An integrated geological characterization of marine ground conditions in the North Sea

Hannah Elizabeth Petrie

Thesis for the degree of Philosophiae Doctor (PhD)
University of Bergen, Norway
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Name: Hannah Elizabeth Petrie
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Scientific environment

This study was conducted within the Geodynamics and Basin Research Group at the University of Bergen Department of Earth Science, Faculty of Mathematics and Natural Science, under the supervision of Christian Haug Eide (University of Bergen), co-supervision of Haflidi Haflidason (University of Bergen) and co-supervision of Timothy Watton (Equinor Energy AS) between August 2020 and September 2023.

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Abstract

The geological characterization of marine ground conditions for wind turbine foundations and anchors at large offshore wind sites is a relatively new field. As such, the establishment of best practices for the integration of geological, geophysical and geotechnical (G, G & G) data is a work in progress. While existing methods give a broadly sufficient basis for the design of offshore wind turbines and their foundations or anchors, current workflows do not give enough weight to understanding how depositional and post-depositional processes have influenced mapped geophysical units and their measured geotechnical properties. This limits experience transfer from developed sites to new ones and the degree of predictability of certain geotechnical conditions.

Together with data acquisition costs, foundation fabrication and installation can constitute up to a third of the overall cost of an offshore wind project. Thus, a better understanding of how geological factors influence ground conditions at offshore wind sites could contribute to significant cost reductions and help countries achieve their renewable energy goals. This is particularly true in offshore wind areas with complex geology, such as formerly glaciated terrains like the North Sea. In this thesis, an integrated geological characterization of the marine ground conditions within the North Sea is presented, based on legacy conventional 2D and 3D seismic data, sub-bottom profiles, borehole reports and literature, in addition to an extensive marine geological dataset acquired at two contrasting offshore wind sites in the Norwegian North Sea during a ten-day cruise with the research vessel G.O. Sars in 2022.

The first part of the thesis deals with the sedimentary, geophysical and geotechnical characteristics of the Late Quaternary deposits at the Utsira Nord floating offshore wind site located within the deep Norwegian Channel ice stream trough. These interpretations are based on seabed and subsurface geomorphologic features studied using high resolution bathymetric data, legacy 2D seismic data, sub-bottom profiles and shallow sediment core data prior to the cruise. The findings are summarized as a conceptual geological model for ground conditions in former ice stream settings with four main units with contrasting geotechnical properties. This model was tested on the cruise and was found to be relatively accurate, with additional till wedges discovered within the main upper till unit in the southeastern part of the site.

A detailed regional study of the evolution of the Late Quaternary depositional environments that were present in the Dogger Bank-Ling Bank-Jutland Bank and Elbe Palaeovalley areas of the southern North Sea is then presented. This is accompanied by a preliminary ground model for the highly heterogeneous Sørlige Nordsjø II bottom-fixed offshore wind site, located on the Ling Bank. This model is based on the integration of geomorphic interpretations from legacy 3D seismic data with seismic facies variations identified on the high-resolution 2D sub-bottom profiler dataset and sedimentary facies variations observed in shallow sediment cores, collected in 2022.

The two sites can be considered end-members of the ground condition types that exist within the Norwegian sector of the North Sea, with 1) deep, clay-rich conditions in the

Norwegian Channel, characterized by a semi-layer cake stratigraphy of subglacial tills and glacimarine to marine, fine-grained sediments and 2) the shallower, highly laterally heterogeneous, broadly sand-rich conditions on the North Sea Plateau, characterized by a wide range of depositional facies, from subglacial till to glacilacustrine and glacifluvial deposits, post-glacial fluvial and tidal channels, and shallow marine systems. In **Articles 1 and 2**, the applicability of the different available offshore wind foundation and anchor concepts to these end-member ground condition zones is investigated, with the aim of producing case studies for the North Sea that combine a detailed geological understanding of the North Sea ground conditions with the engineering implications for the different types of formerly glaciated marine areas. In general, it can be said that the Norwegian Channel is an area suitable for floating offshore wind turbines with suction anchors, because of its clay-rich stratigraphy, though it does contain features that pose potential issues to such infrastructure, such as pockmarks, ice-rafted debris deposits, boulders, stiff glacial diamictons and occurrences of shallow crystalline bedrock that must be assessed and mitigated for on a site-by-site basis. In contrast, the shallower, highly heterogeneous North Sea Plateau areas are best suited to the most common offshore wind foundation type, the monopile, in water depths less than c. 50 m, and multi-legged, supported structures (jackets) in water depths greater than c. 50 m. Key factors influencing foundation design variations on the North Sea Plateau are the distribution and thickness of the different depositional facies relating to the particular subglacial, proglacial and post-glacial processes that have impacted a particular site or turbine location, for example the presence of stiff glacilacustrine lake infills or weak, post-glacial channel infills.

In **Article 3**, a broader look is taken at the ground conditions within the North Sea and other previously glaciated marine areas, the ways in which the Late Quaternary glaciations impacted the geotechnical conditions of the soils and the resulting engineering considerations that are relevant today. Through a range of case studies, we highlight how site characterization methods are and should be evolving as the importance of an integrated approach becomes increasingly apparent through the publication of geological studies from complex wind sites.

Overall, it was found that in previously glaciated terranes, depositional setting and geotechnical conditions are intrinsically linked. It is becoming increasingly apparent to a range of academic and industry players that giving more weight to geological data could enhance the predictability of the geotechnical heterogeneities that inform cost-effective foundation and anchor design processes. However, work practices and guidelines for offshore wind site characterization still have a way to go to become reflective of this.

Sammendrag

Geologiske karakterisering av marine grunnforhold for ankre og fundamenter for vindturbinder store vindkraftverk til havs er et relativt nytt felt. Som sådan er etableringen av beste praksis for integrering av geologiske, geofysiske og geotekniske (G, G & G) data et arbeid som pågår. Selv om eksisterende metoder gir et bredt og tilstrekkelig grunnlag for utforming av havvindturbiner og deres fundamenter eller ankre, legger ikke dagens arbeidsflyt nok vekt på å forstå hvordan avsetnings- og etteravsetningsprosesser har påvirket kartlagte geofysiske enheter og deres målte geotekniske egenskaper. Dette begrenser erfaringsoverføring fra utbygde lokaliteter til nye lokaliteter, og graden av forutsigbarhet for flere geotekniske forhold.

Kostnader til kartlegging, konstruksjon og installasjon av fundament kan utgjøre opptil en tredjedel av den totale kostnaden for et havvindprosjekt. Dermed kan en bedre forståelse av hvordan geologiske faktorer påvirker grunnforholdene ved havvindkraftverk bidra til betydelige kostnadsreduksjoner, og dermed hjelpe land med å nå sine mål for fornybar energi. Dette gjelder spesielt i havvindområder med kompleks geologi, for eksempel i tidligere isdekte områder som Nordsjøen. I denne avhandlingen presenterer jeg en integrert geologisk karakterisering av de marine grunnforholdene i Nordsjøen basert på eldre konvensjonelle 2D- og 3D-seismiske data, penetrasjonsekkoloddsdata, borehullsrapporter og litteratur, i tillegg til et omfattende maringeologisk datasett innhentet ved to kontrasterende havindsområder i den norske Nordsjøen under et ti-dagers tokt med forskningsfartøyet G.O. Sars i 2022.

Den første delen av oppgaven tar for seg de sedimentære, geofysiske og geotekniske egenskapene til de sene kvartære avsetningene på Utsira Nords flytende havvindområde som ligger innenfor den dype Norskekanalens isstrømtrau. Disse tolkningene er basert på geomorfologiske trekk ved havbunnen og undergrunnen studert ved bruk av høyoppløselige batymetriske data, eldre 2D seismiske data, penetrasjonsekkolodd og grunne sedimentkjernedata samlet inn før toktet. Funnene er oppsummert som en konseptuell geologisk modell for grunnforhold i tidligere isstrøminnstillinger med fire hovedenheter med forskjellige geotekniske egenskaper. Denne modellen ble testet på toktet i 2022 og ble funnet å være relativt nøyaktig, men en forskjell er at ytterligere avsetningskiler ble oppdaget i den øvre deformasjonsmorene-enheten i den sørøstlige delen av området.

Den andre delen av oppgaven omfatter en detaljert regional studie av utviklingen av de senkvartære avsetningsmiljøene som var tilstede i Doggerbanken-Lingbanken-Jutlandbanken og Elbe Palaeodal-områdene i den sørlige Nordsjøen. Dette er ledsaget av en foreløpig grunnmodell for det svært heterogene havvindområdet Sørlige Nordsjø II, som ligger på Lingbanken. Denne modellen er basert på integrasjon av tolkninger av geomorfologi fra eldre 3D-seismiske data med seismiske faciesvariasjoner identifisert på høyoppløselig 2D penetrasjonsekkolodd-datasettet og sedimentære faciesvariasjoner observert i grunne sedimentkjerner, samlet inn i 2022.

De to lokalitetene Utsira Nord og Sørlige Nordsjø II kan betraktes som endepunkter av de ulike typene bunnforhold som finnes innenfor den norske delen av Nordsjøen, med 1) generelt dype, leirrike forhold i Norskerenna, preget av en lagkakestratigrafi av subglasiale morener og glasimarine til marine, finkornede sedimenter; og 2) de grunnere, svært lateralt heterogene, sandrike forholdene på Nordsjøplatået, preget av et bredt spekter av avsetningsfacies, fra subglasiale til glasilakustrine og glasifluviale avsetninger, postglasiale elveavsetninger og tidevannskanaler, og grunne marine systemer. I **artikkel 1 og 2** undersøkes anvendeligheten av forskjellige tilgjengelige konsepter for fundamenter og ankre for disse to ytterpunktene med grunnforhold, med sikte på å produsere casestudier for Nordsjøen som kombinerer en detaljert geologisk forståelse av Nordsjøens grunnforhold med de ingeniørmessige implikasjonene for de forskjellige typene tidligere isdekte havområder. Generelt kan det sies at Norskerenna er et område som er egnet for flytende havvindmøller med sugeankre, på grunn av sin leirerike stratigrafi, selv om den området har egenskaper som kan utgjøre potensielle problemer for slik infrastruktur, som f.eks. kopparr, isdroppet materiale, steinblokker, stive glasiale diamiktoner og forekomster av grunne krystallinske berggrunn som må vurderes og håndteres på sted-for-sted-basis. I motsetning til dette er de grunnere, sandrike, men svært heterogene områdene i Nordsjøplatået best egnet til den vanligste havvindfundamenttypen, monopålen, på vanndyp mindre enn ca. 50 m, og flerbeinte, støttede strukturer (trebeinte strukturer eller fagverk) på vanndyp større enn ca. 50 m. Nøkkelfaktorer som påvirker designvariasjoner i fundamentene i Nordsjøplatået, er fordelingen og tykkelsen av de forskjellige avsetningstypene knyttet til de bestemte subglasiale, proglasiale og postglasiale prosessene som har påvirket et bestemt sted eller en bestemt turbinplassering, for eksempel tilstedeværelsen av stive glacilacustrine innsjøutfyllinger eller svake, post-glasiale kanalutfyllinger.

I **artikkel 3** er det tatt et blikk på grunnforholdene i hele Nordsjøen og andre tidligere glasierte havområder, og hvordan de sene kvartære isdekkene påvirket de geotekniske forholdene i jordsmonnet og de resulterende tekniske hensyn som er relevante i dag. Gjennom en rekke case-studier fremhever vi hvordan karakteriseringsmetoder for havvindsområder er og bør utvikle seg etter hvert som viktigheten av en integrert tilnærming blir stadig tydeligere gjennom publisering av geologiske studier fra andre komplekse havvindsområder.

Samlet sett ble det funnet at i tidligere isdekte områder henger er avsetningsforhold og geotekniske forhold tett sammen. Det blir stadig tydeligere for en rekke aktører og industria og akademia at å legge mer vekt på geologiske data kan øke vår evne til å forutsi de geotekniske heterogenitetene i havvindsområder. Dette gir grunnlag for kostnadseffektive fundamenterings- og ankerdesignprosesser. Arbeidspraksis og retningslinjer for karakterisering av offshore vindplasser har imidlertid fortsatt en vei å gå for å reflektere dette.

List of Publications

Petrie, H.E., Eide, C.H., Haflidason, H. and Watton, T., 2022. A conceptual geological model for offshore wind sites in former ice stream settings: the Utsira Nord site, North Sea. *Journal of the Geological Society*, 179(5), pp. jgs2021-163. https://doi.org/10.1144/jgs2021-163

Petrie, H.E., Eide, C.H., Haflidason, H., Brendryen, J. and Watton, T., 2023. An integrated geological characterization of the Sørlige Nordsjø II offshore wind site, southern North Sea. Manuscript under review with *Boreas*.

Petrie, H.E., Eide, C.H., Haflidason, H. and Watton, T., 2023. Integrating geological, geophysical, and engineering considerations at offshore wind sites in buried glacial landscapes: Case studies from the North Sea. Manuscript in preparation for submission to *Marine Geology*, 2023.

- *Article 1 is open access.*

- *Unpublished articles (Articles 2 and 3) will also be open access once published.*

Contents

Introduction

Project Background

The deployment of offshore wind energy is at the core of Europe's energy, climate, and energy security goals (European Commission, 2023). However, installing wind energy infrastructure at sea is inherently more expensive than installing it onshore. The complexity and cost of development are intrinsically linked to the water depths (Fig. 1), the meteorological conditions, and the geological ground conditions (the Dogger Bank, Celtic Array and Saint-Brieuc windfarms are prime examples, Cotterill et al., (2017a, b); Crown Estate, (2014); Van Oord (2023)). One way to reduce manufacturing and installation costs at new, increasingly large and increasingly deep offshore wind sites is to develop a better understanding of how the geological character of the seabed and shallow subsurface impact turbine foundation and anchor design and installation (in addition to inter-array and export cable design), which can account for up to c. 35% of the overall cost of an offshore wind development (Fig 1)(Bhattacharya, 2014; Oh et al., 2018). Understanding the geotechnical implications of the geological setting of a new offshore wind site is particularly important in areas with complex or highly variable geology, where higher uncertainty in the distribution of soil or rock units and their geotechnical properties can result in overconservative foundation design (Muir Wood & Knight, 2013) or in project abandonment (RWE, 2013; Crown Estate, 2014).

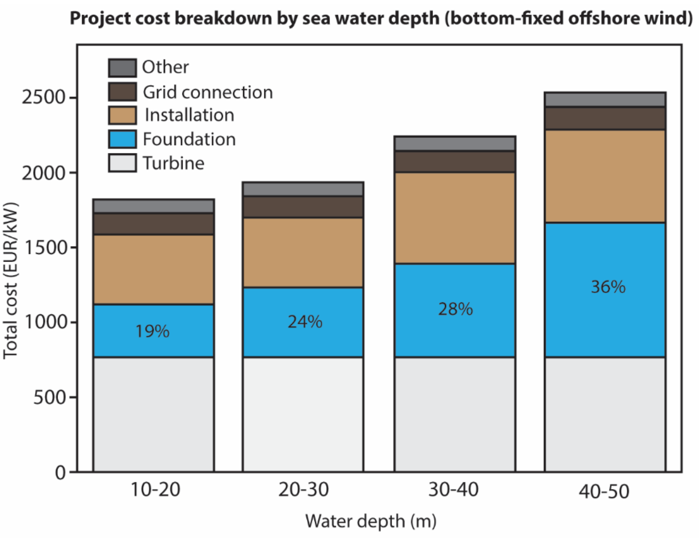

Fig. 1 Bar chart of project cost for bottom-fixed offshore wind farms versus seawater depth, adapted from Oh et al. (2018), showing increasing foundation and installation costs with increasing water depth.

This study focuses on characterizing the ground conditions for offshore wind foundations in the North Sea, where a large number of offshore wind developments are planned, and where the engineering properties of the seabed and shallow subsurface sediments (and rock) have been heavily influenced by the glaciations and related eustatic sea level changes which occurred in the Northern Hemisphere during the Late Quaternary period (Fig. 2) (e.g., Le et al. 2014; Cotterill et al. 2017a; Emery et al. 2019a, b; Prins & Andresen, 2019; Fleischer et al. 2023). Glacially influenced deposits are highly laterally heterogeneous (Fig. 3), can be very poorly sorted, and are often over-consolidated due to having been compressed by icesheets and/or subjected to subaerial weathering and desiccation (Piotrowski et al., 2004; Martin et al., 2017; Cotterill et al., 2017a). Previously glaciated marine areas have also experienced a wide range of depositional environments and processes (Fig. 3) over very short periods of geological time due to rapidly fluctuating sea level during the climatic swings between glacial and interglacial periods (e.g., Coles, 2000; Lambeck et al., 2014; Gibbard et al., 2015). They can also be structurally altered by glacitectonic folds and thrusts formed by the advances of the former icesheets (Jensen et al., 2008; Phillips et al., 2018, 2022; Petrie et al., in review). These characteristics can have a significant impact on the design requirements of offshore wind turbine foundations, such as foundation or anchor type, length, diameter and wall thickness, and therefore the amount of material and capital expenditure required to develop the site (e.g., Kallehave et al., 2015; Jardine, 2020). At the Dogger Bank offshore wind development zone in the British sector of the southern North Sea, for example, geological complexities including major glacitectonic folding and thrusting and the presence of over-consolidated glacilacustrine deposits have reportedly had important implications for foundation design and placement (Cotterill et al. 2017a, b).

The project began in September 2020, with a ten-day marine geological cruise on the R/V G.O. Sars to acquire an extensive sub-bottom profiler and sediment core dataset from Norway's first open offshore wind sites (Utsira Nord and Sørlige Nordsjø II, Fig. 4) planned for June 2021. Due to issues with another research vessel, however, the R/V G.O. Sars was not available to the project until June 2022. The fourth quarter of 2020, the year 2021 and the first two quarters of 2022 were therefore dedicated to collecting and interpreting legacy marine geological data at and near the study areas and studying the Late Quaternary depositional history of the North Sea and geotechnical case studies for offshore wind sites and other types of infrastructure in the region and geologically similar areas. From legacy data alone it was possible to develop a relatively detailed and accurate conceptual geological model for the Utsira Nord floating offshore wind site, and this was used to plan the data acquisition carried out during the cruise.

Abundant legacy 3D seismic data and a geotechnical report formed the basis of the preliminary desktop study of the ground conditions and depositional history of the second study area, Sørlige Nordsjø II, prior to the cruise. 3D seismic attribute time slices such as spectral decomposition were very useful planning aids for data acquisition, allowing features such as seismic anomalies, buried tunnel valley and channel systems and other glacial-related geomorphic features to be mapped and investigated further with the higher resolution sub-bottom profiles and shallow sediment cores.

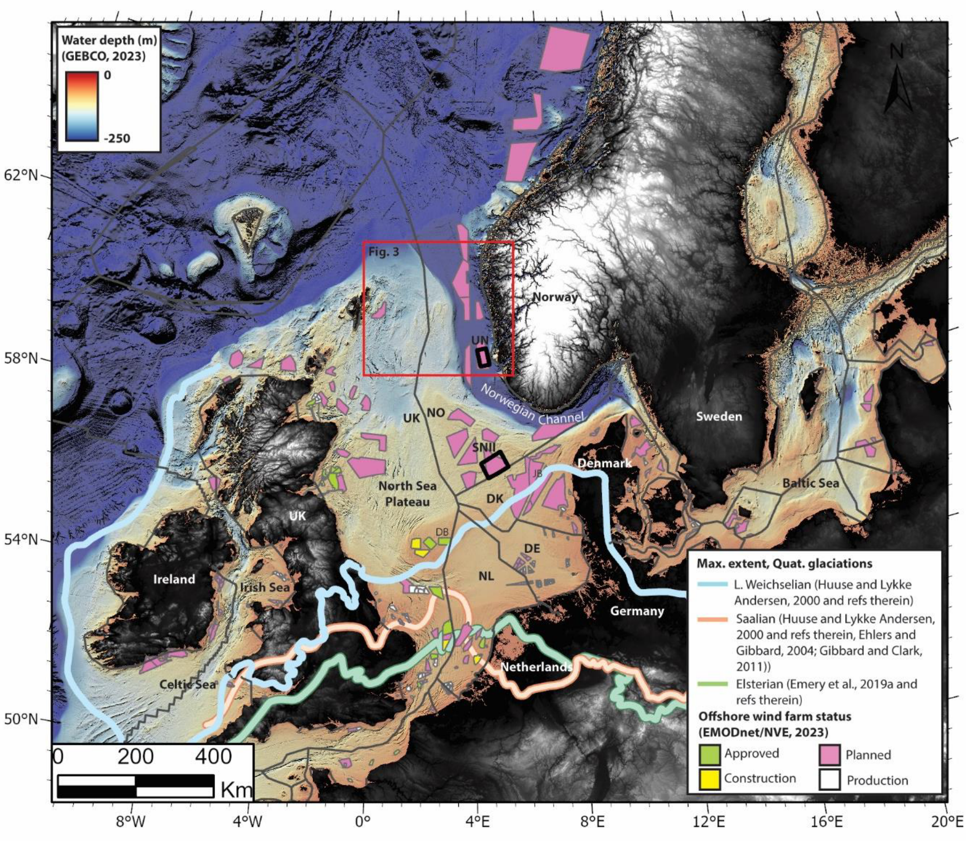

Fig. 2 *Map with current and planned wind sites in the North Sea and surrounding areas showing extent of Late Quaternary icesheet influence on ground conditions. UN-Utsira Nord, SNII, Sørlige Nordsjø II, UK-United Kingdom, NO-Norway, DK-Denmark, DE-Germany, NL-Netherlands, NC-Norwegian Channel, DB-Dogger Bank, JB-Jutland Bank.*

The cruise was carried out over ten days from June 12-22, 2022, in good weather, starting from Bergen. The vessel sailed towards Sørlige Nordsjø II on the southern border of the Norwegian North Sea via Utsira Nord, located off the coast of Stavanger (Fig. 4). Four days and nights were then spent at each site acquiring data. The planned data acquisition was successful, with a total of 10 gravity cores, 3 piston cores, 13 vibrocores and 1600 km of sub-bottom profiles acquired over key localities in Utsira Nord and Sørlige Nordsjø II (Fig. 4).

Analysis of the Sørlige Nordsjø II dataset (seismic interpretation and core-logging) then formed the second part of this study, an integrated geological characterization of the ground conditions and depositional history of the Sørlige Nordsjø II and surrounding area, which is a key area of the southern North Sea for understanding the depositional systems and environmental conditions of the late-glacial to post-glacial period of the Late Weichselian.

The final part of the study involved bringing together the broader findings of the research conducted prior to and during the cruise, to provide an overview of how ground conditions in the North Sea have been impacted by glacial and post-glacial depositional processes, how this has influenced offshore wind site surveying methods, foundation and anchor design, and where opportunities for improving the integration of geological, geophysical and geotechnical data may lie going forwards.

This thesis therefore consists of three individual articles that focus on different parts of the North Sea Late Quaternary stratigraphy, with the common goal of investigating ways in which geological understanding can be better integrated with geophysical observations and geotechnical measurements at offshore wind sites with complex glacially influenced marine ground conditions.

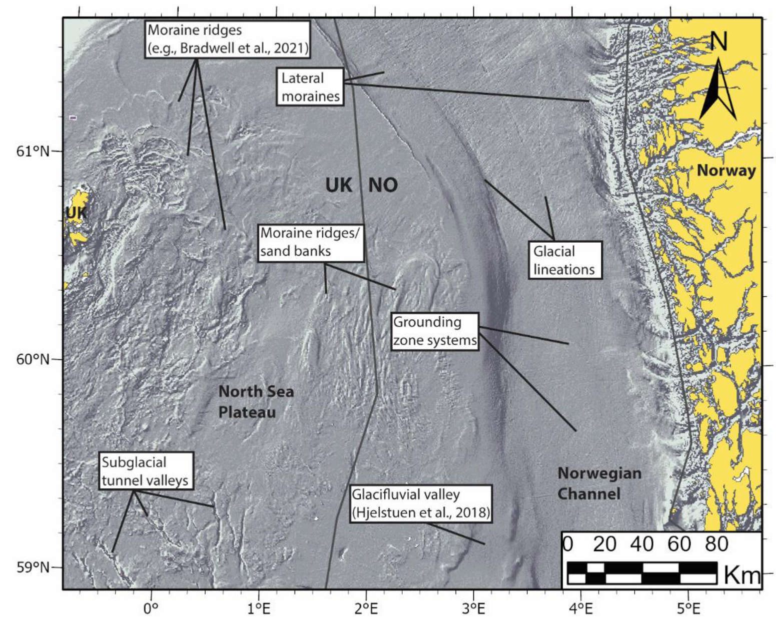

Fig. 3 *The geomorphic imprint of the Late Quaternary British-Irish and Fennoscandian icesheets at the seabed within the North Sea. Bathymetry from Olex AS. Location shown in Fig. 2.* UK-United Kingdom, NO-Norway.

