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

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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.

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
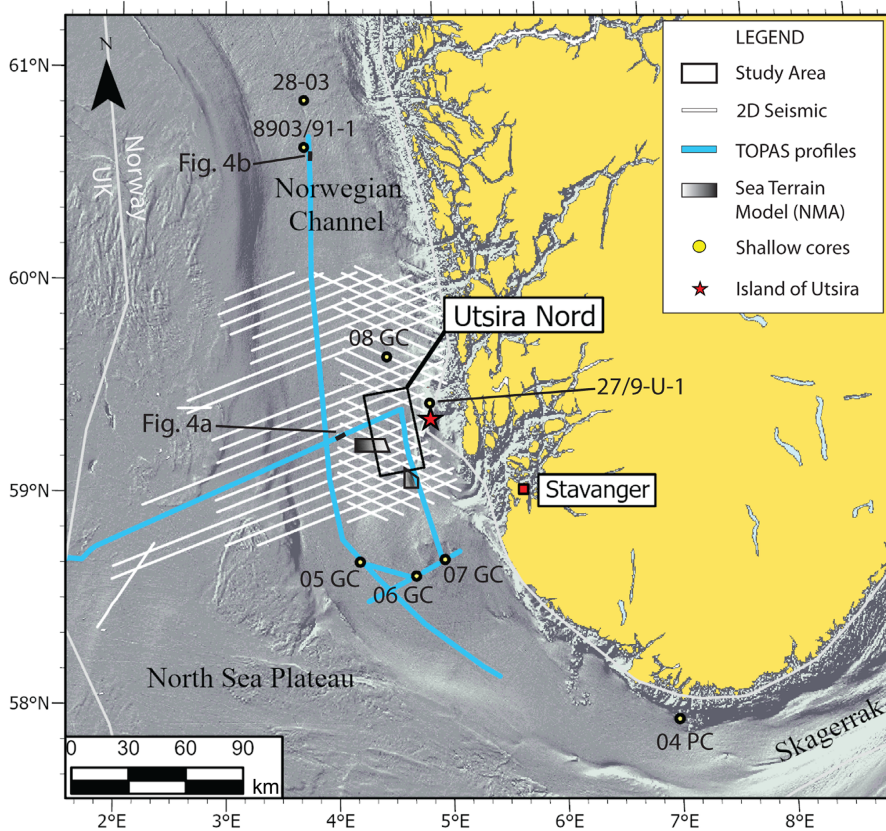
Fig. 1. Bathymetric hill-shaded map of the Norwegian North Sea (www.olex.no) showing the location of the Utsira Nord site, and the dataset used in this study. The site is partly covered by the Norwegian Mapping Authority (NMA) 5 m resolution Sea Terrain Model (Norwegian Mapping Authority 2018); however, 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:
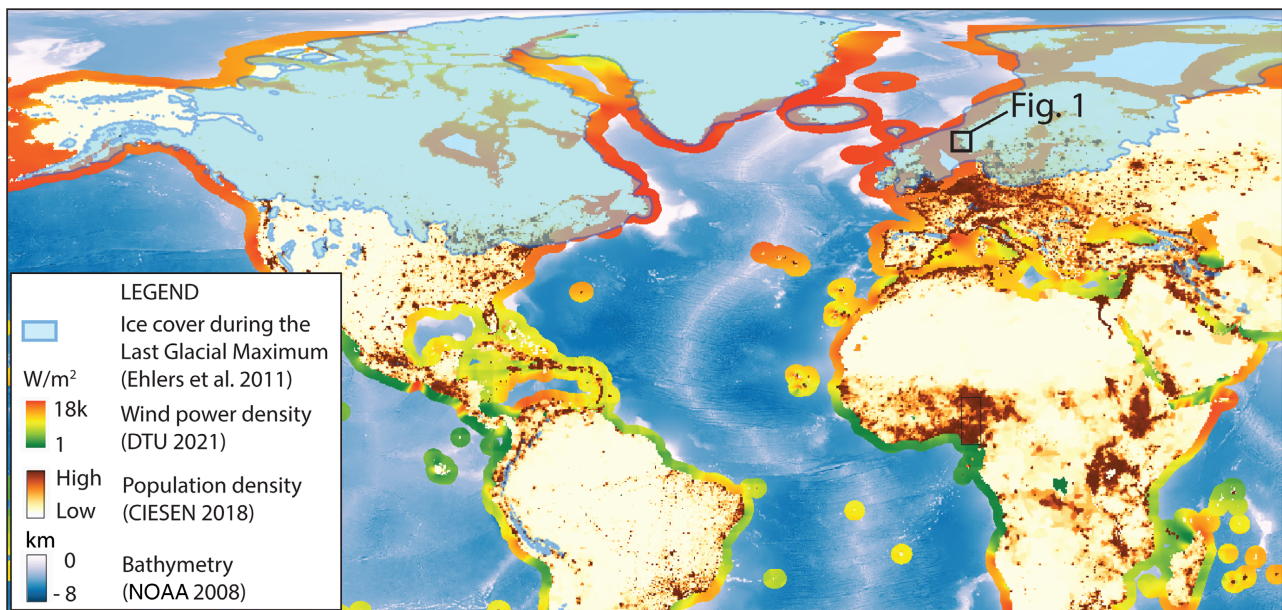

Fig. 2. Ice extent map for the Last Glacial Maximum (*c.* 20 ka) (Ehlers *et al.* 2011), showing how the ground conditions along many northern hemisphere coastlines have been affected by glacial processes during this period. This has been superimposed upon the global distribution of wind resources (wind 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.
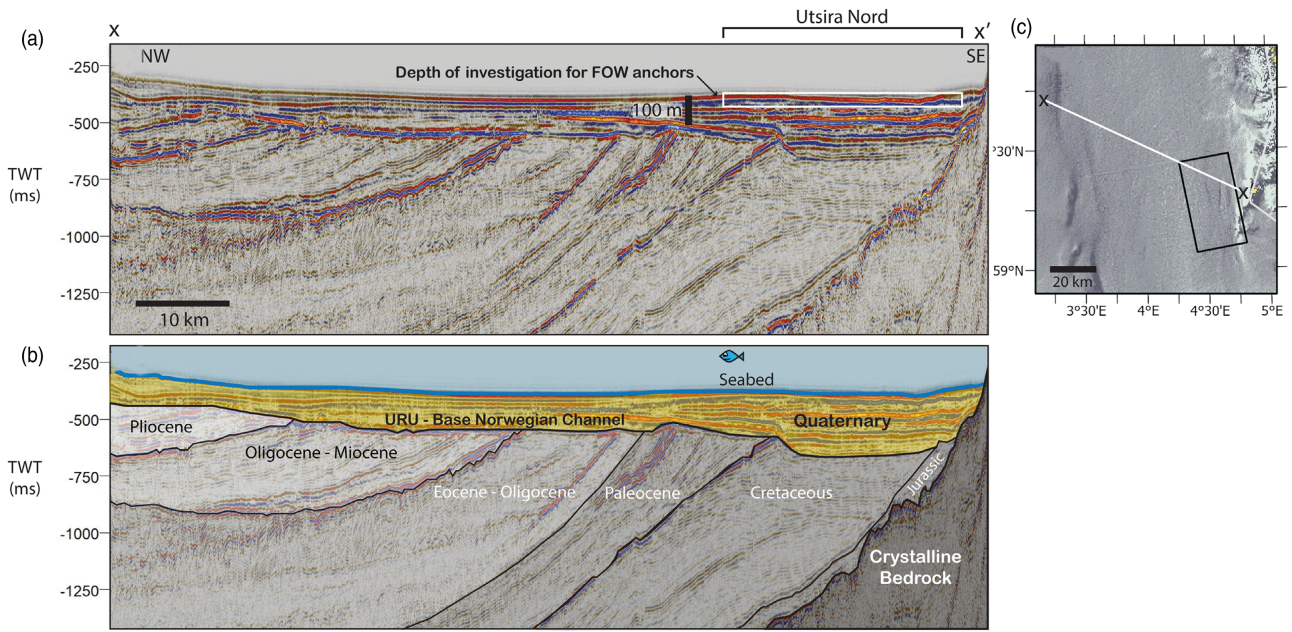
Fig. 3. (**a**) Regional 2D seismic section (x–x') across the Norwegian Channel from survey ST8201 R90 (Line ST-8201-442-955.6398) showing two-way travel time in milliseconds (ms) and depth (m) for the Norwegian Channel late Quaternary infill and standard depth of investigation for FOW anchor site surveys. (**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
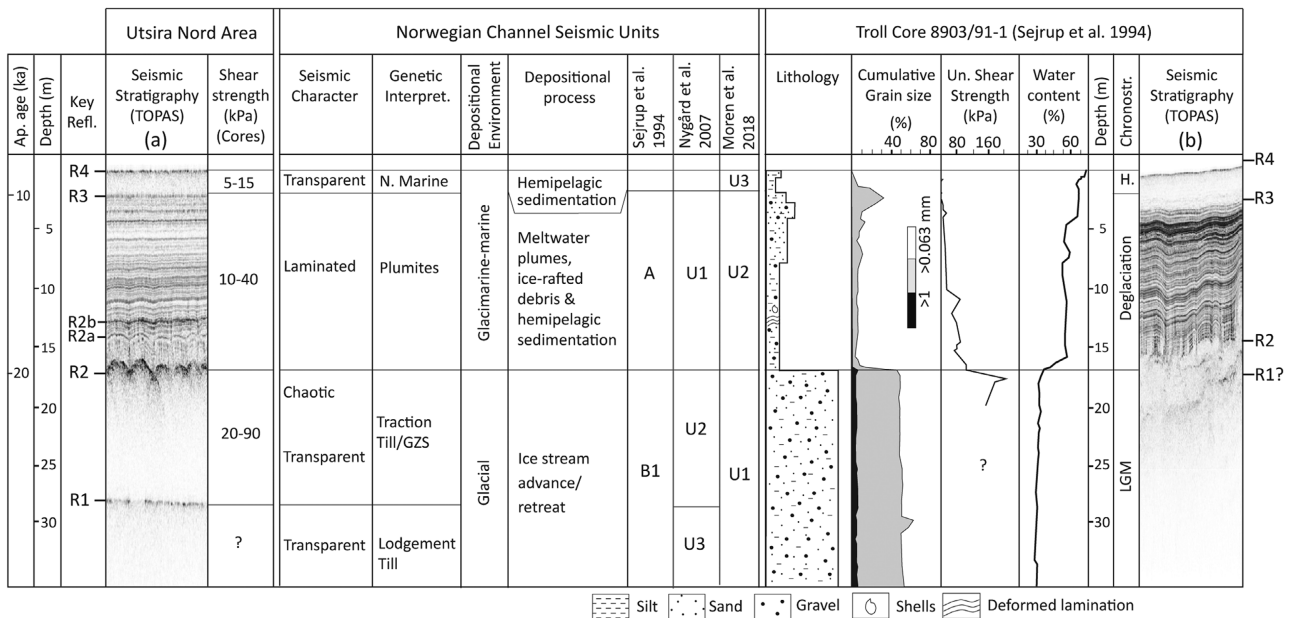

