvial channels occurred and later, a freshwater wetland developed within and along palaeochannel margins or within topographic lows, while woodland occupied dry ground. Before complete marine inundation, coastal tidal creeks and flats deposited under the influence of Early Holocene rise (Wessex Archaeology, 2019a).

The following sites describe the age and geological setting associated with deposition of sediments within the Elbow Formation:

- Horseshoe Point (2): samples at the Humber Estuary yielded 11 radiocarbon dates ranging between 10 180 to 9890 and 8010 to 7860 cal. yr BP
    - interpretation of these sediments suggests deposition in lagoonal settings during the early Holocene, with continuous reworking and associated movement of sediments along the coastal margins (Grant et al., 2024)
    - although these deposits were not interpreted as part of a formation, their timing of deposition is associated with the Elbow Formation
- Skipsea Withow Mere (3): investigation of post-glacial deposits exposed along the cliffside at Skipsea revealed a sequence of preserved peat, gyttja and minerogenic lake deposits, dated to between 9880 and 4500 ^{14}C years BP (Gilbertson et al., 1984; Hull Geological Society, 2011; Humber Archaeology, 2013; reported in RWE (2024a)
- Race Bank (7): radiocarbon and palaeo-environmental analyses were carried out on boreholes BH-CPT-01,11 and BH-G01 (Wessex Archaeology, 2015a)
    - the oldest sediments were identified in BH-CPT-01 (8990 to 8660 cal. yr BP) and BH-CPT-11 (9020 to 8780 cal. yr BP), based on samples taken from stem fragments and common reed (*Phragmites),* respectively
    - the presence of wetland vegetation points to the preservation of early terrestrial environments: Borehole BH-G01 provided a date of 5960 to 5760 cal. yr BP from 4.82 to 4.92 mbsb
    - Borehole BH-G01 also contained the best-preserved environmental sequence, with macrofossils, pollen, molluscs and microfossils indicating a brackish estuarine to tidal marsh environment
    - we assign these as time-equivalent to the Elbow Formation due to the macrofossil assemblage, including typical wetland plants such as sedge and leaves and stems of the common reed (*Phragmites)* (Wessex Archaeology, 2010a, b)

- Dudgeon (9): four samples were taken from peat and gyttja in boreholes BH06 and BH21 from a unit (also comprising sands) termed ‘channel-sediments’, which sits above the Bolders Bank Formation and below the Holocene marine sediments
    - BH06: the deeper sample was dated to 8996 to 8760 cal. yr BP, while the shallower sample yielded a date of 8105 to 7931 cal. yr BP
    - BH21: the lower sample was dated to 9108- to 8447 cal. yr BP and the upper sample to 8978 to 8718 cal. yr BP, placing deposition in MIS 1 (Wessex Archaeology, 2014b)
    - notably, the palaeo-environmental analyses of these channels indicated a tidal environment of brackish creeks surrounded by fern, marshland and hazel-dominated woodland (Wessex Archaeology, 2014b)
    - other radiocarbon dates subsequently sampled from bulk sediment and seeds in BH06 yielded slightly older ages between 10 513 and 9305 cal. yr BP (Brown et al., 2018)
- Norfolk Boreas (19): nine samples were undertaken for radiocarbon dating from three vibrocores at Norfolk Boreas, to the north of Norfolk Vanguard, and are interpreted as part of the Elbow Formation (Wessex Archaeology, 2019a):
    - three radiocarbon dates were acquired from VC039. Dates indicated deposition ranging from 12 890 to 12 690 to 9560-9430 cal. yr BP. There is possibility for reworking of older plant material in the deeper and older sample (12 890 to 12 690), resulting in an uncertain age. However, the younger dates place this deposit as part of MIS 1. The samples showed a mix of brackish and marine species, pointing to a transition from tidal flat to open estuarine conditions
    - two radiocarbon dates were acquired from VC028, with only one successful result, suggesting peat formed 9900-9570 cal. yr BP (MIS 1). The paleoenvironment is interpreted as freshwater wetland with woodland occupying dryland. A marine mollusc found in the upper unit suggested transgressive unit with increasing marine influence in the Early Holocene.
    - four radiocarbon dates were acquired from VC032. Dates indicated deposition between ranging from 11 700-11 260 and 9880-9540 cal. yr BP within MIS 1. Upper samples from VC032 contained brackish foraminifera and ostracods, indicating a tidal flat environment. More marine ostracods were present in the upper part of this unit, suggesting a growing marine influence consistent with rising sea levels during this time. A unit composed of clay and laminated silt above the peat is interpreted as intertidal in origin, suggesting inundation of the project area soon after 9880-9540 cal. yr BP.
- Dogger Bank A (21): one sample acquired from sediments infilling palaeo-channels is 10 750 to 10 580 cal. yr BP (Wessex Archaeology, 2012; RWE, 2024a); this timing of deposition is associated with the Elbow Formation

4.1.20.1 SYNTHESIS AND OUTSTANDING UNCERTAINTIES: BOTNEY CUT AND ELBOW FORMATIONS

Due to its palaeo-environmental complexity, the Botney Cut Formation has often been used as a generic ‘bucket term’ for all late Weichselian channels that likely result from a range of sedimentary processes that occur around the MIS 2 and MIS 1 transition. For example, OWF reports document multiple geological settings associated with this unit, including post-glacial geological settings such as:

- coastal wetlands
- tidal flats
- intertidal to open estuarine settings
- fluvial, lacustrine and marine settings

Post-glacial channel infills are also recorded.

Additionally, the Elbow Formation encompasses a range of geological settings such as:

- coastal wetland to brackish estuarine shallow water
- lagoonal, intertidal and tidal marsh

- coastal and shoreface environments

These recent observations from OWF sites highlight the high degree of complexity of multiple settings that can laterally co-exist at one time, supporting the broad range of environments proposed in Cameron et al. (1992)'s original interpretation.

A clear distinction between the Botney Cut and Elbow Formations has not been established from OWF data, though it is described by Brown et al. (2018), identifying a step change in palaeo-geography and sea-level rise between the two formations. Because the timing of the final, full marine inundation during the Holocene varied spatially with reference to elevation above ordnance datum (OD), the chronostratigraphic chart provides an effective way to visualise these spatial and temporal differences.

Radiocarbon dating of organic material enables stratigraphy to be accurately placed in a chronostratigraphic framework (for example, Sturt et al., 2013; Ward et al., 2006; Gaffney et al., 2007; Waller and Kirby, 2021; Eaton et al., 2024). Where possible, the tops and bases of peat deposits can be sampled to reveal how long the peat-forming environment persisted prior to marine inundation. The oldest peats sampled from an OWF site within the AOI are from Norfolk Vanguard (18). They developed over a period of about 3800 years, with dates ranging from 13 781 to 13 556 and 10 208 to 9911 cal. yr BP (from seven samples). To the north, peat samples from the Norfolk Boreas (19) OWF yielded dates of 12 895 to 12 685 cal. yr BP, with peat development conditions sustained for about 3400 years (Wessex Archaeology, 2019b). Peat ages over 11 700 years suggest deposition in the late Devensian, which could place these sites in the Botney Cut Formation. However, younger, organic-rich deposition in channel fills above the Bolders Bank Formation in the Dudgeon (9) OWF (9108 to 8447 and 8978 to 8718 cal. yr BP) (Wessex Archaeology, 2014b) may suggest peat deposition as part of the Elbow Formation (equivalent to the Naaldwijk Formation or the Basal Peat in the Dutch sector).

The difference in peat ages between the Dudgeon, Norfolk Vanguard and Boreas OWFs acts as a key indicator of the timing of marine inundation into the SNS. This likely reflects a gradual marine inundation from the south via the English Channel, advancing along the coastline. Towards the present day coastline, such as in Dudgeon OWF, a network of late and post-glacial, fluvial channel systems reflects the palaeo-drainage of the area in a lowland coastal environment, following the retreat of ice from the region.

Both formations would benefit from renewed assessment of their lithology and geological setting through targeted biostratigraphy, absolute dating and palynology. This would improve understanding of lateral and vertical variations of various geological settings (and facies deposition) within this time frame (for example, Ward et al., 2006) and support the formal standardisation needed for consistent stratigraphic interpretation in geological and engineering contexts. Improved characterisation will help identify heterogeneity that influences geoengineering constraints and will enhance stratigraphic correlation across international borders; for example, linking peat, commonly associated with the Elbow Formation, to the Basal Peat of the Naaldwijk Formation, Netherlands. Strengthening cross-border stratigraphic correlation between the UK and neighbouring waters is a key ambition (for example, Busschers et al. 2005, 2007, 2008, 2025; Cohen, 2005; Rijsdijk et al, 2005; Hijma and Cohen, 2010, 2011; Hijma et al., 2010; Peeters et al., 2015; Cohen et al., 2017; Coughlan et al. 2018; Hijma et al., 2025).