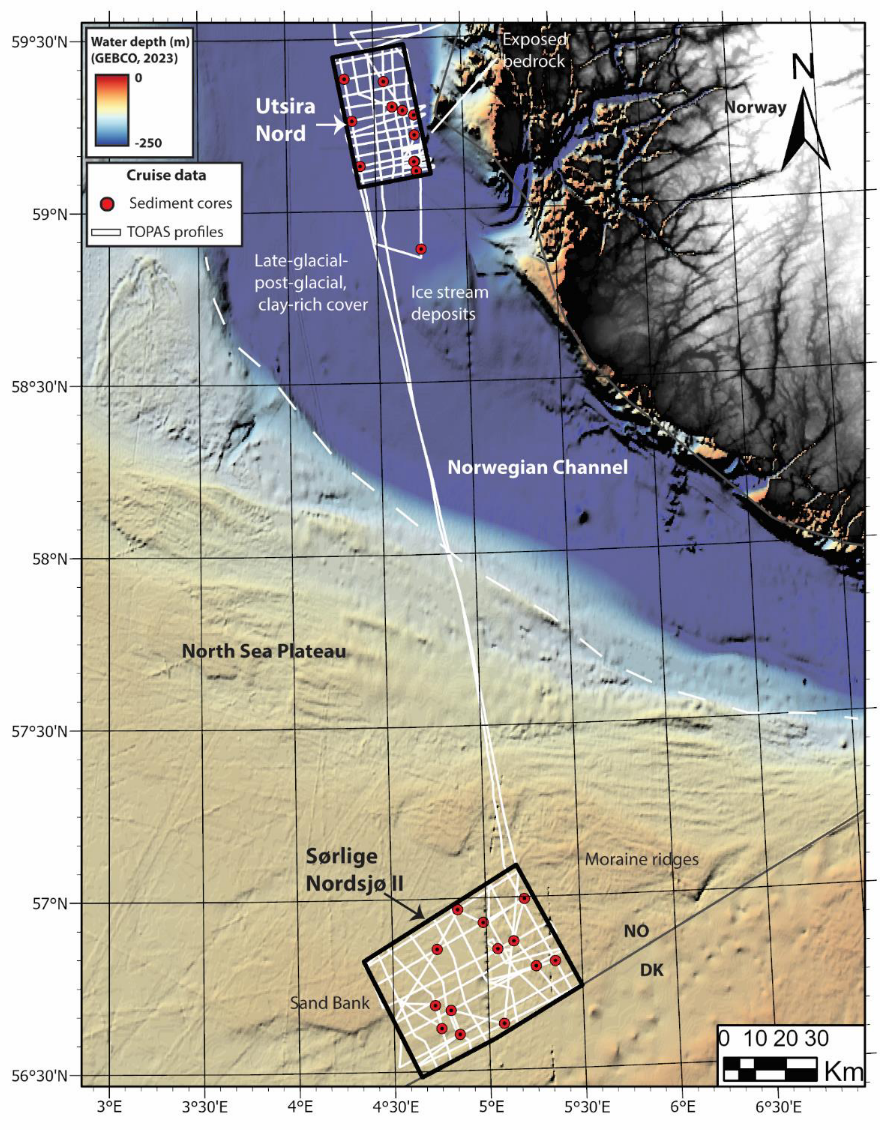

Fig. 4 *Bathymetric map of North Sea (GEBCO, 2023) showing the R/V G.O. Sars cruise route, TOPAS sub-bottom profiler acquisition lines (white lines) and sediment coring locations (red circles). NO-Norway, DK-Denmark.*

State of the art

Site characterization for offshore wind foundation design is a relatively new field, established in the 1990s with the advent of heavy gravity-based turbine structures placed in shallow water offshore Denmark (e.g., Díaz and Guedes Soares, 2020). However, as turbine and foundation technologies have developed, wind turbines have become larger to increase their generating capacity and have moved into progressively deeper waters further offshore to exploit stronger, more reliable wind resources (e.g., IEA, 2019; Díaz and Guedes Soares, 2020; IRENA, 2020). These factors mean that simple gravity-based foundation structures are often no longer sufficient to support the very large turbines and the larger wind and wave loads that they experience further offshore. Instead, various foundation and anchor designs based mainly on those used in deep sea oil and gas infrastructure, which penetrate several metres to tens of metres into the shallow subsurface, have become necessary to support large, deep-water wind turbines (Westgate and De Jong, 2005; Oh et al., 2018; Cerfontaine et al., 2023). However, wind turbines experience different engineering loads than oil platforms, and comprise a much larger number of foundations, spanning much larger areas of the seabed (e.g., Le et al., 2014; Velenturf et al., 2021). Thus, the field of so-called "site characterization" (characterizing the shallow subsurface geological units and their geotechnical properties by collecting geophysical and geotechnical surveys) has had to evolve to evaluate much larger areas of seabed. This represents two main challenges related to the field of geoscience, 1) how best to plan cost-effective data acquisition surveys over large areas which balance cost with reducing the geotechnical uncertainties to an acceptable level to design safe, cost-effective wind foundations and ensure safe and successful installation programmes, and 2) how best to utilize and integrate the available subsurface data to reduce the geotechnical uncertainties between the acquired data points.

In the last few years there has been an increasing focus on tackling these challenges within the wind-related industries and academic communities, for example, through experimenting with new site survey methodologies and seismic techniques (Vardy et al., 2018; Wenau et al., 2018; Yetginer-Tjelta et al., 2022), and through the use of machine learning (Vaaneste et al., 2022) to try to increase the speed and reliability of the geophysical to geotechnical data correlations that inform the design of the offshore wind anchors or foundations. The rationale behind this study stems from the growing consensus that these challenges are particularly pertinent in offshore marine areas that were affected by the Late Quaternary glaciations (Jensen et al., 2008; Kallehave et al., 2015; Le et al., 2014; Cotterill et al., 2017a, b; Coughlan et al., 2020).

Objectives

The overall aim of this study was to investigate how geological conditions at and below the seabed influence the location, design and installation success of offshore wind turbine anchors and foundations in the North Sea, and more broadly in previously glaciated marine areas. The project involved a ten-day marine geological cruise to two planned offshore wind sites in the Norwegian sector of the North Sea. The initial objectives of the study were therefore to investigate the geological history, subsurface stratigraphy and bathymetry of the two study areas and their surroundings to inform a data acquisition plan that would capture the main soil units, their degree of heterogeneity, and potential geohazards or geotechnical challenges at each of the sites. The goal of the cruise was to acquire a dataset of sub-bottom profiles and sediment cores that, together with legacy data and background literature for the region, would facilitate an investigation into the main soil types and their sedimentological, geophysical and geotechnical properties at the sites.

The study is intended to provide an insight into the challenges and advantages that glacially influenced soils represent for the installation of offshore wind infrastructure and a means to open up the field of offshore wind site characterization to geoscientists with a background focused on the deeper subsurface and those without a background in geotechnics. The importance of bridging the existing gaps between geological, geophysical and geotechnical analysis within the field of offshore wind site characterization was identified early in the study and became the overarching goal of the work carried out within each of the presented articles.

The specific goals of the study were therefore to:

- Analyze and integrate interpretations from legacy 2D and 3D seismic data, sediment core data, geotechnical reports, bathymetric data and literature to identify key Late Quaternary depositional systems, processes, environmental changes and sedimentary facies types within the Norwegian North Sea and analogous areas

- Acquire, analyze and interpret sub-bottom profiles and sediment cores from two study areas in the Norwegian North Sea to investigate key geotechnical variations and challenges in various glacially influenced soils

- Investigate how integrated conceptual geological models can facilitate safe and cost-effective foundation design

- Present recommendations for better integration of geological setting and geophysical and geotechnical data in offshore wind site characterization

Study Areas

The two main study areas for this thesis are the Utsira Nord and Sørlige Nordsjø II offshore wind sites, located in the Norwegian sector of the North Sea (Figs 2, 4). Both are characterized by heterogeneous Late Quaternary to Holocene soils at the seabed and within the shallow subsurface. The sites have highly contrasting bathymetric and sedimentary characters from each other and provide an ideal opportunity to compare different types of glacially-influenced marine ground conditions within the North Sea and their implications for Norway's nascent offshore wind development strategy.

Utsira Nord, Norwegian Channel

Utsira Nord is a designated floating offshore wind area located 30 km off the western coast of Norway in the c. 270 m deep waters of the Norwegian Channel, covering a c. 1000 km^2 area of seabed (Figs 2, 4). The Norwegian Channel has a complex glacial history of repeated ice stream activity and sediment transport linked to the advances and retreats of the former Scandinavian or Fennoscandian Icesheet during the last c. 1.1. million years (Sejrup et al., 1994, 1995, 2003, 2005; Nygård et al., 2005, 2007; Hjelstuen et al., 2012, 2018; Ottesen et al., 2016; Reinardy et al., 2017; Morén et al., 2018) (Fig. 3). Ice stream activity has also had an impact on marine ground conditions in other regions with good wind resources, such as the continental shelf of Mid-Norway (Ottesen et al., 2005a, b), the northern UK (Gandy et al., 2019), the Irish Sea (Mellet et al., 2015; Coughlan et al., 2020) and the coastlines of Canada and the northern USA (McClennen 1989; Shaw et al., 2006).

The Norwegian Channel Ice Stream was a c. 200 km wide zone of fast flowing ice within the merged Scandinavian and British-Irish Icesheets (Ottesen et al., 2016). The precise timing of the onset of the ice streaming is uncertain, but the oldest known Quaternary deposit in the Norwegian Channel is a glacial till dated to c. 1.1 Ma (Sejrup et al., 1995). Becker et al. (2018) suggested that the last phase of ice streaming may have been restricted to between 23.3 and 19 ka, while the initial deglaciation and break-up of the ice stream is thought to have started between 19 and 18.7 ka at the North Sea shelf edge, retreating to southern Norway by 17.6 ka (Morén et al., 2018). This resulted in the eventual thinning and decoupling of the merged SIS–BIIS icesheets at 18.7 ka (Lekens et al., 2005; Becker et al., 2018; Hjelstuen et al., 2018). After this, warm coastal currents began to occupy the Norwegian Channel (Sejrup et al., 1994; Haflidason et al., 1995, 1998), with some periodic ice input from the fjord during minor readvances of the SIS (Mangerud et al. 2011).

The geological units defined at Utsira Nord in **Article 1** comprise remnants of hard crystalline bedrock on the landward side of the Norwegian Channel, truncated by the ice stream, juxtaposed with chaotic subglacial ice stream deposits and laminated "plumite" deposited in the glacimarine environment ahead of the retreating ice steam at the end of the last glacial maximum. The chaotic subglacial deposits are exposed at seabed across much of the site, making Utsira Nord an ideal location for studying the geomorphology, sedimentology and physical characteristics of these potentially challenging deposits for offshore wind development.

The frontrunner technology for developing offshore wind in an area as deep as the Norwegian Channel is floating turbines with suction bucket anchors, however, these have not been deployed at scale in areas with exposed glacial tills. Investigating the potential suitability of these deposits for installation of suction bucket anchors was therefore an important contribution to the overall assessment of ground conditions in former ice stream settings.

Sørlige Nordsjø II, southern North Sea

Sørlige Nordsjø II is a designated offshore wind area in the southern Norwegian North Sea, that will likely be developed with bottom-fixed offshore wind, given its water depth range of 50-70m (Figs 2, 4). The site covers c. 2600 km^2 of seabed, located close to the estimated line of maximum extent of the last coalesced North Sea icesheet (Sejrup et al., 2005; Bradwell et al., 2008; Ballantyne, 2010; Hughes et al., 2016; Emery et al., 2019) (Fig. 2). This area experienced rapid variations in icesheet and meltwater dynamics at the end of the last glacial maximum as the climate began to warm and the icesheet began to break apart and destabilize (Hjelstuen et al., 2018; Phillips et al., 2018; Ottesen et al., 2020). Sørlige Nordsjø II therefore represents an important study area for developing a detailed understanding of how the dynamics of the last North Sea ice sheet(s) influenced depositional environmental changes and heterogeneities in soil properties on the North Sea Plateau.

The North Sea Plateau is the term used to describe the shallow parts of the North Sea outside of the Norwegian Channel. In contrast to the Norwegian Channel, the North Sea Plateau was mainly influenced by passive ice, and smaller, less deeply erosive ice streams than the Norwegian Channel Ice Stream (e.g., Graham et al., 2011; Sejrup et al., 2016; Gandy et al., 2021). Being topographically higher than the Norwegian Channel, the North Sea Plateau also experienced a wider range of depositional environments relating to sea level changes during the Late Quaternary glacial and interglacial periods (e.g., Emery et al., 2019a; Andresen et al., 2022; Özmaral et al., 2022; Fleischer et al., 2023). At Sørlige Nordsjø II, these changes are apparent in the range of sedimentary facies present, spanning glacitectonized deposits from before the last interglacial period, to marine sands from the last interglacial period, glacilacustrine, glacimarine and outwash plain deposits from the end of the last glaciation and post-glacial fluvial to marine deposits. The Sørlige Nordsjø II area is also of particular geological interest because it is located immediately north of the Dogger Bank-Jutland Bank gap (Fig. 2), which represented perhaps the only gateway between early post-glacial depositional systems south and north of the Dogger and Jutland Banks.

Summary of Papers

In this section, the main contributions from this research are presented through short summaries of the papers contained within the thesis.

Article 1: A conceptual geological model for offshore wind sites in former ice stream settings: the Utsira Nord site, North Sea

The aim of this article is to present a preliminary conceptual geological model for the Utsira Nord floating offshore wind site that combines an overview of previous knowledge about the complex ice streaming history of the Norwegian Channel with key observations from bathymetric data, legacy conventional 2D seismic data, high-resolution sub-bottom profiles and shallow cores from surrounding areas of the channel.

Large-scale geomorphological features related to ice-stream erosion and deposition were interpreted from a bathymetric map of the North Sea from the Olex AS single beam echosounder database. Smaller-scale features including pockmarks, boulders and iceberg plough marks were interpreted from the Norwegian Mapping Authority's 2018 Sea Terrain Model. The seabed reflection and base of glacial erosion within the Norwegian Channel were interpreted on conventional legacy 2D seismic surveys ST8201 and NPD-KYST-96 acquired from the DISKOS repository. The interpreted surfaces were depth converted and used to generate a thickness map of the Quaternary sedimentary infill of the Norwegian Channel in the Utsira Nord area. Five sub-bottom profiles acquired in 2012 by the University of Bergen were investigated to identify key seismic facies within the upper 50 m of the Norwegian Channel sedimentary infill. These facies were compared to sub-bottom profiler facies in other ice stream infills and other parts of the Norwegian Channel presented in literature, and to sedimentary facies within shallow cores in other parts of the Norwegian Channel. The estimated distribution and thickness of the facies were used to inform the conceptual geological model and accompanying geotechnical risk maps for the Utsira Nord site, highlighting areas with potentially challenging conditions for floating offshore wind anchors.

The conceptual geological model presented defines four main geotechnical units at the Utsira Nord site: (1) exposed glacimarine to marine sediments suitable for suction-type anchors, (2) buried to exposed subglacial traction tills largely suitable for suction-type anchors, (3) buried lodgement till with highly uncertain properties and probably boulders, (4) shallowly buried to exposed crystalline bedrock, which is estimated to form c. 10% of the site and which would require a pile-based anchoring solution.

The model serves as a basis for planning site surveys at Utsira Nord and as a reference for offshore wind sites on other formerly glaciated coasts where ice streaming has been an important land-forming process, such as the northern coastlines of North America and the UK. The study also demonstrates a method that can advance conventional desktop studies towards a more cross-disciplinary and powerful tool for understanding the key geological risks and uncertainties at new offshore wind sites, even with limited data availability.

Article 2: An integrated geological characterization of the Sørlige Nordsjø II offshore wind site, southern North Sea

The objectives of this paper are to build on the existing lithostratigraphic and geotechnical frameworks of the southern North Sea by integrating the results of the marine geological study of the Sørlige Nordsjø II (SNII) offshore wind site with a review of existing geological and geotechnical investigations from SNII and the wider southern North Sea. A preliminary ground model for SNII is presented, which divides the site into two geotechnical provinces and five seismic-based geological units and associated subunits, with contrasting geotechnical properties. An accompanying "risk map", highlighting the key potential geohazards and geotechnical challenges for offshore wind foundation design and installation at the site, is also presented. The contribution also provides a relatively broad overview of the Late Quaternary geology of the southern North Sea and its associated geotechnical properties and potential geohazards for offshore wind foundation installation.

900 km of sub-bottom profiler data was acquired from SNII, converted from raw to SEG-Y files and interpreted using seismic interpretation software. The five defined seismo-stratigraphic units were interpreted with the aid of geomorphic observations from legacy 3D seismic data and comparison to sedimentary facies and multi-sensor core logs from 13 vibrocores and a geotechnical report for a borehole in the southern part of the site.

The preliminary ground model and risk map for the site outlines five main geological units: 1) homogeneous and layered marine sands covering most of the site, with patchy distribution and coarser-grained deposits in the east, 2) buried, layered channel deposits containing organic material and possible associated shallow gas, 3) buried, stiff glacilacustrine clay deposits, 4) a buried, layered, glacitectonized unit incised by tunnel valleys, with a sandy marine infill, and 5) mounded glacial tills and glacitectonized deposits containing boulders, exposed to shallowly buried in the east. Overall, the predominantly sandy shallow stratigraphy within the western part of SNII is likely to be a generally good substrate for any foundation type, though the predominant soil types within the deeper parts of the eastern part of the site are highly uncertain. There are a number of zones which represent potential risks to foundation stability and successful installation of different foundation types including zones affected by salt diapirism and possible gas migration, the eastern area characterized by glacial tills and very coarse marine deposits and the heterogeneities represented by thick localized occurrences of units 2, 3 and 4.

The study demonstrates how the integration of legacy 3D seismic data with high-resolution 2D sub-bottom profiles and shallow sediment cores can be a powerful preliminary method for mapping out geotechnical risks and uncertainties at offshore wind sites in previously glaciated marine areas. It also highlights the importance of the SNII area for understanding the break-up and retreat of the Late Weichselian icesheets.

Article 3: Integrating geological, geophysical, and engineering considerations in buried glacial landscapes: Case studies from the North Sea

The aims of this contribution are to investigate 1) the broad relationships between ground conditions and offshore wind foundation design in the North Sea basin, 2) how a better understanding of late-glacial to post-glacial processes can contribute to more efficient offshore wind site characterization workflows and 3) to define provinces within in the North Sea representing areas with similar broad-scale end-member ground condition characteristics.

The different guidelines, methods and workflows for evaluating the ground conditions at offshore wind sites are reviewed, focusing on how well the three fundamental components of subsurface understanding (geology, geophysics and geotechnical engineering) are integrated. Using the results from **Articles 1 and 2**, and additional case studies from several geologically different offshore wind sites in the North Sea, the geotechnical challenges to cost-effective design and installation of offshore wind turbine foundations in recently glaciated marine areas are discussed.

A simple categorization of the North Sea into four main provinces with similar overarching bathymetric and broad geological characteristics is proposed as a basis for preliminary data acquisition and foundation design strategies: 1) shallow coastal areas where Quaternary sediment cover is relatively thin, with shallow to exposed bedrock, 2) deep coastal areas formerly affected by major Quaternary ice streaming, where shallow bedrock is present locally and Quaternary sediments are predominantly clay-rich (the Norwegian Channel), 3) the moderately deep, predominantly sandy North Sea Plateau, characterized by multi-generational buried tunnel valley systems and heterogeneous terrestrial to shallow marine deposits and 4) the Dogger Bank-Jutland Bank zone, a region of particularly strong glacitectonism and highly heterogeneous soil properties correlating to the maximum position of the last North Sea icesheet.

The investigation found that current data acquisition standards for offshore wind sites do not give enough weight to certain data types such as sedimentary facies data from cores, which in glacially-influenced deposits give crucial insights into the processes which have influenced the geotechnical log signatures on which ground models are largely based. A more geologically integrated approach to ground modelling and site characterization therefore has the potential to improve the predictability of geotechnical variations through relatively low cost changes, such as more emphasis on long sediment core acquisition.

Article 1: A conceptual geological model for offshore wind sites in former ice stream settings: the Utsira Nord site, North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

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A conceptual geological model for offshore wind sites in former ice stream settings: the Utsira Nord site, North Sea

Hannah E. Petrie[1]*, Christian H. Eide[1], Haflidi Haflidason[1] and Timothy Watton[2]

[1] Department of Earth Science, University of Bergen, Allégaten 41, Bergen 5007, Norway
[2] Equinor Energy ASA, PB 8500, Stavanger 4035, Norway
HEP, 0000-0002-1632-9260
* Correspondence: hannah.petrie@uib.no

Abstract: Conceptual geological models of the shallow subsurface that integrate geological and geotechnical information are important for more strategic data acquisition and engineering at offshore wind sites. Utsira Nord is an offshore wind site in the Norwegian North Sea suitable for floating turbines, with an average water depth of 267 m. It covers a 23 × 43 km^2 area within the Norwegian Channel, a trough formed by repeated ice streaming. The goal of this study is to present a preliminary conceptual geological model for the site that combines an overview of previous knowledge about the ice streaming history of the Norwegian Channel with key observations from bathymetric data, 2D acoustic data and shallow cores. Despite limited data, four units with different geotechnical properties can be defined: (1) exposed glacimarine to marine sediments; (2) buried to exposed subglacial traction till; (3) buried lodgement till; (4) shallowly buried to exposed crystalline bedrock. The model serves as a basis for planning site surveys at Utsira Nord and as a reference for offshore wind sites on other formerly glaciated coasts where ice streaming has been an important land-forming process, such as the northern coastlines of North America and the UK.

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Much work has been done to advance our understanding of the Quaternary geology of the North Sea (e.g. Caston 1979; Jansen *et al.* 1979; Sejrup *et al.* 1994, 1995, 2000, 2003, 2016; Haflidason *et al.* 1998; Nygård *et al.* 2005; Lekens *et al.* 2009; Ottesen *et al.* 2016; Phillips *et al.* 2017; Becker *et al.* 2018; Morén *et al.* 2018; Bradwell *et al.* 2021) and the resulting geotechnical conditions for the anchors and foundations of oil and gas platforms (Bjerrum 1973; Amundsen *et al.* 1985; Foged 1987; Thomas 1990; Butenko and Østmo 1991; Ramsey 2002; Prins and Andresen 2021) and bottom-fixed offshore wind turbines (Le Bot *et al.* 2005; Merritt *et al.* 2012; Le *et al.* 2014; Cotterill *et al.* 2017; Emery *et al.* 2019; Cartelle *et al.* 2021). However, the application of this knowledge for floating offshore wind (FOW) technology is still a relatively new field of study. Compared with offshore oil and gas installations, offshore wind turbines require a different set of geotechnical design considerations. On offshore wind farms, turbines are installed in greater numbers, cover much larger areas and are subjected to different loads by the wind and waves (Le *et al.* 2014; Ellery and Comrie 2019). This means that further work on the specific interactions between offshore wind anchors and the soil into which they are embedded is urgently required as part of the targeted research into mooring solutions recommended by Wind Europe (2018) to reduce the cost of FOW. A detailed geological understanding of the foundation and anchoring conditions within new market areas will be an important component of this area of research (Velenturf *et al.* 2021).

Although design methods and procedures for offshore wind infrastructure continue to develop and improve, the learning process for geotechnical site investigation for offshore wind has often been hampered by lack of a 'design-team-led' approach to planning, undertaking and reviewing site investigations (Muir Wood and Knight 2013). This has led to problems such as site surveys being carried out with insufficient understanding of the geological setting, which are not tailored to mitigate the site-specific geotechnical hazards. Other site surveys did not meet the requirements of the foundation designers, who were brought in too late in the development process to influence the survey scope.

The Norwegian North Sea is a new area for the development of offshore wind but is already a mature oil and gas province with publicly available 2D and 3D seismic datasets. Although the resolution of most of these data is too low to be used for geophysical site surveying for offshore wind foundations and anchors, it gives developers the opportunity to gain a good understanding of the geological setting of a site in the early phases of the project; an opportunity often lacking in new offshore wind areas. The two Norwegian sites (both covering areas >1000 km^2) were officially open to bids as of the beginning of 2021, although the bidding process remains in development. The subject of this study is the Utsira Nord site (Fig. 1), located 30 km off the western coast of Norway in the *c.* 270 m deep waters of the Norwegian Channel. The site will be developed as Norway's first large-scale FOW park, covering an area of 1010 km^2. The Norwegian Government intends to divide the site into up to four development areas, which are going through a public hearing process at the time of writing (Norwegian Ministry of Petroleum and Energy 2022). It remains undecided as to when the concession process for developers will begin.

The area in which Utsira Nord is located has a complex geological history of repeated ice stream activity and sediment transport linked to the waxing and waning of the Scandinavian Ice Sheet (SIS) during the last 1.1 myr (Sejrup *et al.* 1994, 1995, 2003, 2005; Nygård *et al.* 2005; Hjelstuen *et al.* 2012, 2018; Reinardy *et al.* 2017). Ice stream activity has also had an impact on marine ground conditions in other previously glaciated regions with good wind resources (Fig. 2), such as the coastlines of Canada (Winsborrow *et al.* 2004), the northeastern USA (McClennen 1989; Shaw *et al.* 2006), the northern UK (Gandy *et al.* 2019), the Atlantic coast of Ireland (Small *et al.* 2018) and the Irish Sea (Mellet *et al.* 2015; Coughlan *et al.* 2020). Understanding the geological and geotechnical heterogeneities of the seabed and shallow subsurface in previously glaciated areas therefore has important

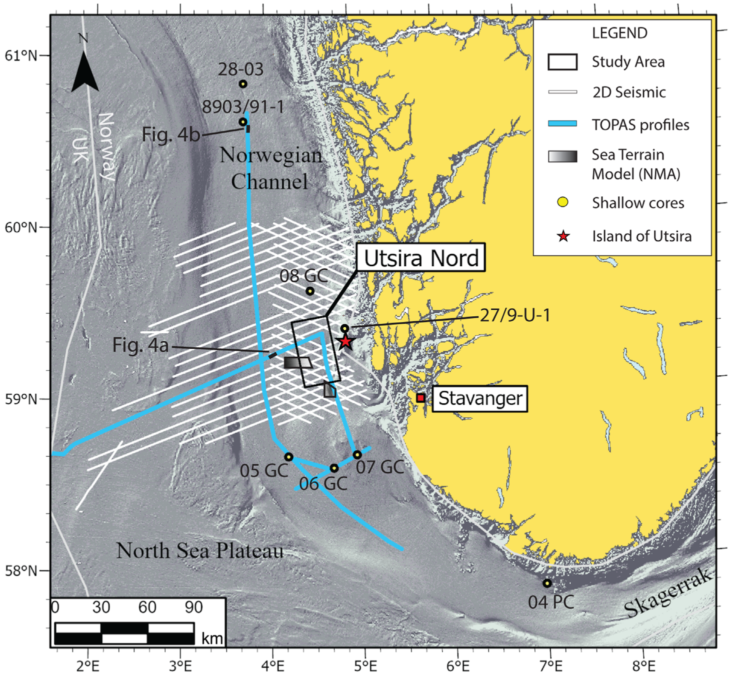

Fig. 1. Bathymetric hill-shaded map of the Norwegian North Sea (www.olex.no) showing the location of the Utsira Nord site, and the dataset used in this study. The site is partly covered by the Norwegian Mapping Authority (NMA) 5 m resolution Sea Terrain Model (Norwegian Mapping Authority 2018); however, the data within 12 nautical miles from the coastline cannot be shown for coastal security reasons. TOPAS acoustic profiles and gravity or piston cores (05-GC to 08-GC, 04-PC) were acquired on a University of Bergen cruise in 2012 (Hjelstuen *et al.* 2018; Morén *et al.* 2018). The 2D seismic surveys (ST8201 R90 and R92) are sourced from the DISKOS repository. Piston core 28-03 and drilled core 8903/91-1 are reference cores for the sedimentary infill of the Norwegian Channel (Sejrup *et al.* 1994, 1995; Klitgaard-Kristensen *et al.* 1998). Drilled core 27/9-U-1 penetrates Jurassic sedimentary bedrock east of Utsira Nord (Rokoengen and Sørensen 1990).

implications for designing safe and cost-effective offshore wind foundations and anchors in these regions.