Fig. 4. (**a**) Summary of the seismic units defined in previous studies of the Norwegian Channel sedimentary infill, tentatively correlated to TOPAS acoustic data west of Utsira Nord (Fig. 1), where a more complete stratigraphy is present than within the site itself. Previously, three broad genetic 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
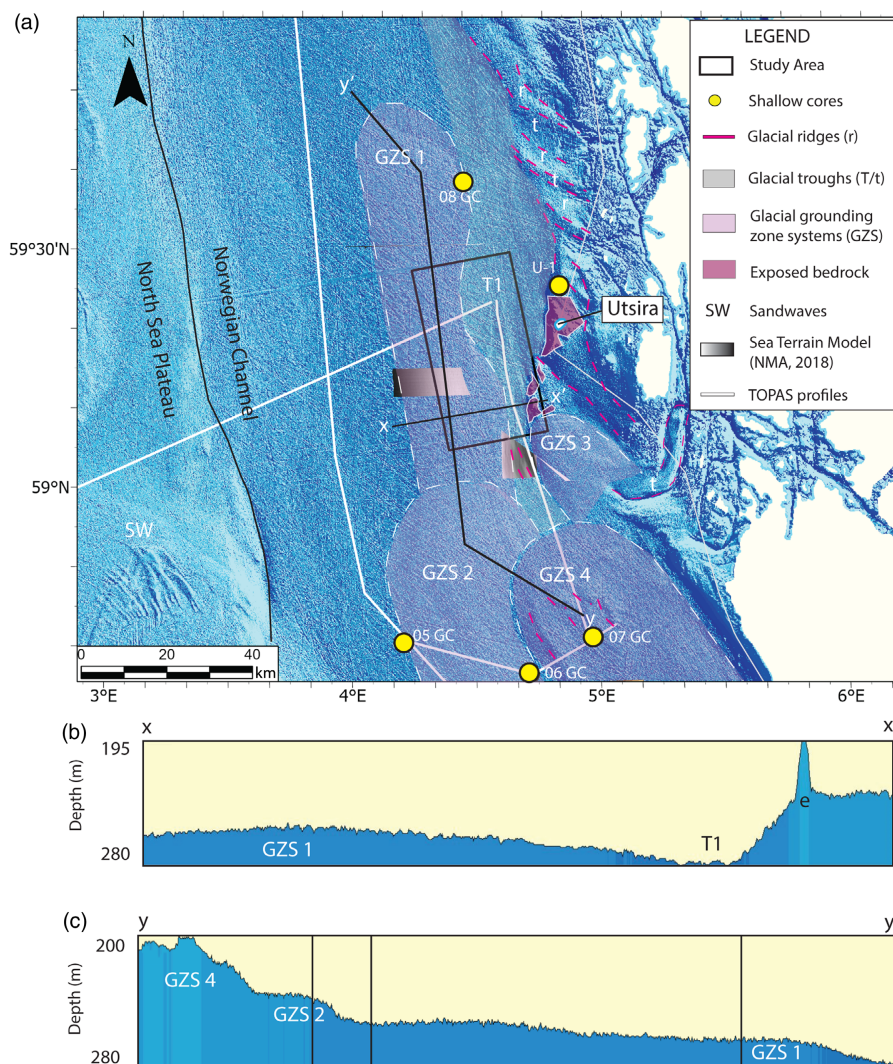

Fig. 5. (a) Olex bathymetric map of the Utsira Nord site and surrounding area showing interpreted geomorphological features. Glacial ridges and troughs are also interpreted on the NMA Sea Terrain Model (Norwegian Mapping Authority 2018) just south of the site in pink stipple. (b) East–west bathymetric 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.
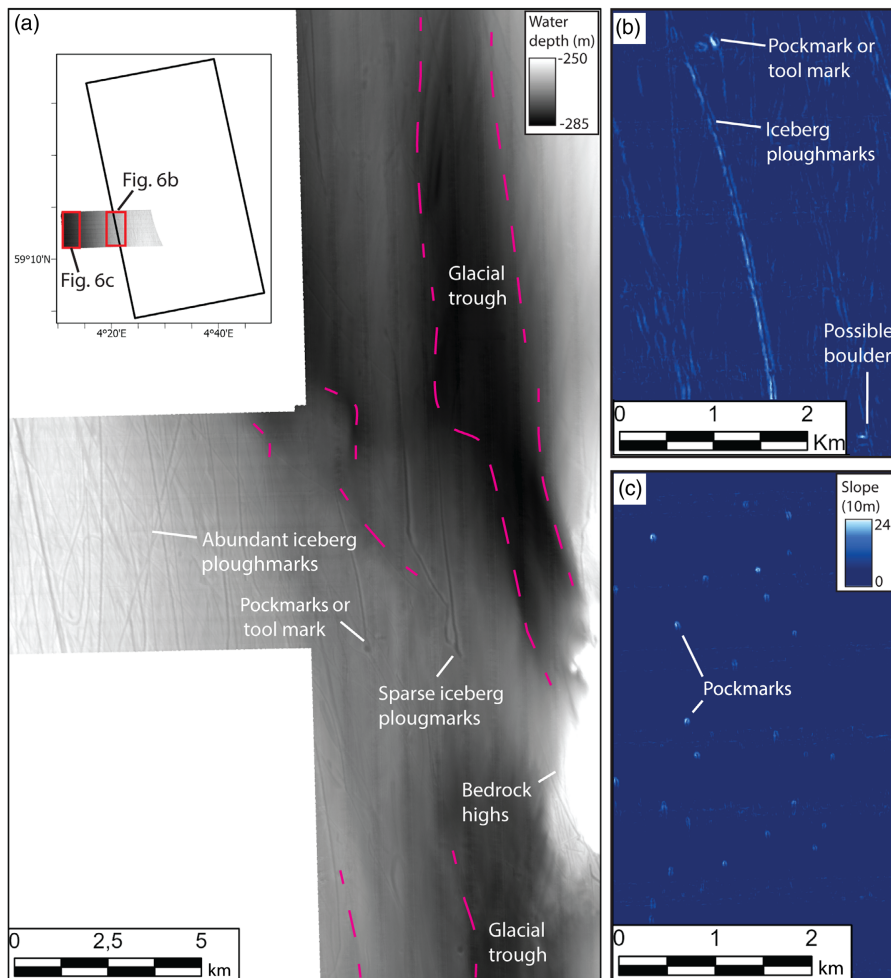
Fig. 6. (**a**) Annotated NMA Sea Terrain Model (Norwegian Mapping Authority 2018) showing glacial troughs and ridges (pink stipple), iceberg ploughmarks and pockmarks or tool marks in and around the Utsira Nord site (exact location cannot be shown owing to coastal security). In the top left corner, 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 conformally 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
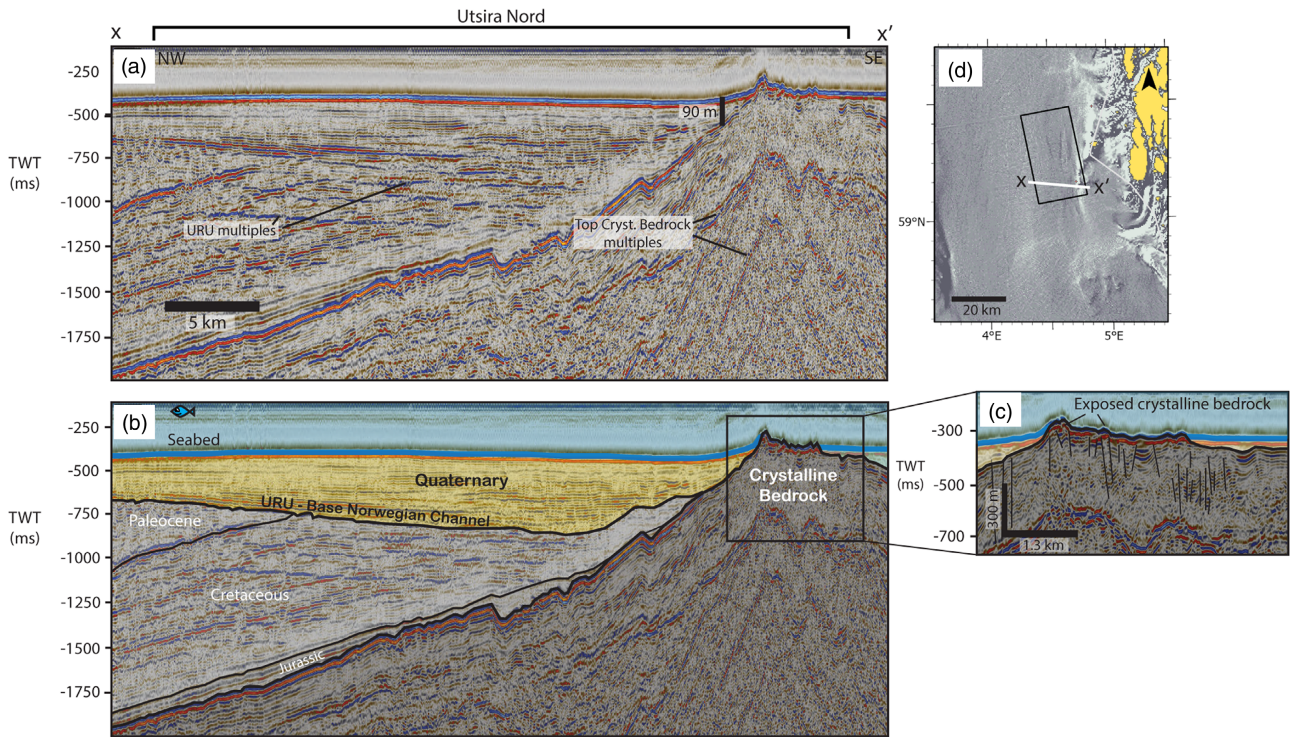
Fig. 7. (**a**) Two-dimensional seismic section (x–x') across southern Utsira Nord from survey ST8201 R92 (Line ST-8201-436-46.2500). (**b**) Interpreted 2D seismic section (x–x') showing outcropping and shallowly buried crystalline bedrock in the southeastern part of Utsira Nord. (**c**) Close-up view 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
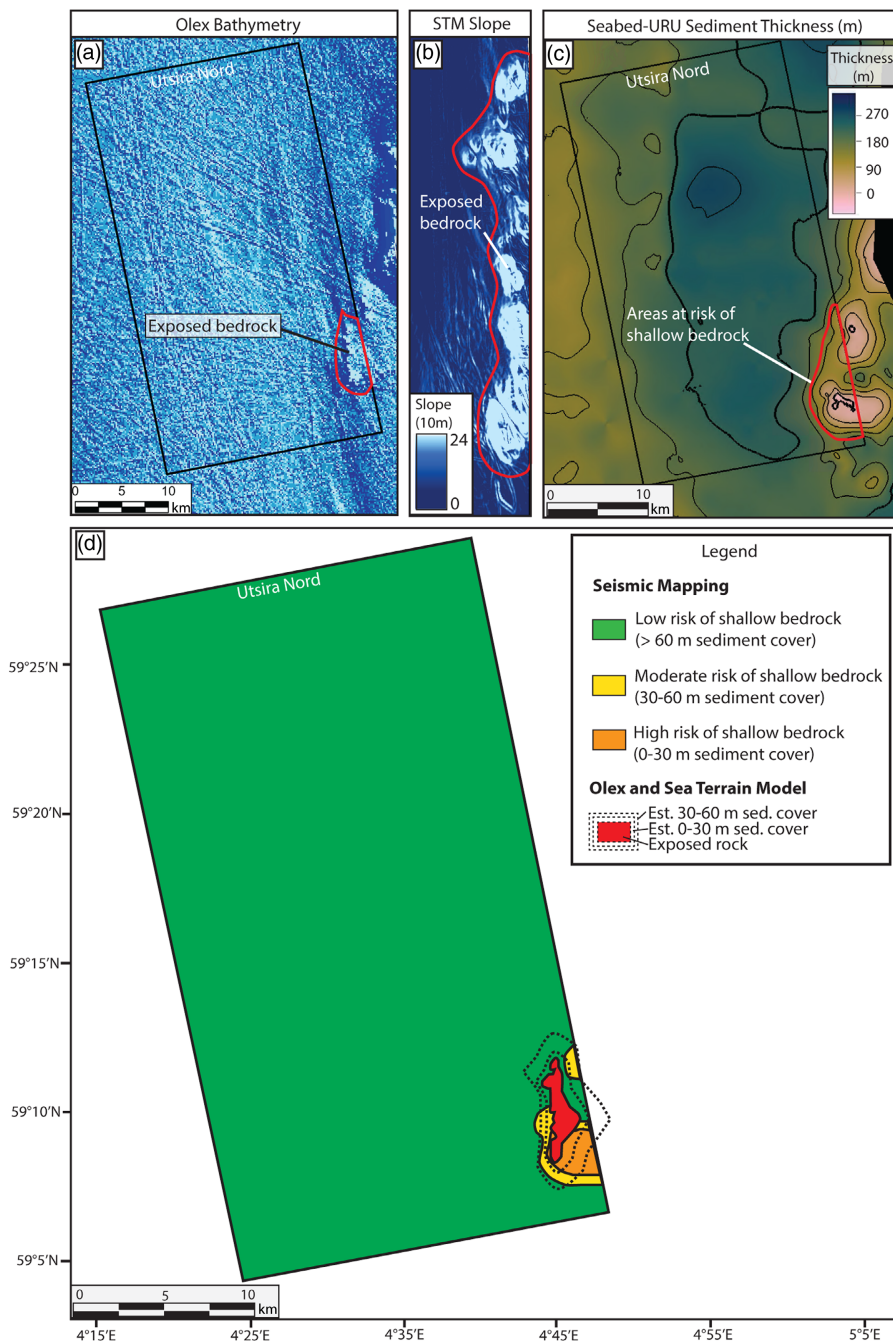

