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

A geological model for Utsira Nord

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While much work has been done to advance our understanding of the Quaternary geology of the Norwegian North Sea (e.g., Sejrup *et al.* 1994, 1995, 2000, 2003, 2016; Haflidason *et al.* 1998; Nygård *et al.* 2005; Lekens *et al.* 2009; Ottesen *et al.* 2016; Morén *et al.* 2018), the application of this knowledge towards floating offshore wind 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).

While 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 market area for the development of offshore wind but is already a mature oil and gas province with publicly available 2D and 3D seismic datasets. With such abundant subsurface data, often lacking in new offshore wind areas, present and future offshore wind projects within the Norwegian North Sea could have a strong advantage over other market areas in terms of giving developers the ability to develop a conceptual 3D geological understanding of the survey area in the early phases of the project. 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 likely be developed as Norway’s first large-scale floating offshore wind park, covering an area of 1010 km^2. The Norwegian Government intends to divide the site into up to three development areas, with the selection process for developers set to begin at the end of 2021 (Norwegian Ministry of Petroleum and Energy, 2021).

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 million years (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, such as the coastlines of Canada, the northern United States and the northern United Kingdom (Fig. 2). Understanding the geological and geotechnical heterogeneities of the seabed and shallow subsurface in previously glaciated areas therefore has important 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 high resolution bathymetric data, 2D seismic data and sub-bottom profiles covering the site, and shallow cores from the surrounding area. We demonstrate a method which 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 geotechnical provinces at the Utsira Nord site to be defined: 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 lodgment till (glacial clays, silts, sands and gravels and boulders) of uncertain geotechnical character and 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 palaeo ice stream systems are common.

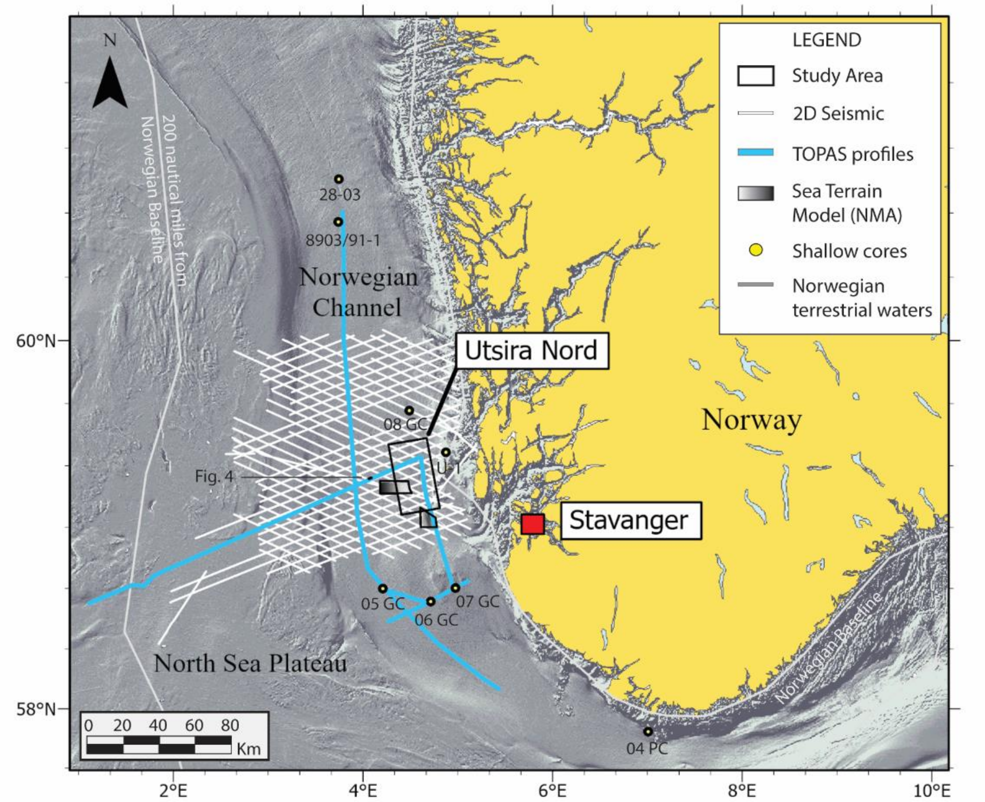


Fig. 1. Bathymetric hill-shaded map of the Norwegian North Sea (www.olex.no) showing the location of the Utsira Nord site, and the dataset used in this study. Two small parts of the site are covered by the Norwegian Mapping Authority (NMA) 5 m resolution Sea Terrain Model (2018). TOPAS acoustic profiles, gravity/piston cores (05-GC-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 & 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 (Klitgaard-Kristensen *et al.* 1998; Sejrup *et al.* 1994, 1995). Drilled core 27/9-U-1 penetrates Jurassic sedimentary bedrock east of Utsira Nord (Rokoengen and Sørensen, 1990).

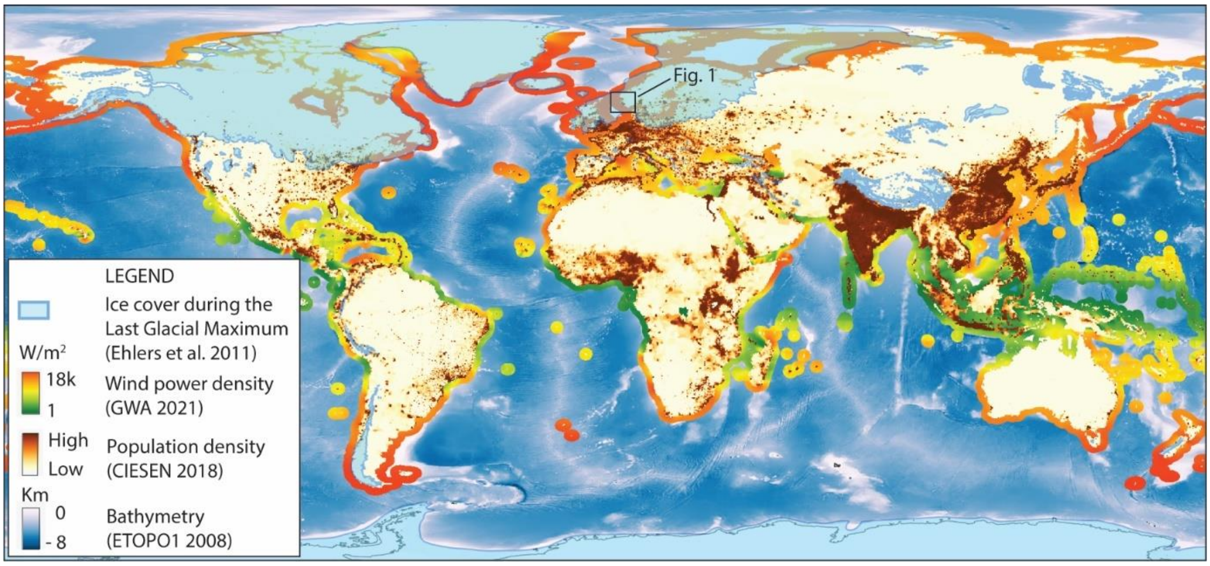


Fig. 2. Global map of ice extent (glaciated areas) during the Last Glacial Maximum (~20 ka) (Ehlers *et al.* 2011), wind power density at 100 m (Global Wind Atlas, 2021) and world population density (CIESIN, 2018) giving an overview of the coastlines where ice streaming has been an important geological process and where good wind resources and large population centers are present. Background bathymetry is from ETOPO1 Global Relief Model (NOAA, 2008).