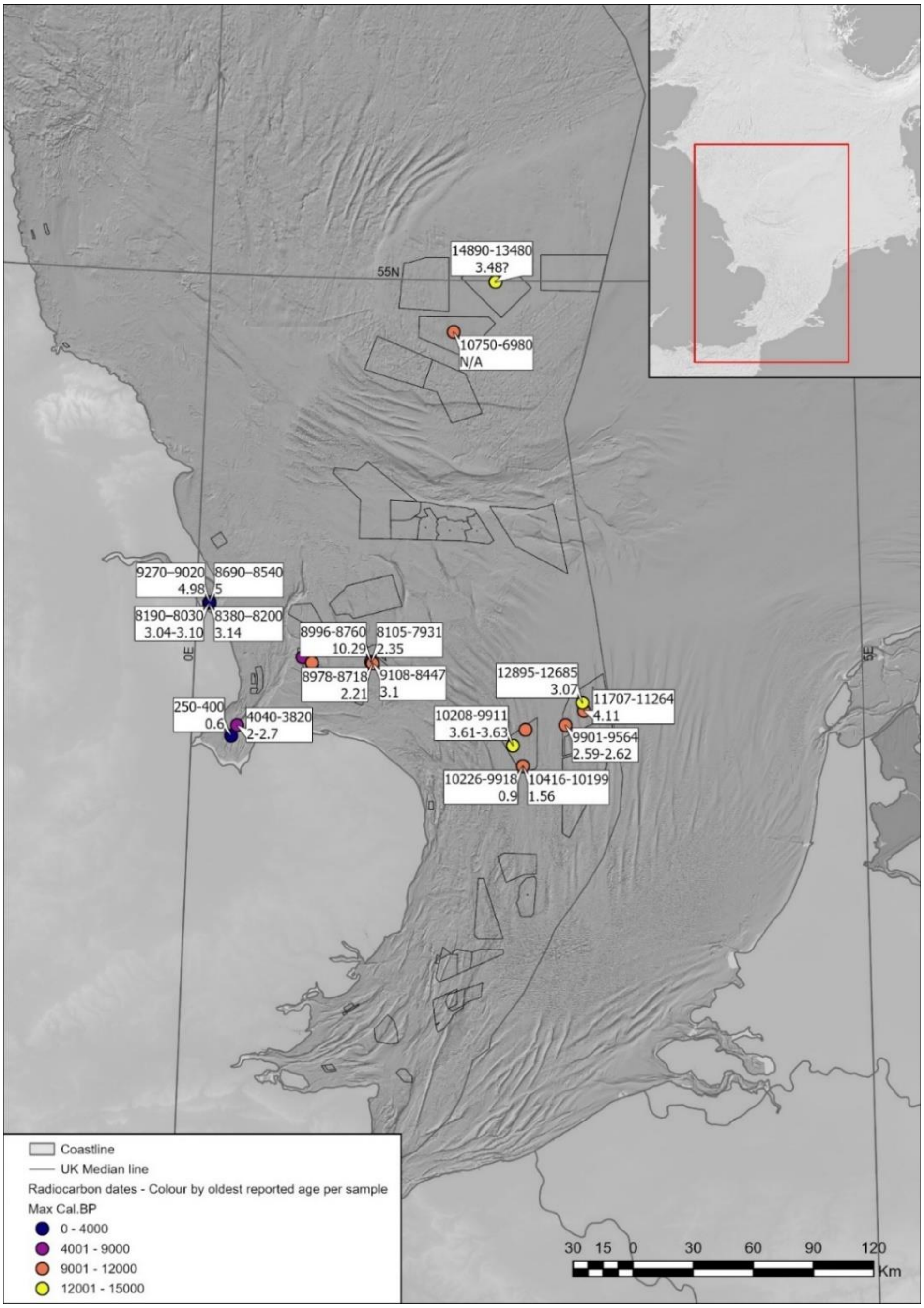

Figure 5 Radiocarbon dates sampled from organic samples. Coloured dots show age range, with younger samples coloured towards the coast (maximum cal. yr BP). Labels show age range (thousand years cal. yr BP) per sample, followed by the depth of sample below seabed (in metres). Onshore DEM from SRTM, GTopo30, GEBCO (Tozer et al., 2019). Bathymetry data from EMODnet 2024. BGS © UKRI 2025.

4.1.21 Post-Devensian transgression formations (Southern Bight Formation, 'Holocene alluvial sands', 'Holocene alluvium', MIS 1)

The youngest strata present within the SNS are Holocene to modern in age, typically comprising unconsolidated, marine, clastic deposits of variable thickness, including sand banks and marine dunes (Stoker et al. 2011). Palaeo-landscape modelling (for example, Sturt et al., 2013; Bradley et al., 2023) and information from the OWF reports indicate progressive transgression across the region, depending on palaeo-topography - that is, sites with a higher

OD would have been inundated last. Regional bathymetry datasets, such as EMODnet Bathymetry[4], can be utilised for regional, present-day, seabed morphological trends.

4.1.21.1 SOUTHERN BIGHT FORMATION

The Southern Bight Formation encompasses all Holocene aged, open-marine deposits, with the term adapted from Rijsdijk et al. (2005). In the Dutch sector, unique members or beds are included within the Southern Bight Formation (for example, the Bligh Bank, Buitenbanken and Indefatigable Grounds formations and the Terschellinger Bank Member).

Marine sediments of the Southern Bight Formation are identified across all OWF sites. Thickness of this unit ranges from 0.2 up to 33.8 m. Of note, Triton Knoll (8) reported up to 6 m of mobile sands, with absent to thin (0.8 to 0.92 m) Holocene sediments elsewhere on the site (Gardline, 2015b). Seismic facies of Holocene sediments are described as generally low amplitude to acoustically transparent sheets, with some internal reflections (RWE, 2024a).

In Race Bank (7), six samples were taken for radiocarbon dating, with three samples failing due to limited organic matter present. Of the three successful dates, one age date, taken from marine shell fragments (*Cerastoderma* sp), indicates 5960 to 5760 cal. yr BP within the OWF farm (Wessex Archaeology, 2015a). The other two samples were taken along the Race Bank (1) export cable route from inside The Wash. Here, the reliability of the two vibrocore samples (VC-EX-21 and VC-EX-34) are questionable due to inconsistencies between the radiocarbon dates and expected environmental conditions, and may suggest possible contamination of the samples (Wessex Archaeology, 2015a). However, they are still populated on the chronostratigraphic chart with a question mark to indicate the tentative result.

4.1.21.1.1 Recent to present day seabed features

Many focused ‘sand wave migration’ studies report the scale and mobility of seabed sediments to understand the morphometric changes of sediment waves (if any) between bathymetry surveys taken one to two years apart (for example, Gardline, 2015b). It is beyond the scope of this report to present the results of all mobility studies undertaken for each OWF site. However, consolidating the available studies on the MDE and producing a map-based summary that illustrates seabed variability (underlain by present day, high-resolution bathymetry data) would be a valuable output.

Prior to development, environmental surveys are undertaken to assess local ecological conditions. Benthic habitat seabed studies identify sensitive seabed features, including biogenic reefs, such as those formed by *Sabellaria spinulosa.* Such reefs support a variety of taxa including commercially important species such as the common lobster Homarus gammarus, brown crab (*Cancer pagurus*) and pink shrimp (*Pandalus montagui*), additionally herring spawning grounds are known to occur in the region (Bibby HydroMap and Benthic Solutions, 2016). Similar to the ‘sand wave migration’ studies outlined above, it is beyond the scope of this report to consolidating existing benthic ecology surveys, however this would provide a valuable output for environmental and development sectors.

4.1.21.2 HOLOCENE ALLUVIAL SANDS AND ALLUVIUM

At the cable landfall sites, including Race Bank (1), Horseshoe Point (2) and Withow Gap (3), thin sedimentary layers at the top of sequence are described as Holocene alluvial sediments, which comprise organic and alluvial channel sequences (for example, Wessex Archaeology (2015a).