Fig. 8. (**a**) Olex bathymetric map showing zone of bedrock highs observed in the southeastern part of the site, interpreted as exposed crystalline bedrock. (**b**) A 10 m slope map generated in ArcGIS from the NMA Sea Terrain Model (Norwegian Mapping Authority 2018) showing a more detailed outline 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.
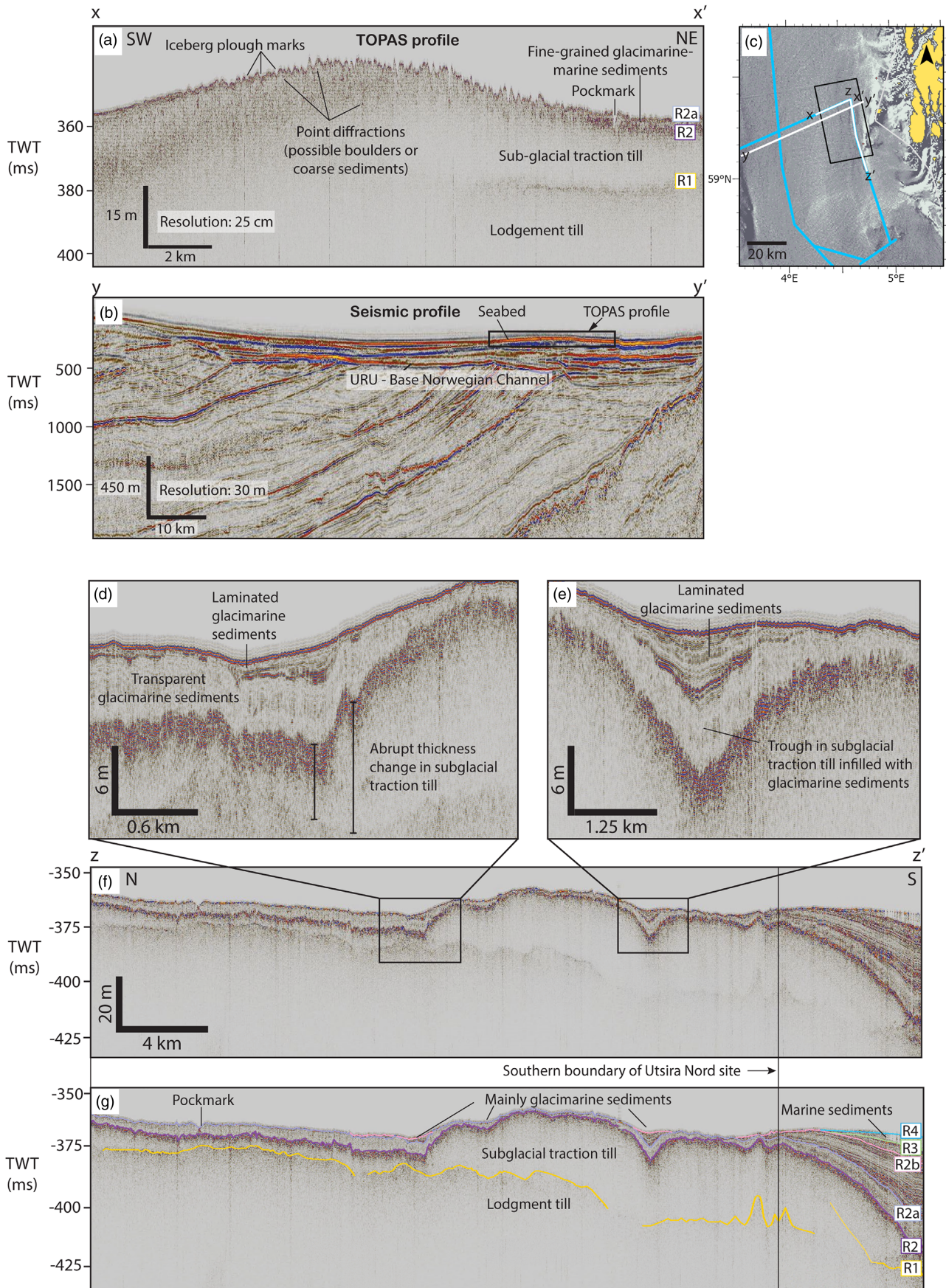
Fig. 9. (a) TOPAS profile x–x' across the northern part of the Utsira Nord site showing key features distinguishable on high-resolution acoustic data compared with conventional 2D seismic profile y–y'. **(b)** Conventional 2D seismic profile y–y' from survey ST8201 R92 (Line ST-8201-220-2804.9135). Location 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
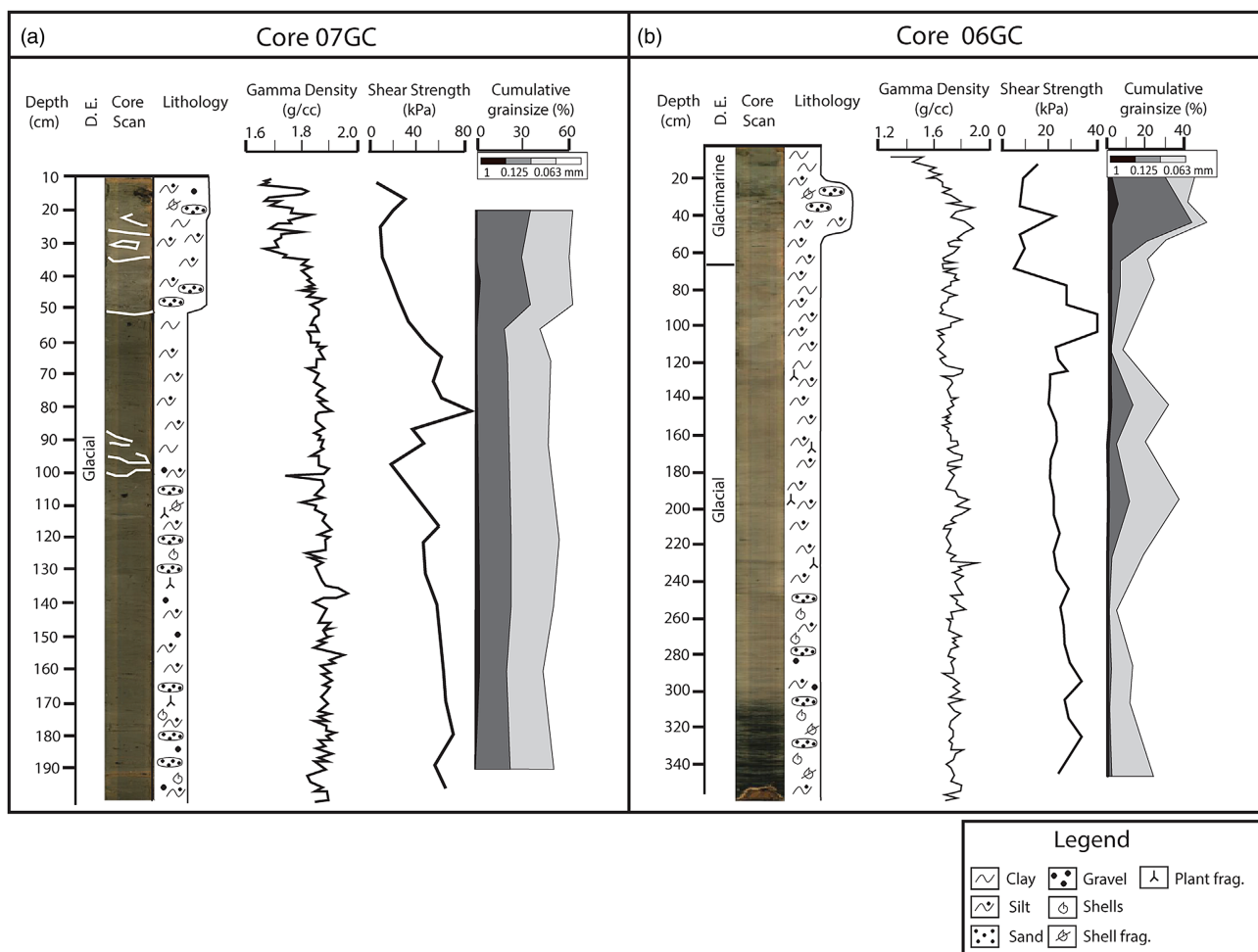

