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A review of subsurface geosystems and de-risking offshore construction in the Danish North Sea

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Abstract
The renewable energy transition has increased the demand for offshore construction in the Danish North Sea energy sector. This development underpins the need for further investigation of potential geological hazards and associated risks to avoid accidents involving people, the environment or infrastructure. A scientific approach to de-risking requires an understanding of the seabed and the buried geosystems. Understanding geosystems is the first step in the de-risking process of offshore construction. In this study, we review three key geosystem elements in the Danish North Sea, represented by (1) shallow stratigraphy and geomorphology, (2) glacial tectonics and salt movement and (3) subsurface fluid migration. We summarise the current state of knowledge of these geosystem elements and identify multiple risks associated with each geosystem in the region. Such investigations are critical for understanding the geotechnical behaviour of the subsurface and identifying and de-risking of potential geohazards during the construction of future energy developments in the Danish North Sea region.

1. Introduction
The Danish North Sea (DNS) is an important asset that provides a suite of important functions and services to Danish and international societies. These include not only fisheries and cargo transportation but also important geosystem services such as oil and gas production, CO_2 storage and offshore renewable energy. In addition to these services, the DNS contains important habitats for a variety of birds, fish and marine mammals (Danish Maritime Authority 2023).

The renewable energy transition will impose increased offshore construction pressure, including windfarms, cable routes and energy islands to the DNS. This places a demand on marine spatial planning, not just for the DNS but the entire North Sea region, which includes the German, British, Dutch, Belgian and Norwegian Exclusive Economic Zones (EEZs; Cotterill *et al.* 2017a; Fleischer *et al.* 2022; Petrie *et al.* 2022; Danish Maritime Authority 2023). The risks associated with these large-scale offshore construction projects are potentially immense, in terms of both geotechnical issues, health and safety and environmental risks, including construction failure, underwater noise, suspended sediments, pollution and changes to marine habitats (Le *et al.* 2014; Degraer *et al.* 2020; Mooney *et al.* 2020). Adding to the complexity of the energy transition is the uncertainty concerning the rentability of offshore wind projects. Sound economic models are going to be crucial for reaching a 6 GW output from offshore wind energy to meet a Danish reduction target of 70% compared to 1991 (Møllgaard *et al.* 2024).

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Abbreviations:
CPT: Cone penetration test
DNS: Danish North Sea
EEZ: Exclusive Economic Zone
GEUS: Geological Survey of Denmark and Greenland
LGM: Last Glacial Maximum
PGM: preliminary ground model

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To facilitate marine planning of the DNS in the energy transition era that builds on safe and sustainable approaches, a comprehensive understanding of the underlying marine geosystems is required. Due to hydrocarbon prospecting and extraction over the last five decades (Adegbamigbe *et al.* 2022), there is already significant knowledge on the deep geology. A similar knowledge base for the shallow geosystems, i.e. the upper 500 m below the seafloor, is only just starting to emerge.

A geosystem is closely related to the term geosystem services. This has been defined as either 'the direct result of the planet's geodiversity' or as providing 'benefits specifically resulting from the subsurface' (Frisk *et al.* 2022). In terms of de-risking offshore construction, we have adopted a more specific definition. Thus, geosystems in this context constitute geological features that influence offshore construction. Through reviewing published literature, this paper describes how knowledge of near-surface geology in the offshore environment of the DNS can help to de-risk the offshore construction process. We focus on three key geosystem elements represented by shallow stratigraphy and geomorphology, glacial tectonics and salt migration and subsurface fluid migration (Table 1).

1.1. Geological background

The North Sea is an epicontinental sea, bordered by the UK to the west, Norway and Denmark to the east and Germany, the Netherlands and Belgium to the south (Fig. 1). The North Sea Basin was initiated as a rift system in the early Triassic, which terminated in the Paleocene (Ziegler 1992). Up to 3000 m of Cenozoic sediments have accumulated in the basin (Cameron *et al.* 1987; Huuse & Clausen 2001; Gołedowski *et al.* 2012; Ottesen *et al.* 2014). The thickness of the sediments representing the Quaternary period (last 2.6 million years) may be up to 800 m in the central North Sea (Nielsen *et al.* 2008; Ottesen *et al.* 2014; Phillips *et al.* 2017). These sediments are typically heterogenous and have been deposited, reworked and deformed largely as a result of glacial processes associated with the cyclic expansion and decay of large ice sheets in north-west Europe (Knudsen & Sejrup 1993; Hughes *et al.* 2016; Rea *et al.* 2018; Batchelor *et al.* 2019; Kirkham *et al.* 2022). During the Elsterian (*c.* 500–400 Kyr BP) and Saalian (*c.* 380–130 Kyr BP) glacial periods, the entire DNS was covered by ice (Van der Vegt *et al.* 2012), which locally resulted in erosion into older Palaeogene or Cretaceous deposits. Prominent remnants of these glaciations are expressed as buried tunnel valleys (Huuse & Lykke-Andersen 2000; Benvenuti *et al.* 2018; Prins *et al.* 2020) or as glaciotectonic complexes (Andersen *et al.* 2005; Winsemann *et al.* 2020). Conversely, the more recent Weichselian glaciation (*c.* 117–11.5 Kyr BP) covered only the northern and western parts of the DNS (Fig. 2D; Hughes *et al.* 2016).