Geological Background

The North Sea

The North Sea is an epicontinental shelf of 50-400 m water depth, located between the United Kingdom and Northern Europe. During the Cenozoic, the North Sea formed a wide depocenter in which up to ca. 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): 1) late Paleocene to early Eocene uplift related to the break-up of the northeast Atlantic and the Iceland plume and 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., Dahlgren and Vorren, 2003; Ehlers *et al.* 1984; Ehlers and Gibbard, 2004; Sejrup *et al.* 2005; Lee *et al.* 2012). It was during the *Fedje* glaciation ~ 1.1 million years ago that the SIS is thought to have extended beyond at least the southwest and mid-Norwegian coastline for the first time (Haflidason *et al.* 1991; Sejrup *et al.* 1994, 1995). 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 which truncate Upper Pliocene clinoforms and the lower part of the Pleistocene sequence (Sejrup *et al.* 1991; Eidvin *et al.* 2000, Graham *et a*l. 2011). In cored sediments sampled above the giant gas field *Troll* (sediment core 8903/91-1), a glacial deposit dated to 1.1 Ma, named the *Fedje* till, is directly superimposed on Oligocene strata (Sejrup *et al.* 1995).

After ~1.0 Ma, the Quaternary climate cycles became more intense, resulting in more extensive glaciations and warmer interglacial periods (Ruddiman *et al.* 1986; Shackleton *et al.* 1990; Jansen *et al.* 1990, 2000). Glacial landforms mapped on bathymetric data and information from sediment cores indicate that the SIS, the British Isles Ice Sheet (BIIS) and the Barents Sea-Kara Ice Sheet eventually merged at 160-140 ka and again during the Late Glacial Maximum at ~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). Along the coast of south and southwestern Norway, an approximately 200 km wide zone of fast-flowing ice known as the Norwegian Channel Ice Stream (NCIS) formed within the merged SIS-BIIS ice sheets (Ottesen *et al.* 2016). 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 ~18 ka (King *et al.* 1996; Sejrup *et al.* 2003; Rise *et al.* 2004; Nygård *et al.* 2005). These 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 initial deglaciation and break-up of the NCIS started between 19-18.7 ka at the North Sea shelf edge, reaching the inner part of Skagerrak by 17.6 ka (Morén *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 were deposited at relatively high rates (220 g/cm^2/ka between 15-13 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, 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.

Seismic- and Litho-stratigraphy of the Norwegian Channel

The base of the Norwegian Channel is defined by a regional 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 rock (Fig. 3). The overlying Quaternary sediments deposited by the NCIS are generally flat-lying and extensive, often with erosive bases that truncate the older channel sediments (Sejrup *et al.* 1995). The term *glacial till* is used to describe sediments which have been transported and then deposited by a glacier, ice sheet or ice stream (Dreimanis and Lundquist, 1984). These sediments tend to contain a mixture of clay, silt and coarser rock fragments ranging from sand and gravel to boulder size. Units of till which are associated with a particular morphological deposit, for example from the sides or front of the glacier, are described as moraines (e.g., *lateral moraine, terminal/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 are not completely preserved but can comprise several generations of till, glacimarine or marine sediments separated by glacial erosion surfaces (Sejrup *et al.,* 1996). The number of preserved sequences decreases southwards towards the Skagerrak Strait, where only the youngest sequence is preserved (Haugwitz and Wong, 1993). The key geotechnical parameters of the Norwegian Channel tills, glacimarine and marine sedimentary units from the *Troll* reference core are defined in Figure 4 and will be further explored within the Results and Discussion sections of this paper.

In previous studies, the upper ~ 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).

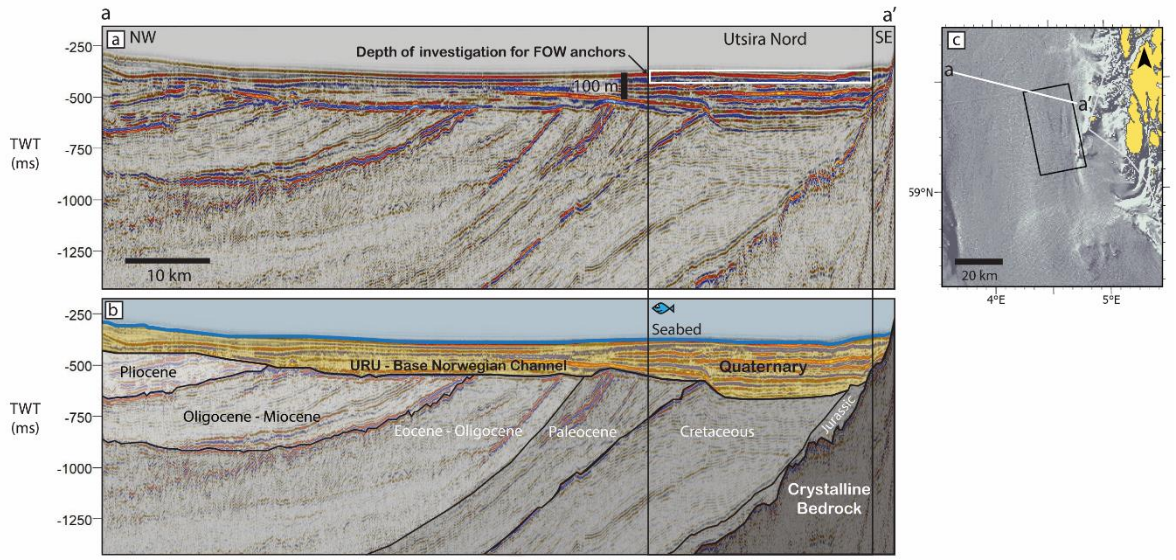


Fig. 3. (a) Uninterpreted regional 2D seismic section (a-a') across the Norwegian Channel from survey ST8201 R92 showing two-way travel time in milliseconds (ms) and depth (m) for the Norwegian Channel late Quaternary infill and standard depth of investigation for FOW anchor site surveys, (b) Interpreted 2D seismic section (a-a') from ST8201 R92 showing outcropping crystalline bedrock along the eastern boundary of the Norwegian Channel, sub-cropping 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 a-a' on Olex bathymetry.

The lowermost unit, interpreted as glacial till, is acoustically homogeneous except for an internal reflector mapped 5-40 m below the top of the unit (R1 in Fig. 4). This internal reflector is mostly found in the outer parts of the Norwegian Channel. Sejrup *et al.* (1994) and Morén *et al.* (2018) group the till above and below this reflector is into one unit (Unit B1 and Unit U1 respectively), while Nygård *et al.* (2007) divide the till into two units (U3 and U2) (Fig. 4). Based on studies of palaeo ice stream systems in Antarctica (O' Cofaigh *et al.* 2007, King *et al.* 2009, Reinardy *et al.* 2011), Morén *et al.* (2018) propose that the internal reflector which 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, over consolidated till (lodgment till) which progressively became buried deeply enough to avoid further deformation. The strong reflector which defines the top of the till (R2 in Fig. 4) is generally highly irregular due to glacial erosion and deformation. Where it has been exposed at the seabed during the last deglaciation, R2 is less distinct and highly perturbated by iceberg plough marks. The base of the till is not generally observed on sub-bottom profiler data due 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 Strait, 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 ca. 220 m through several sequences of tills, very few cores have penetrated the upper till unit in the Norwegian Channel. Those which do have only sampled the upper few metres of the till. Based on the limited core data available (05-GC-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 (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 indicate the presence of boulders or coarse, consolidated material within the tills encountered above the *Troll* field.