The goal of this paper is to present a preliminary conceptual geological model for the Utsira Nord site, which combines an overview of previous knowledge about the complex ice streaming history of the Norwegian Channel with key observations from bathymetric data, 2D seismic data and sub-bottom profiles covering the site, and shallow cores from the surrounding area. We demonstrate a method that can advance conventional desktop studies towards a more cross-disciplinary and powerful tool for understanding the key risks and uncertainties in the ground conditions at new offshore wind sites. Despite limited data coverage, this method allows four main units with different geotechnical properties at the Utsira Nord site to be defined:

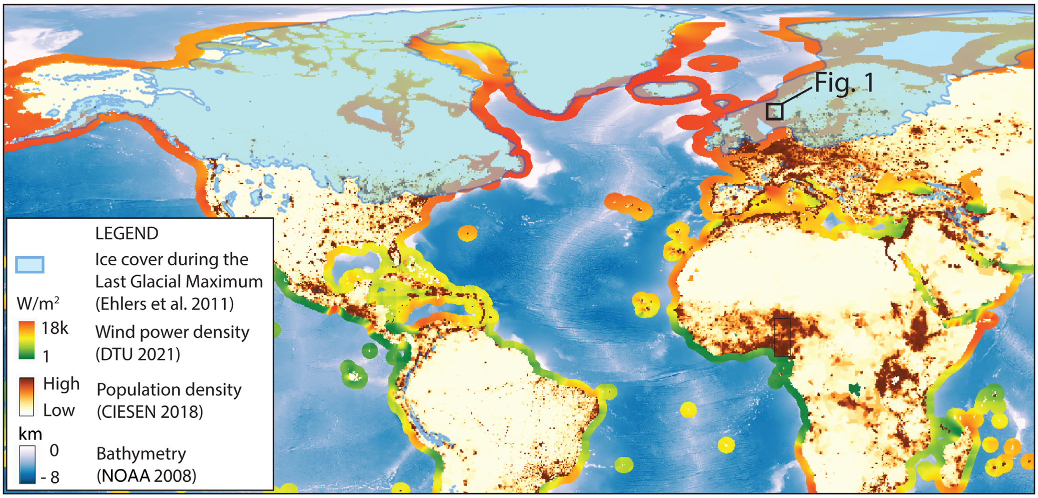

Fig. 2. Ice extent map for the Last Glacial Maximum (*c.* 20 ka) (Ehlers *et al.* 2011), showing how the ground conditions along many northern hemisphere coastlines have been affected by glacial processes during this period. This has been superimposed upon the global distribution of wind resources (wind power density at 100 m from DTU 2021) and world population density (CIESIN 2018) to give an overview of coastlines where offshore wind development is likely (where there are good wind resources and a large market for electricity) and where the ground conditions for such developments are likely to have similarities to those at the Utsira Nord site. Background bathymetry is from ETOPO1 Global Relief Model (NOAA 2008).

(1) exposed glacimarine to marine sediments ('soft' marine clays, silts, sands and gravels) suitable for suction-type anchors; (2) buried to exposed subglacial traction till ('soft' glacial clays, silts, sands and gravels) suitable for suction-type anchors; (3) buried lodgement till (glacial clays, silts, sands and gravels, and boulders) of uncertain geotechnical character; (4) shallowly buried to exposed crystalline bedrock, which would require a pile-based or novel anchoring solution were it to be developed. The model is intended as a starting point for the development of a 'ground truth' model of the site and summarizes the geotechnical properties and design challenges anticipated at the site. This can serve as a basis for planning geotechnical and geophysical site survey activities at the Utsira Nord site, and as a useful reference for offshore wind sites on other formerly glaciated coasts where ice streaming has been an important land-forming process.

Geological background

The North Sea

The North Sea is an epicontinental shelf of 50–400 m water depth, located between the UK, Scandinavia and the northern coastlines of Germany and the Netherlands. During the Cenozoic, the North Sea formed a wide depocentre along the axis of the Central and Viking grabens in which up to *c.* 3 km of sediments were deposited (Gatliff *et al.* 1994). These sediments were sourced from erosion of the landmasses on both sides of the North Sea, which were uplifted during two main phases (Faleide *et al.* 2002; Huuse 2002; Anell *et al.* 2012): (1) late Paleocene to early Eocene uplift related to the break-up of the NE Atlantic and the Iceland plume; (2) the Plio-Pleistocene isostatic response to glacial erosion during the Northern Hemisphere glaciations.

During the Quaternary period (<2.6 Ma), the Northern European landmasses experienced repeated glaciations (e.g. Ehlers *et al.* 1984; Dahlgren and Vorren 2003; Ehlers and Gibbard 2004; Sejrup *et al.* 2005; Lee *et al.* 2012). Across large areas of the North Sea, regional seismic profiles show evidence of extensive glacial erosion in the form of flat-lying Pleistocene beds and incised channels that truncate Upper Pliocene clinoforms and the lower part of the Pleistocene sequence (Sejrup *et al.* 1991; Eidvin *et al.* 2000; Graham *et al.* 2011). Previously, it was believed that widespread ice coverage in the North Sea basin did not occur until the Mid-Pleistocene (50 000 years ago) with the onset of the three major glaciations (the Elsterian, Saalian and Weichselian) recorded in the Pleistocene sedimentary record by generations of infilled subglacial tunnel valleys (Cameron *et al.* 1987; Wingfield 1989, 1990; Ehlers and Wingfield 1991; Praeg 2003; Graham *et al.* 2011). However, evidence from 3D seismic data on the Mid-Norwegian continental shelf indicates a glacial influence in the Norwegian Sea as far back as 2 myr ago, with glacial lineations indicative of grounded ice in the region dating back to 1.5 Ma (Ottesen *et al.* 2009). In the North Sea, more recent studies such as that by Rea *et al.* (2018) that integrate 3D seismic data, climate modelling, and core and wireline log data present evidence for spatially extensive glaciations in the North Sea from the earliest Pleistocene (2.53 Ma) with a merging of the SIS and British–Irish Ice Sheet (BIIS) probably as early as 1.87 Ma.

After *c.* 1.0 Ma, the Quaternary climate cycles became more intense, resulting in more extensive glaciations and warmer interglacial periods (Ruddiman *et al.* 1986; Jansen *et al.* 1990, 2000; Shackleton *et al.* 1990). Glacial landforms mapped on bathymetric data and information from sediment cores indicate that the SIS, the BIIS and the Barents Sea–Kara Ice Sheet eventually merged at 160–140 ka and again during the Late Glacial Maximum (LGM) at *c.* 20 ka, encompassing a large marine area from Svalbard to Ireland (Ehlers and Gibbard 2004; Svendsen *et al.* 2004; Sejrup *et al.* 2005; Lee *et al.* 2012; Hughes *et al.* 2016). The precise timing of when the SIS and BIIS were in confluence in the central North Sea during the LGM has been variously proposed as having occurred between 31 and 24 ka (Sejrup *et al.* 1994, 2009, 2015; Bradwell *et al.* 2008; Ehlers and Gibbard 2008; Toucanne *et al.* 2009), 23 and 18.5 ka (Sejrup *et al.* 2016) and 25.5 and 18.7 ka (Becker *et al.* 2018). The last is based on a sharp drop in accumulation rates measured in sediment cores along the North Sea margin, which Becker *et al.* (2018) attributed to the onset of confluence of the SIS and BIIS cutting off the sediment supply from the south. Within the merged SIS–BIIS ice sheet, along the south and southwestern coasts of Norway, an *c.* 200 km wide zone of fast-flowing ice known as the Norwegian Channel Ice Stream (NCIS) formed (Ottesen *et al.* 2016), although the precise onset of the ice streaming remains unclear. Repeated ice streaming events eroded the underlying bedrock to form the 850 km long, 200–700 m deep Norwegian Channel in which the Utsira Nord site is located (Fig. 1). The oldest known sedimentary deposit within the channel, sampled above the giant gas field Troll in the northern part of the channel (sediment core 8903/91-1) is a glacial deposit dated to 1.1 Ma, named the Fedje till, which is directly superimposed on top of truncated Oligocene strata (Sejrup *et al.* 1995). Glacial debris flows at the mouth of the Norwegian Channel located at the North Sea shelf edge indicate that the NCIS was active at least five times between 0.5 Ma and *c.* 18 ka (King *et al.* 1996; Sejrup *et al.* 2003; Rise *et al.* 2004; Nygård *et al.* 2005). Becker *et al.* (2018) suggested that the latest phase of ice streaming may have been restricted to between 23.3 and 19 ka, on the basis of a new provenance interpretation of the oldest Late Weichselian Ice Rafted Debris (IRD) interval cored on the North Sea Fan. This was previously interpreted as having been sourced from ice streaming in the Norwegian Channel at *c.* 27 ka (Nygård 2003), but may instead have a BIIS or Laurentide icesheet provenance (Becker *et al.* 2018). The following three IRD intervals appear to have the same provenance as one another and are thought to represent 1500 years of ice streaming after 23.5 ka, followed by several hundred years of still-stand and then one or two further advances between 21 and 17.4 ka.

The initial deglaciation and break-up of the NCIS, initiated by an increased rate of ice streaming (Nygård *et al.* 2007), started between 19 and 18.7 ka at the North Sea shelf edge, retreating to the inner part of the Skagerrak by 17.6 ka (Morén *et al.* 2018). This resulted in the eventual thinning and decoupling of the merged SIS–BIIS icesheets at 18.7 ka, inferred from sedimentary and isotopic indications of a rapidly deposited meltwater plume on the Mid-Norwegian margin (Lekens *et al.* 2005; Becker *et al.* 2018; Hjelstuen *et al.* 2018). After this, warm coastal currents began to occupy the Norwegian Channel (Sejrup *et al.* 1994; Haflidason *et al.* 1995, 1998), with some periodic ice input from the fjords during minor readvances of the SIS (Mangerud *et al.* 2011). Sea-level rose rapidly, and fine-grained marine sediments (98% clay to silt in core 28-03, Fig. 1, Klitgaard-Kristensen *et al.* 1998) were deposited at relatively high rates (220 g cm^{-2} ka^{-1} between 15 and 13 ka, Haflidason *et al.* 1998), with occasional coarser input from calved ice. Until 10 ka, the climate remained relatively unstable. Ice retreat was occurring rapidly in the fjords and on the Scandinavian landmass, resulting in continuing high sedimentation rates in the fjords and the Norwegian Channel (Nesje *et al.* 1991; Nesje and Dahl 1993). After 9 ka, the deglaciation was largely over and marine sedimentation rates in the channel became much lower (4 g cm^{-2} ka^{-1}, Haflidason *et al.* 1998). The thickest Holocene sediments (up to 50 m thickness, Morén *et al.* 2018) are found along the western margin of the channel, fed from the North Sea Plateau, and along the eastern margin of the channel offshore western Norway, fed from the western fjords.

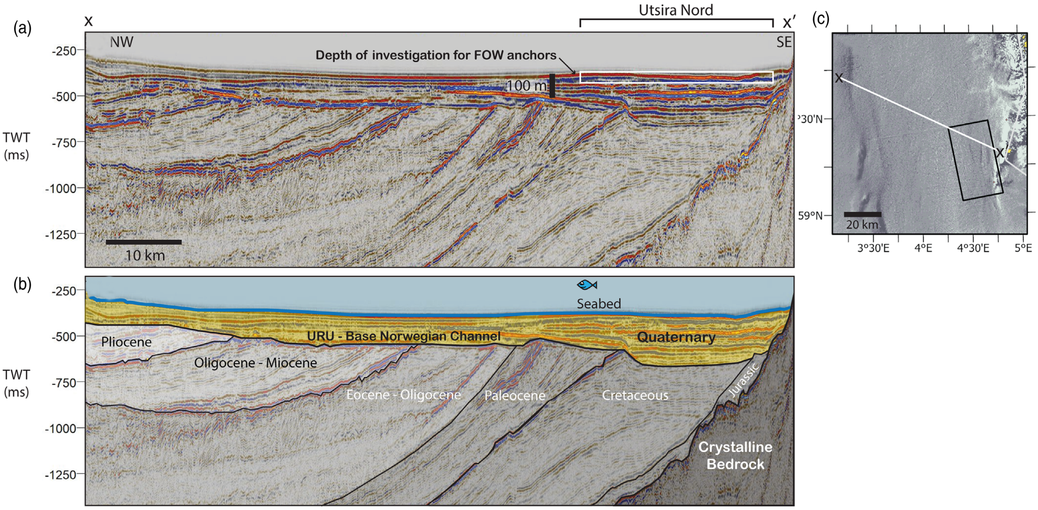

Fig. 3. (**a**) Regional 2D seismic section (x–x') across the Norwegian Channel from survey ST8201 R90 (Line ST-8201-442-955.6398) showing two-way travel time in milliseconds (ms) and depth (m) for the Norwegian Channel late Quaternary infill and standard depth of investigation for FOW anchor site surveys. (**b**) Interpreted 2D seismic section (x–x') showing outcropping crystalline bedrock along the eastern boundary of the Norwegian Channel, subcropping Mesozoic to Cenozoic sedimentary bedrock along the base of the Norwegian Channel and the late Quaternary infill of the channel. (**c**) Location map for profile x–x' on Olex bathymetry.

Seismic stratigraphy and lithostratigraphy of the Norwegian Channel

The base of the Norwegian Channel is defined by an erosion surface known as the Upper Regional Unconformity (URU) (e.g. Sejrup *et al.* 2000; Ottesen *et al.* 2014), which truncates westward-dipping Mesozoic and Cenozoic sedimentary rocks (Fig. 3). The overlying Quaternary sediments are generally flat-lying and extensive, often with bases that truncate the older channel sediments (Sejrup *et al.* 1995). The term glacial till is used to describe sediments that have been transported and then deposited by a glacier, ice sheet or ice stream (Dreimanis and Lundquist 1984). These sediments tend to

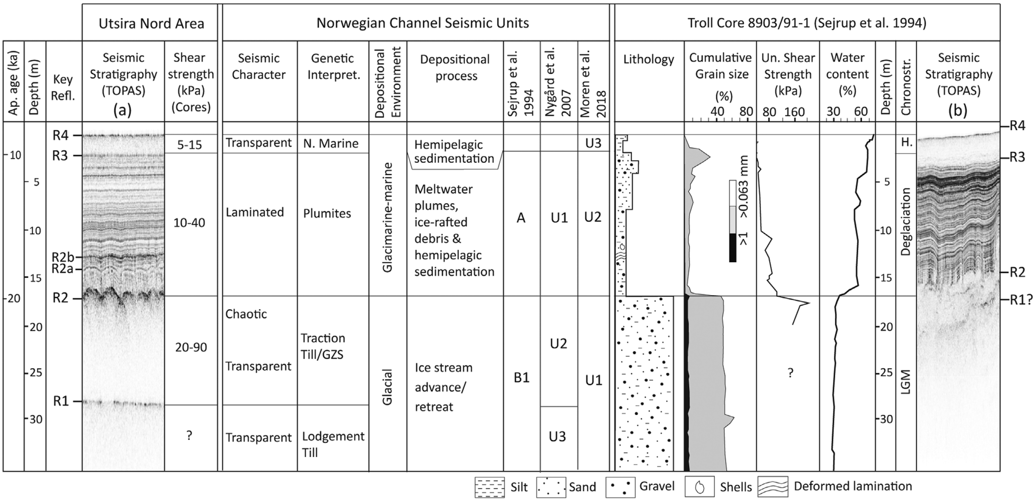

Fig. 4. (**a**) Summary of the seismic units defined in previous studies of the Norwegian Channel sedimentary infill, tentatively correlated to TOPAS acoustic data west of Utsira Nord (Fig. 1), where a more complete stratigraphy is present than within the site itself. Previously, three broad genetic units (glacial, glacimarine and marine) have been defined, based on the acoustic character of the sediments. Shear strength ranges for each of these units measured in gravity cores 50 km south of Utsira Nord are shown to the right of the TOPAS data. (**b**) On the right side of the figure, the reference core for the Norwegian Channel fill (8903/91-1), located 100 km north of Utsira Nord, is adapted from Sejrup *et al.* (1994) to show the key sedimentological and physical characteristics of the genetic units. TOPAS data from a few kilometres south of the Troll core are shown on the far right (TOPAS data quality at the Troll core location is poor). Ap. age, approximate age; Refl, reflections; Interpret, interpretation; N. Marine, Normal marine; Un. Shear strength, undrained shear strength; Chronostr, chronostratigraphy; H, Holocene; LGM, Last Glacial Maximum.

contain a mixture of clay, silt and coarser rock fragments ranging from sand and gravel to boulder size. Units of till that are associated with a particular morphological deposit (e.g. from the sides or front of the glacier) are described as moraines (e.g. lateral moraine, terminal or end moraine). Off western Norway, the Norwegian Channel fill consists of repeated glacigenic sequences comprising till (10–50 m thick) overlain by finer grained glacimarine and marine sediments (Sejrup *et al.* 1996). Commonly, the sequences can comprise several generations of till, glacimarine or marine sediments (Sejrup *et al.* 1996, 2003; Rise *et al.* 2008). The number of preserved sequences decreases southwards towards the south-eastern part of the channel known as the Skagerrak (Fig. 1), where only the youngest sequence is preserved (von Haugwitz and Wong 1993). The key geotechnical parameters of the Norwegian Channel tills, glacimarine and marine sedimentary units from gravity cores south of the Utsira Nord site and from the Troll reference core north of the site are defined in Figure 4 and will be further explored within the Results and Discussion sections of this paper.

In previous studies, the upper *c.* 50 m of the Norwegian Channel sedimentary infill has been subdivided into two to three main acoustic units, based on high-resolution sub-bottom profiler (TOPAS) data correlated to shallow sediment cores (Fig. 4) (Sejrup *et al.* 1994; Nygård *et al.* 2007; Morén *et al.* 2018). The lowermost unit, interpreted as glacial till, is acoustically homogeneous except for an internal reflection mapped 5–40 m below the top of the unit (R1 in Fig. 4). This internal reflection is mostly found in the outer parts of the Norwegian Channel. Sejrup *et al.* (1994) and Morén *et al.* (2018) grouped the till above and below this reflection into one unit (Unit B1 and Unit U1 respectively), whereas Nygård *et al.* (2007) divided the till into two units (U3 and U2) (Fig. 4). Based on studies of ice stream systems in Antarctica (Ó Cofaigh *et al.* 2007; King *et al.* 2009; Reinardy *et al.* 2011), Morén *et al.* (2018) proposed that the internal reflection that defines the upper and lower parts of the till represents a boundary between a softer upper till (traction till), affected by the most recent ice stream deformation, and a lower, overconsolidated till (lodgement till) that progressively became buried deeply enough to avoid further deformation. The strong reflection that defines the top of the till (R2 in Fig. 4) is generally highly irregular owing to glacial erosion and deformation. Where it has been exposed at the seabed during the last deglaciation, R2 is less distinct and is highly disturbed by iceberg ploughmarks. The base of the till is not generally observed on sub-bottom profiler data owing to limited penetration depth; however, the shallowest till unit within the Troll core off western Norway (Sejrup *et al.* 1995) has a thickness of 57 m. Further south in the Skagerrak (Fig. 1), this till has been found to be thinner, around 30 m thick, and deposited directly on Mesozoic bedrock rather than older till layers (Bøe *et al.* 1998). Except for the Troll core, which penetrates *c.* 220 m through several sequences of tills, very few cores have penetrated the upper till unit in the Norwegian Channel. Those that do have sampled only the upper few metres of the till. Based on the limited core data available (05-GC to 08-GC, 04-PC, Fig. 1), the upper part of the till appears to consist mainly of dark grey, fine-grained sediments, with occasional sand and silt lenses and laminae, and gravel- to cobble-sized clasts. It also exhibits deformational structures, such as shear planes and zones

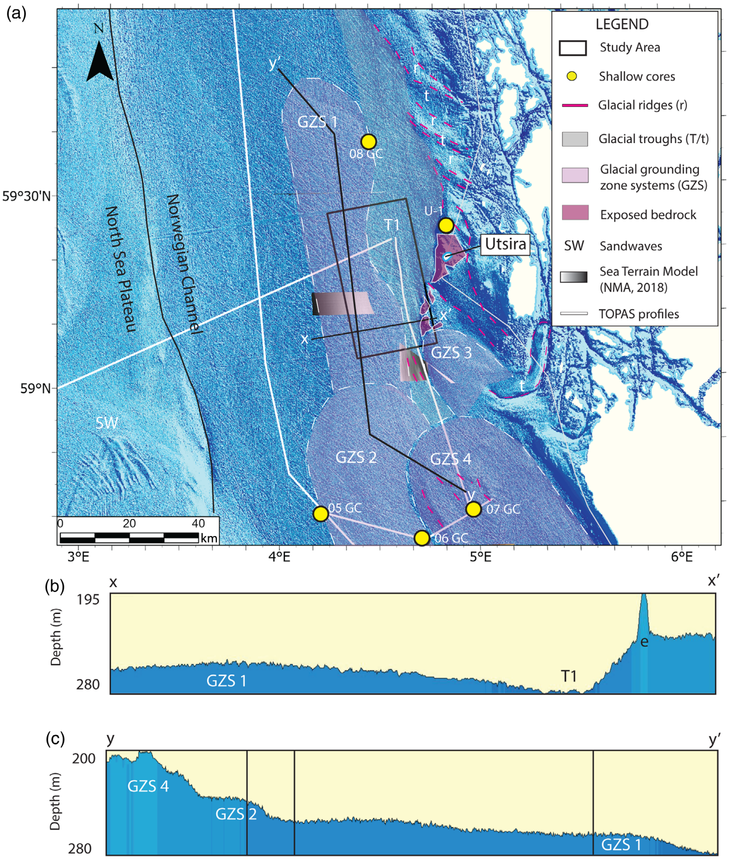

Fig. 5. (**a**) Olex bathymetric map of the Utsira Nord site and surrounding area showing interpreted geomorphological features. Glacial ridges and troughs are also interpreted on the NMA Sea Terrain Model (Norwegian Mapping Authority 2018) just south of the site in pink stipple. (**b**) East–west bathymetric cross-section through GZS 1, trough (T1) and an exposed bedrock high (e) in the southeastern corner of Utsira Nord. (**c**) North–south bathymetric cross-section through GZSs 1, 2 and 4.

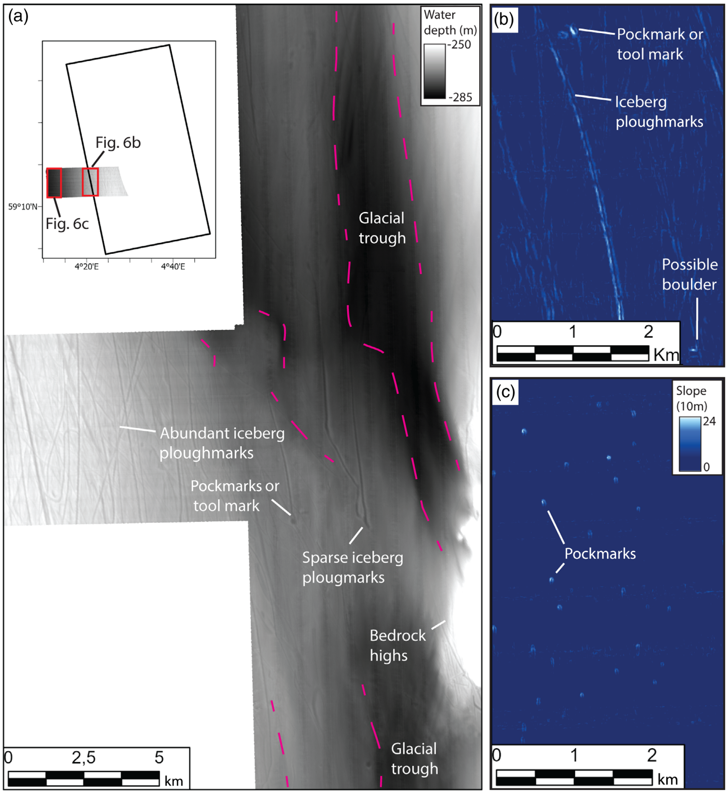

Fig. 6. (**a**) Annotated NMA Sea Terrain Model (Norwegian Mapping Authority 2018) showing glacial troughs and ridges (pink stipple), iceberg ploughmarks and pockmarks or tool marks in and around the Utsira Nord site (exact location cannot be shown owing to coastal security). In the top left corner, the locations of (**b**) and (**c**) are shown. (**b**) Slope map generated in ArcGIS from the Sea Terrain Model showing iceberg ploughmarks, a pockmark or tool mark and a possible boulder along the western side of the Utsira Nord site. (**c**) Slope map showing pockmarks several kilometres west of the Utsira Nord site.

(Morén *et al.* 2018). At the Troll field, the youngest till unit is a very homogeneous clay to silty clay which contains close to 30% sand and 2–3% coarse sand and gravel (Sejrup *et al.* 1995). Drilling and core recovery issues encountered during the collection of the core (Sejrup *et al.* 1995) also imply the presence of boulders or coarse, consolidated material within the tills encountered above the Troll field.

Topographic lows on the till surface, such as glacially eroded troughs, are commonly infilled by an acoustically laminated unit, which is in turn overlain by an acoustically transparent unit (defined respectively as U2 and U3 by Morén *et al.* 2018). In other studies, these units are grouped together as one (Unit A of Sejrup *et al.* 1994; Unit U1 of Nygård *et al.* 2007, Fig. 4). The laminated unit, interpreted as glacimarine sediments deposited rapidly by sediment-laden meltwater plumes during the last deglaciation, reaches maximum thicknesses of up to 100 m, but is generally 5–20 m thick off western Norway and 15–40 m thick off southern Norway (Morén *et al.* 2018). The transition from the underlying till into the laminated glacimarine sediments is correlated in sediment cores with a decrease in sand and coarse material and a marked decrease in undrained shear strength (Sejrup *et al.* 1994; Morén *et al.* 2018). The top of the laminated unit (R3, Fig. 4) is defined by a more regular and lower amplitude reflection than R2. The overlying acoustically transparent unit, interpreted as post-glacial marine sediment, drapes conformably over the laminated sediments, and is generally around 5–10 m thick off western Norway and 5–20 m thick in southern Norway, but can reach thicknesses up to 50 m. Although both the glacimarine and marine units generally consist of fine-grained sediments with occasional shell fragments, there is generally a change in grain-size distribution from the glacimarine to the marine unit. The nature of this change varies in different parts of the Norwegian Channel, with the marine sediments observed to be coarser than the glacimarine sediments off western Norway, whereas in the Skagerrak the marine sediments are observed to be finer than the glacimarine sediments (Morén *et al.* 2018).

Method

This study combines an overview of previous knowledge about the sedimentary infill of the Norwegian Channel with key observations from bathymetric data, 2D seismic data, sub-bottom profiles and shallow cores. Geological interpretations from the data were integrated to define a conceptual geological model for the Utsira Nord site, which is divided into units with contrasting forecast geotechnical properties and implications for FOW anchor design. Although the standard depth of subsurface investigation for seabed anchors today is *c.* 30 m, the model investigates the upper 50 m of the subsurface stratigraphy. This is to contribute towards a more complete understanding of the geological context of the site and to facilitate site investigation planning for possible pile-based anchoring designs that may require a larger depth of investigation. The estimated distribution and thickness of the units have been used to generate risk maps that highlight areas with challenging conditions for FOW anchors.