The Last Glacial Maximum (LGM; 22–18 Kyr BP) represents a phase of major expansion of the Fennoscandian Ice Sheet inducing large variations in geomorphology and sediment distribution across the region. Areas close to the Weichselian ice margin are often marked by an increase in geological complexity, which may involve interlayering of till, meltwater sediments and proglacial lake infill deposits (Fig. 2C). These features may be preserved within buried valleys and other paleo-landscape depressions such as those formed by glaciotectonic deformation (Moreau & Huuse 2014; Prins & Andresen 2019).

During and after the LGM, widespread marsh deposits formed in a boreal semi-submerged landscape of the German North Sea (Coughlan *et al.* 2018). A similar landscape evolution has also been suggested for the south-western part of the DNS based on shallow seismic and acoustic data (Prins & Andresen 2019; Andresen *et al.* 2022) although paleo-environmental constraints on landscape development around the last low-stand are sparse.

Following the last deglaciation, from about 11,000 years BP, most of the DNS was presumably above sea level, forming a low relief landscape with lakes and bogs commonly infilling topographic depressions (Coughlan *et al.* 2018). As the post-glacial landscape became inundated by rising sea-levels, multiple channels were formed in connection with riverine drainage systems (e.g. Elbe Paleo-valley), which gradually transformed into estuaries (Hepp *et al.* 2017, 2019; Prins & Andresen 2019; Andresen *et al.* 2022). Continuation of the Holocene transgression meant that by about

Table 1 Summary of geosystems and their associated risks and methods of identification.

Geosystem	Associated risks	Risk-reducing investigations
Shallow stratigraphy and geomorphology	Unpredicted lateral variations in soil behaviour.	Improved regional stratigraphic models.
Glacial tectonics and salt movement	Unpredicted lithology, potential fluid migration, variation in geotechnical properties.	Mapping past ice movements and their influence on the sediments; describing overburden above salt structures.
Fluid migration	Potential blowouts, changes in soil cohesion/ strength.	Understanding shallow fluid migration paths and mechanisms; mapping shallow gas.