Fig. 10. (a) Core scan photograph and multi-sensor core logs for gravity core 07GC showing sedimentological and physical properties of subglacial traction till (Unit 2-type sediments) 50 km south of the Utsira Nord site. (b) Core scan photograph and multi-sensor core logs for gravity core 06GC showing 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.
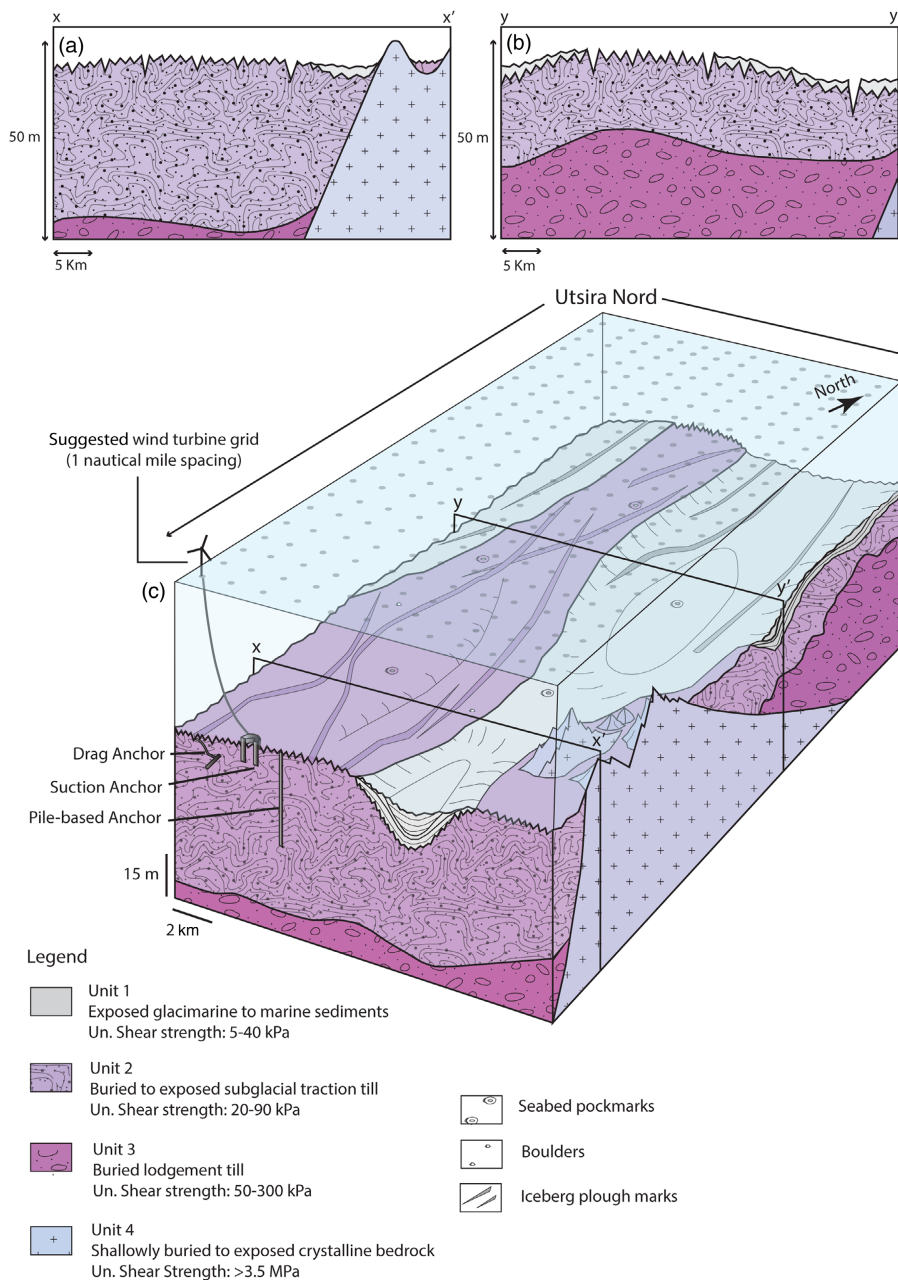
Fig. 11. (**a**) Geosection (x–x') showing how the respective units of the conceptual geological model for Utsira Nord vary in thickness and burial depth across the southern part of the site. (**b**) Geosection (y–y') showing variations across the northern part of the site. (**c**) Geological model for 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;
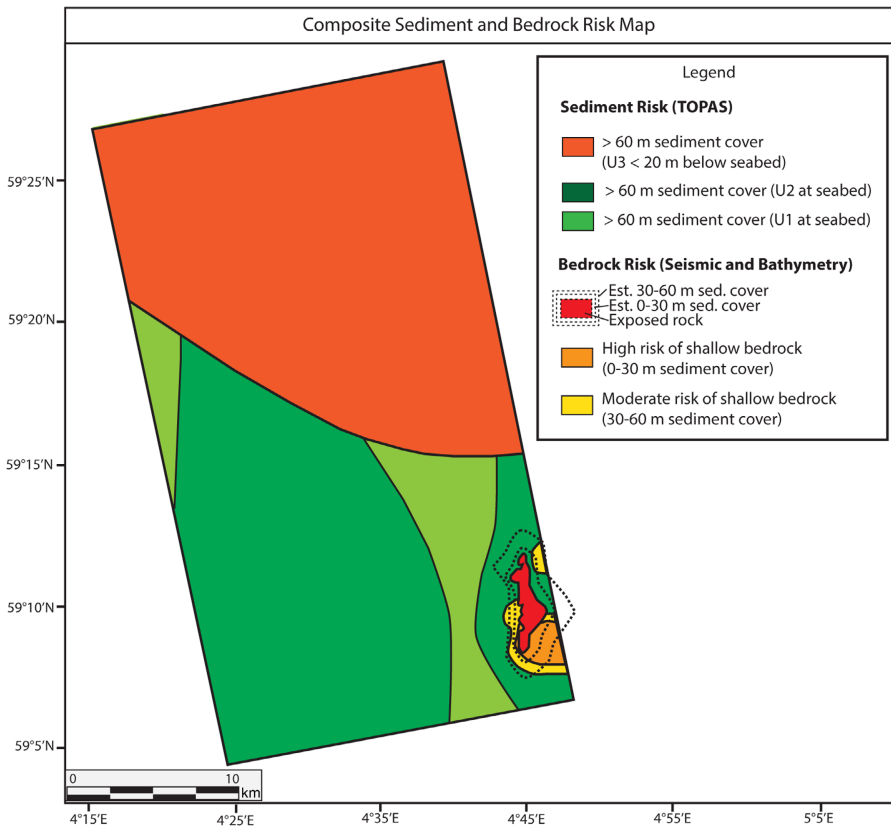
Fig. 12. Composite sediment and bedrock risk map for the Utsira Nord site, which highlights the key geotechnical risks anticipated across different parts of the site. In the southern part of the site, the geotechnical risk is defined by the geotechnical units present at the seabed and the amount of sedimentary 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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Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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References

Abhinav, K.A. and Saha, N. 2017. Effect of scouring in sand on monopile-supported offshore wind turbines. *Marine Georesource Geotechnology*, **35**, 817–828, https://doi.org/10.1080/1064119X.2016.1255687

American Bureau of Shipping 2018. *Guidance Notes on Design and Installation of Drag Anchors and Plate Anchors. March 2017* [updated March 2018]. American Bureau of Shipping, Houston, TX, https://ww2.eagle.org/content/dam/eagle/rulesandguides/current/offshore/248_designinstallationdrag_and_plateanchors/Drag_and_Plate_Anchors_GN_eMar18.pdf

Amundsen, T., Lunne, T., Christophersen, H.P., Bayne, J.M. and Barnwell, C.L. 1985. Advanced deep-water soil investigation at the Troll East Field. *In*: *Offshore Site Investigation (Conference: London) Advances in Underwater Technology and Offshore Engineering: Proceedings of an International Conference*, **3**, 165–186, https://doi.org/10.1007/978-94-011-7358-2

Andreassen, K., Nilssen, L.C., Rafaelsen, B. and Kuilman, L. 2004. Three-dimensional seismic data from the Barents Sea margin reveal evidence of past ice streams and their dynamics. *Geology*, **32**, 729–732, https://doi.org/10.1130/G20497.1

Andreassen, K., Laberg, J.S. and Vorren, T.O. 2008. Seafloor geomorphology of the SW Barents Sea and its glaci-dynamic implications. *Geomorphology*, **97**, 157–177, https://doi.org/10.1016/j.geomorph.2007.02.050

Anell, I., Thybo, H. and Rasmussen, E. 2012. A synthesis of Cenozoic sedimentation in the North Sea. *Basin Research*, **24**, 154–179, https://doi.org/10.1111/j.1365-2117.2011.00517.x

Becker, L.W.M., Sejrup, H.P., Hjelstuen, B.O., Haflidason, H. and Dokken, T.M. 2018. Ocean-ice sheet interaction along the SE Nordic Seas margin from 35 to 15 ka BP. *Marine Geology*, **402**, 99–117, https://doi.org/10.1016/j.margeo.2017.09.003

Bellwald, B., Planke, S. *et al.* 2020. Quaternary and neogene reservoirs of the Norwegian continental shelf: evidence from new 3D seismic data. *Proceedings of the 82nd EAGE Conference and Exhibition*, 8–11 June 2020, Amsterdam, https://doi.org/10.3997/2214-4609.202011459

Bjerrum, J. 1973. Geotechnical problems involved in foundations of structures in the North Sea. *Géotechnique*, **23**, 319–358, https://doi.org/10.1680/geot.1973.23.3.319

Bøe, R., Rise, L. and Ottesen, D. 1998. Elongate depressions on the southern slope of the Norwegian Trench (Skagerrak): morphology and evolution. *Marine Geology*, **146**, 191–203, https://doi.org/10.1016/S0025-3227(97)00133-3

Bradwell, T., Stoker, M.S. and Golledge, N.R. 2008. The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, **88**, 207–226, https://doi.org/10.1016/j.earscirev.2008.01.008

Bradwell, T., Small, D. *et al.* 2021. Pattern, style, and timing of British–Irish Ice Sheet retreat: Shetland and northern North Sea sector. *Journal of Quaternary Science*, **36**, 681–722, https://doi.org/10.1002/jqs.3163

Butenko, G. and Østmo, S.R. 1991. The importance of multidisciplinary geoscience investigations for engineering projects in the Oseberg, Brage and Troll fields. *Geological Society, London, Engineering Geology Special Publications*, **7**, 195–202.