4.2 REGIONAL SUBSURFACE TRENDS

Assessment of the new chronostratigraphic framework reveals several regional trends, presented from oldest to youngest. These include, but are not limited to:

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[4] https://emodnet.ec.europa.eu/en/bathymetry

- Jurassic and Cretaceous bedrock is present at seabed within nearshore sites (Race Bank landfall, Dudgeon and Sheringham Shoal) where the overlying Quaternary deposits are thinner. This is consistent with recent BGS fine-scale mapping offshore Yorkshire and East Anglia (British Geological Survey, 2023; 2024)
- twelve sites penetrate Cretaceous-aged chalk, which are mostly assigned to the Upper Cretaceous and comprise low- to medium-density chalk. Where older, Lower Cretaceous stratigraphy is within the foundation zone (upper 100 m of the subsurface) of the Dudgeon OWF, high-density chalks are identified
- Palaeogene-aged stratigraphy (for example, the London Clay Formation) is within foundation depth (60 m) only in the south of the SNS (Thames Estuary). This unit can be difficult to differentiate from the Harwich, Thanet and Woolwich formations
- the Yarmouth Roads Formation is identified in the centre and towards the east of the SNS, north of Southern Bight (Figure 2) and offshore East Anglian coastline (British Geological Survey, 2024). Although there is limited publicly available information in the UK sector, this is an important heterogeneous unit that can contain organic layers in the Dutch sector and has multiple penetrations in Dutch OWF sites (for example, Deltares, 2017; Fugro, 2018)
- in the UK sector, there is no offshore stratigraphic age control of units conventionally assigned from MIS 12 to MIS 5e (about 450 to 125 ka; Anglian to Wolstonian), resulting in significant age uncertainty during this time. However, based on seismic stratigraphic principals, analysis and reporting common attributes, the following characteristics and associations are outlined:
    - buried tunnel valleys (prior to MIS 2 Devensian glaciation) typically comprise component(s) of subglacial till infill, currently ascribed to the Swarte Bank Formation (MIS 12)
    - the post-glacial (MIS 12) Sand Hole and Egmond Ground formations (MIS 11) are interpreted towards the near-shore sites; the Sand Hole Formation is commonly identified within accommodation space present above tunnel valleys, whereas the Egmond Ground Formation is partially correlated within and over these sequences
    - the Wolstonian spans over 240 ka (three glacial periods: MIS 10, 8 and 6): apart from speculation of the Cleaver Bank and Tea Kettle formations at Dogger Bank, there are no interpreted units of Wolstonian age within the UK sector of the SNS and this is indicated as a major hiatus in the chronostratigraphic framework
    - the Eem Formation (MIS 5e) is only described near Dogger Bank, deposited towards the north of the SNS, with preservation potentially identified nearer the axis of the North Sea basin where accommodation space allowed
    - biostratigraphy data can be used to determine relative age to support interpretation of interglacial sequences that were deposited either during early post-glacial (cold) to late post-glacial (warm) environments (for example, Wessex Archaeology, 2014a)
- the Brown Bank Formation is present towards the centre of the SNS and is age dated to MIS 5d (Norfolk Vanguard and Boreas OWFs). Lithological and seismic descriptions suggest this unit was deposited in multiple phases relating to climatic changes prior to the Weichselian (Eaton et al, 2020), as observed in the Dutch sector (Waajen et al., 2024; 2025)
- the Bolders Bank Formation is recognised to have multiple subunits including buried landforms within the unit (for example, Dove et al., 2017). Although well documented as MIS 2, the lower age limit of the Bolders Bank Formation is uncertain: subunits within it may exclusively represent multiple episodes of glaciation during MIS 2, relating to a dynamic ice margin, but may extend to older time periods, such as MIS 4
- the Dogger Bank Formation is approximately coeval to the Bolders Bank Formation; it is present only around Dogger Bank and shows tripartite stratigraphy relating to modelled phases of ice-sheet expansion and retreat within the region
- the Botney Cut Formation is primarily classified according to seismic stratigraphy and is commonly used to include late Pleistocene glacial and post-glacial deposits through to Holocene fluvial to estuarine deposits. It is often used as a ‘bucket term’, in part due to

its seismotratigraphic characteristics (infilling channels and basins), but also likely due to the broad and sometimes inconsistent use within the literature. New, higher-quality seismic data allows improved differentiation between the Botney Cut and Elbow formations, which can be further informed by radiocarbon dating. Environmental changes (climatic and sea level) are significant during this time and consequently multiple facies types and depositional environments laterally co-exist

- marine transgression and deposition of the Southern Bight Formation (MIS 1) can be traced by the minimum ages of the Elbow Formation across OWF sites. For example, in the centre of the SNS, peats are slightly older (about 1000 years) than near-shore sites, with elevated depths relative to OD

5 Discussion

This report compiles stratigraphic observations from 22 commissioned offshore sites across the SNS and presents a newly developed chronostratigraphic framework based on this information (Table 2 and chronostratigraphic diagram). It draws upon a comprehensive compilation of openly available datasets acquired from offshore UK developments since the early 2000s from The Crown Estate's MDE and open source literature or reports.

Synthesis and assessment of this OWF information, with reference to the current stratigraphic framework as well as recent research advances, has enabled an improved understanding of the shallow subsurface. Building on the regional and formation-specific trends documented within Section 4, this section discusses several thematic research topics that are highlighted by our assessment. Such findings are relevant to the recommended future initiatives that encourage an update to the stratigraphic framework of the region, outlined in Section 5.3.

5.1 THE CHRONOSTRATIGRAPHIC CHART

We developed the chronostratigraphic chart to provide a baseline understanding of the near subsurface in the SNS. It is intended to serve as a regional and practical screening tool for seabed users to identify the lateral and vertical distribution of geological formations per geographical area. Structuring the stratigraphy in this way helps to identify current knowledge gaps, highlights new research questions for future investigation and identifies aspects of the current regional stratigraphy that should be considered for improvement. Benefits include enabling end users to compare subsurface data within a broader geological setting and identify where new data aligns with or diverges from regional trends, which will help advance future iterations of the framework. The chart presented is the first step towards achieving this goal. Importantly, the framework is designed to be iterative and can be updated as new data becomes available, ensuring continued relevance.

A consideration for future projects is how geological, geotechnical and geophysical data can be further integrated to improve our understanding of the complexity of the subsurface. This reveals a clear opportunity and need to realise the full value of the site-specific geophysical, geotechnical and geological data available on the MDE for improving the characterisation of the shallow subsurface. Integrating site-specific information alongside research and correlating observations across the region will improve both the subsurface stratigraphic record and understanding of the palaeo-climatic evolution of the area.

5.2 RESEARCH THEMES

Here we summarise several research themes:

- offshore stratigraphic nomenclature and geoengineering implications
- geology
- geochronology

These themes do not represent an exhaustive review of the literature, but represent knowledge gaps or future research topics identified during this study.

5.2.1 Offshore stratigraphic nomenclature vs. geoengineering constraints

Accurate subsurface characterisation is essential for identifying geoengineering constraints that influence foundation design, turbine placement and long-term operational performance. Inadequate geological understanding can lead to suboptimal operations, increased economic risk and, in the worst cases, poor ground models, which can lead to foundation damage or failure.

A key finding of this report is that modern OWF datasets reveal greater vertical and lateral stratigraphic variability than is currently represented in the existing offshore BGS stratigraphic framework, at least with regard to the information available within the BGS Lexicon. The regional offshore stratigraphic framework established by BGS in the 1990s (for example, Cameron et al., 1992) has not been officially modified since publication. As outlined in Section 2.1, this framework is based on data acquired from the 1960s to the 1990s, imposing certain limitations. These datasets are generally lower in quality, less densely acquired and are based on older scientific models.

While the existing stratigraphic model generally provides a useful framework for classifying new data, there are numerous ways where the previous framework is unsatisfactory. Offshore infrastructure development in the North Sea from the early 2000s has resulted in the availability of extensive new acoustic datasets, including bathymetry, high-resolution 2D and in some cases 3D seismic data, as well as many thousands of new CPTs and boreholes. Collectively, these datasets provide a new opportunity for a fully integrated, regional, subsurface stratigraphic assessment between geological, geophysical and geotechnical data. However, re-assessment has not happened contemporaneously with the publication of these new datasets.

While regular practitioners are aware that many formations have further associated characteristics and nuance, there is increasing awareness that seismostratigraphically observed units comprise multiple subunits deposited through complex glacial and deglacial episodes, each with unique and sometimes dramatically diverging geotechnical properties. For example, multiple members of the Bolders Bank, Dogger Bank, Sand Hole and Yarmouth Roads formations are increasingly being identified (Dove et al., 2017, Cotteril et al., 2017; Arlott et al., 2023 and Deltares, 2017, respectively). Similarly, the Swarte Bank Formation (as a single unit) is commonly attributed to tunnel valley infill, with sequences in the UK observed to contain consolidated tills at the base and upper sequences grading into basinal sand and mud-dominated units associated with the transition towards glaciomarine and glaciolacustrine conditions (for example, Stewart et al., 2012; Moreau and Huuse., 2014). Commonly observed units such as the Botney Cut and Elbow formations are often too generalised in definition to adequately represent site-specific variability to support detailed engineering assessments.

A fundamental characteristic shared by all geological formations is the presence of multiple depositional settings that can occur within the same time interval, but vary dramatically over spatial scales of less than tens to hundreds of metres apart. Each depositional setting produces facies that are characteristic of its sedimentary environment, resulting in distinct soil strengths and geotechnical properties.

While the existing Quaternary BGS stratigraphy is regularly used and predominantly remains effective at broad scales, the stratigraphic framework requires updating to incorporate research advances and observations based on the increasingly extensive and high-resolution data available. Such updates will bring greater detail and accuracy in characterising the subsurface to support a broad range of applications. There is a significant opportunity to link these more nuanced observations with regional environmental processes and events by updating the stratigraphy, as well as the potential to integrate existing classification schemes such as the two-part schemes of Dove et al. (2020) and Nanson et al. (2023).