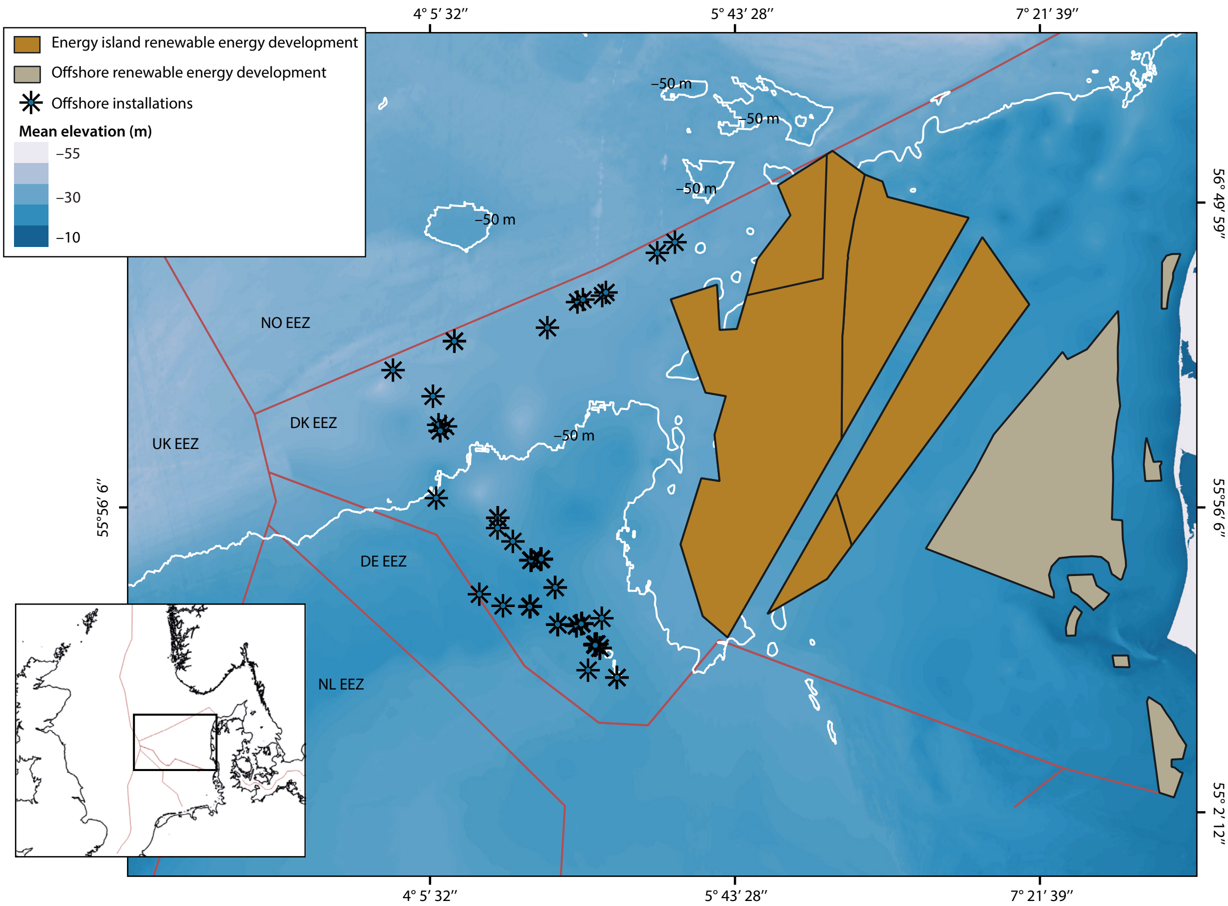

Fig. 1 Map overview of the Danish North Sea (DNS) and some of the offshore activities in the area (Danish Maritime Authority 2023). Base map projection: ETRS89 UTM zone 32N. Background map: EMODnet Bathymetry. **EEZ**: Exclusive Economic Zone. **No**: Norway. **DK**: Denmark. **DE**: Germany. **NL**: Netherlands. **UK**: United Kingdom. **Red lines** indicate EEZs.

9.3 Kyr BP, the DNS was subject to full marine conditions and influenced by strong tidal currents that initiated the deposition of large sand banks, presently known as Little Fisher Bank and the Jylland Bank (Leth 1996; Fig. 3). These features, like many other shallow areas of the DNS, remain hydrographically dynamic with mobile sand units forming the modern seabed (Anthony & Leth 2002; Nørgaard-Pedersen & Rödel 2021).

Our knowledge of North Sea geosystems that identifies the foundation zone for offshore constructions is rooted in the complex Quaternary strata, involving multiple phases of deposition, erosion and glacial loading and unloading. Although several studies on the Quaternary stratigraphy in the North Sea have emerged in recent years (Le Bot *et al.* 2005; Rijsdijk *et al.* 2005; Cotterill *et al.* 2017b; Coughlan *et al.* 2018; Prins & Andresen 2019; Petrie *et al.* 2022), the Quaternary succession of the DNS remains poorly constrained, both in terms of chronostratigraphy, lithological variation and geotechnical properties. Closing this knowledge-gap requires densely spaced and high-resolution data coverage aimed at mapping the shallow geosystems and would provide information that can de-risk offshore services now and in the future.

1.2. De-risking in a geosystem context

Risk, in the context of a geosystem, can be regarded as an assessment of the probability and consequence resulting in a negative impact produced by a specific geosystem element (Copping *et al.* 2020). This could be the likelihood and consequence of a ship grounding in areas with varying water depths, or the likelihood and consequence of a punch-through failure for a jack-up rig, installed on an undiscovered buried valley. A buried tunnel valley poses no risk to a ship passing over it, but if it results in a subsurface failure below a jack-up rig, the consequences can potentially be fatal (Bienen *et al.* 2015). Consequences may also be financial, for example, as recently experienced in the Neart na Gaoithe offshore windfarm in the UK Sector, where the likelihood of wind turbine generator foundation installation failing due to rockhead variability had not been foreseen and had a financial consequence of hundreds of millions of Euros (Watts *et al.* 2021). Such examples illustrate that