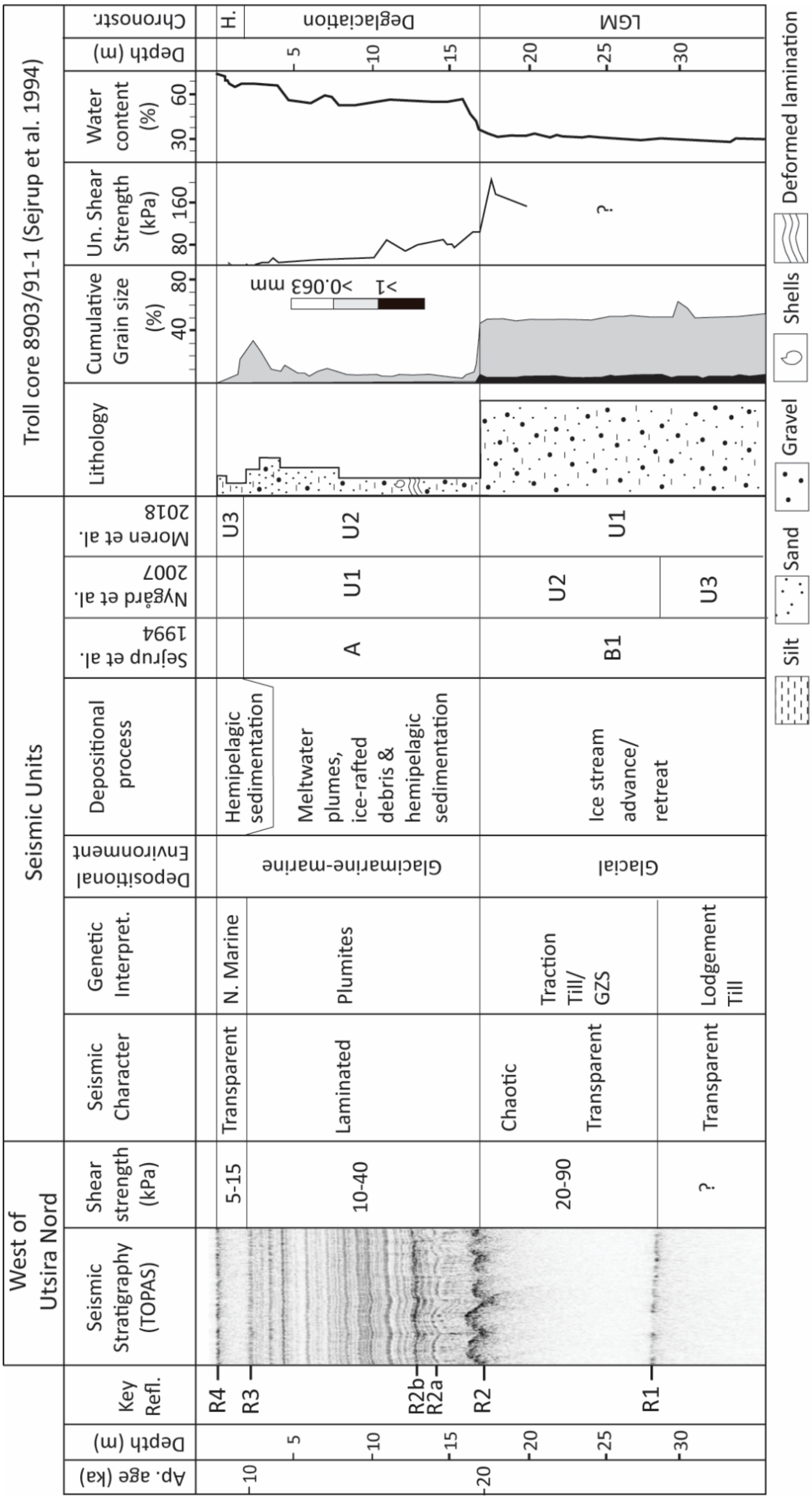


Fig. 4. A summary of the seismic units defined in previous studies of the Norwegian Channel sedimentary infill, correlated to TOPAS acoustic data west of Utsira Nord (Fig. 1). Previously, three broad genetic units (glacial, glacimarine and marine) have been defined, based on the acoustic character of the sediments. The reference core for the Norwegian Channel fill (8903/91-1) is adapted from Sejrup *et al.* (1994) to show the key sedimentological and physical characteristics of the genetic units. Ap. age, approximate age; Refl, reflectors; Interpret, interpretation; N. Marine, Normal marine; Un. Shear strength, undrained shear strength; Chronostr, chronostratigraphy; H, Holocene; LGM, Last Glacial Maximum.

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 in Sejrup *et al.* (1994) and Unit U1 in 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 to 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 reflector than R2. The overlying acoustically transparent unit, interpreted as post-glacial marine sediment, drapes conformably over the laminated sediments, and is generally around 5-10 m thick off western Norway and 5-20 m thick in southern Norway, but can reach thicknesses up to 50 m. While 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 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, while off southern Norway, 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 provinces with contrasting prognosed geotechnical properties and implications for FOW anchor design. While the standard depth of sub-surface investigation for seabed anchors today is ~ 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 investigations for possible pile-based anchoring designs which may require a larger depth of investigation. The estimated distribution and thickness of the four provinces across the site were then used to generate risk maps which highlight areas with challenging conditions for floating offshore wind anchors.

Data

Large-scale geomorphological features related to ice stream erosion and deposition were interpreted on a bathymetric map of the North Sea from the Olex AS single beam echosounder database (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 m x 5 m, however not every cell contains a data point. Finer features such as pockmarks, boulders and iceberg plough marks are therefore not generally distinguishable on the Olex map but were interpreted on the 5 x 5 m Sea Terrain Model from the Norwegian Mapping Authority (2018), which covers two small swathes of the Utsira Nord site (Figs. 5d, 5e).

2D seismic data within the Utsira Nord site and greater Norwegian Channel region (Fig. 1) was sourced from DISKOS (The Norwegian National Data Repository for Petroleum Data) and includes the surveys:

ST8201 (reprocessed surveys R90 and R92), NPD-KYST-96, NSR-04 and NSR-05. The quality of the data is good enough to interpret the broad structural and sedimentary features of the Norwegian Channel, despite the presence of strong multiples of the seabed reflector and base Norwegian Channel reflector (in ST8201 R90, Fig. 6). The seabed reflector and the base of glacial erosion within the Norwegian Channel (the "Upper Regional Unconformity (URU)" reflector) were interpreted and then depth converted using seismic velocities of 1500 m/s (average P-wave velocity for seawater) and 1800 m/s (based on the P-wave velocity of the Quaternary (Nordland Group) sediments encountered in exploration well 35/2-1 (Bellwald *et al.* 2020) respectively. The resulting depth surfaces were used to generate a thickness map of the channel fill and to investigate the regional structure of the channel in the vicinity of the Utsira Nord site. Two parametric sub-bottom (TOPAS) profiles acquired in 2012 by the University of Bergen (details of the cruise are referenced in Hjelstuen et al., 2018) cross the northern and eastern parts of the site (Fig. 1). The TOPAS profiles have a vertical resolution of 25-30 cm, approximately ten times finer than that of the 2D seismic data. The profiles were therefore used to interpret key reflectors, acoustic facies, and seabed features not visible on the 2D seismic profiles.

Four gravity cores and a piston core, all located more than 15 km distance from the Utsira Nord site, were acquired in 2012 by the University of Bergen (the piston core is presented in *Morén et al.* (2018)) (Fig. 1). Sedimentological analysis of the cores were integrated with seismic observations from the TOPAS seismic 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. Shallow core 27/9-U-1, north of Utsira, (Fig. 1) acquired between 96-176 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 an Upper Jurassic age. The overlying Quaternary sediments, however, were not cored or preserved as cuttings in that campaign. Core-logging as part of this 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

Bathymetric Data

The Utsira Nord site is characterized by a trough (T1) along its eastern side, where water depths exceed 280 m, and a shallower, flatter area (Grounding Zone System (GZS) 1) along its western side where water depths exceed 250 m (Figs. 5a, 5b, 5c). A *Grounding Zone System* is a backstepping wedge of subglacial and pro-glacial sediments deposited during the episodic retreat of an ice stream (e.g., Rüther *et al.* 2011). Several GZS's 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, Figs. 5a, 5c). The shallower bathymetry along the western side of the Utsira Nord site (GZS 1) and a small part of the site in the southeast (GZS 3) are therefore also interpreted as Grounding Zone Systems.