Cameron, T.D.J., Stoker, M.S. and Long, D. 1987. The history of Quaternary sedimentation in the UK sector of the North Sea Basin. *Journal of the Geological Society, London*, **144**, 43–58, https://doi.org/10.1144/gsjgs.144.1.0043

Cartelle, V., Barlow, N.L.M., Hodgson, D.M., Busschers, F.S., Cohen, K.M., Meijninger, B.M.L. and van Kesteren, W.P. 2021. Sedimentary architecture and landforms of the late Saalian (MIS6) ice sheet margin offshore of the Netherlands. *Earth Surface Dynamics*, **9**, 1399–1421, https://doi.org/10.5194/esurf-9-1399-2021

Caston, V.N.D. 1979. The Quaternary sediments of the North Sea. *In:* Banner, F.T., Collins, M.B. and Massie, K.S. (eds) *Elsevier Oceanography Series*, **24A**. Elsevier, Amsterdam, 195–270, https://doi.org/10.1016/S0422-9894(08)71349-7

Center for International Earth Science Information Network – CIESIN – Columbia University 2018. *Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11*. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY, https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11; https://doi.org/10.7927/H49C6VHW [last accessed 16 November 2021].

Clarke, B.G., Chen, C.C. and Aflaki, E. 1998. Intrinsic compression and swelling properties of a glacial till. *Quarterly Journal of Engineering Geology*, **31**, 235–246, https://doi.org/10.1144/GSL.QJEG.1998.031.P3.06

Cotterill, C.J., Phillips, E., James, L., Forsberg, C.F., Tjelta, T.I., Carter, G. and Dove, D. 2017. The evolution of the Dogger Bank, North Sea: a complex history of terrestrial, glacial, and marine environmental change. *Quaternary Science Reviews*, **171**, 136–153, https://doi.org/10.1016/j.quascirev.2017.07.006

Coughlan, M., Long, M. and Doherty, P. 2020. Geological and geotechnical constraints in the Irish Sea for offshore renewable energy. *Journal of Maps*, **16**, 420–431, https://doi.org/10.1080/17445647.2020.1758811

Dahlgren, K.I.T. and Vorren, T.O. 2003. Sedimentary environment and glacial history during the last 40 ka of the Vøring continental margin, mid-Norway. *Marine Geology*, **193**, 93–127, https://doi.org/10.1016/S0025-3227(02)00617-5

Dai, S., Han, B., Wang, B., Luo, J. and He, B. 2021. Influence of soil scour on lateral behavior of large-diameter offshore wind-turbine monopile and corresponding scour monitoring method. *Ocean Engineering*, **239**, https://doi.org/10.1016/j.oceaneng.2021.109809

Darvishi Alamouti, S., Bahaari, M.R. and Moradi, M. 2020. Dynamic analysis of a monopile supported wind turbine considering experimental p–y curves. *Ships and Offshore Structures*, **15**, 670–682, https://doi.org/10.1080/17445302.2019.1665910

Deb, P. and Pal, S.K. 2019. Numerical analysis of piled raft foundation under combined vertical and lateral loading. *Ocean Engineering*, **190**, https://doi.org/10.1016/j.oceaneng.2019.106431

de Kluijver, M. 1991. Sublittoral hard substrate communities off Helgoland. *Helgolander Meeresuntersuchungen*, **45**, 317–344, https://doi.org/10.1007/BF02365523

Diesing, M., Coggan, R. and Vanstaen, K. 2009. Widespread rocky reef occurrence in the central English Channel and the implications for predictive habitat mapping. *Estuarine, Coastal and Shelf Science*, **83**, 647–658, https://doi.org/10.1016/j.ecss.2009.05.018

Doherty, P., Gavin, K. and Casey, B. 2011. The geotechnical challenges facing the offshore wind sector. *In*: Geo-Frontiers. Geofrontiers Conference, March 2011, Dallas, TX. American Society of Civil Engineers, 162–171, https://doi.org/10.1061/41165(397)18

Dowdeswell, J.A. and Ottesen, D. 2013. Buried iceberg ploughmarks in the early Quaternary sediments of the central North Sea: A two-million year record of glacial influence from 3D seismic data. *Marine Geology*, **344**, 1–9, https://doi.org/10.1016/j.margeo.2013.06.019

Dowdeswell, J.A., Ottesen, D. and Rise, L. 2006. Flow-switching and large-scale deposition by ice streams draining former ice sheets. *Geology*, **34**, 313–316, https://doi.org/10.1130/G22253.1

Dreimanis, A. and Lundquist, J. 1984. What should be called till? *Striae*, **20**, 5–10, http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=9679649

DTU 2021. *Global Wind Atlas v3*. Wind power density at 100 m: gwa3_250_powerdensity_100 m, DTU, https://data.dtu.dk/articles/dataset/Global_Wind_Atlas_v3/9420803 [last accessed 16 November 2021].

Eamer, J.B.R., Shaw, J., King, E.L. and MacKillop, K. 2021. The inner shelf geology of Atlantic Canada compared with the North Sea and Atlantic United States: insights for Atlantic Canadian offshore wind energy. *Continental Shelf Research*, **213**, https://doi.org/10.1016/j.csr.2020.104297

Ehlers, J. and Gibbard, P.L 2004. Quaternary glaciations – extent and chronology, part 1: Europe. *In*: Rose, J. (ed.) *Developments in Quaternary Science 2*, 1–475, Elsevier B.V., Amsterdam.

Ehlers, J. and Gibbard, P.L. 2008. The extent and chronology of Cenozoic Global Glaciation. *Journal of International Geoscience*, **31**, 211–218, https://doi.org/10.18814/epiiugs/2008/v31i2/004

Ehlers, J. and Wingfield, R. 1991. The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. *Journal of Quaternary Science*, **6**, 313–236, https://doi.org/10.1002/jqs.3390060406

Ehlers, J., Meyer, K. and Stephan, H. 1984. The pre-Weichselian glaciations of North-West Europe. *Quaternary Science Reviews*, **3**, 1–9, https://doi.org/10.1016/0277-3791(84)90003-9

Ehlers, J., Gibbard, P.L. and Hughes, P.D. (eds) 2011. *Quaternary Glaciations – Extent and Chronology: A Closer Look*. Vol. 2, Developments in Quaternary Science 15, Elsevier, Amsterdam, https://booksite.elsevier.com/9780444534477/digital_maps.php [last accessed 17 November 2021].

Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H. and Grogan, P. 2000. The upper Cainozoic of the Norwegian continental shelf correlated with the deep-sea record of the Norwegian Sea and the North Atlantic. *Marine and Petroleum Geology*, **17**, 579–600, https://doi.org/10.1016/S0264-8172(00)00008-8

Ellery, G.D. and Comrie, R.J. 2019. Scoping appropriate feasibility level geophysical and geotechnical survey for offshore wind – offsetting cost against knowledge gain. Cathie Group, https://cathiegroup.com/wp-content/uploads/2019/06/Ellery-GD-Comrie-RJ-Scoping-Appropriate-Feasibility-Level-Geophysical.pdf [last accessed 1 September 2020].

Emery, A.R., Hodgson, D.M., Barlow, N.L.M., Carrivick, J.L., Cotterill, C.J. and Phillips, E. 2019. Left high and dry: deglaciation of Dogger Bank, North Sea, recorded in Proglacial lake evolution. *Frontiers in Earth Science*, **7**, https://doi.org/10.3389/feart.2019.00234

Equinor 2022. How Hywind works, https://www.equinor.com/en/what-we-do/floating-wind/how-hywind-works.html [last accessed 3 March 2022].

Eyles, N. and McCabe, A.M. 1989, The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. *Quaternary Science Reviews*, **8**, 307–351, https://doi.org/10.1016/0277-3791(89)90034-6

Faleide, J.I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R.H., Jordt, H., Fanavoll, S. and Bjerke, M.D. 2002. Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. *Geological Society, London, Special Publications*, **196**, 235–269, https://doi.org/10.1144/GSL.SP.2002.196.01.14

Foged, N. 1987. The need for Quaternary geological knowledge in geotechnical engineering. *Boreas*, **16**, 419–424, https://doi.org/10.1111/j.1502-3885.1987.tb00115.x

Forsberg, C.F., Plank, S., Tjelta, T.I., Svano, G., Strout, J.M. and Svensen, H. 2007. Formation of pockmarks in the Norwegian channel. Proceedings of the 6th International Offshore Site Investigation and Geotechnics Conference: Confronting New Challenges and Sharing Knowledge, September 2007, London.

Fugro Marine GeoServices. 2017. *Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS*. US Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Herndon, **OCS Study BOEM 2018-049**, https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Renewable-Energy/G-and-G-Methodology-Renewable-Energy-Facilities-on-the-Atlantic-OCS.pdf

Gandy, N., Gregoire, L.J., Ely, J.C., Cornford, S.L., Clark, C.D. and Hodgson, D.M. 2019. Exploring the ingredients required to successfully model the placement, generation, and evolution of ice streams in the British–Irish Ice Sheet. *Quaternary Science Reviews*, **223**, https://doi.org/10.1016/j.quascirev.2019.105915

Gandy, N., Gregoire, L.J., Ely, J.C., Cornford, S.L., Clark, C.D. and Hodgson, D.M. 2021. Collapse of the last Eurasian Ice Sheet in the North Sea modulated by combined processes of ice flow, surface melt, and marine ice sheet instabilities. *Journal of Geophysical Research: Earth Surface*, **126**, e2020JF005755, https://doi.org/10.1029/2020JF005755

Gatliff, R.W., Richards, P.C. *et al.* 1994. *United Kingdom Offshore Regional Report: The Geology of the Central North Sea*. HMSO for the British Geological Survey, London.