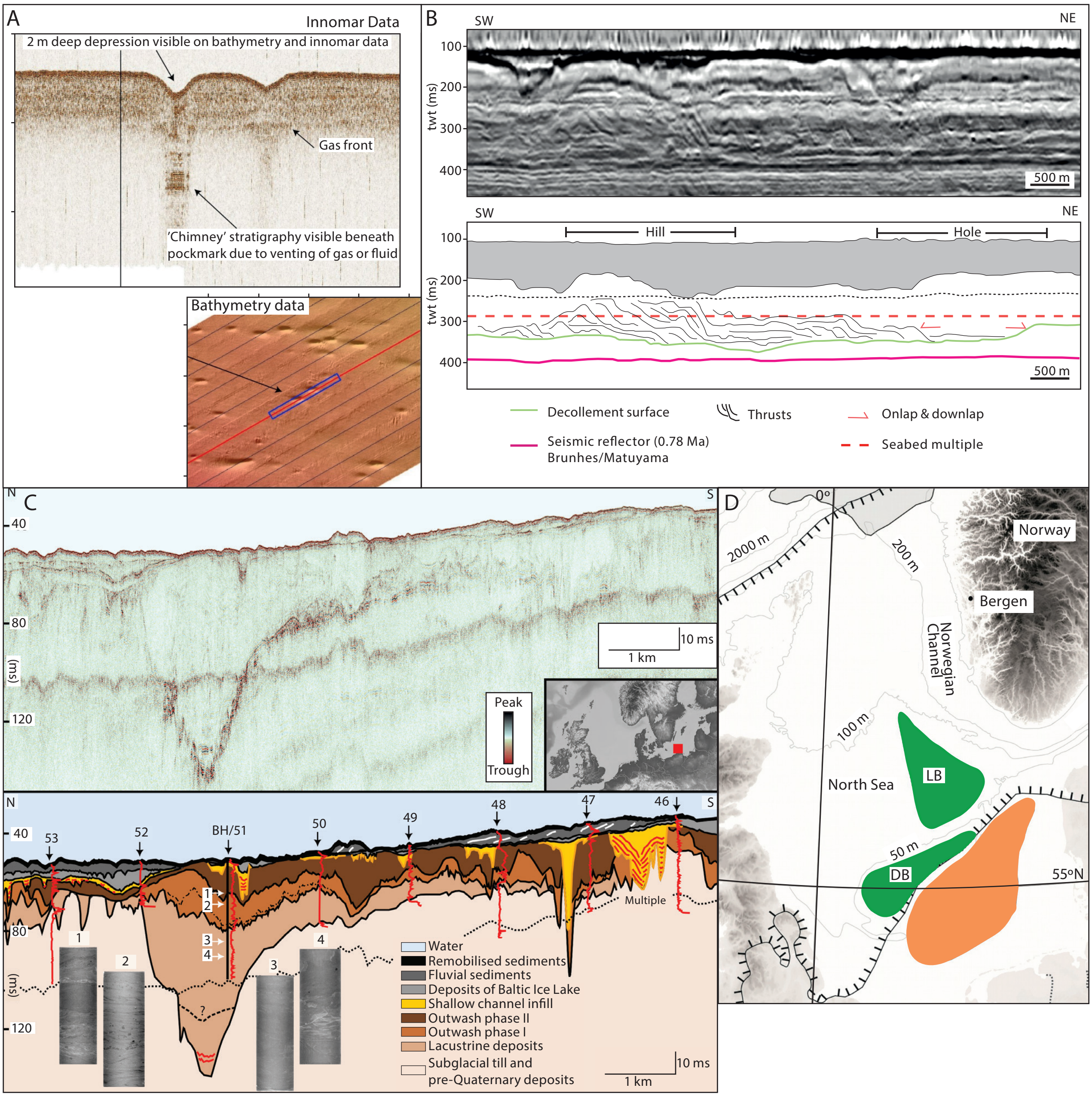

Fig. 2 Overview of different categories of geosystems reported in previous publications. **A**: **Subsurface f**luid migration: flow features represented on Innomar sub-bottom profiler data and Multibeam echosounder data as pockmarks and trapped gas (modified from Owen *et al.* 2021). **B**: Glacial tectonics and salt movement: shown by a seismic profile and model representation of a glaciotectonic complex (modified from Bendixen *et al.* 2017). **TWT**: two-way travel time. **C**: Shallow stratigraphy and geomorphology: here visualised on various geophysical data from the Baltic Sea (modified from Bellwald *et al.* 2023). **D**: Extent of a proposed glacial lake (**orange polygon**) during the Last Glacial Maximum (LGM), which has potentially deposited problematic soft clays over a large area (Green shaded areas indicate **DB** (Dogger Bank) and **LB** (Ling Bank); modified from Hjelstuen *et al.* 2018).

risk is closely related to the interaction between humans and geosystems.