Data

Large-scale geomorphological features related to ice stream erosion and deposition were interpreted from a bathymetric map of the North Sea from the Olex AS single beam echosounder database

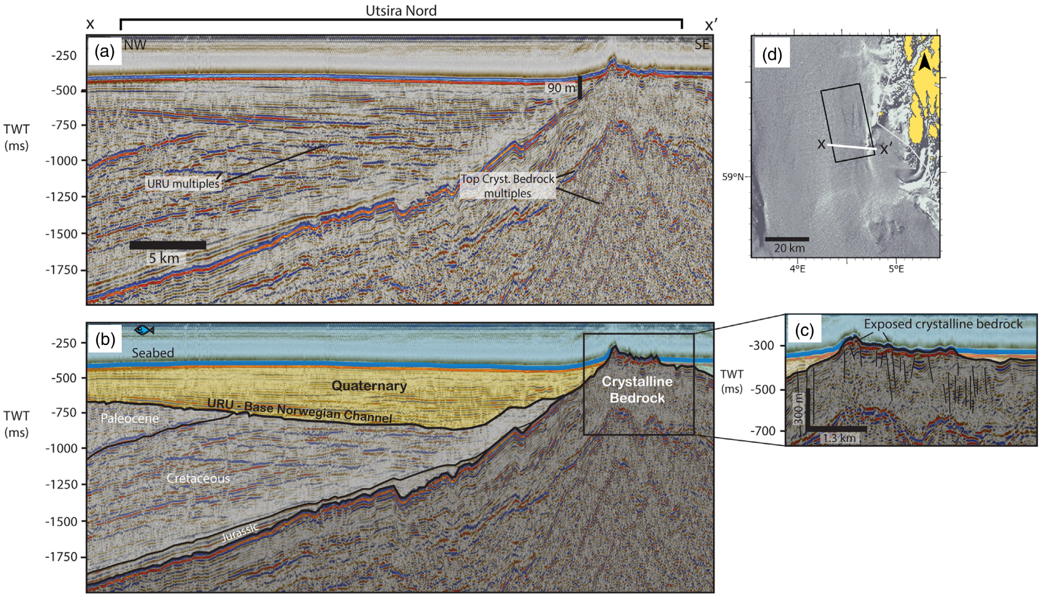

Fig. 7. (**a**) Two-dimensional seismic section (x–x’) across southern Utsira Nord from survey ST8201 R92 (Line ST-8201-436-46.2500). (**b**) Interpreted 2D seismic section (x–x’) showing outcropping and shallowly buried crystalline bedrock in the southeastern part of Utsira Nord. (**c**) Close-up view of the exposed bedrock with interpreted faults. (**d**) Location map for profile x–x’ on Olex bathymetry.

(Fig. 5). The resolution of the map varies spatially depending on the density of seafloor measurements from fishing and other vessels in a particular area. The data are gridded to 5 × 5 m; however, not every cell contains a datum point. Pockmarks, boulders and iceberg ploughmarks are therefore not generally distinguishable on the Olex map but were interpreted on the 5 × 5 m resolution Sea Terrain Model from multibeam echo-sounder data collected by the Norwegian Mapping Authority (2018), which cover part of the Utsira Nord site (Figs 1, 5 and 6a–c). These data were investigated to give an impression of whether pockmarks, boulders and iceberg ploughmarks might be common seabed features within the Utsira Nord site. Many of the data lie within 12 nautical miles of the Norwegian coast, such that their exact location cannot be shown for coastal security reasons. The parts of the data shown in Figures 1 and 5 are outside the 12 nautical mile zone.

Two-dimensional seismic data within the Utsira Nord site and greater Norwegian Channel region (Fig. 1) were sourced from DISKOS (The Norwegian National Data Repository for Petroleum Data) and include the surveys ST8201 (reprocessed surveys R90 and R92) and NPD-KYST-96, which have an estimated vertical resolution of 25–30 m within the shallow subsurface. The data quality was sufficient to allow interpretation of shallow seismic reflections within the Norwegian Channel, despite the presence of strong multiples of the seabed reflection and base Norwegian Channel reflection in ST8201 R92 (Fig. 7). The seabed reflection and the base of glacial erosion within the Norwegian Channel (the ‘Upper Regional Unconformity (URU)’ reflection) were interpreted using ST8201 and then depth converted using seismic velocities of 1500 m s^{-1} (average P-wave velocity for seawater) and 1800 m s^{-1} (based on the P-wave velocity of the Quaternary (Nordland Group) sediments encountered in exploration well 35/2-1 (Bellwald *et al.* 2020) respectively. In other parts of the North Sea, P-wave velocity estimates for the Quaternary sediments of the shallow subsurface vary between 1600 and 1750 m s^{-1} from geotechnical testing at Dogger Bank in the UK North Sea (Cotterill *et al.* 2017) and 1905 m s^{-1} from geotechnical testing in the Danish North Sea (Prins and Andresen 2021). Local geotechnical or geophysically derived velocity estimates from within the Utsira Nord site are required to reduce uncertainty in this regard. The resulting depth surfaces were used to generate a thickness map of the channel fill and to investigate the regional stratigraphy of the channel in the vicinity of the Utsira Nord site. The NPD-KYST-96 lines were not used to generate any seismic surfaces but were used to inform the seismic interpretation of the area by giving an insight into the seismic stratigraphy east of the Utsira Nord site, closer to the Norwegian mainland. Five sub-bottom profiles, acquired in 2012 by the University of Bergen using the Kongsberg Topographic Parametric Sonar (TOPAS) PS18 system (details of the cruise have been described by Hjelstuen *et al.* 2018), were investigated to identify key seismic facies within the upper 50 m of the Norwegian Channel sediment infill. Two of the profiles extend across the northern and eastern parts of the site and form the basis of our understanding of the seismic facies present within the site (Fig. 1). The TOPAS profiles have a vertical resolution of 25–30 cm, approximately 10 times finer than that of the 2D seismic data. The profiles were therefore used to interpret key reflections, acoustic facies and seabed features not visible on the 2D seismic profiles.

Four gravity cores and one piston core, all located at more than 15 km distance from the Utsira Nord site, were acquired in 2012 by the University of Bergen (the piston core 04PC is described by Morén *et al.* 2018) (Fig. 1). Sedimentological analyses and multi-sensor logging of the cores were integrated with seismic observations from the TOPAS profiles to interpret the depositional environment of each seismic facies identified. The core analysis presented in this study includes a short summary of the bulk densities, undrained shear strengths and grain-size distributions for cores 05-GC, 06-GC and 07-GC, which were considered most relevant for the facies present within Utsira Nord. The shallow core 27/9-U-1, north of Utsira (Fig. 1), acquired between 96 and 176 m below seabed as part of the SINTEF IKU shallow drilling project, was used to investigate the underlying Mesozoic sediments at the base of the Norwegian Channel within the site. These sediments were dated by Rokoengen and Sørensen (1990) to a Late Jurassic age. The overlying Quaternary sediments, however, were not cored or preserved as cuttings in that campaign. Core-logging as part of our study found that the sedimentary bedrock north of Utsira consists of unconsolidated to consolidated, fine-grained, shallow marine sand containing wood and shell fragments. However, as the formation occurs at depths greater than the depth of investigation for offshore wind anchors and foundations, the logs are not presented in this paper.

Results

Seabed geomorphology

The Utsira Nord site is characterized by a trough (T1) along its eastern side, where the water depths reach over 280 m, and a shallower, flatter area along its western side where the water depths reach over 250 m (Fig. 5a–c). The shallower area has a mounded geometry, with a curved, steeply dipping northern terminus north of the Utsira Nord site. This geomorphological expression is typical of a deposit of subglacial and pro-glacial sediments called a grounding zone system (GZS), which is a backstepping wedge of sediments deposited during the episodic retreat of an ice stream (e.g. Rüther *et al.* 2011). Several GZSs are interpreted in this part of the Norwegian Channel based on their elongated, mound-like bathymetry with curved, steeply dipping northerly termini (GZS 1-4, Fig. 5a and c). The shallower bathymetry along the western side of the Utsira Nord site (GZS 1) and a small part of the site in the SE (GZS 3) are therefore also interpreted as grounding zone systems. Trough T1 represents the deeper area of the seabed adjacent to the north–south-trending GZS 1. Lineations within the southern part of T1 are observed at the seabed on the NMA Sea Terrain Model (pink stipple, Fig. 5a), which are interpreted to indicate that T1 was probably deepened by glacial erosion.

A chain of rugged bathymetric highs (annotated as exposed bedrock in Figs 5a, b and 6a) is observed in the southeastern corner

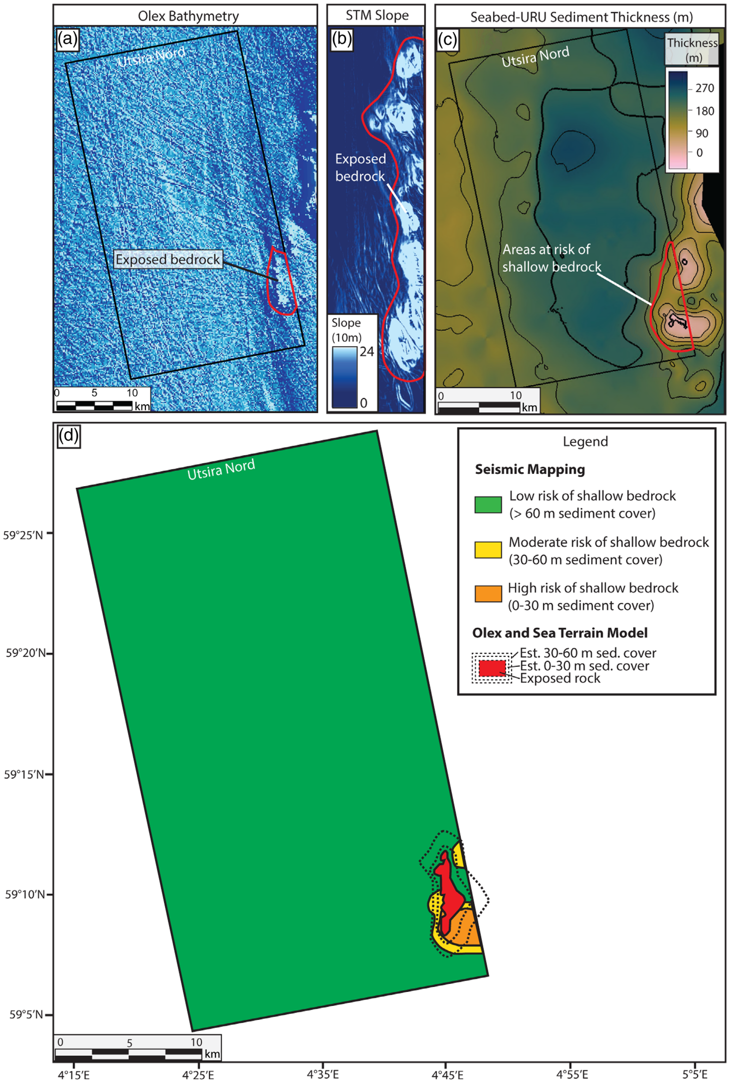

Fig. 8. (**a**) Olex bathymetric map showing zone of bedrock highs observed in the southeastern part of the site, interpreted as exposed crystalline bedrock. (**b**) A 10 m slope map generated in ArcGIS from the NMA Sea Terrain Model (Norwegian Mapping Authority 2018) showing a more detailed outline of part of the exposed bedrock in southeastern Utsira Nord. (**c**) Seabed–URU sediment thickness map, generated from the Seabed and Base Norwegian Channel (URU) reflections interpreted on 2D seismic survey ST8201, showing where Quaternary sediments are thin to absent in southeastern Utsira Nord. (**d**) Risk map for anchoring conditions, based on (**a**)–(**c**), showing where there is low, moderate or high risk of encountering shallow bedrock around the mapped bedrock exposures (estimates from seismic mapping are distinguished from estimates from bathymetric data in the legend). Est. sed. cover, estimated sedimentary cover. STM, Sea terrain model.

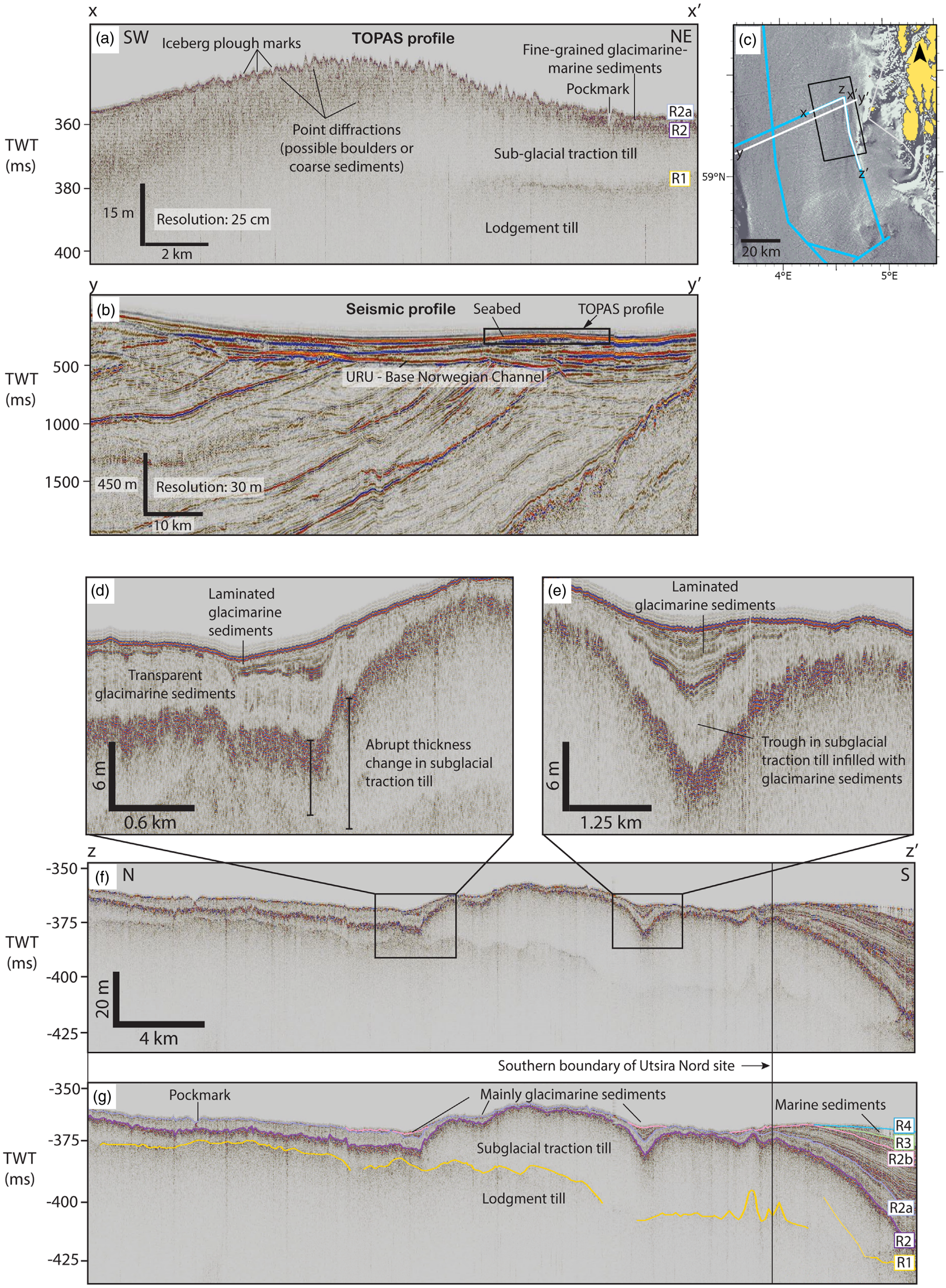

Fig. 9. (**a**) TOPAS profile x–x’ across the northern part of the Utsira Nord site showing key features distinguishable on high-resolution acoustic data compared with conventional 2D seismic profile y–y’. (**b**) Conventional 2D seismic profile y–y’ from survey ST8201 R92 (Line ST-8201-220-2804.9135). Location and depth of penetration of (**a**) is shown in the context of existing 2D seismic data available at the site. (**c**) Location map for profiles x–x’, y–y’ and z–z’ on Olex bathymetry. (**d**) Close-up section from profile z–z’ in (**f**) showing glacimarine sediment infilling a trough in subglacial traction till. (**e**) Additional close-up section of an infilled trough from profile z–z’. (**g**) Interpreted version of TOPAS profile z–z’ showing key reflections R1–R4 and the interpreted genetic units defined between them.

of the site and to the east of the site, the largest of which is the island of Utsira. Within the Utsira Nord site there are three main bathymetric highs, which increase in height southwards from 30 to 85 m above the surrounding seabed. Based on the bedrock geology of the island of Utsira, the highs located within the Utsira Nord site are interpreted as exposed crystalline bedrock comprising trondhjemites, gabbros, tonalites, peridotites and serpentinites termed the Utsira Complex (Ragnhildstveit *et al.* 1998).

East and NE of the site, the seabed is characterized by many curved troughs (t) and ridges (r), which are oblique to the Norwegian Channel. Such features are common along the west coast of Norway and were interpreted by Rise and Rokoengen (1984) as moraines formed between confluent ice flows from the western Norwegian coast and the main NCIS. Ottesen *et al.* (2016) suggested that the sediments from the last glaciation were remoulded into ridges by ice entering the channel from the western Norwegian coast, with stronger erosion occurring between the ridges to form the troughs. Another possible interpretation of these features is that they represent ribbed bedforms termed oblique ribbed moraines (Vérité *et al.* 2021). These are subglacial ridges formed obliquely to the ice flow direction along ice stream margins, between the streaming and non-streaming ice, where the soft subglacial bed is coupled to the ice and subjected to high basal shear stresses. Such features have been reproduced by physical sand–silicon ice sheet models (Vérité *et al.* 2021) and are widely observed along the margins of other former ice streams (Stokes 2018). Despite different possible interpretations of how the oblique troughs and ridges formed, all of the theories point towards a strong glacial influence on the bathymetry of the Utsira area and to the presence of deformed glacial till at or near the seabed.

On the NMA Sea Terrain Model, finer-scale seafloor features are identified in the western and southeastern parts of the site (Figs 5a and 6a, b). In the shallower western part of the site (GZS 1), northward-striking straight to curvilinear features several metres deep, tens of metres wide and several kilometres long are abundant (Fig. 6a and b). These are typical iceberg ploughmarks, scours in the seafloor sediments created by northward-floating icebergs released during the last deglaciation (e.g. Lien 1983) but are also observed in other parts of the North Sea within the Quaternary stratigraphy (e.g. Dowdeswell and Ottesen 2013) and on the Mid-Norwegian Shelf at the Top Pliocene surface (Jackson 2007). In contrast, the deeper trough area (T1) in southern Utsira Nord largely lacks iceberg ploughmarks, and instead is characterized by north-northwestward-striking glacial trough (t) and ridge (r) features of several kilometres in width (Figs 5a and 6a). An exception to this is observed at the southwestern side of the crystalline bedrock exposures, where iceberg plough marks are locally abundant (Fig. 6a).

In the western part of the site, several raised circular features with a central depression that are up to 200 m in diameter and several metres deep are observed (Fig. 6a and b). A few kilometres west of the site, there is a swarm of these features (Fig. 6c). These are interpreted as pockmarks: crater-like features from which water or gas is escaping or has previously escaped and that could indicate the location of small-offset faults within the subsurface. Such features

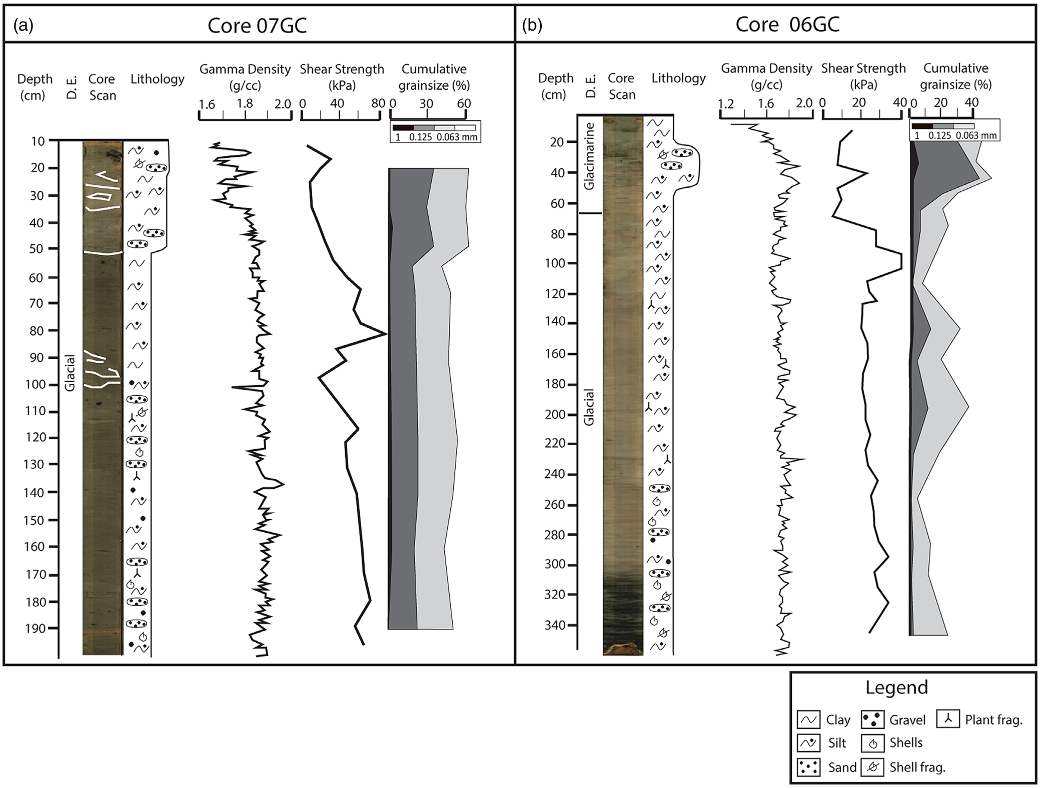

Fig. 10. (**a**) Core scan photograph and multi-sensor core logs for gravity core 07GC showing sedimentological and physical properties of subglacial traction till (Unit 2-type sediments) 50 km south of the Utsira Nord site. (**b**) Core scan photograph and multi-sensor core logs for gravity core 06GC showing sedimentological and physical properties of subglacial traction till (Unit 2-type sediments) overlain by glacimarine (Unit 1-type) sediments located 50 km of the Utsira Nord site. D.E., Depositional Environment, frag., fragments.

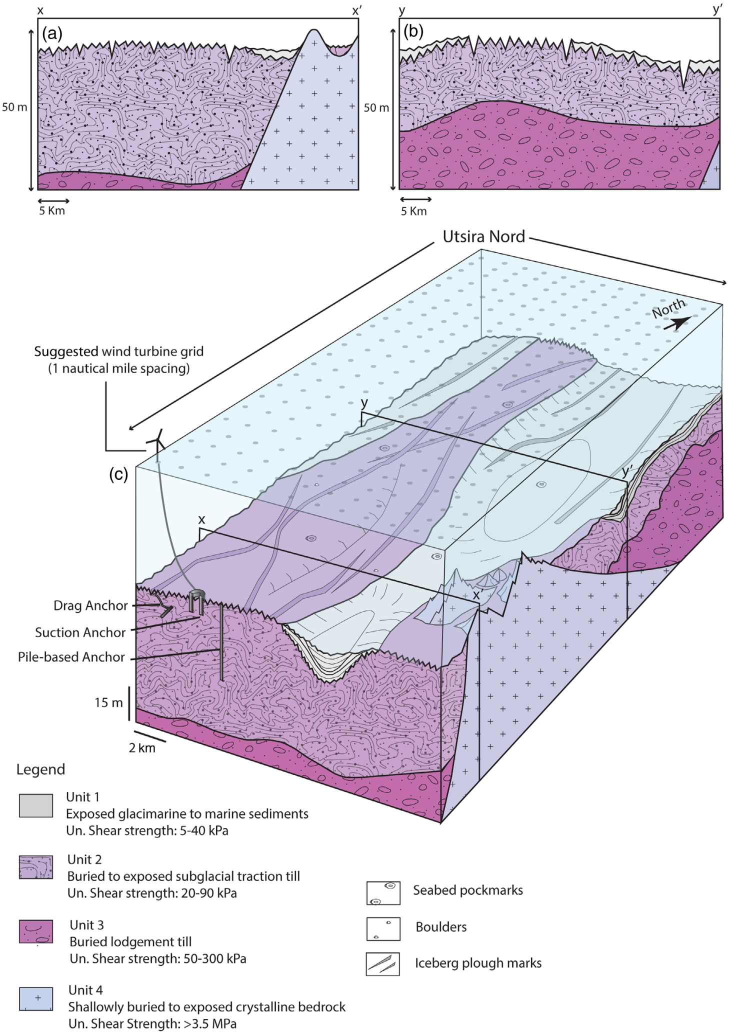

Fig. 11. (**a**) Geosection (x–x’) showing how the respective units of the conceptual geological model for Utsira Nord vary in thickness and burial depth across the southern part of the site. (**b**) Geosection (y–y’) showing variations across the northern part of the site. (**c**) Geological model for Utsira Nord based on the bathymetric and acoustic data covering the site. The upper 50 m of the sub-sea stratigraphy and the seabed are divided into four geotechnical units. The overlying seawater is represented in transparent blue (not to scale), with a suggested grid of floating offshore wind turbines spaced 1 × 1 nautical mile. Schematic drawings of three anchor types give an impression of how vertical and lateral changes in the seabed and the subsurface conditions can affect anchor design and penetration. Sources of undrained shear strength values are given in Table 1.

are common on the seafloor within the Norwegian Channel and can contain lag deposits of gravel and layers of hard methane-derived authigenic carbonates known as MDACs, and associated faunas (Forsberg *et al.* 2007). Above the Troll field, located in the northern part of the Norwegian Channel, previous investigations have indicated that the gas escape that formed the pockmarks is not a continuing process, but one that occurred at the end of the last ice age as gas hydrates stored within the glacial till became destabilized (Forsberg *et al.* 2007). In addition to pockmarks, the Sea Terrain Model also reveals two smaller (over 50 m in diameter and several metres high) raised circular features in the western part of the site (Fig. 6b). Although these probably also represent pockmarks, they might represent boulders or deposits of ice-rafted debris.