Graham, A.G.C., Stoker, M.S., Lonergan, L., Bradwell, T. and Stewart, M.A. 2011. The Pleistocene glaciations of the North Sea basin. *In*: Ehlers, J., Gibbard, P.L. and Hughes, P.D. (eds) *Developments in Quaternary Sciences*, **15**, Elsevier, Amsterdam, 261–278, https://doi.org/10.1016/B978-0-444-53447-7.00021-0

Grasmueck, M., Moser, T.J. and Pelissier, M.A. 2012. Stop treating diffractions as noise – use them for imaging of fractures and karst. Adapted from extended abstract prepared in conjunction with poster presentation at AAPG Hedberg Conference, Fundamental Controls on Flow in Carbonates, 8–13 July 2012, Saint-Cyr-sur-Mer, France. AAPG, Tulsa, OK.

Gupta, B. and Basu, D. 2016. Analysis of offshore wind turbine rigid Monopile Foundation. *In*: Manzanal, D. and Sfriso, A.O. (eds) *From Fundamentals to Applications in Geotechnics*, Proceedings of the 15th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, 15–18 November 2015, Buenos Aires, Argentina, 822–829, https://doi.org/10.3233/978-1-61499-603-3-822

Haflidason, H., Sejrup, H.P., Klitgaard-Kristensen, D. and Johnsen, S. 1995. Coupled response of the late glacial climatic shifts of northwest Europe reflected in Greenland ice cores: evidence from the northern North Sea. *Geology*, **23**, 1059–1062, http://dx.doi.org/10.1130/0091-7613(1995)023%3C1059:CROTLG%3E2.3.CO;2

Haflidason, H., King, E.L. and Sejrup, H.P. 1998. Late Weichselian and Holocene sediment fluxes of the northern North Sea Margin. *Marine Geology*, **152**, 189–215, https://doi.org/10.1016/S0025-3227(98)00071-1

Harris, H. and Whitehouse, R. 2017. Scour development and large diameter monopiles in cohesive soils: evidence from the field. *Journal of Waterway, Port, Coastal and Ocean Engineering*, **143**, https://doi.org/10.1061/(ASCE)WW.1943-5460.0000414

Hjelstuen, B.O., Nygård, A., Sejrup, H.P. and Haflidason, H. 2012. Quaternary denudation of southern Fennoscandia – evidence from the marine realm. *Boreas*, **41**, 379–390, https://doi.org/10.1111/j.1502-3885.2011.00239.x

Hjelstuen, B.O., Sejrup, H.P., Valvik, E. and Becker, L.W.M. 2018. Evidence of an ice-dammed lake outburst in the North Sea during the last deglaciation. *Marine Geology*, **402**, 118–130, https://doi.org/10.1016/j.margeo.2017.11.021

Holeyman, A., Peralta, P. and Charue, N. 2015. Boulder–soil–pile dynamic interaction. *In*: Meyer, V. (ed.) *Frontiers in Offshore Geotechnics III*. Taylor & Francis, London, 563–568.

Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J. and Svendsen, J.I. 2016. The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas*, **45**, 1–45, https://doi.org/10.1111/bor.12142

Huuse 2002. Cenozoic uplift and denudation of southern Norway: insights from the North Sea Basin. *Geological Society, London, Special Publications*, **196**, 209–233, https://doi.org/10.1144/GSL.SP.2002.196.01.13

Ikhennicheu, M., Lynch, M. *et al.* 2020. *Review of the State of the Art of Dynamic Cable System Design*. INNOSEA, https://corewind.eu/wp-content/uploads/files/publications/COREWIND-D3.1-Review-of-the-state-of-the-art-of-dynamic-cable-system-design.pdf [last accessed 17 March 2022].

Jackson, C.A.-L. 2007. Application of three-dimensional seismic data to documenting the scale, geometry and distribution of soft-sediment features in sedimentary basins: an example from the Lomre Terrace, offshore Norway. *Geological Society, London, Special Publications*, **277**, 253–267, https://doi.org/10.1144/GSL.SP.2007.277.01.15

James, R. and Costa Ros, M. 2015. *Floating Offshore Wind: Market and Technology Review Prepared for the Scottish Government*. The Carbon Trust, https://proddrupalfiles.storage.googleapis.com/documents/resource/public/Floating%20Offshore%20Wind%20Market%20Technology%20Review%20-%20REPORT.pdf [last accessed 25 June 2021].

Jansen, E., Sjøholm, J., Bleil, U. and Erichsen, J.A. 1990. Neogene and Pleistocene glaciations in the northern hemisphere and late Miocene–Pliocene global ice volume fluctuations: evidence from the Norwegian Sea. *In*: Bleil, U. and Thiede, J. (eds) *Geological History of the Polar Oceans: Arctic versus Antarctic. NATO ASI Series (Series C: Mathematical and Physical Sciences)*, **308**. Springer, Dordrecht, 677–705, https://doi.org/10.1007/978-94-009-2029-3_35

Jansen, E., Fronval, T., Rack, F. and Channell, E.T. 2000. Pliocene–Pleistocene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. *Paleoceanography and Paleoclimatology*, **15**, 709–721, https://doi.org/10.1029/1999PA000435

Jansen, J.H.F., van Weering, T.C.E. and Eisma, D. 1979. Late Quaternary sedimentation in the North Sea. *In:* Oele, E., Schuttenhelm, R.T.E. and

Wiggers, A.J. (eds) *The Quaternary History of the North Sea*. Uppsala University, 175–187.

Kamb, B. 2001. Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion. *American Geophysical Union, Antarctic Research Series*, **77**, 157–201, https://doi.org/10.1029/AR077p0157

King, E., Sejrup, H.P., Haflidason, H., Elverhøi, A. and Aarseth, I. 1996. Quaternary seismic stratigraphy of the North Sea Fan: glacially-fed gravity flow aprons, hemipelagic sedimentation, and submarine sliding. *Marine Geology*, **130**, 293–315, https://doi.org/10.1016/0025-3227(95)00168-9

King, E.C., Hindmarsh, R.C.A. and Stokes, C.R. 2009. Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream. *Nature*, **2**, 585–588, https://doi.org/10.1038/NGEO581

Klitgaard-Kristensen, D., Sejrup, H.P., Haflidason, H., Johnsen, S and Spurk, M. 1998. A regional 8200 cal. yr BP cooling event in northwest Europe, induced by final stages of the Laurentide ice-sheet deglaciation? *Journal of Quaternary Science*, **13**, 165–169, https://doi.org/10.1002/(SICI)1099-1417(199803/04)13:2%3C165::AID-JQS365%3E3.0.CO;2-%23

Kyrke-Smith, T.M., Katz, R.F. and Fowler, A.C. 2013. Stress balances of ice streams in a vertically integrated, higher-order formulation. *Journal of Glaciology*, **59**, 449–466, https://doi.org/10.3189/2013JoG12J140

Le, T.M.H., Erikson, G.R., Strom, P.J. and Saue, M. 2014. Geological and geotechnical characterization for offshore wind turbine foundations: a case study of the Sheringham Shoal wind farm. *Engineering Geology*, **177**, 40–53, https://doi.org/10.1016/j.enggeo.2014.05.005

Le Bot, S., Van Lancker, V., Deleu, S., De Batist, M., Henriet, J.P. and Haegeman, W. 2005. Geological characteristics and geotechnical properties of Eocene and Quaternary deposits on the Belgian continental shelf: synthesis in the context of offshore wind farming. *Netherlands Journal of Geosciences*, **84**, 140–160, https://doi.org/10.1017/S0016774600023027

Lee, J.R., Busschers, F.S. and Sejrup, H.P. 2012. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. *Quaternary Science Reviews*, **44**, 213–228, https://doi.org/10.1016/j.quascirev.2010.02.027

Lekens, W.A.H., Sejrup, H.P., Haflidason, H., Petersen, G.Ø., Hjelstuen, B. and Knorr, G. 2005. Laminated sediments preceding Heinrich event 1 in the Northern North Sea and Southern Norwegian Sea: origin, processes and regional linkage. *Marine Geology*, **216**, 27–50, https://doi.org/10.1016/j.margeo.2004.12.007

Lekens, W.A.H., Haflidason, H., Sejrup, H.P., Nygård, A., Richter, T., Vogt, C. and Frederichs, T. 2009. Sedimentation history of the northern North Sea Margin during the last 150 ka. *Quaternary Science Reviews*, **28**, 469–483, https://doi.org/10.1016/j.quascirev.2008.11.010

Lien, R. 1983. *Iceberg Scouring on the Norwegian Continental Shelf*. Continental Shelf Institute Publication, **109**, https://doi.org/10.4043/4585-MS

Löhning, T., Kaufmann, K.L. and Groes, J.B. 2021. Drilled pile foundations for offshore wind farms. Proceedings of the Thirty-First International Ocean and Polar Engineering Conference, 20–25 June 2021, Rhodes, 557–563.

Ma, H., Yang, J. and Chen, L. 2017. Numerical analysis of the long-term performance of offshore wind turbines supported by monopiles. *Ocean Engineering*, **136**, 94–105, https://doi.org/10.1016/j.oceaneng.2017.03.019

Ma, H., Yang, J. and Chen, L. 2018. Effect of scour on the structural response of an offshore wind turbine supported on tripod foundations. *Applied Ocean Research*, **73**, 179–189, https://doi.org/10.1016/j.apor.2018.02.007

Mangerud, J., Gyllencreutz, R., Lohne, Ø. and Svendsen, J.I. 2011. Glacial history of Norway. *In:* Ehlers, J., Gibbard, P.L. and Hughes, P.D. (eds) *Developments in Quaternary Science*, **15**. Elsevier, Amsterdam, 279–298, https://doi.org/10.1016/B978-0-444-53447-7.00022-2

Matutano, C., Negro, V., López-Gutiérrez, J.S. and Esteban, M.D. 2013. Scour prediction and scour protections in offshore wind farms. *Renewable Energy*, **57**, 358–365, https://doi.org/10.1016/j.renene.2013.01.048

McClennen, C.E. 1989. Microtopography and surficial sediment patterns in the central Gulf of Maine: a 3.5-kHz survey and interpretation. *Marine Geology*, **89**, 69–85, https://doi.org/10.1016/0025-3227(89)90028-5

Mellet, C., Long, D., Carter, G., Chiverrell, R. and Van Landeghem, K. 2015. *Geology of the Seabed and Shallow Subsurface: The Irish Sea*. British Geological Survey Commissioned Report, **CR/15/057**.

Merritt, A., Schroeder, F., Jardine, R., Stuyts, B., Cathie, D. and Cleverly, W. 2012. Development of pile design methodology for an offshore wind farm in the North Sea. *In*: SUT Offshore Site Investigation and Geotechnics, Proceedings of the 7th International Conference, January 2012, London, 439–448.