Understanding geosystems is the first step in the de-risking process of offshore construction. This typically involves a desktop study, which describes the potential risks at a specific location, based on existing data and knowledge from the literature (e.g. Owen *et al.* 2020). Desktop studies highlight areas that require further investigation and help to inform potential risks associated with the area of interest. During the initial phases of site investigation, the first step is to generate a representative preliminary ground model (PGM) for the investigation area, which is typically based on any existing geophysical, geological and geotechnical data. The PGMs will then subsequently be developed further to form a fully integrated ground model based on additional site investigations and the collection of site-specific data (Cook *et al.* 2014). The PGM will also aid in the survey design to optimise ship time and thus reduce costs. Further advantages from having a high level of

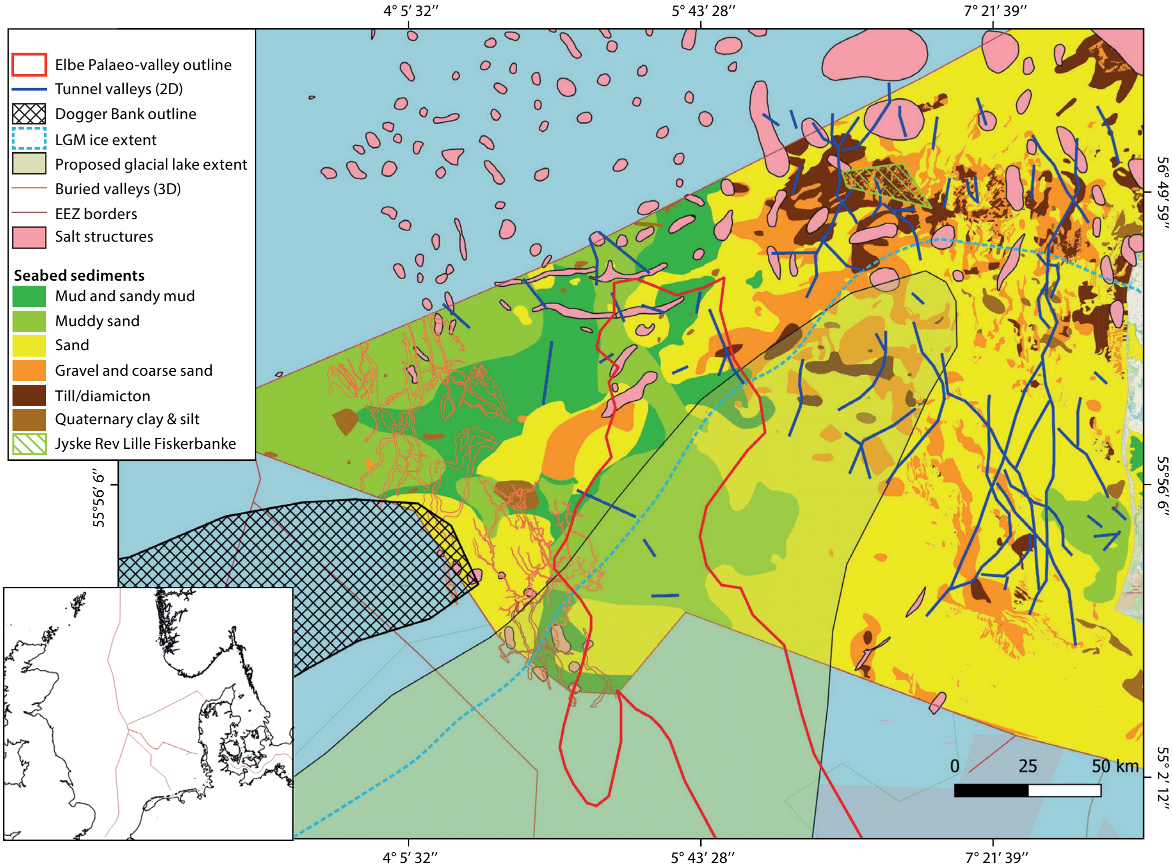

Fig. 3 Overview of the different geosystems at various stratigraphic depths in the Danish North Sea (DNS). **EEZ**: Exclusive Economic Zone. **LGM**: Last Glacial Maximum.

understanding of the geosystems include reducing the risk of project delays due to unforeseen ground conditions. These are extremely costly and not only delay the project itself but also reduce the chance of meeting political goals such as reducing carbon emissions.

2. Geosystem elements and their potential risks

This paper focuses on the potential risks associated with the following three geosystem elements in the DNS (Fig. 2):

1. shallow stratigraphy and geomorphology (Fig. 2C and 2D).
2. glacial tectonics and salt movement (Fig. 2B)
3. subsurface fluid migration (Fig. 2A)

2.1. Shallow stratigraphy and geomorphology

An understanding of the shallow stratigraphy (typically down to 200–500 m below seabed) is the basic framework for gaining information on the subsurface geotechnical properties. Knowing the lateral and vertical variation in lithology and mapping subsurface stratigraphic boundaries are essential for foundation design for large constructions such as wind turbine generators or artificial islands (Fig. 2C).

In the inner Danish waters, a recent desktop study identified a thick succession of weakly consolidated glaciomarine clays (Jensen & Bennike 2022). This resulted in the windfarm project south of Hesselø to be paused and demanded new site investigations to assess the subsurface geological constraints in the area.