Seismic stratigraphy

Two-dimensional seismic profiles give an overview of the geometry and stratigraphy of the Norwegian Channel in the Utsira Nord area (Figs 3 and 7). The base of the channel slopes gently eastwards, defined by a reflection of variable character (the URU) that truncates westward-dipping sedimentary bedrock of Late Jurassic to Pliocene age. This is overlain by the flat-lying Quaternary sediments, which fill the channel. The maximum thickness of the sediment infill on the eastern side of the channel, where Utsira Nord is located, is *c.* 300 m, thinning to *c.* 100 m towards the western side of the Norwegian Channel (Fig. 8c). Utsira Nord is located along the eastern side of the Norwegian Channel, where the NCIS has eroded into Jurassic, Cretaceous and Paleocene sediments (Fig. 7b). The more resistant crystalline bedrock forms a steep-sided wall along the eastern side of the channel and is commonly exposed at the sea floor along the western Norwegian coastline (Figs 7b, c and 8). The crystalline bedrock has a chaotic seismic character, is highly segmented by steeply dipping faults and has a strong hard top reflection and rugged surface (Fig. 7a–c). In some parts of the site, not shown, particularly in the eastern and central areas, the crystalline bedrock faults continue upwards into the sedimentary bedrock and Quaternary sedimentary cover. The location of these faults may correlate with the location of pockmarks on the site;

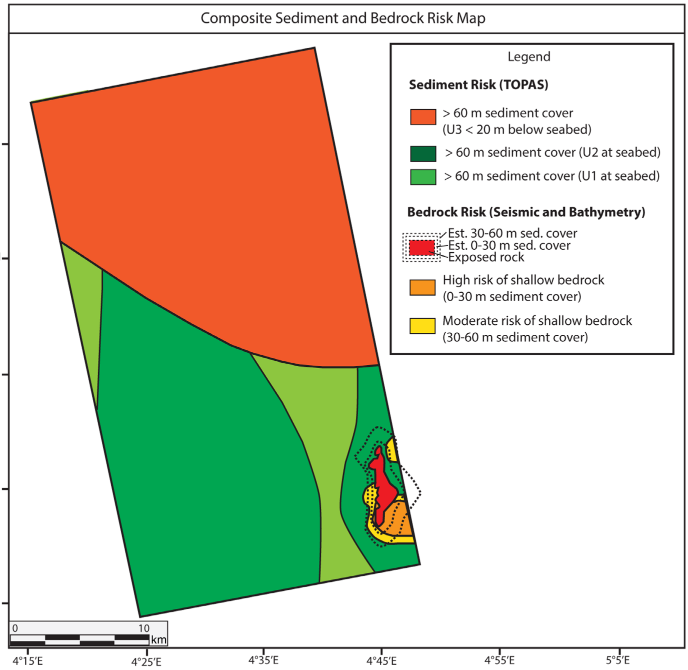

Fig. 12. Composite sediment and bedrock risk map for the Utsira Nord site, which highlights the key geotechnical risks anticipated across different parts of the site. In the southern part of the site, the geotechnical risk is defined by the geotechnical units present at the seabed and the amount of sedimentary cover overlying the crystalline bedrock. Thus, green areas represent the parts of the site with >60 m of sedimentary cover, where soft sedimentary units (U1 and U2) are likely to be >20 m thick, representing good areas for anchor types such as suction and drag anchors. In the southeastern part of the site, areas of mapped exposed bedrock (red) and estimated sediment cover around these (light orange and yellow) are incorporated from Figure 8. In the northern part of the site (dark orange), TOPAS data (Fig. 9) indicate that harder traction till containing gravel and boulders could be present <20 m below the seabed, with potential negative impacts for suction and drag anchor installation.

however, 3D seismic data and greater high-resolution bathymetric data coverage are required to confirm this.

The chain of crystalline bedrock highs identified on the bathymetric data (Figs 5a, 6a and 8a, b) is intersected in several places by some of the 2D conventional seismic lines. As the 2D seismic profiles are spaced *c.* 6 km apart, the seabed–URU thickness map (Fig. 8c) does not resolve all of the bedrock exposures and is used only to estimate the sediment thickness

Table 1. *Risk matrix summarizing the characteristics of the geotechnical units defined at Utsira Nord*

Geotechnical unit	Description	Hazards	Causes	Potential impact	Mitigation
1	Exposed glacimarine to marine sediments Undrained shear strength 5–40 kPa (Gravity and piston cores)	Uneven seabed Poorly consolidated sediment	Pockmarks Iceberg ploughmarks Boulders Recent marine sediments deposited by currents	Variable anchor penetration Obstruction to anchor Seabed scour around anchors	High-resolution seabed mapping (sonar, 3D seismic data) *In situ* testing across site to determine degree of consolidation of recent sediments
2	Buried to exposed subglacial traction till Undrained shear strength 20–90 kPa (Gravity cores)	Sudden lateral variation in soil properties	Glacial troughs with softer sediment infill	Variable anchor penetration	Acquisition of 2D or 3D acoustic data to map filled glacial troughs on finer scale Geophysical attributes to map out internal heterogeneities
3	Buried lodgement till Undrained shear strength 50–300 kPa (Clarke *et al.* 1998)	Buried hard formation at varying depths Highly variable soil properties	Overconsolidation of sediment by repeated ice activity Poorly sorted mixture of clay, silt, sand, gravel, cobbles and boulders	Obstruction to anchor Variable anchor or pile penetration Potential impact increases northward as unit becomes closer to surface	Acquisition of 2D or 3D acoustic data to map top of Unit 3 on finer scale 3D seismic diffraction imaging to locate possible boulders Acquisition of core and *in situ* testing across site to determine variability in soil properties
4	Shallowly buried to exposed crystalline bedrock Undrained shear strength >3.5 MPa (Singh and Murthy 2016)	Uneven seabed Buried hard formation	Rugged bedrock topography with exposed and buried peaks	Obstruction to anchor Shallow refusal Variable pile penetration Pile buckling	High-resolution seabed mapping (sonar, 3D seismic data) and sub-bottom profiling in southeastern part of the site

Colours in the Geotechnical unit column correspond to the units shown in Fig. 11.

Table 2. *Summary of anchor types and soil conditions*

Anchor type	Penetration depth (m) (Fugro Marine GeoServices 2017)	Description	Soil suitability	Advantages	Disadvantages
Suction anchor (or suction caisson) (or suction pile)	5–30	Hollow steel cylinder with a closed top, connected to a pump that creates suction (Vryhof Anchors 2010)	Cohesive soils such as soft clays Can be used in stiffer soils if design adjusted (e.g. thicker walls) Not suitable for bedrock	Suitable for a range of mooring types	If porous sand layers present, can have problems with achieving suction owing to flow of groundwater
Drag anchor	<10	Installed partly or fully beneath the seabed by dragging the anchor through the soil (ABS 2018)	Range of cohesive soil types including sand or stiff clay, layered soils and soft clay (ABS 2018) Not suitable for bedrock	Cheap to produce	Final resting position has degree of uncertainty Can make planning difficult for dense turbine grids Cannot currently be used for shared moorings to reduce number of anchors required
Driven pile anchor	30–70	Hollow steel pipe driven into the seabed with a hammer or vibrator (Ikhennicheu *et al.* 2020)	Range of cohesive soil types including sand and layered soils Not suitable for stiff soils or bedrock	Mature technology widely used for foundation-based offshore wind	Not suitable in water depths greater than 50 m
Drilled pile anchor	30–70	Hollow steel pipe installed by drilling a borehole and cementing the pile or filling the borehole with sediment (Löhning *et al.* 2021)	Stiff soil or bedrock	Allows flat areas with shallow bedrock to be developed	Expensive, time-consuming to install
Gravity anchor	<10	Block of concrete or metal that sits on the seafloor	Wide range of soil and bedrock conditions. Not suitable for very soft soil. Not suitable for slopes	Easy to produce and applicable to a wide range of seabed conditions. Useful if conditions are uncertain	Large size and weight leads to high installation costs (James and Costa Ros 2015)

around the bedrock highs that the 2D lines intersect. The sediment thickness within 1–3 km from the exposed rock areas ranges from 0–30 to 30–60 m (Fig. 8c). This is expressed as a 'risk map' for soft sediment anchors in Figure 8d, where areas with an estimated sedimentary cover of less than 30 m are marked in orange to denote a high risk of soft sediment anchor installation problems and areas with a sedimentary cover of 30–60 m are marked in yellow to denote a moderate risk of soft sediment anchor installation problems. Areas with a sediment thickness of greater than 60 m are shown in green to represent a low risk of soft sediment anchor installation problems, and areas where rocky outcrops have been interpreted on the bathymetric data are marked in red with dashed contours indicating estimated sedimentary thickness around the exposures.

Acoustic facies within the upper subsurface

The TOPAS sub-bottom profiles within Utsira Nord reveal seabed features and acoustic facies within the upper 30–50 m of the subsurface that are not resolvable on the bathymetric and 2D seismic datasets (Fig. 9a v. Fig. 9b). Within the northern part of the site (Fig. 9a), seismic reflections are visible only down to 25 m below seabed. The dominant seismic facies present is a chaotic seismic unit containing abundant high-amplitude point diffractors, which becomes increasingly transparent with depth (Fig. 9a). Based on previous studies of the Norwegian Channel seismic stratigraphy (e.g. Nygård *et al.* 2007; Morén *et al.* 2018) this unit is interpreted as subglacial traction till, which consists of mixed glacial clay, sand, gravel and cobbles deformed by the NCIS. The point diffractors are tentatively interpreted as possible boulders or lenses of coarse, consolidated sediment within the generally fine-grained, muddy–sandy matrix of the till. In the northeastern part of the profile, a faint, relatively flat reflection (R1) occurs 10–20 m below the top of the subglacial till. This type of internal till reflection has been identified in many parts of the Norwegian Channel on high-resolution seismic profiles (Morén *et al.* 2018) and in Antarctic palaeo ice streams (Ó Cofaigh *et al.* 2007; King *et al.* 2009), and is interpreted to represent the boundary between a soft upper layer of subglacial traction till and a more compacted deeper layer of lodgement till.

In the central part of the profile, the subglacial traction till has a mounded geometry and is exposed at the seabed. The seabed is highly furrowed, a characteristic feature of iceberg ploughmarks from the deglaciation period (e.g. Lien 1983). In the northeastern and southwestern parts of the profile, the till is onlapped by a thin (<3 m) transparent seismic unit that fills the iceberg ploughmarks in the underlying till unit. This transparent unit is interpreted as fine-grained glacimarine sediment from the deglaciation period, based on the westward thickening of the unit west of the Utsira Nord site (Fig. 4a), where it exhibits laminations characteristic of glacimarine sedimentation (e.g. Sejrup *et al.* 1989, 1994). In the northeastern part of the profile, a 4 m deep pockmark cuts through both the glacimarine unit and the underlying till. Thick post-glacial marine sediments observed west of the Utsira Nord site are not distinguishable over the western and eastern flanks of the Utsira Nord till, but a few centimetres to tens of centimetres of post-glacial muddy to sandy marine sediments (below the resolution of the TOPAS profile) could be present.

The north–south TOPAS profile in the eastern part of the site reveals variations in the thickness of the upper and lower till units and the overlying glacimarine unit within Utsira Nord (Fig. 9d–g). The flat internal reflection interpreted to define the base of the upper till becomes progressively deeper from north to south, meaning that the upper till layer is 5–15 m thick in the northern part of Utsira Nord, increasing to 15–45 m thick in the southern part. Glacimarine sediments are present at the seabed across the whole profile, with a relatively constant thickness of 7–10 m in the northern half of Utsira Nord. In the southern half of Utsira Nord, the thickness of the glacimarine sediments is more variable, thinning to only a few metres over highs in the glacial till, and thickening to up to 12 m in troughs in the glacial till (Fig. 9d and e). In these troughs, the transparent glacimarine sediments observed across the rest of the profile are overlain by laminated glacimarine sediments. The same laminated facies are observed south of the Utsira Nord site, where the thickness of both the transparent and laminated glacimarine sediment packages increases rapidly to a total thickness of 45 m (Fig. 9f and g). These are overlain by a transparent, southward thickening package thought to represent post-glacial marine sediments that thin to less than 30 cm (below TOPAS resolution) thickness over the Utsira Nord site.

Sediment properties

Key geotechnical properties of some of the acoustic facies identified within Utsira Nord can be estimated from the gravity cores 05–07-GC, located c. 50 km south of the site (Fig. 1) where the same acoustic facies are present at or near the seabed. The range of undrained shear strengths measured within each of the acoustic facies is summarized on the left side of Figure 4, and a brief sedimentological description of the cores is provided here.

The subglacial traction till facies (Fig. 4) is penetrated by cores 07-GC (Fig. 10a) and 06-GC (Fig. 10b). Both cores are located where the till is exposed at or near the seabed, within interpreted grounding zone systems (GZS 4 and GZS 2 respectively) (Fig. 5a). The facies consists of silty clay, with lenses of fine sand, shell fragments, plant fragments, whole shells and gravel. The grain size is uniform throughout, with a sand content between 45 and 60%, and the density of the sediments ranges from 1.65 to 1.95 g cm^{-3}. The undrained shear strength of the till is rather variable, mainly ranging from 20 to 90 kPa. Observed dipping boundaries and contorted lenses are interpreted as deformation structures indicative of deformation either by ice push during the glaciation or iceberg ploughing that took place during deglaciation (shown in white, Fig. 10a).

The glacimarine facies (Fig. 4) is penetrated by cores 05-GC and 06-GC (Fig. 10b) and consists of laminated clay to silty clay with lenses of fine sand, shell fragments and chalk clasts. The density of these sediments ranges from 1.4 to 2.4 g cm^{-3}, and the undrained shear strength is low, ranging between 5 and 25 kPa. In core 05-GC, the glacimarine facies is overlain by normal marine facies consisting of clay with a density of 1.7–2.3 g cm^{-3} and very low undrained shear strengths of between 5 and 15 kPa.

Discussion

Conceptual model for Utsira Nord and how it relates to anchoring of FOW turbines

Based on the distribution and properties of the seismic units identified at Utsira Nord, four main geotechnical units are defined (Fig. 11, Table 1).

Unit 4, crystalline bedrock

The region of exposed to shallowly buried crystalline bedrock within the southeastern corner of the Utsira Nord site, which forms about 10% of the site, is defined as Unit 4. The bedrock consists of hard crystalline rocks (the Utsira Complex, Ragnhildstveit *et al.* 1998), which are likely to have shear strengths greater than 3.5 MPa (Singh and Murthy 2016). Suction anchors, designed for soft homogeneous clays, muds or sands, and driven piles designed for a range of cohesive soils will not be a feasible design concept for this part of the site owing to the risks of obstruction, shallow refusal, variable penetration and buckling owing to the presence of shallow crystalline bedrock (Fig. 12; Tables 1 and 2). Instead, a drilled pile

(Table 2) or new anchoring type would have to be designed to develop this part of the site. Gravity-based anchors (Table 2) might also be a feasible solution; however, the risk of sliding on the rugged, uneven slopes of exposed bedrock will need to be evaluated. Acquisition of higher resolution bathymetry data is required to more accurately assess the steepness of the bedrock slopes if this part of the site is to be developed. If economically feasible, the geophysical site survey should focus on mapping the shallowly buried parts of the bedrock in more detail (Fig. 12; Table 1), ideally using 3D seismic data or a dense grid of 2D seismic lines to better constrain the subsurface extent of the crystalline bedrock and the sediment thicknesses around the exposures. This will give a clearer overview of how close soft sediment anchors can be placed to the bedrock exposures.

Unit 3, lodgement till

The lodgement till layer interpreted beneath Reflection 1 (Fig. 9g) is defined as Unit 3. There is a large uncertainty around the sedimentary and physical properties of this unit, owing to a lack of cores that sample this type of sediment within the Norwegian Channel and ice stream beds in other locations. However, it is likely that the lower till layer is denser than the upper till layer, owing to greater consolidation and less glacial deformation. It is suggested that Unit 3 will exhibit undrained shear strengths at least as high as or higher than those measured in the upper till at the Troll field (80–160 kPa; Sejrup *et al.* 1995). Undrained shear strength of lodgement tills from geotechnical borings onshore UK in the range of 50–640 kPa have been reported by Clarke *et al.* (1998), although the values were mainly below 300 kPa. Heavily over-consolidated tills from Canada with undrained shear strengths of greater than 3000 kPa (Milligan 1976) and up to 1600 kPa in North America (Radhakrishna and Klym 1974) have also been reported. Such extreme consolidation is not anticipated within an ice stream setting such as the Norwegian Channel owing to higher pore-water pressure (Tulaczyk and Kamb 2000; Kamb 2001; Kyrke-Smith *et al.* 2013) and thinner ice cover than passive inter-ice stream areas (Gandy *et al.* 2021). If the Utsira Nord lodgement till is similar to the youngest till unit at the Troll field, a lithology of homogeneous clay to silty clay with around 30% sand and 3% coarse sand and gravel can be expected (Sejrup *et al.* 1995). Although the drilling issues experienced at Troll indicate the presence of boulders or coarse, consolidated sediments within the till units, the distribution of boulders throughout the Norwegian Channel remains highly uncertain. Boulders can represent significant obstructions in the installation of pile foundations for offshore infrastructure (Holeyman *et al.* 2015). An abundance of boulders or coarse sediments at the Utsira Nord site could have a significant impact on potential anchor designs for the site; for example, creating a requirement for increased suction anchor wall thickness. Based on the north–south TOPAS line (Fig. 9g), Unit 3 is likely to mainly occur 45–50 m below the seabed in the southern half of the site and is therefore unlikely to have implications for anchor design considerations in this area. In the northern part of the site, however, Unit 3 appears likely to mainly occur 10–20 m below the seabed (Fig. 12) and must therefore be considered within the anchor design concept. Unit 3 may present a risk to successful penetration of suction anchors designed for clays and muds; however, borehole investigations will be required in the northern part of the site to analyse the physical properties of the Unit 3 sediments further (Table 1). Three-dimensional seismic diffraction imaging to locate possible boulders (e.g. Grasmueck *et al.* 2012; Wenau *et al.* 2018) should also be considered as a method to mitigate the risk of boulder-related installation issues in the northern parts of the site where Unit 3 is likely to be present in the shallow subsurface (Table 1). Such methods focus on more ‘diffraction-friendly processing’ in seismic survey practices (Grasmueck *et al.* 2012) to bring out rather than suppress small-scale discontinuities (such as boulders) in the seismic data.

Unit 2, subglacial traction till

The subglacial traction till layer interpreted between Reflection 1 and Reflection 2 (Fig. 9g) is defined as Unit 2. The sedimentary and physical properties of Unit 2 can be estimated from the shallow cores in the vicinity of the site, which comprise silty clay with sand lenses, gravel, deformation structures and undrained shear strengths of up to 90 kPa. This unit is likely to be suitable for suction type anchors where it extends to at least 30–40 m beneath seabed. This is most likely in the southern part of the site, as discussed above. Unit 2 is likely to be exposed at or within tens of centimetres of the seabed along the shallower central and western parts of the site. Although in the TOPAS data available in this study, Unit 2 has a largely transparent to chaotic seismic character with no obvious internal reflections, sedimentary and structural heterogeneities are well documented within subglacial traction tills in other regions, particularly within grounding zone systems such as GZS 1 at Utsira Nord. In the Bear Island Trough south of Svalbard, for example, traction tills within a GZS at the mouth of the trough (Rüther *et al.* 2011) exhibit structural heterogeneities in seismic data such as high-amplitude stacked blocks, interpreted as glacitectonic imbricate thrust sheets. Structural heterogeneities are also identified in the Bear Island Trough GZS sediment cores, including laminated intervals and shear planes representing lower shear strength zones within the generally massive diamict sediments. Within the ice stream deposits of the Irish Sea, geotechnical borings within the Upper Till Member of the Cardigan Bay Formation have identified a wide range of clast sizes within such tills, ranging from sand to boulder sized (Mellet *et al.* 2015). The Upper Till Member also exhibits a wide range of shear strengths, from 25–630 kPa. The degree of geotechnical heterogeneity within the Utsira Nord traction till should be quantified with a representative sample of *in situ* measurements and borings (Table 2). Additional, often underused geophysical attribute techniques such as inversion, attenuation and P-wave velocity (Velenturf *et al.* 2021) could also be used to map out heterogeneities within Unit 2 more effectively. Sudden lateral variations in soil properties at the seabed of the Utsira Nord site can also be expected where glacial troughs filled with softer, younger sediments are present at the surface of Unit 2 (Table 1). This could result in variable anchor penetration of soft sediment anchors (suction anchors, drag anchors; Table 2) along the boundaries of the troughs. Their extent should therefore be mapped in greater detail as part of the geophysical site survey (Table 1).

Unit 1, glacimarine to marine sediments

The glacimarine sediments that overlie the subglacial traction till layer are defined as Unit 1. Post-glacial marine sediments (the top of which is represented by R4) are observed to largely pinch out south of the Utsira Nord site (Fig. 9g); however, a thin (<25–30 cm) layer of fine-grained marine sediments below the resolution of TOPAS data across the whole site cannot be ruled out. The glacimarine sediments vary in thickness and distribution across the Utsira Nord site (Fig. 12), thickening in the bathymetric lows on the surface of Unit 2 to up to 12 m thickness, and thinning over the highs. The sedimentary and physical properties of Unit 1 can be estimated from the shallow offset cores in the vicinity of the site, which comprise clay to sandy silt with sand lenses, gravel and shell fragments, and have undrained shear strengths of 20 kPa (and up to 40 kPa in piston core 04 PC in the southern part of the Norwegian Channel (Morén *et al.* 2018)). This unit is likely to be suitable for suction type anchors, with due consideration given to the properties of the underlying till. The key hazards associated with Unit 1 (and Unit 2 where it is exposed at the seabed) are the presence of pockmarks, iceberg ploughmarks, possible tool marks and possible boulders or coarse material dropped from icebergs during the deglaciation period. The unevenness of the seabed and the possibility of encountering boulders should be given due consideration during the anchor installation phase but can be mitigated through high-resolution seabed mapping (Table 1). The Unit 1 sediments are likely to be very soft, clay-rich sediments but could also contain poorly consolidated coarser-grained sediments. In both cases, the soft or poorly consolidated surficial sediments could be vulnerable to erosion by ocean current vortices around embedded anchors. This process is known as soil or seabed scour and has been studied at many bottom-fixed offshore wind installations with monopile foundations (Whitehouse *et al.* 2011; Matutano *et al.* 2013; Sørensen and Ibsen 2013; Qi *et al.* 2016; Abhinav and Saha 2017; Tseng *et al.* 2017; Dai *et al.* 2021). If the embedment depth of an anchor or foundation is reduced by the erosion of the soil around it, the response of both the anchor or foundation and the wind turbine to loading from the wind and waves changes (Gupta and Basu 2016; Ma *et al.* 2017, 2018; Tewolde *et al.* 2017; Wang *et al.* 2020) and thus constitutes a major safety and design consideration (Deb and Pal 2019; Darvishi Alamouti *et al.* 2020; Dai *et al.* 2021). *In situ* testing of the Unit 1 and Unit 2 sediments exposed at the seabed within Utsira Nord should be conducted across different parts of the site to facilitate modelling and evaluation of the risk of seabed scour for the specific anchor type chosen (Table 1). Although soil erosion testing has not been a standard part of offshore site surveys to date (Harris and Whitehouse 2017), this will be a particularly important consideration for Utsira Nord as a FOW site, as the majority of soil scour studies have focused on the impacts for bottom-fixed, monopile foundations rather than anchors for FOW turbines. In particular, very little soil scour investigation has been carried out on suction anchors (Yang *et al.* 2020), meaning that there is a lack of field and laboratory data on which to base soil scour estimates for this type of FOW anchor. In addition, the seabed at Utsira Nord and in other parts of the Norwegian Channel is characterized by exposed clay-rich sediments (Units 1 and 2), for which seabed scour estimation remains highly uncertain owing to limited data in areas with such conditions (Harris and Whitehouse 2017).

Key uncertainties

With only sparse and shallow gravity cores in the vicinity of the Utsira Nord site, several key uncertainties remain regarding the sedimentological and geotechnical character of Units 1–3. Although the glacimarine and marine sediments of Unit 1 are generally well represented in previous studies (e.g. Sejrup *et al.* 1994; Morén *et al.* 2018), core locations tend to be tens to hundreds of kilometres apart, making it difficult to forecast what site-scale variations might be present within Unit 1. It should therefore be a topic of investigation to better constrain the lateral and vertical variability in the sedimentary and geotechnical properties of this unit when acquiring site survey data at Utsira Nord. Although Unit 1 is likely to comprise soft, fine-grained sediments, undrained shear strength and grain-size measurements from the site are required to confirm this. Troughs infilled by strongly laminated glacimarine sediments such as those observed along the eastern part of the site are particularly likely to be vertically heterogeneous and may contain sand layers that need to be investigated to indicate suction anchor installation risk.

One of the key uncertainties remaining about Unit 2 is what causes the abundant point diffractors observed on sub-bottom profiles. It should be a goal of coring on the site to try to investigate if boulders or coarse ice-rafted debris deposits might be the cause of diffraction, as widespread distribution of such material on Utsira Nord could present significant installation risks to some anchor types. Existing gravity cores in the vicinity of the site have sampled only the upper tens of centimetres of the subglacial traction till facies. Deeper coring of Unit 2 is therefore required to better understand the vertical and lateral variations in the sedimentary and geotechnical properties of subglacial traction till across the site.

The sedimentological and geotechnical properties of Unit 3 are very uncertain as very little is documented about the sedimentary properties and internal variations within the Norwegian Channel lodgement till, other than studies related to the Troll core, located in the outer part of the Norwegian Channel. Shallowly buried lodgement till may present a risk to successful penetration of suction anchors designed for clays and muds, therefore site investigations should particularly focus on Unit 3 in the northern part of the site where it is situated only 10–20 m below seabed. Unit 3 might be too stiff and/or boulder-rich to be cored by piston corer and may require a drilled coring investigation.

Although the undrained shear strength of the Unit 4 crystalline bedrock is likely to be >3.5 MPa, it is recommended that the fracture density and degree of weathering of the rock are investigated as part of geotechnical site survey investigations to determine the suitability of the rock for drilled pile emplacement if the unit is to be developed. Given the location within the Norwegian Channel, the exposed rocks will most probably be ice-polished, with only highly resistant rock left behind. However, a high density of fractures or other structural weaknesses could affect the competence of the rock to hold an anchor. An additional aspect to be considered within Unit 4 is that rocky marine areas are often characterized by high biodiversity relative to the surrounding soft bottom areas as their surface provides different microhabitats for marine organisms (Wenner *et al.* 1983; de Kluijver 1991; Diesing *et al.* 2009). This should be investigated further as part of the site's eventual environmental impact assessment.

Additional insights from well-studied ice stream sites

As highlighted in Figure 2, large areas of the North American and NW European continental shelves have previously been covered by ice sheets. Parts of those shelves, like the North Sea, have been affected by ice streaming. On the Mid-Norwegian Shelf, for example, several hundred kilometres NE of the Norwegian Channel ice stream trough where Utsira Nord is located, bathymetric and seismic data indicate the presence of at least three ice stream troughs running from the coast of Mid-Norway towards the Norwegian Sea (Trænadjupet, Suladjupet and Sklinnadjupet, Ottesen *et al.* 2002; Dowdeswell *et al.* 2006; Montelli *et al.* 2017). Further north, offshore northern Norway and Svalbard, the continental shelf has also been shaped by ice streaming; for example, the Håsjerringsdjupet trough (Winsborrow *et al.* 2016) and the Bear Island trough (Vorren and Laberg 1997; Andreassen *et al.* 2004, 2008; Ottesen *et al.* 2005). In the UK and Ireland, where the offshore wind industry has been rapidly expanding in recent years, seabed troughs have been carved out by at least 17 ice streams related to the BIIS during the last glaciation (Gandy *et al.* 2019). The Irish Sea in particular is a marine area earmarked for offshore wind development that has been strongly affected by ice streaming during past glaciations (Mellet *et al.* 2015; Coughlan *et al.* 2020). In the northeastern USA, an important growth area for offshore wind, parts of the continental shelf have also been affected by ice streaming; for example, Northeast Channel in the Gulf of Maine (McClennen 1989; Shaw *et al.* 2006) and offshore Massachusetts (Siegel *et al.* 2012), and the Canadian continental shelf has the large Laurentian Channel trough (Winsborrow *et al.* 2004) in addition to smaller ice stream troughs offshore Newfoundland (Shaw and Longva 2017).