A chain of rugged bathymetric highs (annotated as exposed bedrock in Figs. 5a, 5b) is observed in the southeastern corner of the site and to the east of the site, the largest of which is the island of Utsira (Fig. 5a). Within the Utsira Nord site there are three main bathymetric highs, which increase in height southwards from 30 m to 85 m above the seabed. Based on the bedrock geology of the western

Norwegian coastline and the island of Utsira, the highs in Utsira Nord are interpreted as exposed crystalline (metamorphic) bedrock, characteristic of the Norwegian West Coast.

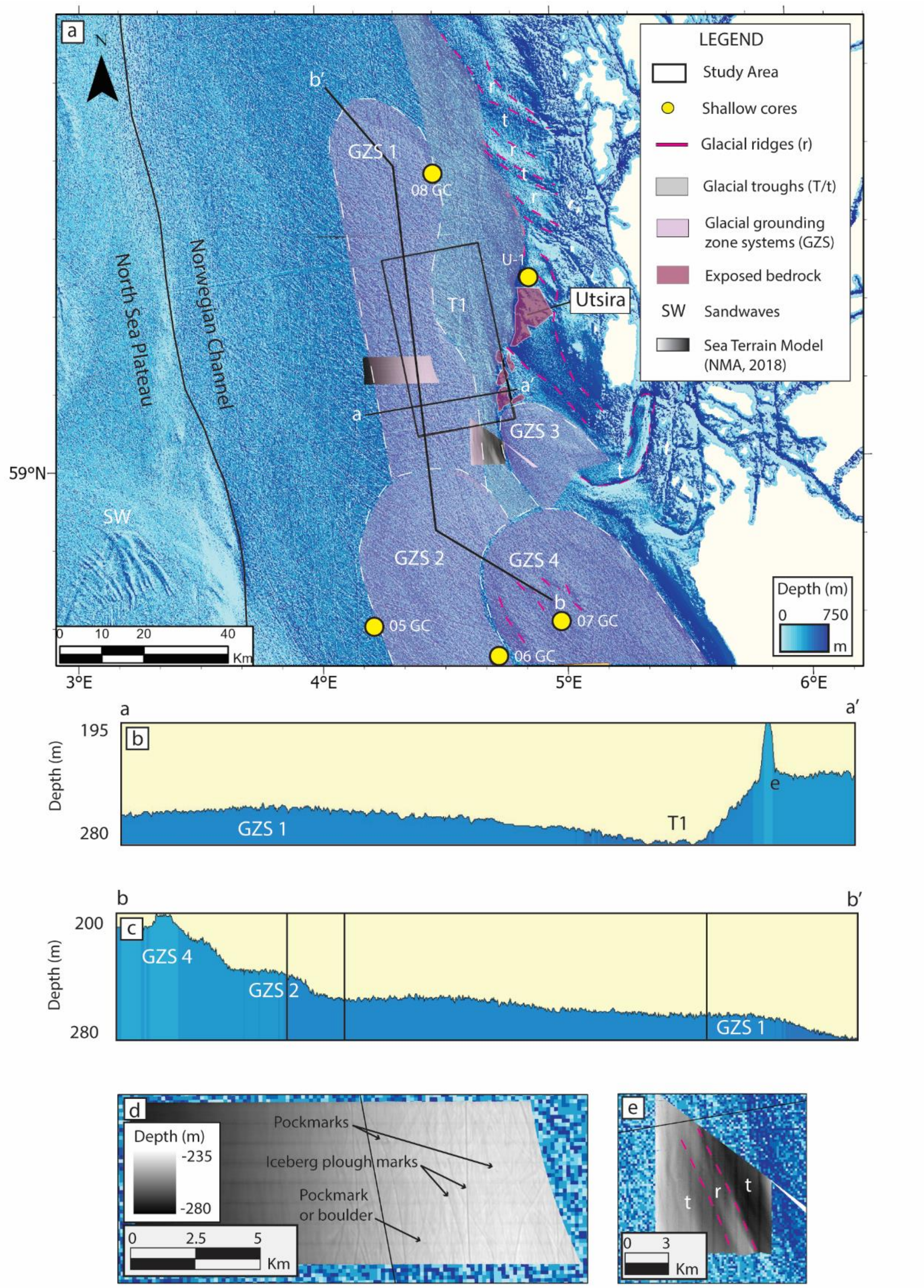


Fig. 5. (a) Olex bathymetric map of the Utsira Nord site and surrounding area showing interpreted geomorphological features (glacial troughs [t] and ridges [r], glacial grounding zone systems [GZS], and sandwaves [sw]), (b) East-west bathymetric cross-section through GZS 1, trough [T1] and an exposed bedrock high [e] in the southeastern corner of Utsira Nord, (c) North-south bathymetric cross-section through GZS 1, 2 and 4, (d) Annotated NMA Sea Terrain Model (2018) showing iceberg plough marks, pockmarks and a possible boulder or pockmark in western Utsira Nord, (e) Glacial troughs and ridges south of Utsira Nord.

East and northeast 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) suggest that the sediments from the last glaciation were remolded into ridges by ice entering the channel from the western Norwegian coast, with stronger erosion occurring between the ridges to form the troughs. Both interpretations point towards a strong glacial influence on the bathymetry of the Utsira area and to the presence of glacial till at or near the seabed.

On the high-resolution Sea Terrain Model (Figs. 5a, 5d, 5e), finer-scale seafloor features are identified in the western and southeastern parts of the site. 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 kilometers long are abundant (Fig. 5d). These are typical iceberg plough marks, scours in the seafloor sediments created by northward-floating icebergs released during the last deglaciation (e.g., Lien, 1983). In contrast, the deeper trough area (T1) in southern Utsira Nord, largely lacks iceberg plough marks, and instead is characterized by north-northwestward striking glacial trough (t) and ridge (r) features of several kilometers' width (Fig. 5e).

In the western part of the site, several raised circular features with a central depression which are over 200 m in diameter and several metres deep are observed (Fig. 5d). These are interpreted as pockmarks, crater-like features from which water or gas is escaping or has previously escaped and which could indicate the location of small-offset faults within the subsurface. Such features are common on the seafloor within the Norwegian Channel (e.g. 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. 5d). While these likely represent smaller pockmarks, they might represent boulders lodged within glacial till or deposits of ice-rafted debris.

2D Seismic Data

2D seismic profiles give an overview of the structure and geometry of the Norwegian Channel in the Utsira Nord area (Fig. 6). The base of the channel slopes gently eastwards, defined by a reflector of variable character which truncates westward-dipping sedimentary bedrock of Late Jurassic through to Pliocene age. The total thickness of the channel infill on the eastern side of the channel, where Utsira Nord is located, is ~300 m, thinning to ~100 m on the western side of the Norwegian Channel (Fig. 7b). Utsira Nord is located along the eastern side of the Norwegian Channel, where the NCIS has eroded into Jurassic, Cretaceous and Palaeocene sediments (Fig. 6b). 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. 6b, 6c, Fig. 7d). The crystalline bedrock has a chaotic seismic character, is highly segmented by steeply dipping faults and has a strong hard top reflector and rugged surface (Figs. 6a, 6b, 6c). In some parts of the site, 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; however, 3D seismic data would be required to confirm this.

The chain of crystalline bedrock highs identified on the Olex bathymetry map (Fig. 5a) are intersected in several places by the 2D conventional seismic dataset. As the 2D seismic profiles are spaced ~ 6 km apart, the seabed depth map (Fig. 7a) and Norwegian Channel thickness map (Fig. 7b) interpreted on the seismic data resolve only two out of the three main bedrock highs identified on the Olex bathymetry in the southeastern corner of Utsira Nord. The thickness of the Norwegian Channel sedimentary infill within 1-3 km from the exposed rock areas, ranges from 0-30 m to 30-60 m (Fig. 7b). This is expressed as a "risk map" for anchoring conditions in Figure 7c, where areas of exposed bedrock are marked in red, areas with sedimentary cover thinner than 30 m are marked in yellow and areas with sedimentary cover thinner than 60 m are marked in white. Areas where additional rocky outcrops are known to exist from bathymetric data are also marked in red, with dashed contours indicating the estimated sedimentary thickness around the exposures.