Milligan, V. 1976. Geotechnical aspects of glacial tills. *In:* Leggett, R.F. (ed.) *Glacial Till – An Interdisciplinary Study*. Royal Society of Canada, Ottawa, Ontario, 269–291.

Montelli, A., Dowdeswell, J.A., Ottesen, D. and Johansen, S.E. 2017. Ice-sheet dynamics through the Quaternary on the mid-Norwegian continental margin inferred from 3D seismic data. *Marine and Petroleum Geology*, **80**, 228–242, https://doi.org/10.1016/j.marpetgeo.2016.12.002

Morén, B.M., Sejrup, H.P., Hjelstuen, B.O., Borge, M.V. and Schäuble, C. 2018. The last deglaciation of the Norwegian Channel – geomorphology, stratigraphy and radiocarbon dating. *Boreas*, **47**, 347–366, https://doi.org/10.1111/bor.12272

Muir Wood, A. and Knight, P. 2013. Site investigation and geotechnical design strategy for offshore wind development. *In*: Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, 2375–2378.

Nesje, A. and Dahl, S.O. 1993. Late glacial and Holocene glacier fluctuations and climate variations in western Norway: a review. *Quaternary Science Reviews*, **12**, 255–261, https://doi.org/10.1016/0277-3791(93)90081-V

Nesje, A., Kvamme, M., Rye, N. and Løvlie, R. 1991. Holocene glacial and climate history of the Jostedalsbreen region, Western Norway; evidence from lake sediments and terrestrial deposits. *Quaternary Science Reviews*, **10**, 87–114, https://doi.org/10.1016/0277-3791(91)90032-P

NOAA 2008. *ETOPO1 Global Relief Model*, https://www.ngdc.noaa.gov/mgg/global/ [last accessed 18 November 2021].

Norwegian Geological Survey 2022. *Marine Maps: Seabed sediments (grain size)*. Available online: https://geo.ngu.no/kart/marin_mobil/ [last accessed 15 March 2022].

Norwegian Mapping Authority 2018. *5 m Sea Terrain Model*, https://kartkatalog.geonorge.no/metadata/kartverket/sjo-terrengmodeller-dtm-5/13b707ad-a379-4bf0-a707-da237d646f44 [last accessed 22 March 2021].

Norwegian Ministry of Petroleum and Energy 2022. Høyring av forslag til inndeling av dei opna områda i utlysingsområde for fornybar energiproduksjon til havs, https://www.regjeringen.no/no/dokumenter/hoyring-av-forslag-til-inndeling-av-dei-opna-omrada-i-utlysingsomrade-for-fornybar-energiproduksjon-til-havs/id2900420/ [last accessed 9 February 2022].

Nygård, A. 2003. *Pleistocene Sedimentary Processes and Glacial History of the Southern Norwegian Continental Margin*. PhD thesis, University of Bergen.

Nygård, A., Sejrup, H.P., Haflidason, H. and Bryn, P. 2005. The glacial North Sea Fan, southern Norwegian Margin: architecture and evolution from the upper continental slope to the deep-sea basin. *Marine and Petroleum Geology*, **22**, 71–84, https://doi.org/10.1016/j.marpetgeo.2004.12.001

Nygård, A., Sejrup, H.P., Haflidason, H., Lekens, W.A.H., Clark, C.D. and Bigg, G.R. 2007. Extreme sediment and ice discharge from marine-based ice streams: new evidence from the North Sea. *Geology*, **35**, 395–398, https://doi.org/10.1130/G23364A.1

Ó Cofaigh, C., Evans, J., Dowdeswell, J.A. and Larter, R.D. 2007. Till characteristics, genesis and transport beneath Antarctic paleo-ice streams. *Journal of Geophysical Research: Earth Surface*, **112**, F03006, https://doi.org/10.1029/2006JF000606

Ottesen, D., Dowdeswell, J.A., Rise, L., Rokoengen, K. and Henriksen, S. 2002. Large-scale morphological evidence for past ice-stream flow on the Norwegian continental margin. *Geological Society, London, Special Publications*, **203**, 245–258, https://doi.org/10.1144/GSL.SP.2002.203.01.13

Ottesen, D., Dowdeswell, J.A. and Rise, L. 2005. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2500-km-long Norwegian–Svalbard margin (57°–80°N). *Geological Society of America Bulletin*, **117**, 1033–1050, https://doi.org/10.1130/B25577.1

Ottesen, D., Rise, L., Andersen, E.S., Bugge, T. and Eidvin, T. 2009. Geological evolution of the Norwegian continental shelf between 61°N and 68°N during the last 3 million years. *Norwegian Journal of Geology*, **89**, 251–265, https://njg.geologi.no/images/NJG_articles/NGT_4_09_Ottesen_scr.pdf

Ottesen, D., Dowdeswell, J.A., Rise, L. and Bugge, T. 2012. Large-scale development of the mid-Norwegian shelf over the last three million years and potential for hydrocarbon reservoirs in glacial sediments. *Geological Society, London, Special Publications*, **368**, 53–73, https://doi.org/10.1144/SP368.6

Ottesen, D., Dowdeswell, J.A. and Bugge, T. 2014. Morphology, sedimentary infill and depositional environments of the Early Quaternary North Sea Basin (56–62°N). *Marine and Petroleum Geology*, **56**, 123–146, https://doi.org/10.1016/j.marpetgeo.2014.04.007

Ottesen, D., Stokes, C.R. *et al.* 2016. Landform assemblages and sedimentary processes along the Norwegian Channel Ice Stream. *Sedimentary Geology*, **338**, 115–137, https://doi.org/10.1016/j.sedgeo.2016.01.024

Phillips, E., Hodgson, D.M. and Emery, A.R. 2017. The Quaternary Geology of the North Sea Basin. *Journal of Quaternary Science*, **32**, 117–339, https://doi.org/10.1002/jqs.2932

Praeg, D. 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea basin. *Journal of Applied Geophysics*, **53**, 273–298, https://doi.org/10.1016/j.jappgeo.2003.08.001

Prins, L.T. and Andresen, K.J. 2021. A geotechnical stratigraphy for the shallow subsurface in the Southern Central Graben, North Sea. *Engineering Geology*, **286**, https://doi.org/10.1016/j.enggeo.2021.106089

Qi, W.G., Gao, F.P., Randolph, M.F. and Lehane, B.M. 2016. Scour effects on p–y curves for shallowly embedded piles in sand. *Géotechnique*, **66**, 648–660, https://doi.org/10.1680/jgeot.15.P.157

Radhakrishna, H.S. and Klym, T.W. 1974. Geotechnical properties of a very dense till. *Canadian Geotechnical Journal*, **11**, 396–408, https://doi.org/10.1139/t74-040

Ragnhildstveit, J., Naterstad, J., Jorde, K. and Egeland, B. 1998. *Geological map over Norway; Bedrock Map Haugesund – M 1:250000*. Norges geologiske undersøkelse, Trondheim.

Ramsey, N. 2002. A calibrated model for the interpretation of cone penetration tests (CPTs) in North Sea Quaternary soils. *In*: Offshore Site Investigation and Geotechnics 'Diversity and Sustainability': Proceedings of an International Conference, 26–28 November 2002, London.

Rea, B.R., Newton, A.M.W. *et al.* 2018. Extensive marine-terminating ice sheets in Europe from 2.5 million years ago. *Science Advances*, **4**, https://doi.org/10.1126/sciadv.aar8327

Reinardy, B.T.I., Larter, R.D., Hillenbrand, C.-D., Murray, T., Hiemstra, J.F. and Booth, A.D. 2011. Streaming flow of an Antarctic Peninsula palaeo-ice

stream, both by basal sliding and deformation of substrate. *Journal of Glaciology*, **57**, 596–608, https://doi.org/10.3189/002214311797409758

Reinardy, B.T.I., Hjelstuen, B.O., Sejrup, H.P., Augedal, H. and Jørstad, A. 2017. Late Pliocene–Pleistocene environments and glacial history of the northern North Sea. *Quaternary Science Reviews*, **158**, 107–126, https://doi.org/10.1016/j.quascirev.2016.12.022

Rise, L. and Rokoengen, K. 1984. Surficial sediments in the Norwegian sector of the North Sea between 60°30' and 62°N. *Marine Geology*, **58**, 287–317, https://doi.org/10.1016/0025-3227(84)90206-8

Rise, L., Olesen, O., Rokoengen, K., Ottesen, D. and Riis, F. 2004. Mid-Pleistocene ice drainage pattern in the Norwegian Channel imaged by 3D seismic. *Quaternary Science Reviews*, **23**, 2323–2335, https://doi.org/10.1016/j.quascirev.2004.04.005

Rise, L., Bøe, R., Ottesen, D., Longva, O. and Olsen, H.A. 2008. Postglacial depositional environments and sedimentation rates in the Norwegian Channel off southern Norway. *Marine Geology*, **251**, 124–138, https://doi.org/10.1016/j.margeo.2008.02.012

Roberts, D.H., Dackombe, R.V. and Thomas, G.S. 2007, Palaeo-ice streaming in the central sector of the British–Irish Ice Sheet during the Last Glacial Maximum: evidence from the northern Irish Sea Basin. *Boreas*, **36**, 115–129, https://doi.org/10.1111/j.1502-3885.2007.tb01186.x

Rokoengen, K. and Sørensen, S. 1990. Late Jurassic sedimentary bedrock north of Utsira, offshore western. Norway. *Norsk Geologisk Tidsskrift*, **70**, 61–63, http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=19679285

Ruddiman, W.F., Raymo, M. and McIntyre, A. 1986. Matuyama 41,000-year cycles: North Atlantic Ocean and northern hemisphere ice sheets. *Earth and Planetary Science Letters*, **80**, 117–129, https://doi.org/10.1016/0012-821X(86)90024-5

Rüther, D.C., Mattingsdal, R., Andreassen, K., Forwick, M. and Husum, K. 2011. Seismic architecture and sedimentology of a major grounding zone system deposited by the Bjørnøyrenna Ice Stream during Late Weichselian deglaciation. *Quaternary Science Reviews*, **30**, 2776–2792, https://doi.org/10.1016/j.quascirev.2011.06.011

Sejrup, H.P., Nagy, J. and Brigham-Grette, J. 1989. Foraminiferal stratigraphy and amino acid geochronology of interglacial and glacial sediments in the Norwegian Channel., northern North Sea. *Norsk Geologisk Tidsskrift*, **69**, 111–124.