For the most part, the sedimentological and physical properties of ice stream deposits have never been studied explicitly with regard to ground conditions for offshore wind foundations and anchors. Of those that have been, the authors are aware of only three studies that focus on areas affected directly by ice streaming. Two of these, by Mellet *et al.* (2015) and Coughlan *et al.* (2020), are studies that focus on the seabed and shallow subsurface of the Irish Sea. The third, Emery *et al.* (2019) is a study of the seismic and lithofacies present at the Dogger Bank offshore wind farm site in the UK sector of the southern North Sea. A recent broad geological study by Eamer *et al.* (2021) compared the ground conditions for offshore wind on the Atlantic Canadian inner shelf, the northern Atlantic coast of the USA and the North Sea but did not specifically focus on the conditions within the ice stream troughs located in these regions.

The Irish Sea is the former site of the largest marine-terminating ice stream of the BIIS (Eyles and McCabe 1989; Roberts *et al.* 2007; Small *et al.* 2018). Unlike the Norwegian Channel, which contains glacimarine sediments in both its inner and outer zones, glacial landforms indicate that the Irish Sea Ice Stream (ISIS) terminated in a marine setting at around 18 ka (Van Landeghem and Chiverrell 2011) but probably moved into a terrestrial setting as it retreated northwards during final deglaciation. This has probably resulted in a more pronounced north–south variation in sediment properties (Mellet *et al.* 2015) than is found within the sediments of the Norwegian Channel.

One of the key differences between the Irish Sea and the Norwegian Channel is that the Irish Sea is much shallower (<150 m), with an actively migrating sandy to gravelly seabed (Mellet *et al.* 2015). Such conditions are more similar to the North Sea Plateau than the Norwegian Channel, which is largely covered by Holocene mud and clay (Norwegian Geological Survey 2022). However, where these surface sands are not present, different stratigraphic units related to the history of the ISIS are exposed at the seabed (Mellet *et al.* 2015). Those that occur within 50 m of the seabed include the Late Weichselian Western Irish Sea Formation, a silty mud facies with sporadic sand, gravel, cobbles and boulders, and relatively low shear strengths ranging from 11 to 63 kPa. This is interpreted as a glacial to glacimarine deposit and compares closely with the interpreted origin and forecast shear strength ranges for Unit 1 of the Utsira Nord site. The stratigraphically lower Cardigan Bay Formation is divided into four members including an Upper (Weichselian) Till Member and a Lower (Saalian) Till Member, which are diamicts of silty, sandy, gravelly clays with distinct differences in their shear strengths and plasticity. The Upper Till Member has an average shear strength of 185 kPa, with thick to very thick beds of gravel and sand recorded in boreholes and flagged as possible hazards to pile drivability. The Lower Till Member has a higher average shear strength of 342 kPa and is far more overconsolidated than the Upper Till Member, most probably because it is older and has experienced more ice advances than the Upper Till Member. At Utsira Nord, pre-Weichselian tills are not anticipated within 50 m of the seabed, so FOW anchors are not likely to encounter tills as hard as the Lower Till Member of the Cardigan Bay Formation. Although the Upper Till Member and Utsira Nord units 2 and 3 were both deposited during the Weichselian glaciation, the Upper Till Member exhibits higher shear strengths than have been forecast for Utsira Nord. However, the average shear strength for the Upper Till Member (185 kPa) lies within the ranges forecast for Utsira Nord's Unit 3 (buried lodgment till), estimated from geotechnical borings onshore UK (<300 kPa, Clarke *et al.* 1998).

In contrast to the bathymetric troughs created by the Norwegian Channel and Irish Sea Ice Streams, geomorphological evidence of ice streaming is observed in the subsurface at the Dogger Bank offshore wind farm site, in the southern North Sea (Emery *et al.* 2019). Streamlined subglacial bedforms within a 15 km wide corridor interpreted on seismic data are thought to indicate that fast ice flow occurred in the region during the last glacial maximum (Emery *et al.* 2019). These features occur next to a thrust-block moraine complex, which indicates that the ice-streaming occurred within a surge-type system, which rapidly advances, compressing the sediments ahead of it, and then stops and stagnates. Unlike the Norwegian Channel, the North Sea Plateau where Dogger Bank is located has very low relief, meaning that subglacial meltwater routing probably had a stronger influence on the location of the ice streaming than the topography did. The thrust-block moraine complex is highly deformed and heterogeneous, probably more so than the deformed traction tills within the Utsira Nord site, owing to the surging nature of the Dogger Bank ice stream. However, the shear strength values measured within the Dogger Bank tills are similar to those forecast for the Utsira Nord tills. Grounding zone systems, such as those identified within Utsira Nord, are absent in the Dogger Bank ice stream trough, probably indicating that the ice stagnated *in situ* rather than experiencing the retreats and still-stands that occurred during the deglaciation of the Norwegian Channel Ice Stream (Morén *et al.* 2018). The Dogger Bank moraines were eventually overlain by subaerial glacial outwash sediments, followed by lacustrine sediments as a pro-glacial lake formed ahead of the retreating BIIS margin. These were subsequently transgressed by post-glacial marine sediments, which are largely sandy in nature.

Although the Dogger Bank and Utsira Nord sites have some similarities such as the presence of deformed subglacial till, the geomorphological features and modes of deposition of the tills are rather different owing to the differences in ice stream topography and dynamics between the two areas. The Norwegian Channel lacks Late Weichselian subaerial outwash and glaciolacustrine deposits, which are fine-grained and overconsolidated, and the overlying Holocene marine sands, which can be mobile. The Utsira Nord conceptual model is therefore more applicable to areas with topographically constrained ice streaming such as the Irish Sea Ice Stream than to low-relief surge type ice streams, more of which probably exist on the low-relief North Sea Plateau.

Anchoring options for FOW

As a relatively immature technology, the geotechnical considerations for FOW anchor design and installation have not yet been studied as widely as those for bottom-fixed offshore wind foundations. In the early stages of offshore wind development, many offshore wind turbines had self-weighted, concrete foundation structures known as gravity base foundations, which were used in water depths of less than 10 m (Wu *et al.* 2019). The main geotechnical consideration for this type of foundation was that the ground conditions below seabed had adequate bearing capacity (Doherty *et al.* 2011); that is, were competent enough that the foundation would not sink. Therefore, flat seabed areas characterized by shallow or exposed bedrock, compacted clays or sandy soils were all appropriate ground conditions for gravity base foundations. Gravity anchors (Table 2) are a similar kind of technology, where a self-weighted structure is used as an anchor rather than a foundation. This type of anchor has never been applied to FOW turbines. It is unlikely to be a viable solution in the water depths applicable for FOW, where anchors with greater load-bearing capacity are required to withstand stronger wind and waves.

Before the 2010s, most wind farms were developed in areas where water depths did not exceed 30 m (Doherty *et al.* 2011). Since then, bottom-fixed turbines have been able to move into a wider depth range, usually between 20 and 40 m. Today, most bottom-fixed offshore wind farms have monopile foundations, which are typically a single steel tube of 3–8 m diameter, driven, hammered or drilled into the seabed depending on the ground conditions (Westgate and De Jong 2005). Some offshore wind farms use multiple-piled structures, which can be used in deeper waters and in areas with non-homogeneous soils (Westgate and De Jong 2005). Where the seabed is very soft, piles cannot be supported. In contrast, where there are very overconsolidated soils it may be difficult to drive the piles into the seabed. If hard bedrock is present at the seabed, piles must be driven or cemented into a pre-drilled borehole in the rock; however, this can be challenging and expensive especially if the bedrock level is variable, such as at the Celtic Array project offshore Ireland, which was ultimately scrapped because of such challenges (Mellet *et al.* 2015). Monopiles have never been used as anchors at floating offshore windfarms but could perhaps be considered where the seabed conditions are not suitable for soft sediment anchor types (suction and drag anchors; Table 2).

Where the seabed is characterized by thick, soft, clay-rich soils, gravity base foundations and pile-based foundations cannot be supported. In the case of pile-based anchors, prohibitively long piles would be required in such ground conditions (Westgate and De Jong 2005). In this case, a type of foundation called a suction bucket (or suction caisson or suction pile) can be deployed. Although suction bucket foundations can work well in both sands and soft clays, they are most suited to homogeneous soils where differential settlement is less likely to be an issue (Westgate and De Jong 2005). Overall, there is a limited amount of installation data for suction bucket foundations in different soil types relative to that which is available for pile foundations, meaning that a rather detailed installation analysis is required prior to the design of a given suction bucket foundation.

Suction buckets can be deployed as anchors and are one of the more common solutions chosen for FOW projects to date (Hywind Scotland, Statoil 2015; Hywind Tampen, Equinor 2022). Soil heterogeneities such as thin layers or lenses of coarse but low-permeability sediment can cause suction foundations and anchors to become stuck during installation. This could be a possible issue within Units 1–3 at the Utsira Nord site, where lenses of coarse material from ice rafting could be present. Suction buckets can also experience installation problems when the seabed is uneven, which can prevent the foundation from reaching its total penetration depth if not considered in the design of the anchor (Sturm 2017). On the western side of the Utsira Nord site, iceberg ploughmarks are particularly abundant and should be taken into consideration if suction bucket anchors are deployed.

FOW turbines can either be supported by a platform that is moored to the seabed by anchors, called a tension-leg platform, or the turbine can comprise a single floater that is moored to the seabed by anchors. In the case of floaters, several anchoring options are available (Table 2). Suction anchors and pile anchors are similar to their corresponding foundation designs, as described above. At the Hywind Scotland floating offshore windfarm, built in 2017, five floating turbines are moored to suction anchors at a water depth of 105 m, in the Buchan Deep, offshore NE Scotland (Equinor 2022). The ground conditions at Hywind Scotland consist of a thin (40–90 cm) veneer of Holocene sand and gravelly sand with areas of sandwaves located close by. Beneath the Holocene sediments lie the (Quaternary aged) Forth, Witch Ground, Wee Bankie, Coal Pit and Aberdeen Ground Formations, which consist of layers of varying thickness and extent of glacial diamict, clay, mud, sand and gravel (Statoil 2015). We have not found any published studies on whether any challenges were experienced during installation of the suction anchors or whether there have been any post-installation challenges such as scour or migration of the nearby sandwaves. Overall, practical experience with the short-term and long-term behaviour of suction anchors used for offshore wind turbines is limited (Sturm 2017). However, sample testing and monitoring from the increasing number of floating offshore wind turbines using suction anchors will allow these to be better understood.

The seabed conditions encountered at Hywind Scotland are not directly applicable to the Utsira Nord site, where glacial till and fine-grained glacimarine sediments are expected rather than Holocene sands and gravels. The new Hywind Tampen FOW development, soon to be installed with suction anchors along the northwestern side of the Norwegian Channel (Equinor 2022), is likely to have more similar ground conditions to the Utsira Nord site (i.e. the presence of fine-grained glacimarine to marine sediments from the deglaciation of the Norwegian Channel Ice Stream) rather than the Holocene sand and sandwaves that are more common outside the Norwegian Channel (Norwegian Geological Survey 2022). Lateral shear moraines have been reported along the northwestern margin of the channel by Ottesen *et al.* (2012), Sejrup *et al.* (2016) and Morén *et al.* (2018), but in this study we have not found information regarding the thickness of the glacimarine and marine sedimentary cover above the moraines. TOPAS lines presented by Morén *et al.* (2018) indicate that the glacimarine and marine facies generally thicken westwards and are relatively thick over the top of morainal features in the central northern part of the Norwegian Channel. This implies that the Hywind Tampen area has a reasonably thick covering of glacimarine and marine sediments suitable for suction anchor installation. The Utsira Nord site, characterized by exposed to shallowly buried grounding zone systems and troughs filled with softer glacimarine sediments, is tentatively suggested as a more heterogeneous and potentially challenging site for suction anchors.

Another option for FOW anchoring is to use drag anchors, which are a metal structure installed into the soil by dragging the anchor along the seabed (Table 2). These are applicable to a wide range of soil types but have some drawbacks relative to suction anchors in that their emplacement location is more uncertain and they cannot, currently, be used for shared moorings (as planned for Hywind Tampen). A drag anchor has been successfully deployed for over a decade at the FOW demonstration project Hywind Demo (Equinor 2022), located only 20 km from the Utsira Nord site. Based on the marine geology map of the Norwegian Geological Survey (2022), the Hywind Demo is anchored in an area of fine-grained sediment adjacent to areas of exposed gravelly sand containing cobbles and boulders and small areas of exposed bedrock. If similar conditions are encountered at Utsira Nord, the drag anchor concept used at Hywind Demo could be a possible solution if the sediments are too heterogeneous for suction anchors.

Conclusions and further work

In this study, we demonstrate a method that can advance conventional desktop studies towards a more cross-disciplinary and powerful tool for understanding the key risks and uncertainties in the ground conditions at new offshore wind sites despite limited data availability. The conceptual geological model presented defines four main geotechnical units at the Utsira Nord FOW site: (1) exposed glacimarine to marine sediments suitable for suction-type anchors; (2) buried to exposed subglacial traction till suitable for suction-type anchors; (3) buried lodgement till with highly uncertain properties and probably boulders; (4) shallowly buried to exposed crystalline bedrock, which is estimated to form *c.* 10% of the site and which will probably require a pile-based or novel anchoring solution. To inform effective anchoring design and reduce installation problems, we recommend that initial geophysical and geotechnical site surveys at Utsira Nord focus on reducing the following key uncertainties: (1) the sedimentological and geotechnical character of Units 1–3 including the site-scale variability within each of the units, the sand content of the laminated trough-infill sediments in Units 1 and what geological conditions lead to the abundant point diffractors on sub-bottom profiles within Unit 2; (2) the sedimentological and geotechnical properties of Unit 3, which are particularly uncertain owing to an almost complete lack of core sampling of lodgement tills within the Norwegian Channel. Although the ground conditions at every offshore wind farm site are unique, the key units and associated data acquisition requirements identified within the Utsira Nord conceptual geological model are of relevance to current and future offshore wind developments in other formerly glaciated marine areas such as the coastlines of Canada, the northern USA, the northern UK, Ireland and the Mid-Norwegian Shelf, particularly within ice stream channels in these regions such as the Irish Sea.

Offshore wind developers in Norway should use the lessons learned from previous offshore wind projects relating to insufficient understanding of geological setting and site surveys that did not meet the requirements of foundation designers, to avoid the need for additional surveys late in the development process, installation problems and overconservative design solutions. As the Norwegian authorities develop new offshore renewable energy licensing legislation, the importance of acquiring seabed, subsurface and environmental data as early as possible in the licensing and project development process should not be underestimated, regardless of who will pay the bill. Early data acquisition can facilitate both cost-effective and efficient foundation and anchoring design and installation, thus contributing towards a faster roll-out of Norwegian offshore wind. The openness of future data also needs to be clarified. Publicly available site survey data, such as are available from the Netherlands and the USA, could improve our understanding of the geological and environmental conditions at future offshore wind sites. Making offshore wind site survey data from the Norwegian North Sea publicly available could greatly benefit future Norwegian offshore wind projects and those within other previously glaciated areas.

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Data availability The Olex AS bathymetric database is available from Olex AS, Trondheim, for a fee. The Norwegian Mapping Authority Sea Terrain Model is publicly available from the Norwegian Mapping Authority; however, use of the data located within 12 nautical miles from the coastline requires permission from the Norwegian Armed Forces. Seismic survey ST8201 is publicly available from the Norwegian National Data Repository for Petroleum Data (DISKOS), whereas seismic survey NPD-KYST-96 is only available with DISKOS membership. The TOPAS data analysed in this study are not publicly available, but high-resolution images of the data can be made available by the corresponding author on reasonable request.

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Article 2: An integrated geological characterization of the Sørlige Nordsjø II offshore wind site, southern North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Jo Brendryen, Timothy Watton

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Article 3: Integrating geological, geophysical and engineering considerations at offshore wind sites in buried glacial landscapes: Case studies from the North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

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Synthesis

Main Results

Utsira Nord and the Norwegian Channel

With the legacy dataset, four geotechnical units can be defined in the foundation zone for floating offshore wind anchors in the Utsira Nord region of the Norwegian Channel. Unit 1 comprises exposed, normally consolidated, clay-rich glacimarine to marine sediments, deposited during and after the deglaciation of the Norwegian Channel and proven to be an ideal substrate for suction bucket anchors in the northern Norwegian Channel at the Hywind Tampen wind farm. However, in parts of the Norwegian Channel where mounded sub-glacial deposits like grounding zone systems or lateral moraines are present at and close to seabed, the ground conditions for installing large numbers of soft-sediment anchors are essentially untested. At Utsira Nord, we define two main till facies, Unit 2, a shallower, normally consolidated, exposed to shallowly buried subglacial traction till, formed by the ice stream deforming its own bedload, and Unit 3, a deeper, likely overconsolidated, buried lodgement till facies. Preliminary observations from the sub-bottom profiler dataset acquired in 2022 (Article 3, Fig. 9f) indicate that the legacy data based conceptual geological model and risk map outlined in **Article 1** are relatively accurate in terms of the distribution and thickness of the main geotechnical units defined, though additional internal reflections have since been observed within the interpreted lodgement till unit (Unit 3) at the base of the trench in the southeastern part of the site, adjacent to the shallowly buried crystalline bedrock. These reflections define a number of wedge-shaped sub-packages in the trench, which may have more variable geotechnical properties than the more homogeneous-looking, two-layer structured deformation and traction tills that characterize the western and northern parts of the site.

Utsira Nord also highlights an important aspect of the marine ground conditions along Norway's coastline, which is the presence of many exposed to shallowly buried, hard, crystalline bedrock remnants (defined as Unit 4 in the southeastern corner of Utsira Nord), that have managed to withstand the massive erosive power of the ice stream. These features present a significant risk of damage to soft-sediment anchors during installation, though are easily visible on sufficiently dense sub-bottom profiler datasets such that they can be avoided. However, the rocky nature of Norway's coastline raises an important question about cost-effective anchor design at potential future nearshore offshore Norwegian wind sites, with steep, crystalline bedrock surfaces likely to require much more expensive installation procedures (drilling) than the deeper, clay-covered areas further offshore.

Ground models are a 2D or 3D summary of the geological units defined within the shallow subsurface and at the seabed at particular offshore wind sites, and their geotechnical properties (DNV, 2018), but these are rarely published. This means that conceptual geological models which integrate geological and geotechnical information, like those presented in **Articles 1 and 2**, can raise awareness and stimulate discussion both within industry and academia about how conventional site characterization methods can become more cross-disciplinary and contribute to better and earlier understanding of the key risks and uncertainties at new offshore wind sites, even with limited, preliminary datasets.

The main geotechnical units and associated data acquisition requirements identified at Utsira Nord in **Article 1**, such as a need for better diffraction imaging for boulder mapping and more extensive core investigations in glacial till facies, are of relevance to other ongoing and future offshore wind developments. Other formerly glaciated marine areas with good offshore wind resources, where ice streaming has locally been an important land-forming process, include the coastlines of Canada, northern USA, northern UK, northern Ireland, the Irish Sea and the Mid-Norwegian Shelf.

Sørlige Nordsjø II and the North Sea Plateau

Article 2 demonstrates a methodology for integrating observations from 3D seismic attribute maps with those from high resolution 2D sub-bottom profiles and shallow sediment cores to map out key potential geotechnical risks and uncertainties at offshore wind sites with highly heterogeneous depositional facies distributions. Five main seismic-based units were defined within the upper c. 40 m of the subsurface stratigraphy at the Sørlige Nordsjø II wind site, and the distribution and likely geotechnical properties of these used to define five types of geotechnical risk zones for offshore wind foundations. These included:

- Low risk zones, where the upper c. 40 m of the stratigraphy is predominantly medium density sand with layered, low shear strength channel infills and loose surficial sand cover in the upper c. 10 m of the stratigraphy, likely suitable for all foundation types

- Medium risk (1) zones, where heterogeneous glacitectonized deposits with overconsolidated, coarse diamictons and very coarse beach type deposits occur, likely suitable for all pile-based foundation types but possible unsuitable for suction caissons

- Medium risk (2) zones, where overconsolidated glacilacustrine and layered, glacitectonized deposits are present, also possibly unsuitable for suction caissons

- High risk (1) zones, where low shear strength layered sediments are present within buried valleys, which would require foundation alterations that could be avoided through micrositing to avoid the few buried valleys

- High risk (2) zones where further investigation into the impacts of shallow salt diapirism are required

This is the first study that the authors are aware of in which a possible interplay between deglaciation and shallow salt diapir dynamics is observed. This is indicated by areas of raised seabed and shallow subsurface geomorphic features found c. 100 m above the caps of two salt diapirs. Deeper high-resolution seismic and coring is required to ascertain if the movement of the salt has caused significant alterations in soil properties, other than those observed in shallow sub-bottom profiler and vibrocore data (probable lifting and desiccation of clay deposits). Any increase in the likelihood of gas seepage around shallow diapirs in active hydrocarbon areas might also be an important area of further study in southern North Sea offshore wind sites. In this dataset, there was strong evidence of structural deformation above the salt, but no conclusive evidence of gas seepage associated with this.

Article 2 highlights the usefulness of legacy 3D seismic datasets in mature hydrocarbon provinces like North Sea, which despite their low resolution relative to typical site survey seismic profiles, still contain useful amplitude and frequency variations within the seabed reflection pair which can allow important geomorphic features to be mapped out prior to acquisition of expensive high-resolution seismic data. Identification of geomorphic features in the shallow subsurface can also represent a powerful aid to understanding the distribution and genesis of seismic and sedimentary facies identified in high-resolution 2D acoustic data and cores when acquisition of UHR 3D seismic is not affordable.

The study also contributes to building an understanding of the depositional evolution of the Dogger Bank-Jutland Bank-Elbe Palaeovalley-Ling Bank areas of the southern North Sea during and after the retreat of the Late Weichselian icesheet(s). The presence of small, localized glacilacustrine infills at the site, for example, indicate that the large ice-dammed lakes that existed north and south of Dogger Bank did not extend as far north and east as Ling Bank, as tentatively postulated by Roberts et al. (2018), while clear signs of lateral accretion in the interpreted fluvial Unit 2 facies are consistent with theory of Sejrup et al. (2016) and Hjelstuen et al. (2018) that the Ling Bank was a zone of major fluvial erosion and deposition at the end of the Late Weichselian, likely exploiting a weakness or gap between the glacitectonic complexes of the Dogger and Jutland Banks. In addition, the presence of glacimarine sedimentation at the site, within the Sørlige Nordsjø II palaeovalley, indicates that the sea began to encroach on the area much earlier than previous reconstructions have indicated (e.g., Gaffney, 2017), closer to c. 23-18 ka when the retreating icesheet was still present in the region, than c. 10 ka when the icesheets had fully retreated from the North Sea.

Ground conditions for offshore wind foundations in the North Sea

Articles 1 and 2 highlight the contrast in ground conditions between the deep Norwegian Channel ice stream trough and the shallow, formerly terrestrial, North Sea Plateau. As these were found to constitute essentially two "end-members" of ground condition types, **Article 3** was used as an opportunity to investigate further ground condition end-member types in the North Sea and beyond. On the basis of literature case studies and reports from planned, existing and failed offshore wind developments,

Article 3 therefore outlines a broad-scale classification system for ground conditions for offshore wind foundations and anchors for the whole North Sea (Article 3, Fig. 10).

These are:

- **Province 1:** shallow coastal areas where Quaternary sediment cover is relatively thin, with shallow to exposed bedrock
- **Province 2:** the Norwegian Channel (a deep coastal area formerly affected by major Quaternary ice streaming, where shallow bedrock is present locally and Quaternary sediments are predominantly clay-rich)
- **Province 3:** the North Sea Plateau (the moderately deep, predominantly sandy, central parts of the North Sea characterized by multi-generational buried tunnel valley systems, heterogeneous terrestrial to shallow marine deposits and mild to moderate glacitectonism)
- **Province 4:** the Dogger Bank-Jutland Bank zone, a region of strong glacitectonism and highly heterogeneous soil properties correlating to the maximum position of the last North Sea icesheet(s)

The suitability of the defined ground condition provinces for different foundation and anchor types for offshore wind turbines are also explored in **Article 3**. Though a range of design solutions are often applicable and also depend on factors other than ground conditions (for example water depth, supply chain considerations, turbine size), the classification system represents a basis for defining the key geological constraints and risks that should be considered during first pass foundation or anchor design discussions. Broadly speaking, where bedrock is present in the “foundation zone” of the subsurface, the properties of this and the properties of the overlying Quaternary cover will both exert a strong influence on foundation/anchor design and placement considerations. Where bedrock is not a consideration, the distribution and properties of the depositional and possibly the structural facies related to the glacial and inter-glacial processes of the Late Quaternary will be the primary influencers of the ground conditions and thus the geotechnical design considerations. There do not appear to be many other regional-scale summaries of ground conditions in the literature, except for a broad comparison of the North Sea and the Canadian and North American North Atlantic coastlines by Eamer et al. (2021). **Article 3** is therefore intended as a useful and thus far relatively unique reference for geological considerations for offshore infrastructure development in the North Sea and other previously glaciated marine areas.

Perspectives

Improving integration of geological, geophysical, and geotechnical data

Better integration of subsurface data has an important role to play in improving the cost-efficiency of offshore wind developments. **Articles 1 and 2** demonstrate methodologies for integrating detailed information about depositional setting with available geophysical, geological and geotechnical data to summarize the key potential constraints and uncertainties for offshore wind anchors or foundations at a particular site affected by the Late Quaternary glaciations. The sentiment of this approach is recommended as a means of improving the site survey approaches used today at offshore wind sites, in which geotechnical and geophysical observations are typically correlated with relatively little weight given to relating these to depositional facies variations or structural provinces. This is something that should also continue to be a priority in the field of numerical ground-modelling which uses machine learning to correlate geophysical and geotechnical data.

Foundation installation data is routinely measured and often shared in geotechnical reporting, however, is rarely, if ever, used in geologically-focused studies of offshore wind areas. Comparison of such data to depositional facies and glacitectonic structures during and after site characterization could provide an additional means of understanding how geotechnical and geological character are linked in Late Quaternary depositional and glacitectonized units.

New data acquisition strategies

As outlined in **Article 3**, new data acquisition strategies are evolving out of necessity in the relatively young field offshore wind site characterization, because the standard approaches inherited from the characterization of much smaller oil and gas infrastructure sites are often insufficient for developing the necessary understanding of the ground conditions and their heterogeneities across very large wind sites in complex geological provinces. These include acquisition of targeted UHR 3D seismic surveys rather than very densely spaced 2D profiles where stratigraphy and geotechnical data are very challenging to correlate e.g., at Dogger Bank, and offshore Ireland, increasing awareness of the importance of seismic-CPT logs to give better seismic to geotechnical log ties and aid machine-learning based ground modelling, and increasing awareness of the potential of collecting geological data at offshore wind sites i.e., continuous cores for CT scanning and sedimentary logging, which is rarely if ever carried out during offshore wind site surveys.