Future stratigraphic updates should also be supported by a geological-systems approach, accompanied by comprehensive updates to the BGS Lexicon that provide information on key attributes such lithology and coded facies information for each formation that include:

- lithogenesis
- geological setting
- unit heterogeneity
- associated landforms
- potential chronological controls

Updating the offshore stratigraphic lexicon this way would enhance desk-based studies and improve preliminary assessments for future offshore development. Failure to integrate new information from offshore datasets could limit our understanding of subsurface heterogeneity and architectural complexity, and could inhibit key applications within the marine sector.

5.2.2 Geology

Deposits formed in similar geological settings often share comparable facies and properties. For this reason, 'pre-glacial and bedrock geology', 'glacial', 'interglacial' and 'post-glacial deposits' are grouped and discussed together.

5.2.2.1 PRE-GLACIAL AND BEDROCK GEOLOGY

The geotechnical variability observed within the Chalk Group is driven by factors such as porosity, compaction, tectonics, diagenesis and periglacial weathering, leading to major differences in rock properties between OWF sites. Detailed offshore mapping and synthesis between OWF sites would enable zoning of these geotechnical variations, improving the contact between Upper and Lower Cretaceous stratigraphy, hardground occurrences and high-density chalk units.

There is limited information from early to middle Pleistocene deposits. In the public record, little raw geological data is available for lithology, depositional environments and age constraints of multiple stratigraphic units including the Smith's Knoll, Westkapelle, Yarmouth Roads, Tea Kettle and Cleaverbank formations. These early to middle Pleistocene deposits are expected to be widely distributed across the SNS, but have not received recent significant research attention. This could be because they are not penetrated in OWF sites or because open-source data is not available for this stratigraphy.

In particular, the Yarmouth Roads Formation is present at shallower intervals below the seabed in the Dutch sector, forming a highly variable stratigraphic unit. One example is from Hollande Kust West, where 'Unit D', interpreted as the Yarmouth Roads Formation (although deeper stratigraphy is not ruled out), contains medium-dense to dense sand alternating with interbeds of stiff to hard clay and organic matter. Deposition is interpreted within a fluvio-deltaic environment (Fugro, 2018).

Where possible, tying units, lithological descriptions and interpretation across international borders will help improve our understanding of the pre-glacial and bedrock geology.

5.2.2.2 GLACIAL DEPOSITS

Glacial deposits commonly exhibit high soil heterogeneity, reflecting both primary depositional variability and secondary processes such as glaciotectonic deformation. As a result, reconstructing glacial processes has been a central component of ground-modelling efforts. It is worth noting that the Swarte Bank and Bolders Bank formations are here ascribed to the Anglian and Devensian, respectively, consistent with the traditional model of three primary glaciations within the North Sea: Anglian, Wolstonian and Devensian (for example, Long et al., 1988; Cameron et al., 1992). This model has been challenged in the central and northern North Sea, with evidence of more phases of glaciation, potentially even during the early Quaternary (for example, Stewart et al., 2012; Newton et al., 2024; Scourse, 2024).

It is not currently believed that glaciation prior to the Anglian (about 450 ka) affected the SNS, with earlier glaciations expected to be less extensive across north-west Europe (for example, Batchelor et al., 2019; Ottesen et al., 2025), broadly congruent with the global shift to more intense glaciation and longer cold climate phases following the mid-Pleistocene transition (1.25 to 0.7 Ma).

5.2.2.2.1 Summary of improved efforts for understanding glacial stratigraphy in the southern North Sea

Within this assessment, we have not identified evidence of glaciation inconsistent with the traditional three primary glaciations model, but this results in part from the significant absence of age data (pre-late Devensian) across the region. We do, however, observe that both the Swarte Bank (MIS 12) and Bolders Bank (typically MIS 2) formations are observed to comprise multiple till members in places, indicative at least of multiple phases of glaciation.

Sedimentary infill units of tunnel valleys (MIS 12) are linked to deglacial settings, mapped from seismostratigraphic packages. The upper units of tunnel valleys (typically ascribed to the

Swarte Bank Formation) can be near-identical to those deposited as part of an interglacial cycle (for example, the Egmond Ground Formation).

The chronostratigraphic framework highlights significant uncertainty around the potential presence of deposits associated with the Wolstonian glaciation(s) in the offshore environment (MIS 10, 8 and 6). The well-documented occurrence of Wolstonian- and Saalian-aged deposits in neighbouring sectors of the North Sea, such as the Dutch sector (for example, Busschers et al., 2025), offers a clear research target and collaboration opportunities.

Although glacial deposits can be challenging to date and accurately place chronostratigraphically due to the common absence of organic-rich material or units aged over 100 ka, younger glacial units ages may be bracketed by dating the over- and underlying interglacial units up to MIS 5d (for example, Small et al., 2017).

Late Devensian (MIS 2) glaciation has seen significant research attention over the last 20 years, which has been relied upon commercially by offshore infrastructure developments to effectively understand site-specific conditions (for example, Cotterill et al., 2017a, b). Continued research to refine these models is encouraged, particularly the transition from glacial to interglacial environments, since this is a process repeated over multiple glacial/interglacial cycles. Such research enables correlations between coexisting geological settings, illustrating how they generate laterally variable sediment types across relatively short spatial scales (Sections 4.1.20 – 4.1.21).

5.2.2.3 INTERGLACIAL AND LATE GLACIAL DEPOSITS

In contrast to the glacial stages (in particular, the Devensian glaciation), interglacial periods have been notably under-studied within the SNS. Limited accommodation space was left during the early to middle Pleistocene, therefore there is less preservation of extensive interglacial deposits from the middle to late Pleistocene (Cameron et al., 1992; Cohen et al., 2017). Here, we assess how improving our understanding of the spatial distribution and variability of commonly occurring interglacial deposits could improve our subsurface assessments.

As a shallow epicontinental basin, the interaction between global sea-level change and regional glacio-isostatic effects on the SNS has resulted in the complex, cyclical transition between terrestrial and marine geological settings. This has played an important part in the significant lateral and vertical complexity of sedimentary records, which are also an important analogue for modern environmental change. Targeted research on interglacial settings and sedimentological processes should become a higher priority as interglacial deposits (the Yarmouth Roads, Sand Hole, Egmond Ground, Eem, Brown Bank, Elbow, Botney Cut and Southern Bight formations) are regularly encountered in offshore developments.

As part of this initiative, further biostratigraphic data - for example, microfossils and palynology - is required to better understand the regional correlation of interglacial deposits. Sedimentary records contain fundamental information on the climatic evolution of the region and the number of geological settings and facies differences are an important part of ground-model characterisation. Such units may contain geohazards or geoengineering constraints, for example, peat units deposited in marginal marine conditions or the lateral pinching out (onlapping) of soil units onto antecedent topography created by previous glacial events.

Future research should focus on:

- formation-specific characteristics to improve correlation across a broad area
- detailed mapping of subunits to better understand distribution and heterogeneity
- identifying the presence of soft organic material per geological unit
- the use of erosional boundaries as regional markers for stratigraphic correlation

Erosive glacial processes can create new accommodation space (for example, tunnel valleys). There appears to be a clear spatial correlation between underlying glacial topographical lows and overlying interglacial deposits, such as the Sand Hole Formation (MIS 11) that overlies the Swarte Bank Formation (MIS 12). This phenomenon appears to be repeated in the transition from the late Pleistocene to the early Holocene, and the occurrence of the Botney Cut Formation and the younger Elbow Formation.

Lateral variability is observed in the Brown Bank Formation (MIS 5 to 4 transition), tying subsurface architecture with environmental change during an early glacial period. Here, the deposition of discrete interbedded sand- to clay-dominated units reveals consecutive shallow-marine depositional phases relating to sea-level variation (Waajen et al., 2025). The number of interbedded units also differs between the UK and Dutch sectors (Eaton et al., 2020; Waajen et al., 2025, respectively), suggesting a laterally variable, marine, coastal setting across a few tens of kilometres.

There are currently no open-source records of MIS 3 sediments in the stratigraphy offshore the UK SNS sector from OWF sites. However, this absence may reflect commercial confidentiality or the limited availability of targeted sampling and age dating. Evidence for MIS 3 sediments in the region is presented in a Wessex Archaeology report (Wessex Archaeology, 2015b), which includes OSL ages obtained from two samples collected in the East Coast Regional Environmental Characterisation study (Limpenny et al., 2011). The two dated cores yielded ages of 30.4 ± 6.9 ka (VC27c) and 36 ± 5 ka (VCWA9b), both consistent with deposition during MIS 3. The report concluded that further dedicated investigations were required to better define the palaeo-geography of MIS 3 in the SNS.

New initiatives for improved mapping around the Southern Bight's geomorphological evolution, which includes mid-Devensian-aged sediments, are currently being undertaken (for example, Vervoort et al., 2026). This would improve our understanding on the presence or absence of possible 'missing' stratigraphy, as observed in MIS 3 on the chronostratigraphic diagram.