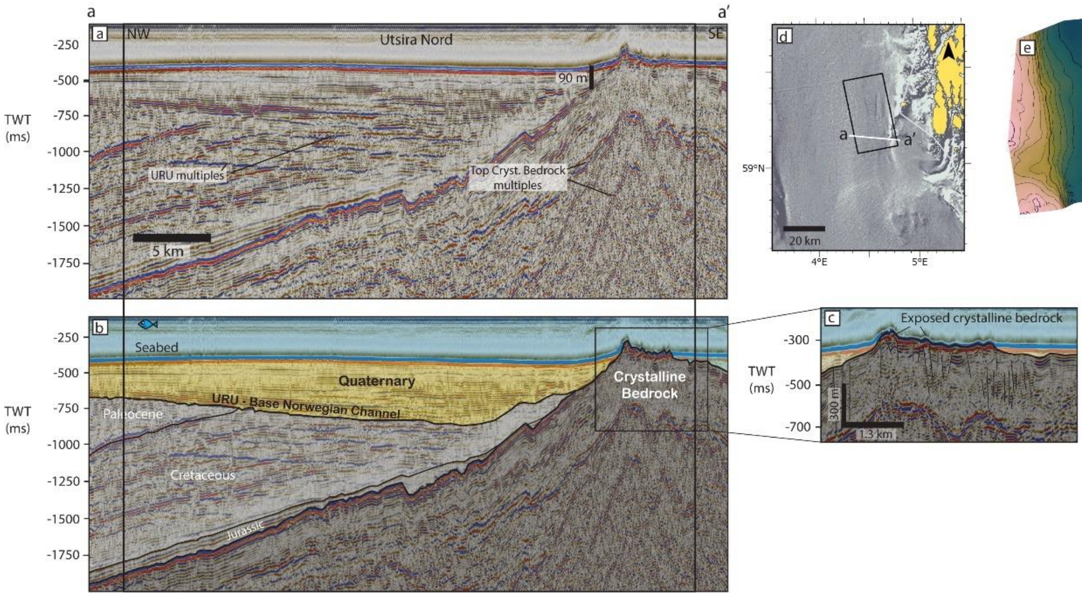


Fig. 6. (a) Uninterpreted 2D seismic section across southern Utsira Nord from survey ST8201 R90, (b) Interpreted 2D seismic section from ST8201 R90 showing outcropping and shallowly buried crystalline bedrock in the southeastern part of Utsira Nord, (c) A more detailed view of the exposed bedrock with interpreted faults, (d) Location map for profile a-a' on Olex bathymetry (e) Location map for profile a-a' on the 2D seismic seabed depth surface.

Sub-bottom Profiles

The TOPAS sub-bottom profiles within Utsira Nord reveal seabed features and acoustic facies within the upper 30-50 m of the subsurface which are not resolvable on the bathymetric and 2D seismic datasets (Fig. 8a vs Fig. 8b). Within the northern part of the site (Fig. 8a), seismic reflectors are only visible 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. Based on previous studies of the Norwegian Channel seismic stratigraphy (e.g., Nygard *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 reflector occurs 10-20 m below the top of the subglacial till. This type of internal till reflector 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 (O' 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 lodgment till.

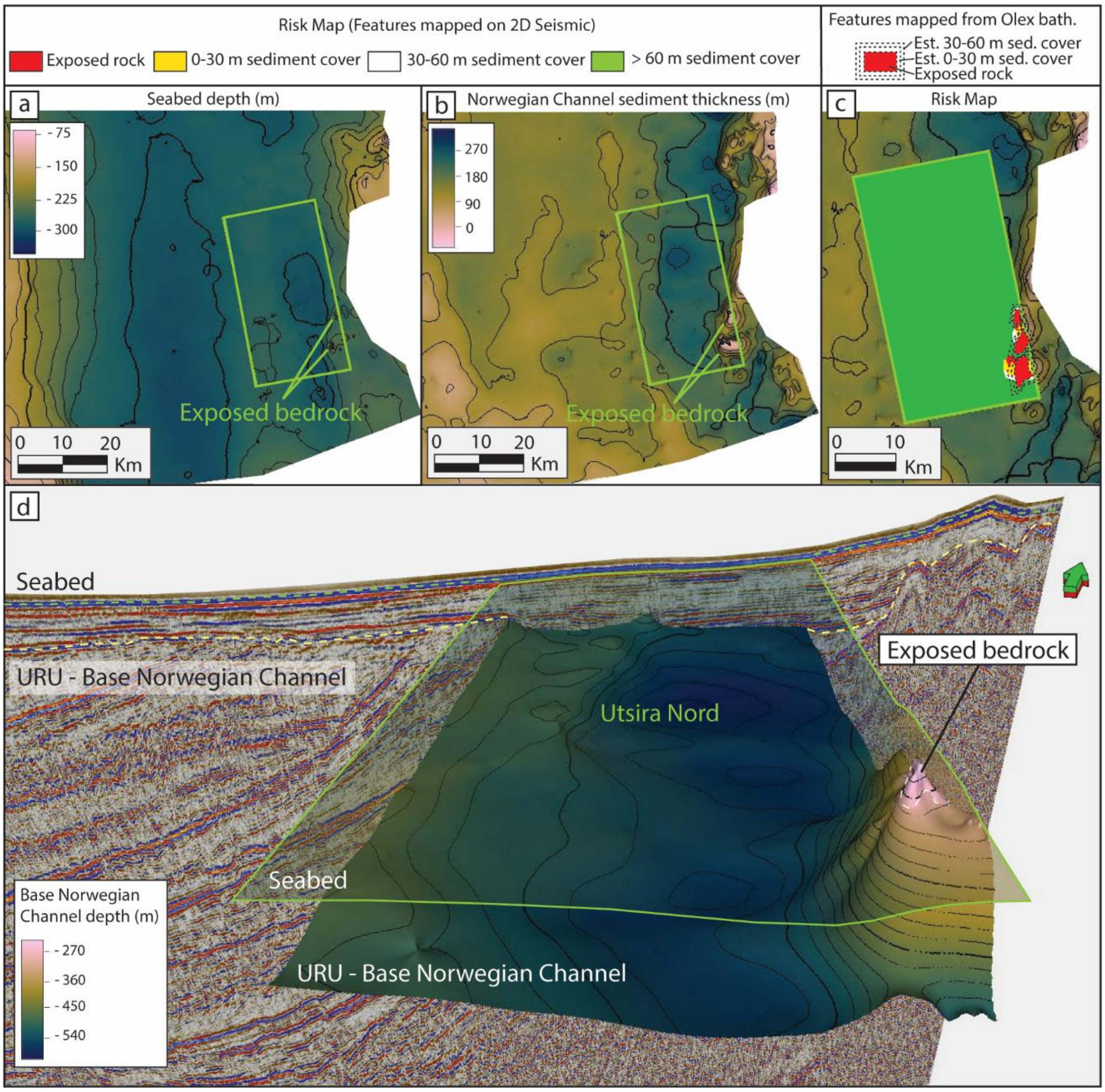


Fig. 7. (a) Seabed depth map interpreted on 2D seismic survey ST8201 (R90 & R92), showing the location of Utsira Nord in green. Bedrock highs observed in the southeastern part of the site are interpreted as exposed crystalline bedrock, (b) Seabed – Base Norwegian Channel sediment thickness map, showing where Quaternary sediments are thin to absent in southeastern Utsira Nord, (c) Risk map for anchoring conditions, based on (b) and bathymetric data where seismic data are absent (bath, Bathymetry; Est. sed. cover, estimated sedimentary cover, (d) Seabed depth map and Base Norwegian Channel depth map (Upper Regional Unconformity-URU) within the Utsira Nord site showing a semi-regional 2D seismic profile across the northern part of the site from survey ST8201 R90 exhibiting the seismic character of buried crystalline bedrock to the east of the site and sub-cropping sedimentary rock at the base of the channel to the west of the site. The extent of crystalline bedrock exposed at the seabed as far as can be determined from 2D seismic is shown with white stippled line.