Data availability and knowledge transfer in academia and industry

Data availability in the field of offshore wind site characterization is very mixed from country to country and site to site. Countries such as the Netherlands, the UK and the USA have taken a very positive approach to data release, with national archives of extensive geophysical and geotechnical datasets from offshore wind site surveys freely available for download. This is highly useful for both education and research and for use in industry desktop study work. This approach is not taken everywhere, or has not been decided upon in some countries, such as Norway, but the benefits should not be underestimated. In this project, there has also been a very positive experience regarding openness between academia and industry, with great engagement with the research done in this project, and UiB's future aims in this field. To date, the Dogger Bank offshore wind development project, Forewind, remains the most extensive documented industry-academia collaboration on offshore wind, with the publication of a large number of detailed, geologically focused papers that have revealed the complexities hidden beneath the surface of the North Sea, previously largely unrecognized within the geological literature. More collaborations like this would be of great benefit to the offshore wind community at large and could contribute greatly to education and the cost-efficiency of offshore wind.

Future work

The extensive dataset collected at Utsira Nord and Sørlige Nordsjø II has inspired a number of Master's thesis projects and additional marine geological cruises to the sites, to be undertaken within 2023 and 2024. These will constitute continuing research into the geophysical and geotechnical properties of the different depositional facies types found within the Norwegian Channel and on the North Sea Plateau, through for example, triaxial testing of the traction till units identified at Utsira Nord, detailed seismic interpretation and sedimentary and multi-sensor core-logging of the sub-bottom profiler dataset and gravity and piston cores collected at Utsira Nord and further sedimentary logging of the Sørlige Nordsjø II vibrocores to enable a deeper understanding of the facies variations and depositional ages of the facies there. Additional cruises to the site will focus on investigating UHR and tomographic seismic techniques to aid visualisation of subsurface heterogeneities that are difficult to image using conventional techniques, such as boulder distribution within glacial tills, stratigraphic boundaries within infilled tunnel valleys and occurrences of shallow gas in solution, all of which represent important geohazards to offshore wind foundations. More generally, an important step forward in the field of geological characterization of ground conditions for offshore wind, especially in glacial settings, will be the development of depositional facies and geomorphic data bases, which bring together the learnings from different offshore wind site case studies, onshore field examples etc, which provide information on the geophysical properties, geotechnical properties, scale and distribution of different facies types, for example Late Weichselian moraines or glacilacustrine deposits.

Conclusions

Overall, the articles presented in this thesis are intended as a basis for opening the relatively young field of large-scale offshore wind site characterization to geoscientists and engineers alike, including those with backgrounds in other fields. The thesis presents the results from an integrated geological characterization of the seabed and shallow subsurface conditions for offshore wind foundations within the North Sea. Moreover, integration of legacy datasets, background regional knowledge of the region's Late Quaternary glaciations and a targeted high-resolution marine data acquisition and interpretation campaign have allowed methodologies for ground modelling and risk mapping at offshore wind sites to be explored, and a broad zonal classification system of the North Sea ground conditions to be defined.

In **Article 1**, a conceptual geological model for the planned Utsira Nord floating offshore wind site in the Norwegian Channel is presented, and the link between ice stream geomorphology and ground conditions investigated. In general, the geotechnical properties of sub-glacial ice stream deposits, particularly lodgement tills, are highly uncertain, due to their resistance to gravity core sampling, and due the sparseness of deployment of floating wind turbine anchors in such deposits. Installations to date have been located in the younger, late-glacial to post-glacial fine-grained sediment cover, and so grounding zone system lodgement and traction tills such as those interpreted at Utsira Nord, and other similar parts of ice stream infills have yet to be investigated by full-scale site surveying.

In **Article 2**, focus is shifted to the ground conditions at the Sørlige Nordsjø II bottom-fixed offshore wind site, formed beneath the vast areas of more passive ice that repeatedly occupied the North Sea during the Late Quaternary. In this area, the ground conditions are highly heterogeneous, having experienced repeated phases of terrestrial and marine deposition, with some facies more predominant than others in particular areas depending on the specific depositional systems which occupied them during the glacial and interglacial periods.

In **Article 3**, a number of case studies from other parts of the North Sea, and further afield, demonstrate that correlation of geotechnical data and seismic interpretation can be very challenging in glacially influenced settings, which often requires on-the-fly innovations and decisions to be made during the site characterization process. Overall, however, glacial soils do not have to be a showstopper in the development of offshore wind when adequate investigation and testing of the site-specific heterogeneities and their implications for the installation strategy/design of the turbine foundations are carried out. However, mitigation of challenging ground conditions is still often focused on the "what" (not the "why") of the soil heterogeneities, limiting how much previous site characterization experiences can contribute to future site investigations and installation strategies at sites with similar ground conditions. Improved integration across geology, geophysics and geotechnical engineering, along with knowledge transfer and data openness are key to innovating how site characterization is carried out, increasing efficiency and reducing costs.

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Appendices

Appendix 1 – Conference Abstracts

Norwegian Geological Society Winter Conference 2021 (Online)

An integrated geological characterization of marine ground conditions for offshore wind foundations in the North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

March 2021

Available online
https://www.geologi.no/konferanser/vinterkonferanser/abstracts/file/245-abst-vk21

The North Sea is set to become an important player in the burgeoning offshore wind industry. A better understanding of how marine ground conditions influence the foundations of offshore wind installations is required in order to bring down project development costs and achieve the renewable energy goals of the EU's Green Deal. This study investigates two recently announced offshore wind sites in the Norwegian sector of the North Sea; Utsira Nord and Sørlige Nordsjø II. The sites are extensive, covering c. 1000 Km2 and 2600 Km2 respectively. The increasing size of offshore wind sites represents a significant challenge with regards to characterizing geological heterogeneity, particularly within the Late Quaternary glacial-marine deposits of the North Sea. The main aims of this study are to 1) Investigate how the geological conditions at and below the seabed influence the location and design of offshore wind foundations and anchors, 2) Acquire high resolution acoustic data and cores to investigate the key geotechnical risks to offshore wind developments and provide recommendations for the scope of site surveys in geologically heterogeneous areas and 3) Investigate the potential for integrated geological-geotechnical modelling to predict geotechnical risks across geologically heterogeneous sites to facilitate safe and lower-cost foundation design. The sub-objectives of the study are to analyse and interpret the geophysical, marine and geotechnical data at the two sites, to identify and classify key "geotechnical facies" and their distribution, and to establish workflows and test modelling techniques for acquiring and integrating geological and geotechnical data at offshore wind sites in the North Sea. As a relatively new and rapidly growing industry, an integrated overview of site survey planning and ground modelling techniques for offshore wind is currently lacking. This study aims to fill that gap and contribute towards a more consistent method of characterizing marine ground conditions at offshore wind sites in the North Sea.

European Association of Geoscientists and Engineers 2nd Global Energy Transition Conference (Online)

A conceptual geological model for Utsira Nord offshore wind site in the Norwegian North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

November 2021

https://doi.org/10.3997/2214-4609.202121033

Geoscience has a fundamental role to play in the development of safe, cost-effective offshore wind installations. Conceptual geological models of the seabed and shallow subsurface are key to planning efficient data acquisition programs and designing appropriate infrastructure at prospective sites in the early phases of development. Additionally, a better understanding of the soil-structure interactions of offshore wind turbines is urgently required if renewable energy goals are to be met. A detailed geological understanding of the turbine foundation or anchor substrates within new offshore wind areas will be an important component of this. In this study, a conceptual geological model for the Utsira Nord site in the Norwegian North Sea is presented, bringing together an overview of previous knowledge about the complex ice streaming history of the Norwegian Channel together with key observations from high resolution bathymetric data, 2D seismic data, sub-bottom profiles, and shallow cores. Despite limited data coverage, four main geological-geotechnical provinces can be defined: 1) buried lodgment till, 2) buried to exposed sub-glacial traction till suitable for suction-type anchors, 3) exposed glacimarine to marine sediments suitable for suction-type anchors and 4) shallowly buried to exposed crystalline bedrock which will likely require a pile-based or novel anchoring solution.

European Academy of Wind Energy 18th PhD Seminar (Bruges)

Geological considerations for offshore wind foundations at "Sørlige Nordsjø II", Norwegian North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

November 2022

https://phd2022.eawe.eu/program/book-of-abstracts/

1. Introduction

A better understanding of how offshore wind turbine foundations interact with geological substrates is required to optimize their design and reduce costs. An important component of this will come from developing a more detailed geological and geotechnical understanding of the foundation substrates within new offshore wind areas. The Norwegian North Sea represents a new area for the development of offshore wind, with two >1000 km^2 sites announced in 2020 and a recent government announcement signalling plans to develop 30 GW of offshore wind capacity by 2040. In this study, we focus on the geological conditions at the Sørlige Nordsjø II (SNII) site, located 140 km offshore, along the southern border of the Norwegian North Sea. Here the water depths range from 50-70 m: extending beyond the maximum depth of any bottom-fixed offshore wind farm developed to date. For this reason, a detailed understanding of possible design challenges relating to the geological substrate will be particularly important at SNII. During the Quaternary period (<2.6 million years ago), the southern North Sea was occupied repeatedly by icesheets, glacial outwash plains, and a moving coastline dictated by changing sea level. As a result, the distribution, thickness, and geotechnical properties of the soil units present within the shallow subsurface (<50-100 m) can vary significantly from one foundation location to another. The aims of this contribution are therefore to 1) present the preliminary results from a newly acquired geological dataset from SNII, and 2) to define key geological units within the shallow subsurface and their implications for site survey planning, foundation design and installation at SNII.

2. Methods and Data

In this study we combine an overview of previous knowledge about the geological history of the southern North Sea with observations from bathymetric data, 2D and 3D seismic data, and sub-bottom profiles and shallow cores collected from SNII in June 2022 by the University of Bergen. The preliminary geological interpretations from these data are integrated to define a conceptual geological model for SNII, which divides the upper 50 m of the stratigraphy into geological units likely to have contrasting geotechnical properties and implications for foundation design.

2D and 3D seismic data were sourced from the Norwegian National Data Repository for Petroleum Data (surveys DG15001, MC3D-NDB2008 and ST99M1-AREA 3) and PGS Geophysical AS (survey MC3D-NDB2013) (Fig. 1b). The seabed reflection was interpreted, and depth converted using a seismic velocity of 1500 m/s (average P-wave velocity of seawater). The depth converted surfaces were then used to identify geomorphic features on the seabed and compared with the geomorphology of the wider region on bathymetric maps [1] (Fig. 1a). Seismic variance and amplitude attribute extractions were made for the seabed surface, and for time slices below seabed, to identify buried features and those with a subtle surface expression. The features identified on the seismic data were then targeted for further investigation during a University of Bergen marine geological cruise on the R/V G.O. Sars in June of this year. This included collecting parametric sub-bottom profiles with the Kongsberg TOPAS PS18 sonar system and vibro-cores collected with the Geo-Corer 6000 High Frequency Vibro Core System at various locations across the site (Fig. 1c). In total, 900 km of sub-bottom profiles and 13 vibro-cores (total combined length 67 m) were collected within the upper 6 m of the subsurface. These are currently undergoing sedimentological analysis, multisensor core-logging and planning for geotechnical analysis. The sub-bottom profiles are being interpreted in the seismic interpretation software Petrel to map out the distribution and thickness of the distinguishable seismic units (e.g., Figs. 2a, 2b). The sub-bottom profiles give an approximately ten-fold increase in resolution across the geomorphological features identified on the 3D seismic (25 cm vs~25 m), allowing a more thorough investigation of the stratigraphic architectures within the different features. During the cruise, each of the seismic units were sampled by the vibro-corer to investigate the sedimentological and geotechnical properties of the unit and thus the implications for offshore wind foundation design and site survey planning.

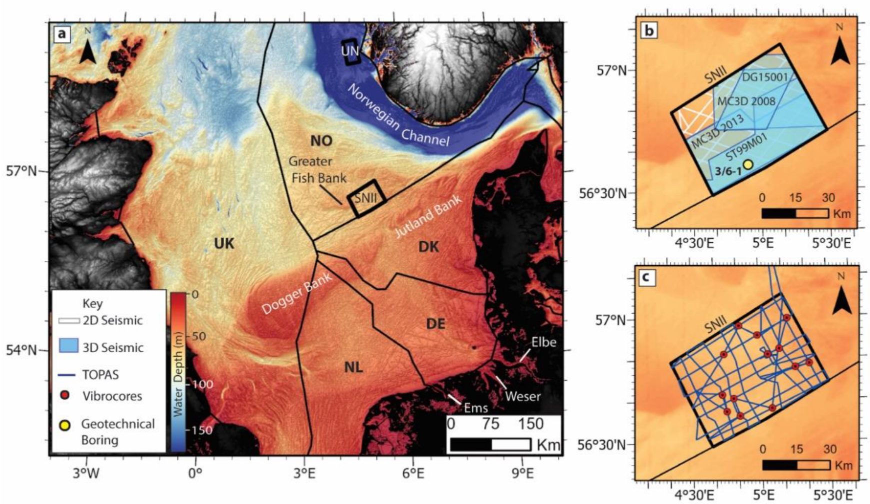

Figure 1: (a) Locations of announced Norwegian offshore wind sites Utsira Nord (UN) and Sørlige Nordsjø II (SNII). Bathymetry (seafloor depth map) [1], (b) existing 2D and 3D seismic data at SNII and geotechnical boring 3/6-1 [2], c) newly acquired vibro-core and sub-bottom profiler (TOPAS) data at SNII, collected by University of Bergen.

3. Results

SNII can be divided into two provinces (Fig. 2): a shallow (~50 m deep) eastern province characterized by mounded and ridge-like features on the seabed comprising mud, sand, gravel and boulders, and a 50-70 m deep western province with a smooth seabed consisting of sand to gravelly-muddy sand ([3]) (Fig. 2). The mounds and ridges in the eastern province are related to a chaotic seismic unit consisting of multiple generations of sediment deposition and valley incision (Unit 5, Fig. 2b), interpreted as a remnant glacial landscape comprising glacitectonized (glacially deformed) sediments. This unit is often exposed at the seabed in the eastern part of SNII but is locally covered by a transparent seismic unit with a smooth surface, interpreted as post-glacial marine sand (Unit 1a, Fig. 2b). In the western province, Unit 5 is overlain by several different seismic units whose thickness and distribution vary laterally. The oldest of these (Unit 4, Figs. 2a, 2d) is a flat-lying to deformed, layered unit which infills lows in Unit 5, which likely represents glacimarine to marine sands from the previous interglacial period (the Eemian). In the south-western part of the site, Unit 4 is locally incised and infilled by a transparent seismic unit (Unit 3, Fig. 2a) which likely correlates with the stiff to hard glacilacustrine clays assigned a Weichselian age (the last glacial period) within boring 3/6-1 (Fig. 1b, [2]). Within southern and central parts of the site, incisions, and depressions within Units 4 and 5 are infilled by a seismic unit with medium to high amplitude, inclined internal reflections (Unit 2, Figs. 2a, 2d), indicating a layered sedimentary deposit likely of fluvial origin. Along the boundary between the western and eastern provinces, Unit 2 sediments appear to have been disturbed by an overlying low to medium amplitude, layered, seismic unit (Unit 1b, Figs. 2b, 2d), interpreted as shallow marine sediments deposited as sea level began to rise after the last glaciation. Unit 1b is onlapped in turn by a transparent seismic unit (Unit 1a) interpreted as open marine sediments deposited as the area became fully submerged by the North Sea.

4. Discussion

The next phase of this project will focus on evaluating the sedimentological and physical properties of geological Units 1-5, and the implications of their distribution and thickness for offshore wind foundation design. Key factors to be investigated include: 1) the stiffness of glacitectonized Unit 5, given that it has likely been compressed by ice during both the Weichselian and Saalian glacial periods, 2) the geotechnical properties of sandy Unit 4, 3) the stiffness of localised Unit 3 and whether the contrasting properties of Units 3,4 and 5 are likely to cause any foundation challenges, 4) the sedimentology and geotechnical properties of estuarine Unit 2 and whether these deposits present any risks to site survey operations such as use of jack-up rigs. Remaining uncertainties which cannot be addressed in this study but are recommended as follow up topics for full-scale site surveying of SNII include 1) in-situ and geophysical investigation of Unit 5 to determine whether boulders are widespread or rare in occurrence, 2) soil scour evaluation for surficial sand Units 1a and 1b for the foundation type chosen.

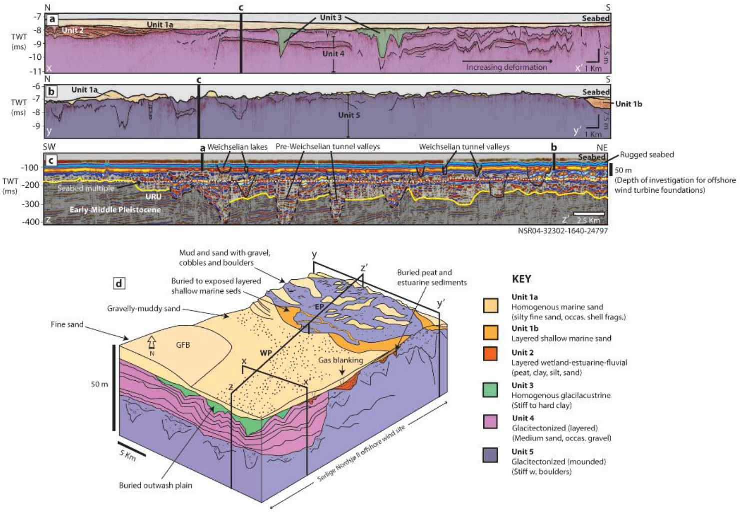

Figure 2: (a) Sub-bottom profile from western SNII, (b) Sub-bottom profile from eastern SNII, (c) 2D seismic section across SNII showing the deeper subsurface stratigraphy, (d) Conceptual geological model for SNII showing key geological units. GFB, Greater Fish Bank; WP, Western Province; EP, Eastern Province.

5. Conclusions

The conceptual geological model presented in this study defines five geological units: 1) homogeneous and layered marine sands covering most of the site, with patchy distribution in the east, 2) buried estuarine channel deposits common within central and southern parts of the site, containing organic material and associated biogenic gas, 3) buried, stiff, glacilacustrine clay deposits, 4) buried, layered, glacitectonized glacimarine-marine sands and 5) mounded glacial tills/glacitectonized deposits containing boulders, exposed in the east. The next phase of the project will focus on investigating the sedimentological and geotechnical characteristics of the defined geological units through core analysis and comparison to correlatable units within other sectors of the southern North Sea.

Acknowledgements

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European Association of Geoscientists and Engineers 3rd Global Energy Transition Conference (The Hague)

Geological Conditions for Offshore Wind Turbine Foundations at the Sørlige Nordsjø II site, Norwegian North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

November 2022

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A better understanding of how offshore wind turbine foundations interact with geological substrates is required to optimize design and reduce costs. An important component of this will come from developing a more detailed geological and geotechnical understanding of the foundation substrates within new offshore wind areas, such as the Norwegian North Sea. In this study, we focus on the geological conditions at the Sørlige Nordsjø II site, located along the southern border of the Norwegian North Sea. We present a conceptual geological model which combines an overview of previous knowledge about the geological history of the southern North Sea with observations from bathymetric data, 2D and 3D seismic data, and recently acquired sub-bottom profiles and shallow cores collected from the site in June 2022 by the University of Bergen. Based on our preliminary analyses, five main geological units are defined: 1) homogeneous and layered marine sands covering most of the site, with patchy distribution in the east, 2) buried estuarine channel deposits containing organic material and associated biogenic gas, 3) buried, stiff glacilacustrine clay deposits, 4) buried glacitectonized glacimarine-marine sands and 5) mounded glacial tills/glacitectonized deposits containing boulders, exposed in the east.

Geoscience Energy Society of Great Britain 1st Energy Geoscience Conference 2021 (Aberdeen)

Working smarter in offshore wind site characterization and ground modelling: integration, integration, integration!

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

May 2023

The range of offshore wind foundation technologies available today have grown to a large extent out of the geotechnical engineering competencies developed from the offshore oil and gas sector, and the associated developments in near surface and shallow geophysics. Indeed, many of those who work in offshore wind site characterization and ground modelling have a technical background in geophysics, geology or geotechnical engineering related to the offshore oil and gas industry. Thus, the relatively young but rapidly growing offshore wind industry is a perfect example of the wide applicability of geoscience in the energy mix and the possibilities for two-way learning in the energy sector.

While similar types of shallow geophysical data are required for site characterization for both oil and gas and offshore wind infrastructure, some new challenges relating to management, interpretation and integration of these data have presented themselves as wind farms have grown in size and moved into areas of more geologically complex seabed. As wind farm sites cover much larger areas of seabed than an individual oil platform, very large datasets of seabed and subsurface geophysical (and geotechnical) data are required to adequately characterize the soil conditions for the design of offshore wind turbine foundations. Characterizing the seabed over larger areas is also more challenging in terms of workload and understanding a wider range of geological conditions between turbine locations. These challenges are being tackled through detailed seismic stratigraphic analyses of new offshore wind areas with a focus on characterizing the geotechnical properties of the different stratigraphic units, particularly in complex areas impacted by glacial processes and post-glacial terrestrial processes, such as the North Sea. However, the geological and geotechnical aspects are often not as well integrated as they might be, perhaps due to issues with communication or sharing of these large datasets. This is an area in which experience and workflows from hydrocarbon exploration could be beneficial, in terms of interpreting, synthesizing, and communicating results from very large geophysical and well datasets.

In this study, interpretations from legacy 2D and 3D seismic datasets are combined with newly acquired shallow subsurface data to better understand how the marine ground conditions within the Norwegian sector of the North Sea will impact the design and installation of offshore wind foundations and anchors. The main focus areas are the Utsira Nord floating offshore wind site and the Sørlige Nordsjø II bottom-fixed offshore wind site, located at water depths which will push the boundaries of existing bottom-fixed foundation technologies. The aims of this contribution are therefore to 1) present the results from a newly acquired geological dataset from Utsira Nord and

Sørlige Nordsjø II which targeted key heterogeneities and possible geohazards at the sites with sub-bottom profiling and shallow coring, 2) to define the key geological units within the shallow subsurface and their implications for site survey planning, foundation design and installation in formerly glaciated marine areas such as the North Sea and 3) to emphasize the importance of conceptual geological models for cross-disciplinary communication and collaboration in energy geoscience.

European Association of Geoscientists and Engineers Near Surface Geoscience Conference 2023 (Edinburgh)

Integrating geological and geotechnical considerations in buried glacial landscapes

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

September 2023

Introduction

Geology and geotechnics are inextricably linked fields, but during offshore wind site surveying, the geological and geotechnical methods for analysing the variability and geohazards at the site are often poorly integrated. Geotechnical subdivisions of the shallow subsurface are usually linked to the geological setting via correlation using acoustic profiles. However, sedimentary logging of cores, which allows subtle facies changes indicating transitions in depositional environment to be identified, are not standard during geotechnical investigations because the sampling needs to be conducted on intact cores that have not been split open. This means that important geological features can be missed or underestimated in terms of their impact on operational efficiency during installation or on the stability of the structures in the longer term. Buried glacial landscapes such as the North Sea are particularly variable geological terrains (e.g., Cotterill et al. 2017; Andresen et al. 2022) where detailed geological understanding needs to underpin geotechnical sampling and modelling (e.g., Prins and Andresen, 2021) to properly predict the types of challenges which may be encountered at a particular site, and at a particular depth or location within the site. In this study, we investigate how geology and geotechnics in the field of offshore wind can be integrated more effectively and present the findings of two case studies characterizing marine ground conditions in contrasting parts of the Norwegian North Sea (the deep Norwegian Channel and the shallow southern North Sea Plateau, Fig. 1).

Methods and Data

In this study we combine an overview of the types of marine ground conditions that occur within the Norwegian Channel, a marine trough formed by repeated late Quaternary ice streaming, versus the shallower plateau area of the Norwegian sector of the southern North Sea, which was repeatedly covered by the British-Irish and Fennoscandian icesheets during the late Quaternary period. A 2D sub-bottom profiler and shallow sediment core dataset consisting of gravity and piston cores from the Utsira Nord (UN) offshore wind site in the Norwegian Channel, and vibrocores from the Sørlige Nordsjø II (SNII) offshore wind site in the southern Norwegian North Sea were analysed using 2D seismic interpretation integrated with observations from legacy conventional 2D and 3D seismic data, bathymetry data, legacy geotechnical reporting (Fugro, 2000; Hammer et al. 2016) and key literature from the Norwegian Channel and other areas formerly affected by ice streaming, and from the British, Danish and German sectors of the southern North Sea. The shallow sediment core dataset was analysed using multi-sensor core-logging, including gamma density and magnetic susceptibility measurements, sedimentological logging, cumulative grainsize analysis and measurement of shear strength by cone apparatus and triaxial testing. Detailed sedimentological interpretation with a focus on the evolving late glacial to post-glacial depositional environments were integrated with seismic observations and core logs to define conceptual geological models and environmental reconstructions for the Norwegian North Sea during the late Quaternary period that subdivide the shallow subsurface into depositional units with different geotechnical properties and implications for offshore wind turbine foundation design and installation.

Results

Integrated geological desktop studies of UN (Petrie et al. 2022a) and SN II (Petrie et al. 2022b) have demonstrated that the Norwegian Channel and the North Sea Plateau area outside of the channel (Fig.1a) effectively represent two end members of marine ground conditions for offshore wind foundations in the Norwegian North Sea. The UN site and wider Norwegian Channel have water depths of over 200 m and are only suitable for floating offshore wind, which has been tested at Hywind Demo south of UN and is being scaled up in the northern part of the channel at Hywind Tampen. Ground conditions within the Norwegian Channel are characterized by sub-glacial till units with varying degrees of over consolidation, laminated, soft cohesive glacimarine deposits laid down during periods of ice stream retreat, and soft, cohesive post-glacial marine sediments which vary in thickness from a few centimetres to tens of metres thickness within the channel. The glacimarine to marine sediments and the upper parts of the sub-glacial tills beneath them, are broadly ideal for suction buckets, the most common type of floating offshore wind anchor, though complexities could arise from the presence of ice-rafted, coarser grained deposits, and where the soft sediment cover above older, overconsolidated till deposits or sedimentary bedrock are thin. Recently acquired sub-bottom profiles and core logs from Utsira Nord (Fig. 1c) indicate additional internal complexities such as localized wedges of dense sediment within the till unit, particularly in the south-eastern part of the site, where streaming ice appears to have fed into the channel from nearby Boknafjorden, which were not identified on the previous dataset presented in Petrie et al. (2022).