5.2.2.3.1 Post-glacial deposits (late Devensian and early Holocene)

This period has been the focus of significant archaeological research within the palaeo-landscape community (for example, Fitch et al., 2022). Mapping the distribution of late Pleistocene to Holocene landscape features and dating high organic-content deposits helps to understand the landscape evolution of low-lying coastal plains around the North Sea and provides insights on the inhabitation and migration of ancient people within the region.

One of the key challenges of mapping and distinguishing pre-transgression units is that they are not deposited as thick or laterally continuous deposits. As such, it can be difficult to correlate observations across large lateral areas. However, consistent observations across numerous OWF sites indicates there is scope to improve the characterisation of the Botney Cut and Elbow formations from a geological-settings perspective to better link lithology, depositional environment and geotechnical properties.

5.2.3 Geochronology: a need for more data

Common absolute dating methodologies applied offshore typically include radiocarbon dating and OSL. Other dating methods are available, such as cosmogenic nuclide dating, amino-acid racemisation and isotopic methods; however, these approaches have had limited application within the North Sea.

Biostratigraphy and microfossils provide relative dating techniques, helping correlation between sites using characteristic fossil assemblages within well-established frameworks. Microfossils help provide detailed environmental signatures while palynology uses preserved pollen and spores to help reconstruct vegetation changes that help assign biozones (pollen and microfossil zones or subzones) within a chrono-lithostratigraphic framework (for example, Periplus Archeomare, 2025).

In the UK sector of the SNS, several major thematic regional projects have focused on establishing absolute chronologies, for example the BRITICE-Chrono project[5] targeted sediments associated with the MIS 2 glaciation (Clark et al., 2022a, b). Additionally, archaeological interest in areas such as 'Doggerland' has led to a relatively dense cluster of

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[5] https://www.bgs.ac.uk/news/project-findings-provide-essential-insight-into-the-last-british-irish-ice-sheet/

late-glacial to Holocene dates associated with pre-marine incursion in the region (for example, Gaffney et al., 2007; Cohen et al., 2017; Brown et al., 2018). However, there remains limited regional absolute-age constraints for glacial and interglacial sediments prior to MIS 2 due to the age-range limitations, with difficulty for absolute-age dating over about 100 ka. In older sediments, biostratigraphy would be suited to better understand environmental signatures relating to glacial versus interglacial palaeo-climates.

In the UK, there is no requirement for OWF developers or contractors to obtain geochronological data. Consequently, a systematic programme of works that integrates new OWF-derived results into an offshore biostratigraphic and absolute-dating database in existing frameworks does not exist. Appendix 2 attempts to collate the data found on the MDE and provides references identified from OWF results. Such data comes from radiocarbon data and OSL dates, which are openly available, for example those reported in commercially commissioned studies by Wessex Archaeology (2014a, 2015a, 2019a) and academic publications (Ward et al., 2006; Grant et al., 2024; Waajen et al., 2025). Access to open-source biostratigraphic reports is more limited, with only summary information publicly released (for example, Wessex Archaeology (2014b)). By way of comparison, under the Dutch model, the Netherlands Enterprise Agency (RVO) factors in both dating and biostratigraphy of offshore Dutch soils with the scope of works for each OWF development, resulting in systematic documentation from several boreholes per OWF site. This has led to an enhanced understanding of the subsurface stratigraphy offshore the Netherlands. Such data is made open source and is available online through the RVO data portal[6] and provided in studies such as Periplus Archeomare (2025).

There is a clear need for more geochronological data, particularly within the UK sector, to support basin-wide stratigraphic correlation of glacial and interglacial sediments. Such improvements would:

- advance our understanding of past environmental changes
- provide valuable insights into palaeo-environments
- correlate lithological units across sites
- help test sea-level models, enabling better constraints on the timing of marine inundation across lowland areas in the late Pleistocene

More routine acquisition of geochronology data as part of OWF developments would improve the detail and accuracy of regional subsurface characterisation and would benefit all practitioners.

5.3 RECOMMENDED FUTURE INITIATIVES

Increased and ever-improving geophysical and geotechnical data inevitably results in more detailed observations that require continual improvement of our scientific models. Based on the evidence documented within this report, we propose several future initiatives to progress more detailed and accurate characterisation of the subsurface stratigraphy, benefiting a range of applications and end users including commercial, research and marine management. These initiatives are listed here; sections 5.3.1 and 5.3.2 require a phased and structured approach.

5.3.1 Updated Quaternary stratigraphic framework for the Southern North Sea

This report demonstrates the clear need for an updated and improved stratigraphic model for the SNS. This recommendation is further bolstered by recent offshore wind site investigation data and academic publications, as well as by presentations and discussions at scientific conferences including the Geological Society ‘Energy Group’ Offshore Wind Symposiums (November 2024; September 2025). One routinely observed trend highlights significantly more vertical and lateral variations of subsurface stratigraphy than is captured within the current BGS Quaternary stratigraphy.

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[6] https://offshorewind.rvo.nl/

While the existing stratigraphic framework is often broadly accurate, observations from high-resolution OWF data offer the capacity to observe and formally document more detail, such as:

- seismostratigraphic characterisation
- upper and lower formation boundary descriptions
- lithogenesis / geological setting (e.g., glaciolacustrine, fluvial, estuarine, marine)
- associated landforms
- description of origin

These attributes are currently not populated for offshore units in the BGS Lexicon database.

Updates to the BGS stratigraphic framework should be comprehensively recorded within the BGS Lexicon to promote effective and consistent use. This may also include the integration of BGS RCS codes (BGS, 2020) to help define constituent lithologies for named units, which encompass UDCS codes (Cooper et al., 2006), relevant for Quaternary- and Holocene-aged stratigraphy. In addition, the development of an offshore, established, unified biostratigraphic framework will improve our understanding of environmental indicators and the relationship between lithostratigraphy and biostratigraphy. Development will likely involve a phased approach, with this report and the source OWF information serving as baseline evidence.

A harmonised and robust stratigraphic framework should:

- integrate geophysical, geotechnical and geological datasets to develop a geological unitisation database
- create nuanced observations made possible by modern data (higher resolution and increased spatial coverage)
- account for research advances made by academic and industrial scientists
- be well integrated, with observations and models from neighbouring North Sea countries to enable formation-aware geotechnical interpretation

Because there are multiple connected research, policy and industry groups invested in the North Sea marine space, a siloed, unilateral approach should be avoided. Cross-sector collaboration and partnership will ultimately enable a better informed and more robust model. Ultimately, improving the detail and accuracy of the stratigraphic framework will enable more effective assessment to de-risk a range of marine applications and provide a stronger basis for predictive subsurface assessments.

5.3.2 Creation of comprehensive geotechnical data catalogue by geological unit within a geological formation

Seismostratigraphic characterisation provides insight into the geological processes that formed individual subsurface units. When these interpretations are integrated with ground-truthing data such as boreholes, cores and CPTs, the resulting lithological information can be used to classify geotechnical units with specific engineering characteristics. An updated offshore stratigraphic framework, underpinned by an expanded RCS database, incorporating ‘geological setting’ (for example, glaciofluvial; glaciomarine; subglacial; fluvial; estuarine; marine) could assign and extrapolate several qualitative and quantitative geotechnical properties to better inform predictive subsurface models.

Once geological unitisation is complete within a stratigraphic framework that considers lateral and vertical variability (driven by geological setting), open-source CPT datasets could be ingested into a geotechnical database. Such a database would provide Min-Median-Max (or P90-P50-P10) ranges for parameters such as CPT tip resistance (qc), sleeve resistance (fs) and pore pressure (u2). A filtering tool could then allow users to select settings such as ‘estuarine’ or a specific formation like ‘Botney Cut Formation’, returning analogue geotechnical parameter ranges for similar geological conditions. It is important to note that geotechnical parameters may vary significantly within a single formation due to differences in geological setting and/or geological history, as outlined in section 5.3.1 above. Given this uncertainty, an alternative approach might involve recognising characteristic CPT log patterns that occur in comparable geological settings. In all cases, the ideal solution would be an open-source database that allows users to explore geotechnical variability within and between geological settings, drawing on datasets from nearby sites.

The increasing availability of high-quality site investigation data, together with advances in numerical modelling, machine-learning methods and probabilistic analysis, combined with an improved stratigraphic framework will enable more robust, reusable predictive models that can be efficiently updated and applied to areas with sparser data coverage. This represents a major opportunity to move beyond descriptive datasets toward predictive, formation-aware ground models that support early-stage engineering assessments.

One example of an existing geotechnical database that could be adapted to incorporate geological elements, such as geological setting or environment-based classifications, is the framework presented by Zheng et al. (2026). Their system illustrates how large, geotechnical datasets can be standardised and centralised, and how a statistical workflow can be used to provide a probabilistic soil classification model. Building on this existing workflow, geological information could be incorporated directly into the database structure. Doing so would allow the database to ingest new CPT datasets and automatically link CPT log characteristics to geological formation information based on patterns learned from paired CPT and core-derived geotechnical data. The resulting product would be an adaptive geological-geotechnical reference dataset capable of returning formation-conditioned CPT parameter ranges and probabilistic soil type predictions, supporting reproducible and statistically robust ground model development across sites.