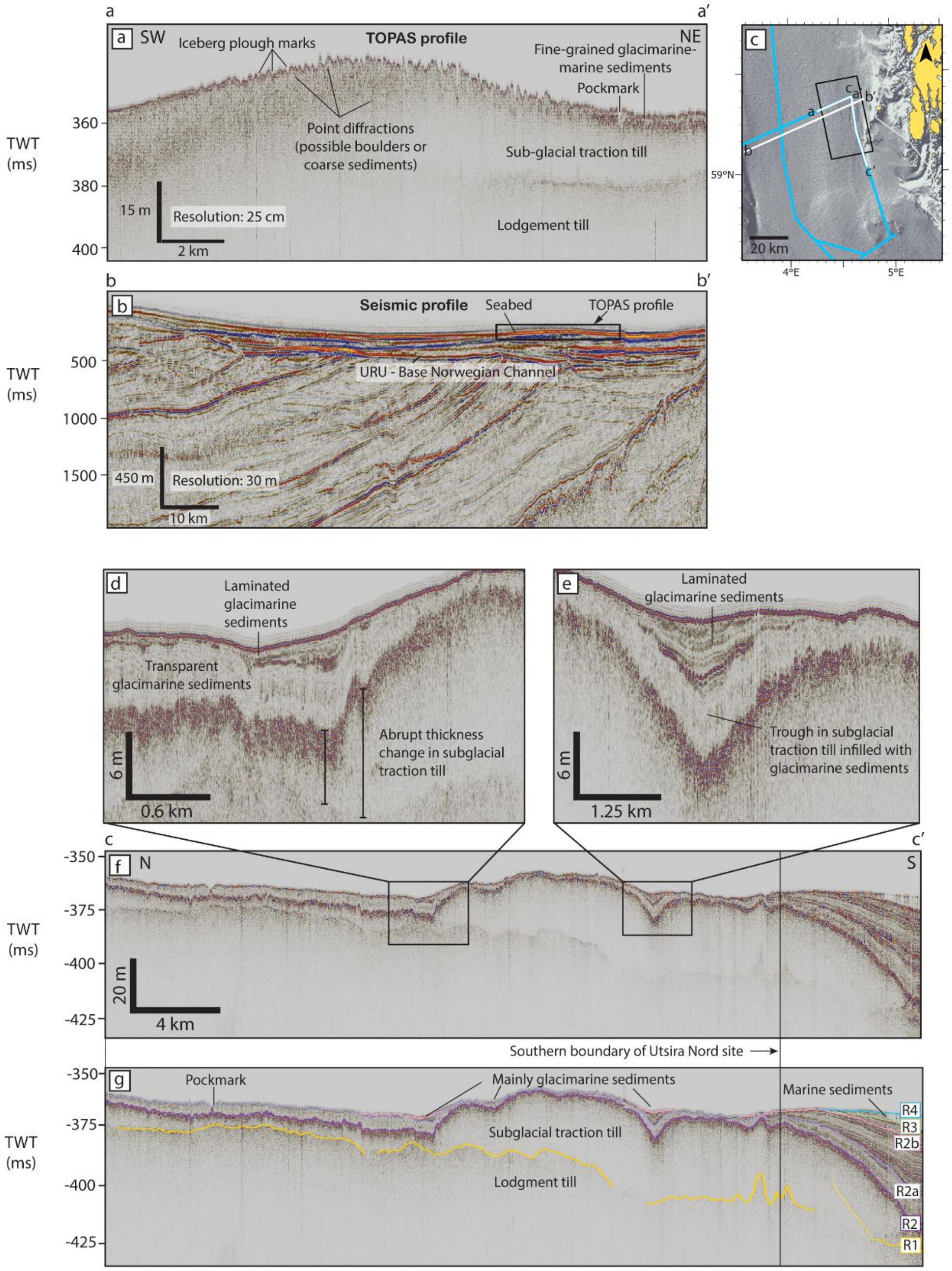


Fig. 8. (a) Uninterpreted TOPAS profile a-a′ across northern Utsira Nord showing key features distinguishable on high-resolution acoustic data compared with conventional 2D seismic profile b-b′, (b) conventional 2D seismic profile b-b′ from survey ST8201 R92. Location and depth of penetration of (a) is shown in the context of existing 2D seismic data available at the site, (c) Location map for profiles a-a′, b-b′ and c-c′ on Olex bathymetry, (d) Zoomed-in section from profile c-c′ showing glacimarine sediment infilling a trough in sub-glacial traction till**,** (e) Additional zoomed-in section of an infilled trough from profile c-c′, (g) Interpreted version of TOPAS profile c-c′ showing key reflectors R1-R4 and the interpreted genetic units defined between.

In the central part of the profile, the subglacial traction till has a mounded geometry and is exposed at the seabed. The seabed here is highly furrowed, a characteristic feature of iceberg plough marks 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 which fills the iceberg plough marks in the underlying till unit. In the northeastern part of the profile, a 4 m deep pockmark cuts through both the glacimarine unit and the underlying till. 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, where it exhibits laminations characteristic of glacimarine sedimentation (e.g., Sejrup *et al.* 1989, 1994). 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 centimeters to tens of centimeters of post-glacial muddy to sandy marine sediments (below the resolution of the TOPAS profile) could be present.

A 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 (Figs. 8d, 8e, 8f, 8g). The flat internal reflector 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 meters over highs in the glacial till, and thickening to up to 12 m in troughs in the glacial till (Figs. 8d, 8e). 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. These are overlain by a transparent, southwards thickening package thought to represent post-glacial marine sediments which thin to less than 30 cm (below TOPAS resolution) thickness over the Utsira Nord site.

Gravity Cores

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

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

The glacimarine facies (Fig. 4) is penetrated by cores 05-GC and 06-GC 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 1.4-2.4 g/cm^3, while the undrained shear strength is low, ranging between 5-25 kPa. In core 05-GC, the glacimarine facies is overlain by normal marine facies (Fig. 4). This consists of clay with a density of 1.7-2.3 g/cm^3 and very low undrained shear strengths of between 5-15 kPa.

Discussion

Conceptual Model for Utsira Nord and how it relates to anchoring of floating offshore wind

Based on the distribution and properties of the seismic units identified at Utsira Nord, four main geotechnical provinces are defined (Fig. 9, Table 1).

The region of exposed to shallowly buried crystalline bedrock within the southeastern corner of the Utsira Nord site, which comprises about 10% of the site, is defined as Province 4. The bedrock likely consists of very hard metamorphic rock such as gneiss, which has a shear strength greater than 3.5 MPa (Singh and Murthy, 2016). Suction anchors designed for soft clays and muds and driven piles designed for sandy soils will not be a feasible design concept for this part of the site due to the risk of obstruction, shallow refusal, variable penetration and buckling (Table 1, Table 2). Instead, a drilled pile or a novel anchoring system will likely be required to develop this part of the site (Table 2). Gravity-based anchors (Table 2) might also be a feasible solution, however the risk of sliding on the rugged, uneven slopes of exposed bedrock (with an average gradient of up to 8°) will need to be evaluated. This may require acquisition of higher resolution bathymetry data to more accurately assess the steepness of the bedrock slopes. If economically feasible, the geophysical site survey should focus on mapping the shallowly buried parts of the bedrock in more detail (Table 1), ideally using 3D seismic 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.