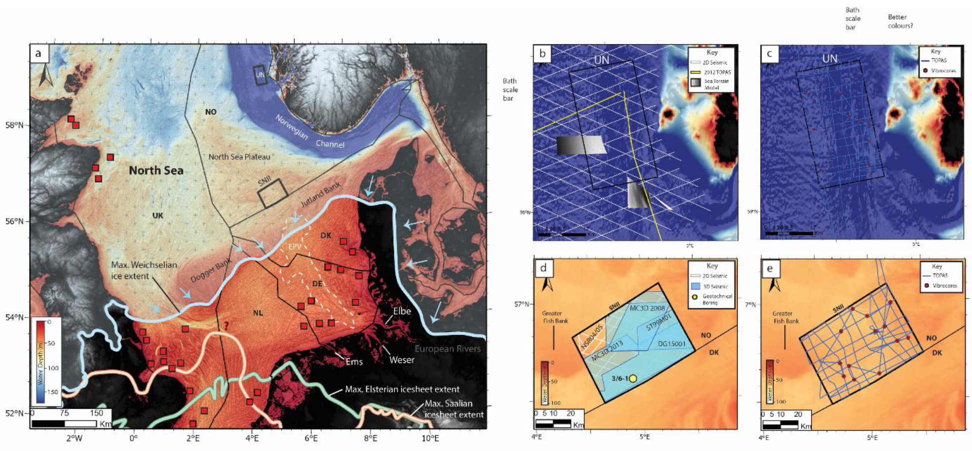

***Figure 1**. **a)** GEBCO (2020) bathymetric hill-shaded map of the North Sea showing locations of UN and SNII offshore wind sites, maximum extent of late Quaternary icesheets and location of fully commissioned offshore wind farms (red squares) (TGS, 2023), **b)** legacy 2D seismic data, sub-bottom profile data (Hjelstuen et al. 2018) and high-resolution bathymetric data at UN, **c)** sub-bottom profiler and vibrocore dataset at UN acquired in 2022, **d)** legacy 2D and 3D seismic data covering SNII (MC3D 2013, PGS; all other surveys, DISKOS), **e)** sub-bottom profiler and vibrocore dataset at SNII acquired in 2022 by University of Bergen.*

In contrast, marine ground conditions at SNII and elsewhere on the North Sea Plateau (e.g., Dogger Bank), are characterized by a much wider range of sedimentary facies types and variations in geotechnical properties both vertically and laterally. Water depths are generally less than 100 m, often suitable for bottom-fixed offshore wind foundations, though SNII, reaching water depths of 70 m is deeper than the world's deepest bottom-fixed offshore wind farm to date. At SNII, sub-bottom profiles, 3D seismic attribute time slices, geotechnical report 3/6-1 (Fugro, 2000) and shallow core data (Figs. 1d, 1e) indicate that the western side of SNII was a low-lying glacial outwash plain at the end of the last glacial maximum, likely fed by both glacial meltwater from the retreating British-Irish and Fennoscandian Icesheets to the north, east and west, glacial lake drainage from ice-dammed lakes north and/or south of the Dogger Bank glacitectonic complex and fluvial input from the Elbe Palaeovalley to the south. Beneath loose, relatively homogeneous Holocene marine deposits therefore, the western side of SNII is highly heterogeneous, with very soft, possibly peat- and gas-bearing incised channel infills and localized stiff, desiccated proglacial lake infill deposits within a substrate of glacially eroded Eemian interglacial marine sands and remnants of older, folded substrate left between Saalian tunnel valleys. The eastern side of the site is characterized by a rugged, remnant glacial landscape (Unit 5), with thin, sandy pebble-rich glacial till deposits overlying the older interglacial sand deposits. The subglacial and glacially reworked older deposits locally display folding on sub-bottom profiles, within mounds and ridges which are exposed at seabed, or covered by tens of centimetres of loose, pebbly to sandy marine deposits. A 20 km long valley runs from southeast to northwest along the eastern part of the site (Fig. 2c) which incises into the underlying glacitectonized deposits (Unit 5) and is characterized by multiple generations of infilling and erosion (Fig. 2a, 2b, 2d), divided broadly into Units 3b, Unit 2 and Unit 1. The upper part of Unit 2 is cored (Fig. 2) and reveals a low shear strength, laminated clay containing plant fragments and cold-water marine foraminifera, truncated, and overlain by medium-grained shelly marine sands. The lower parts of Unit 2 and Unit 3b are not cored, but exhibit patchy to semi-continuous, very strong amplitudes on sub-bottom profile (Fig. 2d) which could indicate much stiffer or coarser deposits below the soft, laminated clays in the shallow part of the valley.

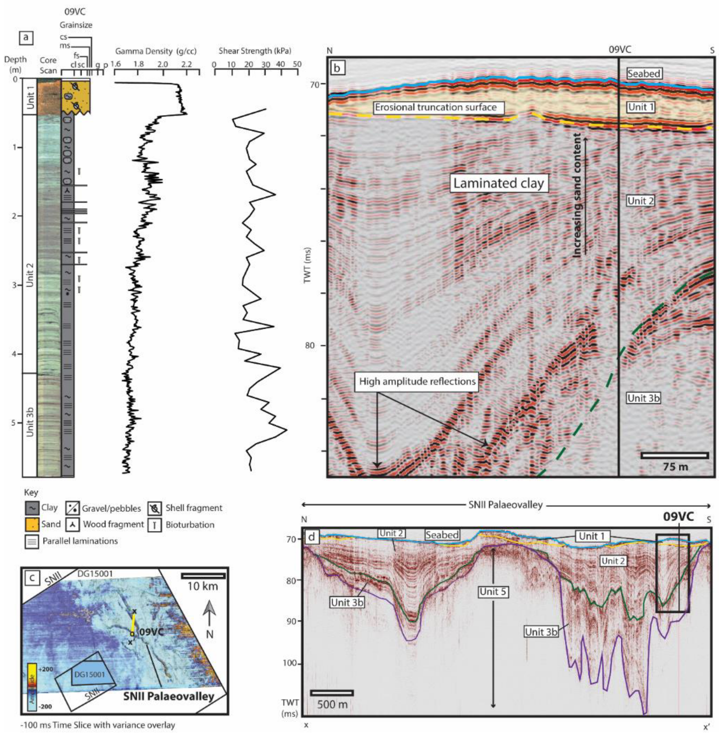

*Figure 2. **a)** Core-scan photograph, sedimentological log, gamma density and shear strength measurements from vibrocore 09, located within the infill of a Palaeovalley system in eastern SNII, **b)** sub-bottom profile correlated to vibrocore 09 showing the erosional surface marking marine inundation of the infilled valley, truncating the laminated clays below (extent of the profile is shown by a black outlined box in (d), **c)** seismic time-slice approximately 30 ms below seabed, showing the soft acoustic signature of the infill of the Palaeovalley, **d)** N-S profile across two branches of the Palaeovalley and vibrocore 09, showing multi-generational erosion and infilling of the valley system.*

Discussion

One of the main uncertainties around marine ground conditions in the Norwegian Channel is the degree of over consolidation and heterogeneity within deeper subglacial tills below the reach of gravity core sampling and masked by the chaotic nature of the seismic facies exhibited by subglacial tills on sub-bottom profile data. Such facies can reach over-consolidation ratios that are problematic for suction anchor installation in other ice stream troughs such as the Irish Sea, but no such operational information has yet been published for suction anchor installation in the Norwegian Channel e.g., from Hywind Tampen. SNII has experienced a very different depositional history and so different geotechnical challenges need to be considered. The loose surficial sand deposits of Unit 1 need to be investigated for scour risk in this shallower setting, particularly the fine-grained deposits in the western part of the site. For the coarser surficial deposits in the eastern part of the site, probably representing reworked moraines, this is less likely to be an issue, but the zones containing pebble-rich layers represent potential installation hazards to suction or pile-based jacket foundations. The various underlying incisional features found in both the eastern and western parts of the site are interpreted as late Weichselian subglacial to proglacial erosional features, with their infill recording a range of depositional environments in time and space. 3/6-1 encounters a 10 m thick lake infill of hard clays up to 280 kPa in shear strength which are likely to have become overconsolidated due to subaerial exposure and desiccation, and such facies are reported to have been a challenge at the Dogger Bank offshore wind zone. In contrast, other proglacial lake and channel features at the site are infilled by very soft, layered deposits, which have clearly avoided the processes which resulted in overconsolidated in other parts of the site, and are interpreted as lacustrine to marine influenced systems which continued to be supplied with freshwater from icesheet melt/ice dammed lakes/the Elbe river system until they began to be inundated by the sea encroaching from the north (upper Unit 2/Unit 1). In the western part of the site, the soft infills are unlikely to cause significant challenges to foundation installation, but their properties do need to be accounted for in the required length of the piles/buckets, and the risk of the presence of peats and shallow gas also need to be taken into account during borehole sampling. In the eastern part of the site, the incised Palaeovalley is up to 20 m deep, with at least 6 m of very soft clay infill in its upper parts, while the surrounding substrate (Unit 5) is likely to be significantly coarser and stiffer. The Palaeovalley represents a significant deviation in geotechnical character from the majority of the eastern part of the site, and should probably be avoided.

Conclusions

The potential geotechnical challenges represented by facies heterogeneities at UN and SNII demonstrate the importance of integrating an understanding of depositional environment changes during the end of the last glaciation with the resulting impact on the geotechnical properties of the sediments laid down during this period and their distribution. Though characterizations of the subsurface based mainly on geotechnical values give rapid and reasonable prediction of marine ground conditions for foundations across increasingly large and complex offshore wind sites, the value of understanding what these values represent in terms of sedimentary facies and the processes which altered and influenced their properties, to create analogues that can be applied to future sites, should not be underestimated.

Acknowledgements

This work is funded by the Akademia Agreement at UiB. Thanks to the crew, students and staff who assisted with the acquisition of data at UN and SNII on R/V G.O. Sars in 2022, particularly Jo Brendryen who assisted with core-logging. Thanks to PGS for providing seismic survey MC3D 2013 and to ENI for providing geotechnical report 3/6-1.

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Appendix 2 – Media Articles

Debate article in *Dagensnæringsliv:*

«For Norge kan bunnfast havvind være mer utfordrende enn flytende»

Author: Hannah Petrie

18th May 2023

Available online: https://www.dn.no/innlegg/havvind/energi/geologi/for-norge-kan-bunnfast-havvind-vare-mer-utfordrende-enn-flytende/2-1-1449930

Kompleks havbunn ved Sørlige Nordsjø II gjør det vanskeligere med bunnfast havvind enn i resten av Europa. Nær norskekysten er bunnforholdene enklere og gjør flytende havvind mer attraktivt.

Sørlige Nordsjø II, et av områdene regjeringen har pekt ut for å etablere bunnfast havvind, ligger langs danskegrensen to hundre kilometer sørvest for Kristiansand. I dette området ligger havbunnen opp til 70 meter under havoverflaten, noe som er dypere enn de danske og britiske bunnfaste havvindparkene i Nordsjøen.

Sørlige Nordsjø II vil derfor presse grensene for teknologi for bunnfast havvind. Dette betyr at området sannsynligvis vil kreve robuste fundamenter i stedet for rimeligere fundamenter som brukes i grunnere vann i dag.

I tillegg til større dybde viser også seismiske data at bunnforholdene ved Sørlige Nordsjø II er svært varierende. Etter å ha vært dekket av isbreer, breelver og innsjøer ble området erodert av elvekanaler og deretter oversvømt av havet. På grunn av dette varierer bunnforholdene svært mye både nedover i løsmassene og mellom ulike deler av området.

Under Sørlige Nordsjø II er det også saltforekomster og forkastninger som kan lede naturgass fra kilometervis under bakken. Disse saltforekomstene kan også bli brukt til å lagre hydrogen i fremtiden.

På grunn av den geologiske kompleksiteten, geofarer som grunn naturgass og stor vanndybde kan det å utvikle Sørlige Nordsjø II vise seg å være mer utfordrende enn å utvikle Norges andre havvindområde, Utsira Nord. Dette til tross for at den må utvikles flytende havvind som er mye mindre utprøvd.

Ved Utsira Nord ligger havbunnen 270 meter under havoverflaten. Dette området ligger 30 kilometer utenfor kysten av Haugesund og dekker et areal som er større enn både Oslo og Bergen kommune til sammen. Havbunnen i dette området ligger så dypt at det krever flytende havvindturbiner

Havbunnen og de øverste få meterne med sedimenter i dette området består for det meste av mudder, men også sand og grus. Dette området vil sannsynligvis være egnet for sugeankre, som er standard ankertype for flytende havvind i dag. Disse ankrene vil dog i store deler av Utsira Nord stikke ned i dypere sedimenter som også er svært harde og kan inneholde store mengder steinblokker. Dette kan føre til at sugeankrene må gjøres mer hardføre enn det som har vært vanlig hittil.

Modifikasjonene som kreves på Utsira Nord vil sannsynligvis være enklere og billigere enn de modifikasjonene som kreves for fundamentering på Sørlige Nordsjø II.

De samme sugeankervennlige og relativt enkle forholdene finnes langs nesten hele kysten av Sør- og Vest-Norge, i det som kalles Norskerenna.

Havvindparken Hywind Tampen, med flytende havvind, er allerede utbygd i nordlige deler av Norskerenna og viser at flytende havvind kan være veldig attraktivt for Norge.

Havvind er fortsatt en relativt ny teknologi, og vi lærer nye metoder for forbedring og kostnadsreduksjon hele tiden. For Norge, som har mål om å produsere 30 gigawatt med elektrisitet fra havvind innen 2040, må havvindforskning prioriteres. En grundig kartlegging av havbunnsforholdene ved de utpekte havvindområdene Utsira Nord og Sørlige Nordsjø II, samt andre fremtidige konsesjonsområder, er en stor og omfattende utfordring for geologer og ingeniører, men vil bidra til å redusere kostnadene for denne fortsatt kostbare teknologien, både i Norge og resten av verden.

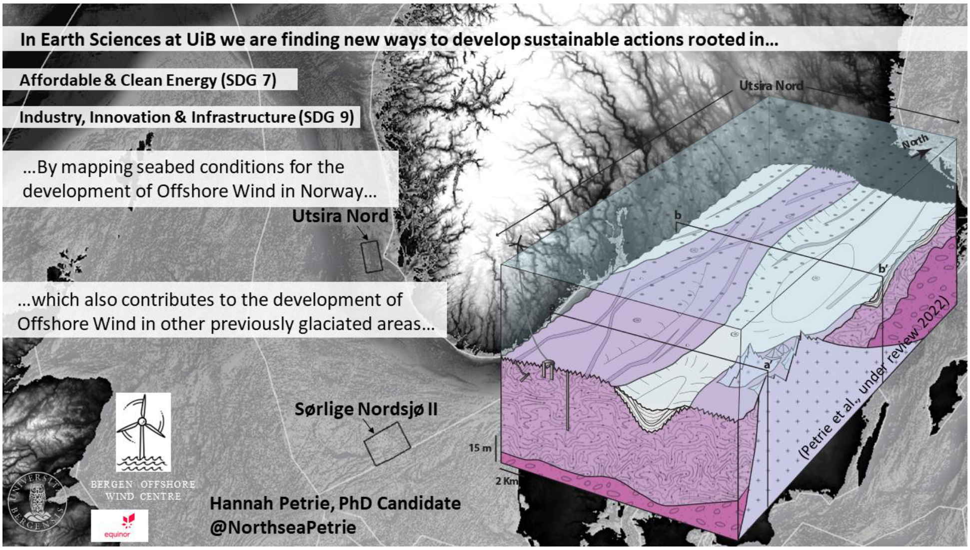
Skal vi nå våre mål må denne forskningen prioriteres i dag, og data fra havbunnen må gjøres tilgjengelig for forskning og utvikling.

Appendix 3 – Conference Posters

Sustainable Development Goals Conference, Bergen, February 2022

Digital Poster Video Presentation – Developing sustainable actions in Earth Sciences

Hannah Petrie



In Earth Sciences at UiB we are finding new ways to develop sustainable actions rooted in…

Affordable & Clean Energy (SDG 7)

Industry, Innovation & Infrastructure (SDG 9)

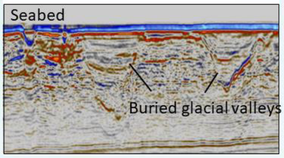
…By mapping seabed conditions for the development of Offshore Wind in Norway…

…which also contributes to the development of Offshore Wind in other previously glaciated areas…

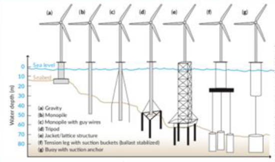
Hannah Petrie, PhD Candidate
@NorthseaPetrie

Why study the seabed?

The seabed in Norway is complex due to past glaciations…

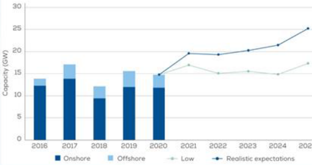


Mapping the seabed conditions allows an efficient anchoring strategy to be chosen



O'Kelly & Arshad (2016)

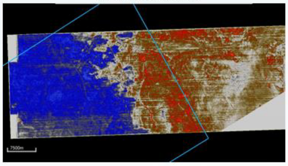
So that offshore wind turbines can be rolled out faster, cheaper and safely



Wind Europe (2020)

How do we study the seabed?

Recycling old oil exploration data to understand the rocks and soils at the seabed



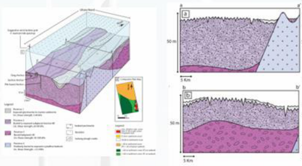
Collecting new data at the chosen offshore wind sites

G.O. Sars

E.A. Lorentzen, Havforskningsinstitutet

E.A. Lorentzen, Havforskningsinstitutet

Investigating new ways to communicate our findings across different disciplines working with offshore wind



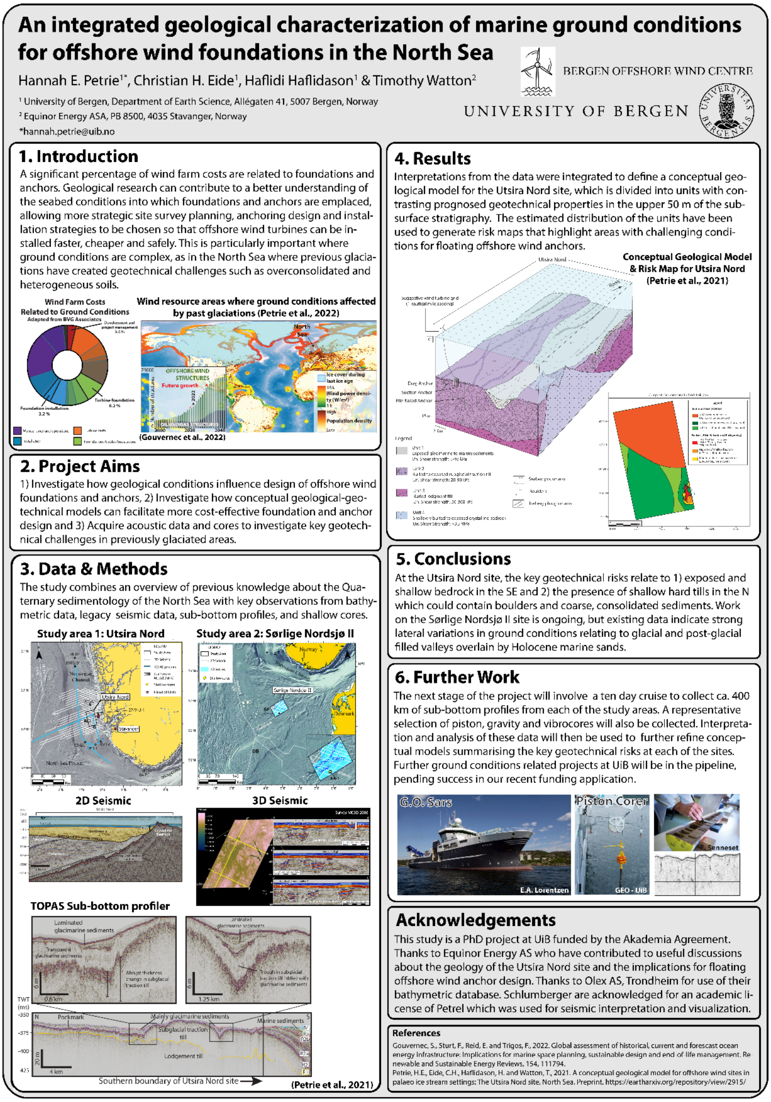
(Petrie et al., under review 2022)

FORCE seminar – "Joining Forces", Stavanger, April 2022

Poster Presentation – An integrated geological characterization of marine ground conditions for offshore wind foundations in the North Sea

Hannah E. Petrie, Christian H. Eide, Haflidi Haflidason, Timothy Watton

[Joining Forces: Solving the energy challenge together - The Norwegian Petroleum Directorate (npd.no)]



An integrated geological characterization of marine ground conditions for offshore wind foundations in the North Sea

Hannah E. Petrie[1*], Christian H. Eide[1], Haflidi Haflidason[1] & Timothy Watton[2]

[1] University of Bergen, Department of Earth Science, Allégaten 41, 5007 Bergen, Norway
[2] Equinor Energy ASA, PB 8500, 4035 Stavanger, Norway
*hannah.petrie@uib.no

BERGEN OFFSHORE WIND CENTRE

UNIVERSITY OF BERGEN

1. Introduction

A significant percentage of wind farm costs are related to foundations and anchors. Geological research can contribute to a better understanding of the seabed conditions into which foundations and anchors are emplaced, allowing more strategic site survey planning, anchoring design and installation strategies to be chosen so that offshore wind turbines can be installed faster, cheaper and safely. This is particularly important where ground conditions are complex, as in the North Sea where previous glaciations have created geotechnical challenges such as overconsolidated and heterogeneous soils.

Wind Farm Costs Related to Ground Conditions
Adapted from BVG Associates

Wind resource areas where ground conditions affected by past glaciations (Petrie et al., 2022)

(Gouvernec et al., 2022)

2. Project Aims

1) Investigate how geological conditions influence design of offshore wind foundations and anchors, 2) Investigate how conceptual geological-geotechnical models can facilitate more cost-effective foundation and anchor design and 3) Acquire acoustic data and cores to investigate key geotechnical challenges in previously glaciated areas.

3. Data & Methods

The study combines an overview of previous knowledge about the Quaternary sedimentology of the North Sea with key observations from bathymetric data, legacy seismic data, sub-bottom profiles, and shallow cores.

Study area 1: Utsira Nord

Study area 2: Sørlige Nordsjø II

2D Seismic

3D Seismic

TOPAS Sub-bottom profiler

Southern boundary of Utsira Nord site →

(Petrie et al., 2021)

4. Results

Interpretations from the data were integrated to define a conceptual geological model for the Utsira Nord site, which is divided into units with contrasting prognosed geotechnical properties in the upper 50 m of the subsurface stratigraphy. The estimated distribution of the units have been used to generate risk maps that highlight areas with challenging conditions for floating offshore wind anchors.

Conceptual Geological Model & Risk Map for Utsira Nord (Petrie et al., 2021)

5. Conclusions

At the Utsira Nord site, the key geotechnical risks relate to 1) exposed and shallow bedrock in the SE and 2) the presence of shallow hard tills in the N which could contain boulders and coarse, consolidated sediments. Work on the Sørlige Nordsjø II site is ongoing, but existing data indicate strong lateral variations in ground conditions relating to glacial and post-glacial filled valleys overlain by Holocene marine sands.

6. Further Work

The next stage of the project will involve a ten day cruise to collect ca. 400 km of sub-bottom profiles from each of the study areas. A representative selection of piston, gravity and vibrocores will also be collected. Interpretation and analysis of these data will then be used to further refine conceptual models summarising the key geotechnical risks at each of the sites. Further ground conditions related projects at UiB will be in the pipeline, pending success in our recent funding application.

Acknowledgements

This study is a PhD project at UiB funded by the Akademia Agreement. Thanks to Equinor Energy AS who have contributed to useful discussions about the geology of the Utsira Nord site and the implications for floating offshore wind anchor design. Thanks to Olex AS, Trondheim for use of their bathymetric database. Schlumberger are acknowledged for an academic license of Petrel which was used for seismic interpretation and visualization.

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18th European Academy of Wind Energy PhD Seminar, Bruges, November 2022

Poster Presentation – Offshore wind at the University of Bergen

Hannah E. Petrie

Offshore Wind at the University of Bergen

The Geodynamics and Basin Studies Group, the Quaternary Earth Systems Group and the Bergen Offshore Wind Centre are all involved with projects addressing the challenges associated with the development of offshore wind technology

Hannah E Petrie
University of Bergen
hannah.petrie@uib.no

Overview – Wind at UiB

The **Geodynamics and Basin Studies Group** and **Quaternary Earth Systems Group** at UiB started their offshore wind journey in 2020 with the Equinor-funded Akademia project *"Marine geological ground surveys for offshore wind sites"* and will build on this with >10 further MSc, PhD and post-Doc projects in 2023-2024, funded by the Norwegian Research Council via the *4SWIND Project.*

The focus of these projects is to investigate the **geotechnical conditions of the seafloor** on the Norwegian Continental Shelf, and the implications for the design and installation of offshore wind turbine foundations and anchors.

Many other departments at UiB are also involved with offshore wind-related research, all of which are affiliated with the **Bergen Offshore Wind Centre.** Affiliated groups include the **Geophysical Institute**, the **Faculty of Law** and many others.

4SWIND Project: Advancing seismic seabed survey techniques and optimal site-selection for offshore wind farms

The aim of 4SWIND is to improve **collaboration between geology, geophysics and geotechnics** in Norwegian and European academia.

The products will be: a **map of anchoring conditions** on the Norwegian Continental Shelf, two seismic tomography datasets, an Ultra-High resolution 3D seismic dataset, sediment cores with geotechnical testing and a **compiled dataset of geotechnical properties** of soil types/landforms on the NCS.

Laboratory facilities

The **GEOTEK Multi-Sensor Core Logger** enables measurements of gamma ray attenuation, P-wave velocity, Magnetic Susceptibility and RGB images of sediment cores.

The **ITRAX XRF core scanner** combines X-ray reflectance, X-ray imaging and optical imaging. The output data are considered a semi-quantitative measure of elemental composition.

ProCon X-Ray CT-ALPHA CT Scanner is customized to scan sediment cores. 3D X-Ray imagery is visualized using the Avizo Fire 3D analysis software.

Marine geological cruises

The **R/V G.O. SARS** is owned by the Institute of Marine Research and the University of Bergen. Its main duties are research operations within the areas of **fishery, acoustics, environment and geology.**

A cruise in June 2022 to the offshore wind sites **Utsira Nord and Sørlige Nordsjø II** collected 1600 km of sub-bottom acoustic profiles (TOPAS), 13 vibro-cores, 10 gravity cores and 3 piston cores. **Cruises for the 4SWIND project are planned in 2023-24**.

REFERENCES
1 – Photograph taken by Hannah Petrie on G.O. Sars, 2022
2 – Photograph taken by Eivind Senneset, UiB web pages
3 – Photograph taken by Hannah Petrie on G.O. Sars, 2022
4 – Photograph taken by GCE Ocean Technology, 2021

UNIVERSITY OF BERGEN

ACKNOWLEDGEMENTS
Equinor is acknowledged for funding through the Akademia Agreement.
Other academic institutions involved in securing funding for the 4SWIND project include NTNU and UiT. The partners involved with funding 4SWIND, along with the Norwegian Research Council include Geo Provider, Equinor, Volcanic Basin Research, NGU, NGI and Mareano.

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