- enhance marine spatial planning, enabling more precise, data-driven decision making by providing a standardised repeatable unitisation workflow that is consistent across the SNS
- improve desk-based studies for geotechnical assessments by comparing known geotechnical trends per geological formation and/or sub-units from offset sites
- create the foundation for new predictive, data-driven ground models that incorporate quantified uncertainty to optimise offshore infrastructure engineering solutions. This will leverage existing regional datasets to better constrain statistical relationships, including median and end-member values

5.3.3 Quantitative modelling of geotechnical properties from geophysical data

Novel integration of geotechnical and geophysical data, such as synthetic CPTs, offers the capacity to further predict geotechnical and material properties directly from geophysical data. While these efforts can provide useful information and should be progressed, we stress that accurate stratigraphic assessment and geological mapping remain an integral part of accurately characterising and understanding the subsurface.

5.3.4 Improved data sharing

This study was made possible by integrating the openly available datasets and reports published on The Crown Estate's MDE with further supporting resources (Section 2). Continually working towards more data and information sharing and following the 'FAIR'[7] data principles will support higher quality and more efficient work, as well as accelerate innovation.

5.3.5 Improved geospatial products

As was the case with developing the existing offshore BGS stratigraphic framework, geological mapping and developing an accurate, fit-for-purpose stratigraphy are symbiotic processes. As outlined in Finlayson et al. (2025), a new generation of geospatial products (for example, likelihood of seabed change; the potential presence of boulders; lateral and vertical soil heterogeneity; improved Quaternary thickness; interpreted gas or fluid in the shallow subsurface) at multiple scales is required to meet the needs of the modern marine sector. A recent NERC-commissioned analysis also estimated that public investment in the production of

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[7] Findable, accessible, interoperable, re-usable

(BGS) marine geoscientific spatial products and information resulted in a 40 to 200 times return on investment for offshore wind (UKRI-NERC, 2025). BGS and other geospatial agencies should work collaboratively wherever possible to meet this demand.

5.3.6 Collaboration, partnerships and funding

There is an enormous amount of expertise and knowledge on the stratigraphy of the North Sea spread across academic, commercial and geological survey organisations. Targeted collaboration and partnerships, both national and international, are required to address key uncertainties and information gaps (for example, sections 4.2 and 5.2), which can accelerate progress by capitalising on the specific assets and capabilities of different individuals and groups. There are numerous mechanisms to support this, including joint industry partnerships, studentships and funded research networks. Arguably, these mechanisms have been under-exploited within the offshore renewables sector, noting, however, that it is a relatively immature industry within a volatile energy market. BGS hopes to progress this initiative of working towards a harmonised and robust chronostratigraphic model for the region by working with partners to undertake technical work and integrating the best available data and information.

5.3.7 Provide a chronostratigraphic update across the UKCS

This project focuses on the SNS; however, there are multiple other offshore areas in the UK (Celtic Sea; Central North Sea; Northern North Sea; the Solent, etc.) that would hugely benefit from the development of a harmonised chronostratigraphy as presented herein. This can be undertaken based on the wealth of existing data available on the MDE, recent research advances and expertise spread across multiple sectors.

6 Conclusions

This report compiles and integrates stratigraphic observations from 22 commissioned OWF sites across the SNS and presents a newly developed chronostratigraphic framework based on this data. It is intended to stand alone as a comprehensive reference, with the accumulated information advancing our understanding of the region through a synthesis of datasets acquired from UK OWF developments since the early 2000s. Assessment of this OWF information, with reference to the current stratigraphic framework as well as recent research advances, has enabled an improved understanding of the shallow subsurface.

The newly developed, preliminary chronostratigraphic framework and report aim to provide baseline evidence to benefit a broad range of end users and applications. The chronostratigraphic chart aims to serve as a screening tool to more effectively contextualise site-specific data and observations within the broader regional setting. This framework is intended as a preliminary assessment; more investment is needed to fully update the stratigraphic model through joint industry partnerships and funded research networks.

Several regional and geological, formation-specific trends are documented within this report, alongside several outstanding uncertainties. We hope this work represents an initial step towards updating and refining the stratigraphy of the SNS. Considering this, we identify several emerging research themes and propose future initiatives to facilitate and accelerate this process. Key priorities include multidisciplinary integration of geophysical, geological and geotechnical data for improving mapping and prediction of detailed lithofacies associations per formation, underpinned by detailed classification codes such as geological setting. This work would provide the foundation for a comprehensive integrated geologically-conditioned geotechnical data catalogue.

As sediment heterogeneity is often a source of risk and unanticipated ground conditions, with direct implications for geoengineering constraints and geohazards, improved classification schemes will strengthen predictive spatial and temporal awareness of variable facies distribution, helping to quantify uncertainties at any given site. Moreover, development of a unified dating and biostratigraphic database would improve understanding of geological settings and placement of lithostratigraphy within a chronostratigraphic framework. Crucially, an updated stratigraphic framework cannot be developed in isolation; multidisciplinary engagement and cross-sector collaboration is essential for meaningful progress.

The UK is world leader in offshore wind, providing about 17 per cent of the UK's electricity and 32 000 jobs (projected to rise to 100 000 by 2030). Employing strategic initiatives for the SNS and the UKCS, as outlined in this report, will support the UK's energy transition to clean, reliable and secure energy, supporting economic growth and sustainable development (Human Economics, 2025).

Appendix 1 Summary of open-source reports and references utilised for building the stratigraphic framework

Site	Reports utilised	References: papers, Dogger Bank data portal and MDE
Race Bank cable route and OWF	Geotechnical and archaeological reports	Dong Energy, 2015 Fugro, 2015 Wessex Archaeology, 2010a Wessex Archaeology, 2010b Wessex Archaeology, 2015a
Hornsea cable route: Horseshoe Point	Paper	Grant et al., 2024
Lincs OWF	Archaeological report	Wessex Archaeology, 2006b.
Hornsea One and Three OWF	Papers Geophysical and environmental reports	Bibby HydroMap and Benthic Solutions, 2016 Fugro, 2016 McDermott et al., 2011 RPS, 2018
Dogger Bank A OWF	Papers Environmental statements Archaeological reports	Cotterill et al., 2017a. Cotterill et al., 2017b Emery et al., 2019 Phillips et al., 2022 Roberts et al., 2018 RWE, 2024a RWE, 2024b Wessex Archaeology, 2012 Wessex Archaeology, 2013 Wessex Archaeology, 2014a
Sophia (previously Dogger Bank Teesside B)	Environmental statement report	Wessex Archaeology, 2014a
Triton Knoll OWF	Papers g Geophysical and consultancy reports	Arlott et al., 2023 ChalkRock Ltd, 2015b Gardline, 2015a Gardline, 2015b

Site	Reports utilised	References: papers, Dogger Bank data portal and MDE
Dudgeon OWF	Papers Archaeological and consultancy reports	Brown et al., 2018 ChalkRock Ltd, 2015a Wessex Archaeology, 2014b
East Anglia ONE OWF	Archaeological report	Wessex Archaeology, 2018a
East Anglia TWO OWF	Archaeological report	Wessex Archaeology, 2018b
Galloper OWF	Geoarchaeological review	Gardline, 2014
Greater Gabbard OWF	Geotechnical survey	Marine Geosystem, 2006
Gunfleet Sands OWF	Geotechnical and geophysical integration	RPS Hydrosearch, 2004
Humber Gateway OWF	Geotechnical	GEMS, 2009
London Array West OWF	Interpretative report	Gardline, 2005a Gardline, 2005b
Norfolk Boreas OWF	Archaeological reports and papers	Eaton et al., 2020 Eaton et al., 2024 Royal Haskoning DHV, 2019 Wessex Archaeology, 2018e Wessex Archaeology, 2018f Wessex Archaeology, 2019a Wessex Archaeology, 2019b
Norfolk Vanguard West and East OWFs	Papers	Eaton et al., 2020 Eaton et al., 2024 Wessex Archaeology, 2017 Wessex Archaeology, 2018c Wessex Archaeology, 2018d
Sheringham Shoal OWF	Geotechnical integration study Soil investigation study	Gardline, 2008 SCIRA Offshore Energy Ltd, 2007
Thanet OWF	Archaeological assessment	Wessex Archaeology, 2006a Wessex Archaeology, 2006c
Westermost Rough OWF	Geoarchaeological report Seismic report	Gardline, 2011 Maritime Archaeology Ltd, 2013

Appendix 2 Compilation of absolute chronological data available on the MDE across the southern North Sea