The lodgment till layer interpreted beneath reflector 1 (Fig. 8g) is defined as Province 3. There is a large uncertainty around the sedimentary and physical properties of this province, due to a lack of cores which sample this type of sediment within the Norwegian Channel and other paleo ice stream systems. However, it is likely that the lower till layer is denser due to greater consolidation and less glacial deformation. It is suggested that Province 3 will exhibit undrained shear strengths at least as high or higher than those measured in the upper till at the *Troll* field (80-160 kPa, (Sejrup et al. 1995)). The undrained shear strength of lodgment 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, however such extreme consolidation is not anticipated within a paleo ice stream such as the Norwegian Channel due 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 lodgment 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. An abundance of boulders or course sediments could have a significant impact on the anchor design for the Utsira Nord site, for example a requirement for increased suction anchor wall thickness. Based on the north south TOPAS line (Fig. 8g), Province 3 is likely to mainly occur 45-50 m below the seabed in the southern half of the site and is therefore unlikely

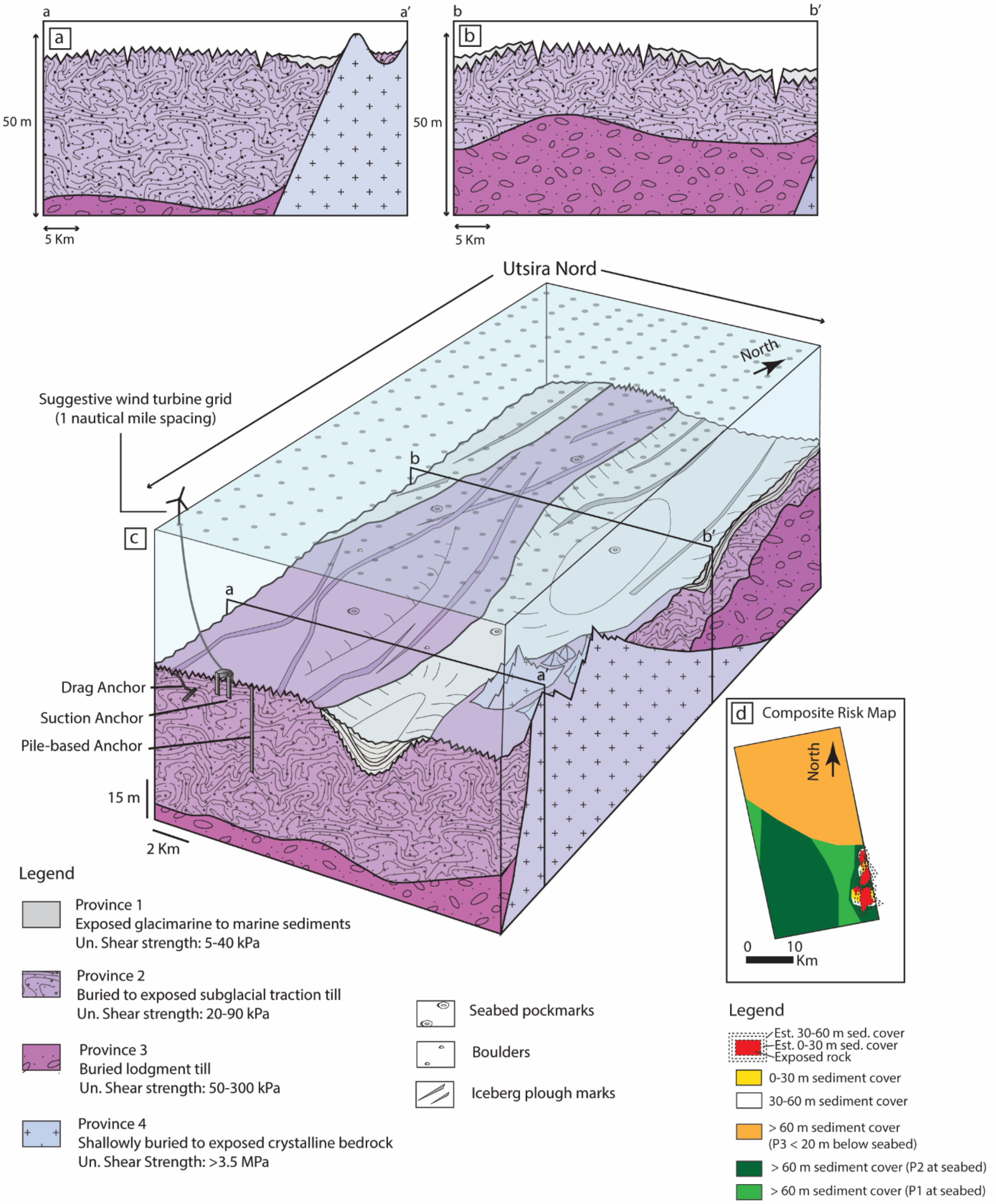


Fig. 9. (a) Geosection a-a’ showing how the respective provinces of the conceptual geological model for Utsira Nord Conceptual vary in thickness and burial depth across the southern part of the site, (b) Geosection b-b’ showing variations across the northern part of the site, (c) Geological model for 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 provinces. The overlying seawater is represented in transparent blue (not to scale), with a suggestive grid of floating offshore wind turbines spaced 1 x 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 impact anchor design and penetration. Sources of undrained shear strength values are given in Table 1, (d) Composite risk map combining the bedrock versus sediment cover risk map from Fig. 7c with a visual representation of the estimated distribution and thickness of Provinces 1-3 across the Utsira Nord site.

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

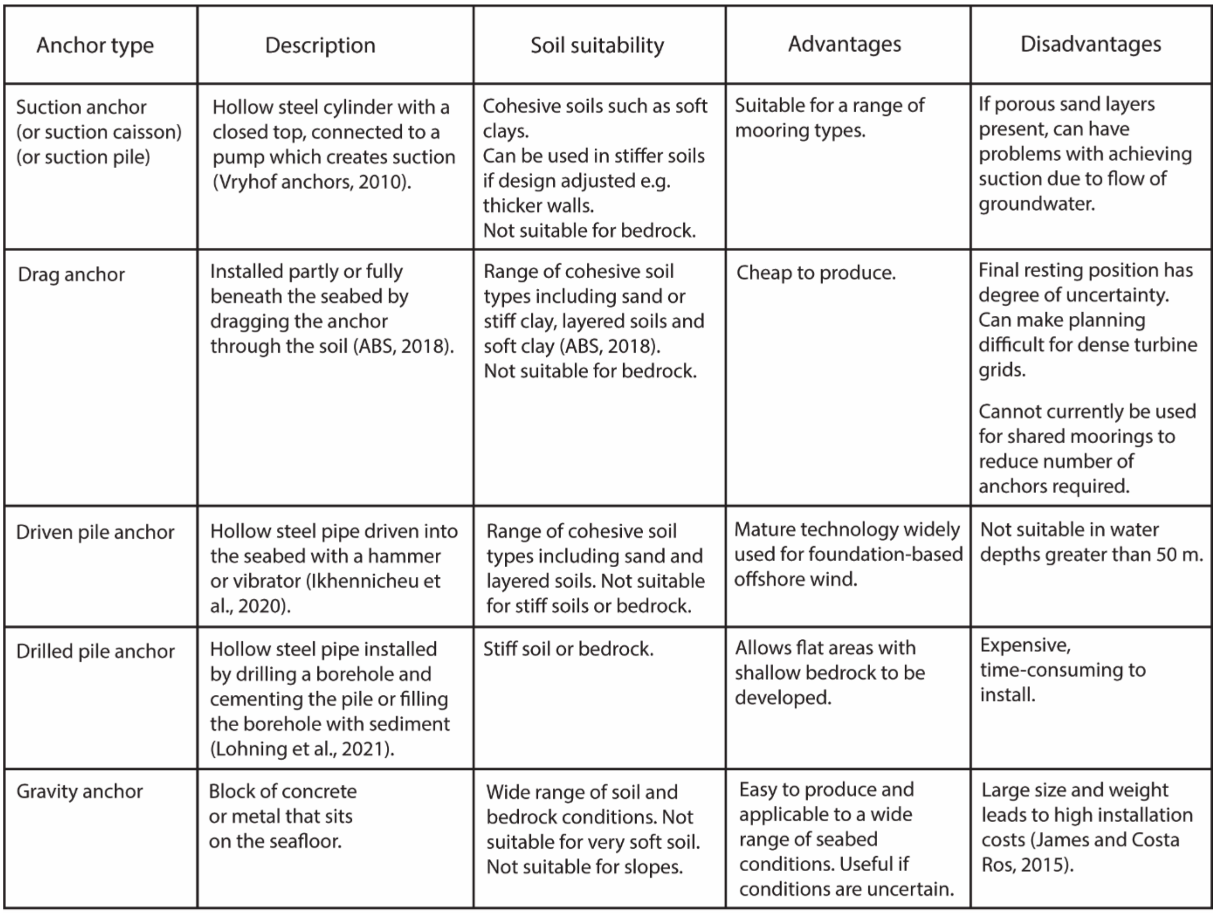
Geological Province	Description	Hazards	Causes	Potential Impact	Mitigation
1	Exposed glacimarine to marine sediments Un. Shear strength: 5-40 kPa (Gravity and piston cores)	Uneven seabed	Pockmarks Iceberg Scours	Variable anchor penetration	High resolution seabed mapping (sonar, 3D seismic)
			Boulders	Obstruction to anchor	
		Poorly consolidated sediment	Recent marine sediments deposited by currents	Seabed scour around anchors	In-situ testing across site to determine degree of consolidation of recent sediments
2	Buried to exposed subglacial traction till Un. 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
3	Buried lodgment till Un. Shear strength: 50-300 kPa (Clarke et al., 1998)	Buried hard formation at varying depths	Overconsolidation of sediment by repeated ice activity	Obstruction to anchor Variable anchor/pile penetration *Potential impact increases northward as province closer to surface	Acquisition of 2D or 3D acoustic data to map Top Province 3 on finer scale Acquisition of core and in-situ testing across site to determine variability in soil properties
		Highly variable soil properties	Poorly sorted mixture of clay, silt, sand, gravel, cobbles, boulders		
4	Shallowly buried to exposed crystalline bedrock Un. Shear Strength: >3.5 MPa (Singh and Murthy, 2016)	Uneven seabed	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) and sub-bottom profiling in south eastern part of the site
		Buried hard formation			