In the DNS, numerous site surveys have been carried out in relation to offshore construction, but efforts to synthesise the results between sites have been sparse (Prins & Andresen 2021; Petrie *et al.* 2024). Integrating geotechnical data with robust stratigraphic models has the potential to reduce both risks and costs in relation to offshore construction (Velenturf *et al.* 2021; Petrie *et al.* 2024) and help avoid delaying large-scale offshore construction projects.

Ice-dammed lakes typically form massive deposits of soft clay, which can pose a hazard for the development of offshore windfarms. A phase of ice-dammed lake development during the Last Glacial Maximum has been suggested for the DNS area (Hjelstuen *et al.* 2018;

Fig. 2D). The geographical extent of this lake phase is bound by uncertainties although recent observations support a wider presence across the central and southern DNS (Andresen *et al.* 2022; Knutz *et al.* 2022). Further work is needed to constrain these clay-rich units in terms of lateral extent, thickness and geotechnical properties.

Understanding the subsurface geology requires knowledge of the stratigraphic units, their distribution and their lithological variation. However, in order to generate a predictive subsurface model, the geological history and depositional environment need to be constrained, which require the geomorphology and sedimentological processes of the subsurface to be interpreted (Cotterill *et al.* 2017a).

The shallow subsurface in the North Sea contains multiple different glacial geomorphologies, including prominent positive landforms such as eskers and moraine ridges (Dove *et al.* 2017; Emery *et al.* 2019; Mellett *et al.* 2020) and paleo-coastline deposits, e.g. aggradational bars, which are well known in onshore Denmark. Buried negative landforms that are less expressive in the terrestrial terrain are commonly observed in the offshore seismic profiles as various forms of channels and troughs. These predominantly erosional features range from small troughs formed locally in a tidal paleo marsh setting (Coughlan *et al.* 2018) to kilometre-scale buried valleys formed by fluvial or subglacial processes. The Elbe Paleo-valley forms a major depressional feature of composite erosional channels that intersects the DNS in a SSE–NNW direction (Lonergan *et al.* 2006; Stewart *et al.* 2013; Moreau & Huuse 2014; Ottesen *et al.* 2014; Cotterill *et al.* 2017b; Prins & Andresen 2019; Emery *et al.* 2020; Prins *et al.* 2020). Depending on their origin and subsequent geological evolution, e.g. the character of sedimentary infill, buried valleys pose different risks for offshore construction, particularly deployment of jack-up rigs and design of appropriate wind turbine foundations. Peats have frequently been reported from within buried valleys as well as the surrounding fluvial plains (Coughlan *et al.* 2018; Hepp *et al.* 2019), and these pose a risk for cable routings, as they increase the risk of overheating (Bellwald *et al.* 2024).

By assembling and integrating all the available sub-surface information, geological models can be produced that describe spatial variations in buried geomorphology, litho-stratigraphy and depositional environments. Subsequently, geotechnical information can be added, or inferred, to generate a ground model that will be used for spatial site planning of offshore installations. An example is the Dogger Bank windfarm area, where intensive data collection and the integration of geological and geotechnical data have been suggested to potentially reduce the need for drilling, thus lowering the cost of the site survey investigations (Cotterill *et al.* 2017a).

2.2. Glacial tectonics and salt movement

The glaciation history of the DNS has led to variable glaciotectonic effects on the geosystems. Deformation in a subglacial or proglacial environment occurs when the weight of a moving ice sheet exerts a lateral stress component in the subsurface strata, causing failure or brittle deformation, which propagates through the ice-contact zone (Andersen *et al.* 2005). This results in thrusting and folding of the pre-existing strata, which may lead to stacking and repetition of the sedimentary sequences (Bennet & Glasser 2009) introducing geological heterogeneity and unpredictability in the area (Fig. 2B).

Glaciotectonic complexes are found throughout the North Sea providing evidence of ice-marginal processes during the last and previous glaciations (Andersen *et al.* 2005; Larsen & Andersen 2005; Bendixen *et al.* 2017; Cotterill *et al.* 2017b; Pedersen & Boldreel 2017; Owen *et al.* 2020). Some of the most well-studied glaciotectonic deformation structures are found on the island of Mors in Denmark, where diatomite and ash layers show extensive folding of Paleocene–Eocene deposits (Klint & Pedersen 1995).