Type	Site	Lab No./ ID	Material dated	Core	X	Y	Depth mbsf (mbss)	Radiocarbon dating			OSL dating				Other	
								Age BP	Age range cal. BC (95.4%)	Age range cal. yr BP (95.4%)	Total dose rate (Dr) (Gy.ka-1)	Equivalent dose (De) (Gy)	Age (ka)	Considerations & analytical validity	Notes	Reference
Radiocarbon date	Norfolk Vanguard	UB-36846	Seeds: *Nuphar lutea* 2×; *Nymphaea alba* 2×, *Juncus* sp. 1×, *Cyperaceae* 1/2×; leaves: *Sphagnum* sp. 25×	VC074	464000.93	5853014.97	0.9	8955 ± 46	8277–7969	10226–9918	n/a	n/a	n/a			Wessex Archaeology, 2018d
Radiocarbon date	Norfolk Vanguard	UB-36847	Seeds: *Betula* sp. 3×, *Solanum* sp. 2×, *Chenopodium* sp. 1×, *Caryophyllaceae* 1×, *Betula* sp. 5×, *Lycopus europaeus* 1×, *Potamogeton* sp. 1×, *Nymphaea alba* 1×, Cyperaceae 15×; catkin scale: *Betula* sp. 1×	VC074	464000.93	5853014.97	1.56	9122 ± 49	8467–8250	10416–10199	n/a	n/a	n/a			Wessex Archaeology, 2018d
Radiocarbon date	Norfolk Vanguard	UB-36848	Seeds: *Lycopus europaeus* 1×, *Juncus* sp. 2×, Asteraceae 1×, *Carex* sp. 2×, *Ranunculus* sp. 0.5	VC076	458994.6	5863171.76	3.61–3.63	8936 ± 47	8259–7962	10208–9911	n/a	n/a	n/a			Wessex Archaeology, 2018d
Radiocarbon date	Norfolk Vanguard	UB-36849	Seeds: *Potamogeton* sp. 5×	VC076	458994.6	5863171.76	3.91–3.93	11863 ± 55	11832–11607	13781–13556	n/a	n/a	n/a			Wessex Archaeology, 2018d
Radiocarbon date	Norfolk Vanguard	UB-36850	Seeds: *Ceratophyllum* sp. 1×, *Menyanthes trifoliata* 2×	VC085	465321.16	5871195.82	1.75–1.77	10192 ± 47	10142–9758	12091–11707	n/a	n/a	n/a			Wessex Archaeology, 2018d
Radiocarbon date	Norfolk Vanguard	UB-36851	Seeds: *Menyanthes trifoliata* 2×	VC085	465321.16	5871195.82	2.07–2.09	8856 ± 48	8220–7795	10169–9744	n/a	n/a	n/a			Wessex Archaeology, 2018d
OSL	Norfolk Vanguard	GL17076	n/a	VC085	465321.16	5871195.82	5.10–5.30	-	-	-	2.43 ± 0.22	139.0 ± 8.7	57.2 ± 6.4	None - accept age	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2018d
OSL	Norfolk Vanguard	GL17077	n/a	VC085	465321.16	5871195.82	4.60–4.80	-	-	-	2.19 ± 0.21	152.0 ± 8.7	69.5 ± 7.7	None - accept age	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2018d
OSL	Norfolk Vanguard	GL17078	n/a	VC107	499791.68	5848922.33	1.00–1.25	-	-	-	2.37 ± 0.22	141.7 ± 6.6	59.8 ± 6.2	Significant feldspar contamination - accept as minimum age estimate	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2018d

OSL	Norfolk Vanguard	GL17079	n/a	VC079	466749.74	5853859.05	4.15–4.35	-	-	-	2.42 ± 0.22	139.1 ± 6.3	57.6 ± 5.9	Overdispersion in the interpolated to applied regenerative-dose ratio - accept tentatively	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2018d
OSL	Norfolk Vanguard	GL17080	n/a	VC079	466749.74	5853859.05	0.75–1.00	-	-	-	1.96 ± 0.18	131.2 ± 7.4	66.8 ± 7.1	Potentially significant U disequilibrium - accept tentatively	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2018d
OSL	Norfolk Vanguard	GL17081	n/a	VC074	464000.93	5853014.97	5.00–5.36	-	-	-	1.75 ± 0.16	144.3 ± 7.3	82.4 ± 8.5	None - accept age	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2018d
OSL	Norfolk Boreas	GL17154 - quartz	n/a	VC016	488684	5869659	1.70–2.00 (-40.90 to -41.20)	-	-	-	2.19 ± 0.17	182.1 ± 15.0	83.2 ± 9.5	Accept	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2019a
OSL	Norfolk Boreas	GL17153 - quartz	n/a	VC016	488684	5869659	2.65–3.00 (-41.85 to -42.20)	-	-	-	2.14 ± 0.17	149.6 ± 11.1	69.8 ± 7.7	Accept	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2019a
OSL	Norfolk Boreas	GL17155 - quartz	n/a	VC047	502211	5896931	2.55–3.00 (-37.05 to -37.50)	-	-	-	2.23 ± 0.18	135.1 ± 7.2	60.5 ± 5.8	Overdispersed interpolated to applied regenerative-dose ratio	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2019a
OSL	Norfolk Boreas	GL17156 - quartz	n/a	VC047	502211	5896931	3.70–4.00 (-38.20 to -38.50)	-	-	-	2.38 ± 0.20	186.0 ± 11.6	78.9 ± 8.3	Overdispersed interpolated to applied regenerative-dose ratio	Dose Rate (Dr) and Equivalent Dose (De) and resulting OSL age estimates	Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-39471	Betula sp., Typha sp.	VC028	485146	5873305	2.59–2.62 (-33.79 to -33.82)	-	-	-	-	-	-		FAILED	Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-38188	Bud scales	VC028	485146	5873305	2.59-2.62	8749 ± 40		9900-9570	n/a	n/a	n/a			Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-39473	Organic material with *Sphagnum* sp. leaves	VC032	494379	5880618	3.61	9124 ±77		10500-10180	n/a	n/a	n/a		outlier	Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-38189	*Menyanthes trifoliata* seed	VC032	494379	5880618	3.83 (-35.73)	8697 ±45		9880–9540	n/a	n/a	n/a			Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-39474	Lamiaceae, *Ranunculus sp.*, *Menyanthes trifoliata* seeds	VC032	494379	5880618	3.95	8894 ± 78		10210-9710	n/a	n/a	n/a			Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-38190	Bulk sediment	VC032	494379	5880618	4.11 (-36.01)	9992 ±51		11710–11260	n/a	n/a	n/a			Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-39471	*Menyanthes trifoliata* seed	VC039	493714	5884543	2.96	8510 ± 58		9560-9430						Wessex Archaeology, 2019a

AMS radiocarbon dates	Norfolk Boreas	UBA-38191	*Menyanthes trifoliata* seed	VC039	493714	5884543	3.07 (-35.77)	10881±60		12895–12685	n/a	n/a	n/a		outlier	Wessex Archaeology, 2019a
AMS radiocarbon dates	Norfolk Boreas	UBA-39472	*Menyanthes trifoliata, Betula sp.*, Characeae oospores, *Typha* sp.	VC039	493714	5884543	3.13	10435 ± 66		12550-12080						Wessex Archaeology, 2019a
AMS radiocarbon dates	Dudgeon	SUERC-52113 (GU34111)	Marine shell : *Cerastoderma*	BH 06	388191.4	5904885	2.35	7549 ± 31	6155–5981	8105–7931	n/a	n/a	n/a		δ13C relative to VPDB = 0.0 ‰	Wessex Archaeology, 2014b
AMS radiocarbon dates	Dudgeon	SUERC-51293 (GU33574)	Marine shell : *Littorina*	BH 06	388191.4	5904885	10.29	8324 ±32	7046–6810	8996–8760	n/a	n/a	n/a		δ13C relative to VPDB = -3.9 ‰	Wessex Archaeology, 2014b
AMS radiocarbon dates	Dudgeon	SUERC-51295 (GU33576)	Marine shell : *Cerastoderma*	BH 21	388971.6	5904258.2	2.21	8295 ± 32	7028–6768	8978–8718	n/a	n/a	n/a		δ13C relative to VPDB = -6.4 ‰	Wessex Archaeology, 2014b
AMS radiocarbon dates	Dudgeon	SUERC-51294 (GU33575)	Marine shell : *Cerastoderma*	BH 21	388971.6	5904258.2	3.1	8398 ± 32	7158–6497	9108–8447	n/a	n/a	n/a		δ13C relative to VPDB = -9.9 ‰	Wessex Archaeology, 2014b
AMS radiocarbon dates	Dudgeon	GU-34111	Marine shell : *Cerastoderma*	BH06	388191.4	5904885	2.25	7549 ± 31	6461–6381	8411–8331	n/a	n/a	n/a		0.0 ‰	Brown et al., 2018
AMS radiocarbon dates	Dudgeon	GU-33574	Marine shell: *Littorina*	BH06	388191.4	5904885	10.29	8324 ± 32	9450–9259	7500–7309	n/a	n/a	n/a		-3.9 ‰	Brown et al., 2018
AMS radiocarbon dates	Dudgeon	UBA-33301	Bulk sediment	BH06	388191.4	5904885	11.4	9755 ± 52	9306–9140	11 256–11 090	n/a	n/a	n/a		Cal BC 93.5%	Brown et al., 2018
AMS radiocarbon dates	Dudgeon	UBA-33302	Bulk sediment	BH06	388191.4	5904885	11.68	10221 ± 68	10 226–9671	12 176–11 621	n/a	n/a	n/a		Cal BC 0.7%	Brown et al., 2018
AMS radiocarbon dates	Dudgeon	UBA-30873	*Betula* seed (11×)	BH06	388191.4	5904885	12.35	10629 ± 89	10 780–10 442	12 730–12 392	n/a	n/a	n/a		Cal BC 93.7%	Brown et al., 2018
AMS radiocarbon dates	Dudgeon	UBA-30872	*Betula nana* seeds (22×)	BH06	388191.4	5904885	12.4	10655 ± 65	10 772–10 578	12 722–12 528	n/a	n/a	n/a		Cal BC 92.9%	Brown et al., 2018
Radiocarbon dates	Race Bank	SUERC-59063	Cockle shell 1×	VC-EX-021	318270	5868118	0.6 (-12.53)	660±29	1550–1700 (cal. AD)	250–400	n/a	n/a	n/a		Cable Route	Wessex Archaeology, 2015
Radiocarbon dates	Race Bank	SUERC-59064	Cockle shell 1×	VC-EX-034	321315	5873334	2-2.7 (-28.93–29.63)	3933 ±29	2090–1870	4040–3820	n/a	n/a	n/a		Cable Route	Wessex Archaeology, 2015