to have implications for anchor design considerations in this area. In the northern part of the site however, Province 3 appears likely to mainly occur 10-20 m below the seabed and must therefore be considered within the anchor design concept. Province 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 analyze the physical properties of the Province 3 sediments further (Table 1).

The subglacial traction till layer interpreted between Reflector 1 and Reflector 2 (Fig. 8g) is defined as Province 2. The sedimentary and physical properties of Province 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 province 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. Province 2 is likely to be exposed at or within tens of centimeters of the seabed along the shallower central and western parts of the site. Sudden lateral variations in soil properties can be expected where glacial troughs filled with softer, younger sediments are present at the surface of Province 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, so their extent should be mapped in greater detail as part of the geophysical site survey (Table 1).

The glacimarine sediments which overlie the subglacial traction till layer are defined as Province 1. Post-glacial marine sediments are not visible on the TOPAS profiles which cover Utsira Nord, however a thin (< 25-30 cm) layer of fine-grained marine sediments across the whole site cannot be ruled out. The glacimarine sediments vary in thickness and distribution across the Utsira Nord site, thickening in the bathymetric lows on the surface of Province 2 to up to 12 m thickness, and thinning over the highs. The sedimentary and physical properties of Province 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, shell fragments and undrained shear strengths of 20 kPa (and up to 40 kPa in piston core 04 PC in southern Norwegian Channel (Morén et al. 2018)). This province 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 Province 1 (and Province 2 where it is exposed at the seabed) are the presence of pockmarks, iceberg plough marks and possible boulders/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 Province 1 sediments are likely to be very soft, clay-rich sediments but could also contain poorly consolidated coarser-grained sediments vulnerable to scouring around emplaced anchors. In-situ testing of the Province 1 and Province 2 sediments exposed at the seabed should be conducted across different parts of the site to evaluate the risk of seabed scour (Table 1).

Table 2. *A summary of anchor types and soil conditions*



Anchor type	Description	Soil suitability	Advantages	Disadvantages
Suction anchor (or suction caisson) (or suction pile)	Hollow steel cylinder with a closed top, connected to a pump which 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 due to flow of groundwater.
Drag anchor	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	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	Hollow steel pipe installed by drilling a borehole and cementing the pile or filling the borehole with sediment (Lohning et al., 2021).	Stiff soil or bedrock.	Allows flat areas with shallow bedrock to be developed.	Expensive, time-consuming to install.
Gravity anchor	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).

Key Uncertainties

With only several sparse and shallow gravity cores in the vicinity of the Utsira Nord site, several key uncertainties remain regarding the sedimentological and geotechnical character of Provinces 1-3. Although the glacimarine and marine sediments of Province 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 kilometers apart, making it difficult to prognose what sort of site-scale variations might be present within Province 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 province when acquiring site survey data at Utsira Nord. Although Province 1 is likely to comprise soft, fine-grained sediments, undrained shear strength and grainsize 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 inform suction anchor installation risk.

One of the key uncertainties remaining about Province 2 is what sets up 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 only sampled the upper tens of centimeters of the subglacial traction till facies. Deeper coring of Province 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 Province 3 are very uncertain as very little is documented about the sedimentary properties and internal variations within the Norwegian Channel lodgment till, other than studies related to the *Troll* core, located in the outer part of the Norwegian Channel. Shallowly buried lodgment till may present a risk to successful penetration of suction anchors designed for clays and muds, therefore site investigations should particularly focus on Province 3 in the northern part of the site where it is situated only 10-20 m below seabed. Province 3 might be too stiff and/or boulder-rich to be cored by piston corer and may require a drilled coring investigation.

While the undrained shear strength of the Province 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 province is to be developed. Given the location within the Norwegian Channel, the exposed rocks will most likely 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 Province 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.

Conclusions and further work

In this study, we demonstrate a method which 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 provinces at the Utsira Nord floating offshore wind 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 lodgment till with highly uncertain properties and likely boulders and 4) shallowly buried to exposed crystalline bedrock which will likely require a pile-based or novel anchoring solution of which approximately 10% of the site is estimated to comprise. In order 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 Provinces 1-3 including the site-scale variability within each of the provinces, the sand content of the laminated trough-infill sediments in Province 1 and what geological conditions lead to the abundant point diffractors on sub-bottom profiles within Province 2 and 2) the sedimentological and geotechnical properties of Province 3, which are particularly uncertain due to an almost complete lack of core sampling of lodgment tills within the Norwegian Channel. The key provinces and their associated data acquisition requirements identified at Utsira Nord are of relevance to current and future offshore wind developments in other formerly glaciated marine areas such as the coastlines of Canada, the northern United States, the northern United Kingdom and the rest of the Norwegian coastline, particularly within palaeo ice stream channels in these regions.

Offshore wind developers in Norway should use the lessons learned from previous offshore wind projects relating to insufficient understanding of geological setting and poor collaboration between site survey planners and foundation designers to avoid the need for unplanned additional data acquisition, installation problems and overconservative design solutions. As the Norwegian authorities develop the 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 and could contribute towards faster decarbonization of the European power sector. 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.

Acknowledgments

This study is part of a PhD project at the University of Bergen funded and carried out in collaboration with Equinor Energy AS. We would like to thank the geologists, geophysicists and geotechnical engineers within the Equinor who have contributed to useful discussions about geological concepts for the Utsira Nord site, and their implications for floating offshore wind anchor design. Thanks to Olex AS, Trondheim for giving us permission to use their bathymetric data in several of the figures in this paper. Schlumberger are acknowledged for an academic license of Petrel which was used for seismic interpretation and visualization.

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