Glaciotectonic thrust complexes alter the existing stratigraphy through deformation with potentially discontinuous sedimentary sequences as a result, such as allochthonous slabs of fine-grained material in a sandy matrix. This introduces increased heterogeneity and facies unpredictability in the area. A concrete example of glaciotectonically induced heterogeneity can be found in the Jammerbugt area, where the Upper Cretaceous chalk units have been deformed by glaciotectonic activity, leaving a depression that was subsequently filled with Eemian Weichselian deposits (Pedersen & Boldreel 2017). Similar effects are seen in the British North Sea sector, where the rugged surface of thrust complexes has facilitated deposition of fine-grained material within lakes or ponds, some of which may contain organic-rich deposits, e.g. peat or gyttja (Cotterill *et al.* 2017a). For the final risk assessment, variability in lithology and structural character induced by glacial tectonics need to be integrated into the geotechnical ground model (Velenturf *et al.* 2021). Beyond the negative effects of glacial deformation and substratum complexities, ice loading may also be beneficial for offshore foundations as it enhances burial compaction and may lead to over-consolidation expressed by high shear strength and sediment stiffness (Le *et al.* 2014).

Deformation of the near surface sediments can also occur as a result of salt movement (Rank-Friend

& Elders 2004). And there is evidence of Quaternary faulting related to these salt movements (Huuse *et al.* 2001). The most prominent influence these deep salt structures pose on offshore construction is through the faulting of the near-surface sediments as well as fluid migration through these faults.

2.3. Subsurface fluid migration

Subsurface fluid migration is a naturally occurring process in sedimentary basins, principally driven by sediment compaction, decomposition of organic matter and development of localised pressure gradients (Judd & Hovland 2009). Evidence of fluid migration within geosystems is seen as crater-like depressions, or pockmarks, on the seafloor (Lohrberg *et al.* 2020; Andresen *et al.* 2021) or in the form of gas chimneys, pipes and buried pockmarks on seismic data (Fig. 2A; Cartwright *et al.* 2007; Andresen *et al.* 2008; Andresen 2012; Moss *et al.* 2012).

Sea- or lake-floor pockmarks on bathymetry data (Reusch *et al.* 2015; Lohrberg *et al.* 2020; Andresen *et al.* 2021) or pockmarks at the present day land surface (Bogoyavlensky *et al.* 2020) are documented from many sites globally – particularly sites located in hydrocarbon-prone sedimentary basins such as the DNS, where enhanced fluid flow, commonly associated with salt-induced geological structures, is prevalent (Huuse *et al.* 2010; Knutz 2010) or along permafrost or gas hydrate regions (Walter Anthony *et al.* 2012).

Seafloor pockmarks may pose a risk to offshore installations. If fluid expulsion is active, overpressurised pore fluids may yield low sediment stability or fluidisation of sediments below the crater or rim of the pockmark (Hovland *et al.* 2002; Chuvilin *et al.* 2020). In the Norwegian North Sea sector, seafloor pockmarks are a common feature in offshore windfarm development areas, which needs to be assessed in terms of fluid migration activity and potential risks (Petrie *et al.* 2022). Locations of focused fluid seepage may also present issues due to marine habitat protection of bubble reefs. These bioherms are formed by chemosynthetic organisms that use methane as an energy source whilst precipitating authigenic carbonate (Noble-James *et al.* 2020).

Fluid escape and the presence of shallow gas may also occur without a prominent seafloor expression. Gas in the shallow subsurface is found across most of the DNS, where fine-grained sediments with organic content are present, or where geological conditions are amenable to vertical gas migration (Etiope 2009; Vielstädte *et al.* 2015; Petersen & Smit 2023). In a de-risking context, it is important to understand the spatial distribution and geological context of subsurface gas accumulations as they can lead to gas blowouts or undermine foundations for offshore installations. Thus, understanding the gas migration pathway through geosystems, whether related to natural processes or induced by human activities, such as oil and gas production (Hornafius *et al.* 1999) or wind turbine foundation is crucial for reducing risk elements in offshore construction (Coughlan *et al.* 2021).

2.4. Combined risk elements

Fluid migration within glaciotectonised areas is a case of combined risk elements that can influence the geotechnical properties within a geosystem. Fluid or gas migration may occur along thrust planes of the deformation complex, thus acting as a conduit for deeper fluids, which may reach the subsurface stratum and cause foundation conditions to deteriorate (Velenturf *et al.* 2021). Similar fluid migration issues may be relevant near large salt structures (Fig. 3).

3. From geosystems to ground models

This paper highlights the importance of understanding geosystem elements that carry potential hazards for future energy developments in the DNS. Improving this knowledge will reduce physical, environmental and financial risks associated with the expected increase in offshore construction activities. This risk reduction is essential for avoiding accidents, project delays or cancellations for large offshore renewable projects that are a key component in meeting decarbonisation and net zero targets (Møllgaard *et al.* 2024).

The geosystems risk analyses should be treated as an integrated approach, since interference with one system can pose new unknown risks in other systems. For instance, although the lithological succession may appear static, the strain and loading induced from site survey drilling and construction or piling may alter the physical properties in the subsurface by compaction and fluid expulsion. Mitigation of subsurface interactions occurring during the construction phase requires modelling of subsurface behaviour based on knowledge from the geological models and geosystem elements.