Radiocarbon dates	Race Bank	SUERC-59065	Cockle shell fragments 3×	BH-G01	353905	5907279	4.82- 4.92 (-28.57–28.67)	5497 ±30	4010–3810	5960–5760	n/a	n/a	n/a		OWF	Wessex Archaeology, 2015
Radiocarbon dates	Race Bank	FAILED	*Phragmites*	BH-G01	353905	5907279	8.73 (-32.48)	n/a	n/a	n/a	n/a	n/a	n/a		OWF	Wessex Archaeology, 2015
Radiocarbon dates	Race Bank	SUERC-59066	Stem fragments	BH-CPT-01	359483	5899409	0.0–0.85 (-21.05–21.90)	7965 ±30	7040–6710	8990–8660	n/a	n/a	n/a		OWF	Wessex Archaeology, 2015
Radiocarbon dates	Race Bank	SUERC-59067	*Phragmites*	BH-CPT-11	358583	5904620	0.35– 0.45 (-21.55–21.65)	8038 ±30	7070–6830	9020–8780	n/a	n/a	n/a		OWF	Wessex Archaeology, 2015
Radiocarbon dates	Race Bank	FAILED	*Tellina* shell 1×	BH-G01	353905	5907279	7.82– 7.92 (-31.57–31.67)	n/a	n/a	n/a	n/a	n/a	n/a		OWF	Wessex Archaeology, 2015
Radiocarbon dates	Race Bank	FAILED	Stem fragment	BH-G01	353905	5907279	8.63– 8.73 (-32.38–32.48)	n/a	n/a	n/a	n/a	n/a	n/a		OWF	Wessex Archaeology, 2015
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101122	*Phragmites australis* (leaf fragment)	GT2-04-VC	307286	538837	3.05	7120 ± 26	n/a	8010–7860	n/a	n/a	n/a		δ¹³C relative to VPDB = −25.0	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-107852	Bulk sediment: humic acid fraction	GT2-04-VC	307286	538837	3.1	7478 ± 26	n/a	8370–8190	n/a	n/a	n/a		δ¹³C relative to VPDB = −27.3	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101123	Bulk sediment: humic acid fraction	GT2-04-VC	307286	5934398	3.14	7499 ± 26	n/a	8380–8200	n/a	n/a	n/a		δ¹³C relative to VPDB = −27.4	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101118	*Phragmites australis* (leaf fragment)	GT2-06-VC	307399	5934434	2.78	7112 ± 26	n/a	8010–7860	n/a	n/a	n/a		δ¹³C relative to VPDB = −25.0	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-107856	*Quercus* sp. stem/branch, outer 5 rings	GT2-06-VC	307399	5934434	3.04–3.10	7331 ± 25	n/a	8190–8030	n/a	n/a	n/a		δ¹³C relative to VPDB = −27.5	Grant et al., 2024

Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101124	Bulk sediment: humic acid fraction	GT2-06-VC	307399	5934434	3.2	7468 ± 26	n/a	8370–8190	n/a	n/a	n/a		δ¹³C relative to VPDB = −28.5	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101125	*Phragmites australis* (leaf fragment)	GT2-07-VC	307668	5934392	4.63	7217 ± 26	n/a	8170–7960	n/a	n/a	n/a		δ¹³C relative to VPDB = −28.8	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101126	*Quercus* sp. stem/branch, outer 5 rings	GT2-07-VC	307668	5934392	4.77	7316 ± 26	n/a	8180–8030	n/a	n/a	n/a		δ¹³C relative to VPDB = −27.5	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101127	Bulk sediment: humic acid fraction	GT2-08-VC	307664	5934594	4.98	8179 ± 26	n/a	9270–9020	n/a	n/a	n/a		δ¹³C relative to VPDB = −27.5	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-107857	Bulk sediment: humic acid fraction	GT2-08-VC	307664	5934594	5	7825 ± 25	n/a	8690–8540	n/a	n/a	n/a		δ¹³C relative to VPDB = −28.1	Grant et al., 2024
Radiocarbon dates	Horseshoe Point, East Lindsey, Lincolnshire - cable Route Hornsea	SUERC-101128	Bulk sediment: humic acid fraction	GT2-08-VC	307664	5934594	5.06	8879 ± 26	n/a	10 180–9890	n/a	n/a	n/a		δ¹³C relative to VPDB = −27.0	Grant et al., 2024
Radiocarbon dates	Dogger Bank A	SUERC-37341	Unknown: original report not available. Acquired from 'palaeochannel features'	BH1026	429357	6069520	n/a	9440 ±30	n/a	10750–10580	n/a	n/a	n/a		Samples from palaeo-channel features.	Wessex Archaeology, 2012
Radiocarbon dates	Dogger Bank A	SUERC-37344	Unknown: original report not available. Acquired from 'palaeochannel features'	ABH1124A				6190 ±30		7240–6980						Wessex Archaeology, 2012
Radiocarbon dates	On edge of Sofia	SUERC-72882	Unknown: possibly from reworked peat?	T2-143VC-239			2.39	16477 ±66		19395 ±208	n/a	n/a	n/a		143VC recorded 244cm of shelly sands with occasional reworked peat intraclasts resting over a channel infill. May be erroneous due to contamination.	Roberts et al., 2018

Radiocarbon dates	Sofia (was Dogger Bank Teeside B)	SUER C-43887 - original report not available	Original report not available	?	?	?	2.24			13810–13480					Samples from sandy peat & organic clay features from Kettle holes - Windermere/ Bølling-Allerød Interstadial,	Wessex Archaeology, 2013 Wessex Archaeology, 2014a
Radiocarbon dates	Sofia (was Dogger Bank Teeside B)	SUER C-43891 - original report not available	Original report not available. Sandy peat and organic clay	BH1282?	449959	6096989	3.48?	n/a	n/a	14890–14010	n/a	n/a	n/a		Samples from sandy peat & organic clay features from Kettle holes - Windermere/ Bølling-Allerød Interstadial,	Wessex Archaeology, 2013 Wessex Archaeology, 2014a
Radiocarbon dates	Withow Gap at Skipsea	Unknown	Original report not available. Peat.					9880 ±60	9470–9240						Taken from a base peat sample	Brigham and Jobling, 2013 Gilbertson et al., 1984
Radiocarbon dates	Withow Gap at Skipsea	Unknown	Original report not available. Peat.					4500 ±50	3370–3080						Taken from a base peat sample	Brigham and Jobling, 2013 Gilbertson et al., 1984

Abbreviations

AOI	Area of interest
BGS	British Geological Survey
CPT	Cone penetration test
DEM	Digital elevation model
ka	Thousand years (ago)
LEX	BGS Lexicon of Named Rock Units
Ma	Million years (ago)
mbsb	Metres below seabed
MDE	Marine Data Exchange
MIS	Marine Isotope Stage
NERC	Natural Environment Research Council
OD	Ordnance datum
OSL	Optically stimulated luminescence
OWF	Offshore wind farm
RCS	BGS Rock Classification Scheme
RVO	Netherlands Enterprise Agency
SNS	Southern North Sea
TD	Total depth
UDCS	Unlithified Deposit Coding Scheme
UKCS	UK Continental Shelf

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The British Geological Survey holds most of the references listed 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://ukrinerc.on.worldcat.org/discovery

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