Sejrup, H.P., Aarseth, I. and Haflidason, H. 1991. The Quaternary succession in the northern North Sea. *Marine Geology*, **101**, 103–111, https://doi.org/10.1016/0025-3227(91)90065-C

Sejrup, H.P., Haflidason, H., Aarseth, I., King, E., Forsberg, C.F., Long, D. and Rokoengen, K. 1994. Late Weichselian glaciation history of the northern North Sea. *Boreas*, **22**, 1–13, https://doi.org/10.1111/j.1502-3885.1994.tb00581.x

Sejrup, H.P., Aarseth, I. *et al.* 1995. Quaternary of the Norwegian Channel: glaciation history and palaeoceanography. *Norsk Geologisk Tidsskrift*, **75**, 65–87.

Sejrup, H.P., King, E., Aarseth, I., Haflidason, H. and Elverhøi, A. 1996. Quaternary erosion and depositional processes: western Norwegian fjords, Norwegian Channel and North Sea Fan. *Geological Society, London, Special Publications*, **117**, 187–202, https://doi.org/10.1144/GSL.SP.1996.117.01.11

Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Haflidason, H. and Nesje, A. 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. *Quaternary Science Reviews*, **19**, 667–685, https://doi.org/10.1016/S0277-3791(99)00016-5

Sejrup, H.P., Larsen, E. *et al.* 2003. Configuration, history and impact of the Norwegian Channel Ice Stream. *Boreas*, **32**, 18–36, https://doi.org/10.1080/03009480310001029

Sejrup, H.P., Hjelstuen, B.O. *et al.* 2005. Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology*, **22**, 1111–1129, https://doi.org/10.1016/j.marpetgeo.2004.09.007

Sejrup, H.P., Nygård, A., Hall, A.M. and Haflidason, H. 2009. Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. *Quaternary Science Reviews*, **28**, 370–380, https://doi.org/10.1016/j.quascirev.2008.10.019

Sejrup, H.P., Hjelstuen, B.O., Nygård, A., Haflidason, H. and Mardal, I. 2015. Late Devensian ice-marginal features in the central North Sea – Processes and chronology. *Boreas*, **44**, 1–13, https://doi.org/10.1111/bor.12090

Sejrup, H.P., Clark, C.D. and Hjelstuen, B.O. 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: evidence from the North Sea. *Geology*, **44**, 355–358, https://doi.org/10.1130/G37652.1

Shackleton, J., Berger, A. and Peltier, W.R. 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **81**, 251–261, https://doi.org/10.1017/S0263593300020782

Shaw, J. and Longva, O. 2017. Glacial geomorphology of the Northeast Newfoundland Shelf: ice-stream switching and widespread glaciotectonics. *Boreas*, **46**, 622–641, https://doi.org/10.1111/bor.12240

Shaw, J., Piper, D.J.W. *et al.* 2006. A conceptual model of the deglaciation of Atlantic Canada. *Quaternary Science Reviews*, **25**, 2059–2081, https://doi.org/10.1016/j.quascirev.2006.03.002

Siegel, J., Dugan, B., Lizarralde, D., Person, M., DeFoor, W. and Miller, N. 2012. Geophysical evidence of a late Pleistocene glaciation and paleo-ice stream on the Atlantic Continental Shelf offshore Massachusetts, USA. *Marine Geology*, **303–306**, 63–74, https://doi.org/10.1016/j.margeo.2012.01.007

Singh, S. and Murthy, P.S.K. 2016. GNEISSES – strengths and mineralogical compositions. *International Journal of Innovative Research in Science, Engineering and Technology*, **5**, 3658–3663, http://www.ijirset.com/upload/2016/march/171_Mechanical.pdf

Small, D., Smedley, R.K. *et al.* 2018. Trough geometry was a greater influence than climate ocean forcing in regulating retreat of the marine-based Irish-Sea Ice Stream. *Geological Society of America Bulletin*, **130**, 1981–1999, https://doi.org/10.1130/B31852.1

Sørensen, S.P.H. and Ibsen, L.B. 2013. Assessment of foundation design for offshore monopiles unprotected against scour. *Ocean Engineering*, **63**, 17–25, https://doi.org/10.1016/j.oceaneng.2013.01.016

Statoil 2015. Physical Environment. *In*: *Hywind Scotland Pilot Park Project – Environmental Statement*, https://www.equinor.com/content/dam/statoil/documents/impact-assessment/Hywind/Statoil-Environmental%20Statement%20April%202015.pdf [last accessed 12 March 2022].

Stokes, C.R. 2018. Geomorphology under ice streams: moving from form to process. *Earth Surface Processes and Landforms*, **43**, 85–123, https://doi.org/10.1002/esp.4259

Sturm, H. 2017. Design aspects of suction caissons for offshore wind turbine foundations. *In*: *Foundation Design of Offshore Wind Structures: Proceedings of TC 209 Workshop – 19th ICSMGE*, 20 September 2017, Seoul.

Svendsen, J.I., Alexanderson, H. *et al.* 2004. Late Quaternary ice sheet history of northern Eurasia. *Quaternary Science Reviews*, **23**, 1229–1271, https://doi.org/10.1016/j.quascirev.2003.12.008

Tewolde, S., Höffer, R. and Haardt, H. 2017. Validated model-based development of damage index for Structural Health Monitoring of offshore wind turbine support structures. *Procedia Engineering*, **199**, 3242–3247, https://doi.org/10.1016/j.proeng.2017.09.344

Thomas, S. 1990. *Geotechnical Investigation of UK Test Sites for the Foundations of Offshore Structures*. Department of Energy, UK, Offshore Technology Report, **OTH 89 294**.

Toucanne, S., Zaragosi, S. *et al.* 2009. A 1.2 Ma record of glaciation and fluvial discharge from the West European Atlantic margin. *Quaternary Science Reviews*, **28**, 2974–2981, https://doi.org/10.1016/j.quascirev.2009.08.003

Tseng, W.C., Kuo, Y.S. and Chen, J.W. 2017. An investigation into the effect of scour on the loading and deformation responses of monopile foundations. *Energies*, **10**, 1190, https://doi.org/10.3390/en10081190

Tulaczyk, S. and Kamb, W.B. 2000. Basal mechanics of ice stream B, West Antarctica. 1. Till mechanics. *Journal of Geophysical Research*, **105**, 463–481, https://doi.org/10.1029/1999JB900329

Van Landeghem, K.J. and Chiverrell, R.C. 2011. *Irish Sea, R3 Wind Farm Development Zone. Geological Appraisal of Swath Bathymetry and Seismo-stratigraphic Data Collected by Centrica*. Report prepared for Centrica. University of Liverpool.

Velenturf, A.P.M., Emery, A.R. *et al.* 2021. Geoscience solutions for sustainable offshore wind development. *Earth Science, Systems and Society*, **1**, 10042, https://doi.org/10.3389/esss.2021.10042

Vérité, J., Ravier, É *et al.* 2021. Formation of ribbed bedforms below shear margins and lobes of palaeo-ice streams. *Cryosphere*, **15**, 2889–2916, https://doi.org/10.5194/tc-15-2889-2021

von Haugwitz, W.R. and Wong, H.K. 1993. Multiple Pleistocene ice advances into the Skagerrak: a detailed seismic stratigraphy from high resolution seismic profiles. *Marine Geology*, **111**, 189–207, https://doi.org/10.1016/0025-3227(93)90130-N

Vorren, T.O. and Laberg, J.S. 1997. Trough mouth fans – Palaeoclimate and ice-sheet monitors. *Quaternary Science Reviews*, **16**, 865–881, https://doi.org/10.1016/S0277-3791(97)00003-6

Vryhof Anchors 2010. *Anchor Manual 2010*. Vryhof Anchors, Capelle a/d IJssel, https://pdf4pro.com/amp/view/the-guide-to-anchoring-vryhof-6ac27.html [last accessed 15 July 2021].

Wang, L., Zhou, W., Guo, Z. and Rui, S. 2020. Frequency change and accumulated inclination of offshore wind turbine jacket structure with piles in sand under cyclic loadings. *Ocean Engineering*, **217**, https://doi.org/10.1016/j.oceaneng.2020.108045

Wenau, S., Stange, N., Keil, H., Ramos, C. and Spiess, V. 2018. A seismic beamforming approach for the detection of boulders in the shallow sub-seafloor. *In*: Conference Proceedings, 3rd Applied Shallow Marine Geophysics Conference, September 2018, Porto, Portugal, **2018**, 1–5, https://doi.org/10.3997/2214-4609.201802672

Wenner, E.L., Knott, D.M., van Dolah, R.F. and Burrell, V.G., Jr 1983. Invertebrate communities associated with hard bottom habitats in the South Atlantic Bight. *Estuarine, Coastal and Shelf Science*, **17**, 143–158, https://doi.org/10.1016/0272-7714(83)90059-8

Westgate, Z.J. and De Jong, J.T. 2005. *Geotechnical Considerations for Offshore Wind Turbines*. Report for MTC OTC Project, https://www.researchgate.net/publication/252536016_Geotechnical_Considerations_for_Offshore_Wind_Turbines

Whitehouse, R.J.S., Harris, J.M., Sutherland, J. and Rees, J. 2011. The nature of scour development and scour protection at offshore windfarm foundations. *Marine Pollution Bulletin*, **62**, 73–88, https://doi.org/10.1016/j.marpolbul.2010.09.007

Wind Europe 2018. Floating offshore wind energy: A Policy Blueprint for Europe, https://windeurope.org/wp-content/uploads/files/policy/position-

papers/Floating-offshore-wind-energy-a-policy-blueprint-for-Europe.pdf [last accessed 1 July 2021].

Wingfield, R. 1989. Glacial incisions indicating Middle and Upper Pleistocene ice limits off Britain. *Terra Nova*, **1**, 528–548, https://doi.org/10.1111/J.1365-3121.1989.TB00430.X

Wingfield, R. 1990. The origin of major incisions within the Pleistocene deposits of the North Sea. *Marine Geology*, **91**, 31–52, https://doi.org/10.1016/0025-3227(90)90131-3

Winsborrow, M.C.M., Clark, C.D. and Stokes, C.R. 2004. Ice streams of the Laurentide ice sheet. *Géographie Physique et Quaternaire*, **58**, https://doi.org/10.7202/013142ar

Winsborrow, M., Andreassen, K., Hubbard, A., Plaza-Faverola, A., Gudlaugsson, E. and Patton, H. 2016. Regulation of ice stream flow through subglacial formation of gas hydrates. *Nature Geoscience*, **9**, 370–375, https://doi.org/10.1038/ngeo2696

Wu, X., Hu, Y. *et al.* 2019. Foundations of offshore wind turbines: a review. *Renewable and Sustainable Energy Reviews*, **104**, 379–393, https://doi.org/10.1016/j.rser.2019.01.012

Yang, Q., Yu, P., Liu, Y., Liu, H., Zhang, P. and Wang, Q. 2020. Scour characteristics of an offshore umbrella suction anchor foundation under the combined actions of waves and currents. *Ocean Engineering*, **202**, https://doi.org/10.1016/j.oceaneng.2019.106701