Integrated models that compile all geophysical, geological and geotechnical data are key for defining the interaction between geosystem services and the risk associated with a specific geosystem (Prins & Andresen 2021; Velenturf *et al.* 2021; Bellwald *et al.* 2023). The model presented by Prins & Andresen (2021) included scattered data points from the Central Graben area from 11 site surveys including seven cone penetration tests (CPTs), which are 1D geotechnical measurements of the strength of the sediments. The data spread highlights the need for a better regional understanding of the subsurface geology. The development of offshore windfarm sites requires large amounts of geophysical, geotechnical and geological data to ground truth the engineering properties of the subsurface. And as such, regional ground models can be improved, providing a better foundation for the de-risking process in future offshore construction projects. The improvements shown in the integrated ground models that are currently being produced in relation to large-scale wind energy projects like the Ten Noorden van de Waddeneilanden Wind Farm Zone in the Netherlands (see offshorewind.rvo.nl) have a huge potential for extrapolation to wider areas. It also shows how a quantitative approach to integrating geological, geophysical and geotechnical data sets provides additional detailed information that also helps in the de-risking process (Karkov *et al.* 2022).

In the Irish Sea, data collected for Ireland's marine resource program were used to map geotechnical and geological constraints for offshore construction (Coughlan *et al.* 2020; Guinan *et al.* 2020). A similar approach could be adopted in the DNS where offshore geological data made available from different industry and academic sources allow for qualitative interpretations and early-stage geological models to be established. By leveraging a general understanding of the soil properties, implications for foundation type and design, and potential risks, these models provide a valuable service for decision-makers in marine spatial planning and the offshore energy industry (Coughlan *et al.* 2020; Guinan *et al.* 2020). Data density has improved drastically in some areas of the DNS, particularly in association with a proposed energy island (Knutz *et al.* 2022), and as the renewable energy transition progresses, a growing amount of geophysical and geotechnical data will become available. Much of these data will be available to the public through the marine raw material database 'MARTA' (GEUS 2024), which means that an increasingly larger proportion of the DNS can be described, for example, involving detailed ground models and stratigraphic schemes, which ultimately allows for a more robust risk analyses.

4. Conclusions

For the DNS, three geosystems potentially containing hazards and forming risks to offshore construction have been identified (Table 1). These are:

1. Shallow stratigraphy and geomorphology: here, unknown variations in soil strength and lithological variations across the DNS pose a risk for offshore construction if it is not resolved through a better general understanding or through site survey investigations. This includes mapping of geomorphological features, which can contribute to large local lithological variations within a stratigraphic unit (e.g. erosional valleys or coarse-grained coastal deposits) but which also helps highlight areas that require further investigation.
2. Glacial tectonics: including the postdepositional alteration of the subsurface resulting in unexpected lithological variations (e.g. chalk in a quaternary setting) and potential fluid migration paths, resulting in unexpected geotechnical properties.
3. Fluid migration: here, the presence of gas in the sediment causes a variety of potential hazards like expulsion to the water column, loss of sediment cohesion and strength and potential blowouts.

This review of geosystems in the DNS shows that there are multiple risks associated with each geosystem. It highlights the need for a general understanding of these geosystems and provides information on good practice for understanding and mitigating these risks. Because the near-surface geology of the DNS is so diverse, there is a need for a broad geological model that can be continuously improved upon. This model should inform the desktop studies and subsequent integrated ground models for offshore construction projects.

As we have shown, most regional geosystems and their distribution are known; however, we still lack specific knowledge on how the systems are interlinked, which exact geotechnical properties they have as well as the challenges they pose. As the renewable energy transition continues, more data will need to be gathered about these geosystems, and how to handle the risks associated with them. With increased use of oil and gas technology applied on shallow data, the resolution and accuracy will also gradually increase. To this end, some initiatives have already been established. These include a large-scale mapping project funded by the Danish Energy Agency, to screen Danish waters for areas that are unfit for windfarm construction and the NOARG project, funded by Geocenter Denmark (see *https://www.geocenter.dk/projekter/2023-2/*), which aims to map and improve our understanding of buried valleys in the DNS. Such projects will increase regional knowledge of the geosystems in the DNS and how they might pose a risk to future offshore construction.

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Author contributions

LTP: Conceptualisation, formal analysis, methodology, visualisation, writing – original draft, writing – review and editing. KJA: Conceptualisation, writing – original draft, writing – review and editing. MO: Conceptualisation, writing – original draft. PK: Conceptualisation, writing – review and editing.

Competing interests

The authors declare no competing interests.

Additional files

None provided.

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