DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2022/20**

A desk study of the geological succession below a proposed energy island, Danish North Sea

Report prepared for EnergiNet

Paul C. Knutz, Erik S. Rasmussen, Karen Dybkjær,
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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

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APPENDICES

1. Introduction

Construction of energy islands acting as hubs for large windfarms is a key element in the transition to sustainable energy forms as endorsed by the Danish Government. A shallow water area with depths of <30 m covering 2.5 km by 2.5 km on the southernmost part of "Lille Fiskerbanke", ca. 100 km due west of Thorsminde, has been designated as a potential location for the first energy island in the North Sea (Fig. 1).

EnergiNet has requested GEUS to provide a desk-top study of the geology below the proposed Energy Island location, hitherto named Area of Interest (AOI), and its immediate surroundings, based on existing data and information. Previously, GEUS has published a screening report with focus on shallow data, e.g. seismic and cores, requested by the Danish Energy Agency (Owen et al. 2020). The present study involves a closer inspection of the geological succession down to Top Chalk (ca. 1200 m depth), based on the available seismic data and nearby industry wells. Special attention is placed on the uppermost 500 m interval of Miocene and Quaternary deposits that are well covered by existing data. As part of the project data base GEUS has received selected shallow seismic survey lines and reports from geotechnical boreholes that were acquired in 2022.

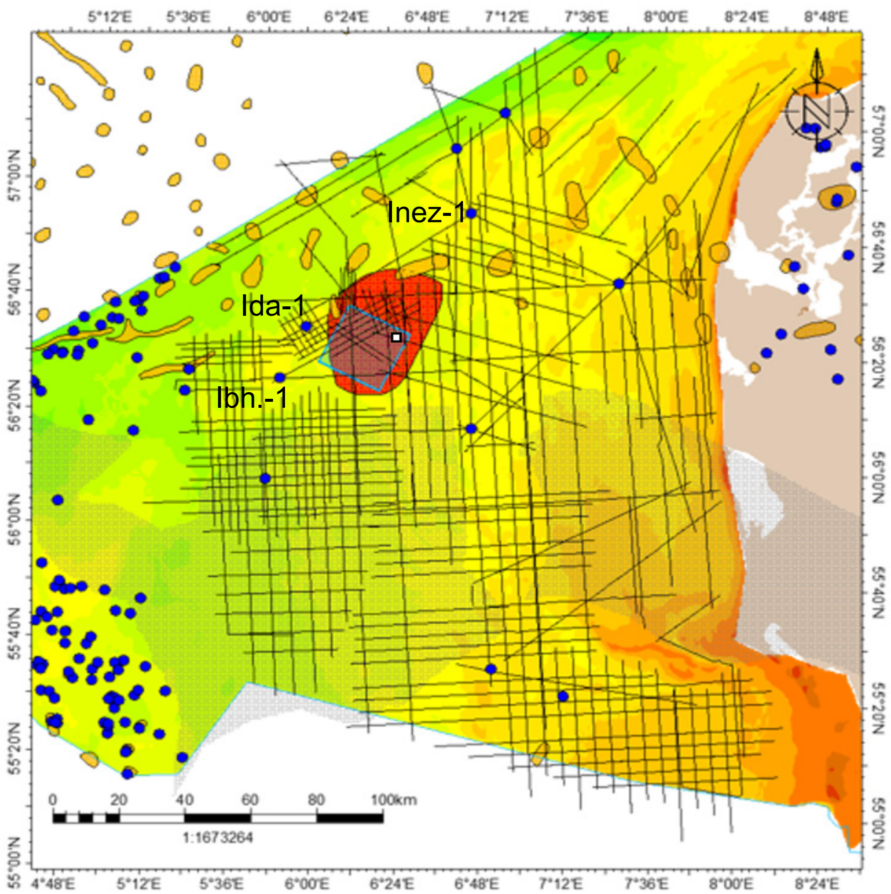


Figure 1. Proposed location of an energy island in the Danish North Sea, about 100 km west of Thorsminde, marked by white square. Red polygon defines the surrounding area designated for windfarms. Exploration wells (blue dots), salt diapirs (yellow filled areas) and selected deep seismic data (lines) are indicated. The blue rectangle is a 3D seismic survey. Seabed bathymetry is based on Emodnet.

2. Regional geology

The AOI is located in the eastern North Sea along the northern boundary of the Danish-Norwegian Basin which toward south is delimited by the WNW-ESE trending Ringkøbing-Fyn Ridge (Vejbæk, 1997). This basement structure is likely covered by Lower Permian strata with Rotliegendes sandstone (263-258 million years ago) forming the oldest geological deposits in the region (Doornenbal & Stevenson, 2010). The ensuing Upper Permian succession is characterized by salt deposits formed during the Zechstein period (257-254 million years ago). The thickness of the salt deposits display marked variations due to movements that are caused by the low density of rock salt (halite) compared to quartz (Peryt et al. 2010). These movements have over time produced salt diapirs that may reach thicknesses of >1800 m at the apex.

During the upper Cretaceous (100-66 million years ago) the area was covered by a warm epicontinental ocean that stimulated production of calcareous algae and reef-building organisms. This led to widespread formation of chalk formations which are known from both wells and outcrops in north-west Denmark (Anderskouv & Surlyk, 2011). The onset of the Cenozoic (last 65 million years) is marked by a transition from chalk deposits to clastic sediments, primarily clays.

The Top Chalk horizon has been mapped over several investigative stages using different generations of seismic data (Huuse, 1999; Vejbæk et al., 2007). The chalk surface is situated 1000-1200 m below the AOI (Fig. 2). North and east of the area the Chalk has been uplifted by diapirs of Permian salt. These vertical movements, caused by differential material densities, are associated with multiple tectonic phases movements during the Cenozoic and the effects of compaction-decompaction by continental ice sheets over the last 2.7 Ma (Rank-Friend and Elders, 2004; Knutz, 2010). The salt movements can influence the integrity of younger sedimentary packages, including faults, fluid escape and erosional features.

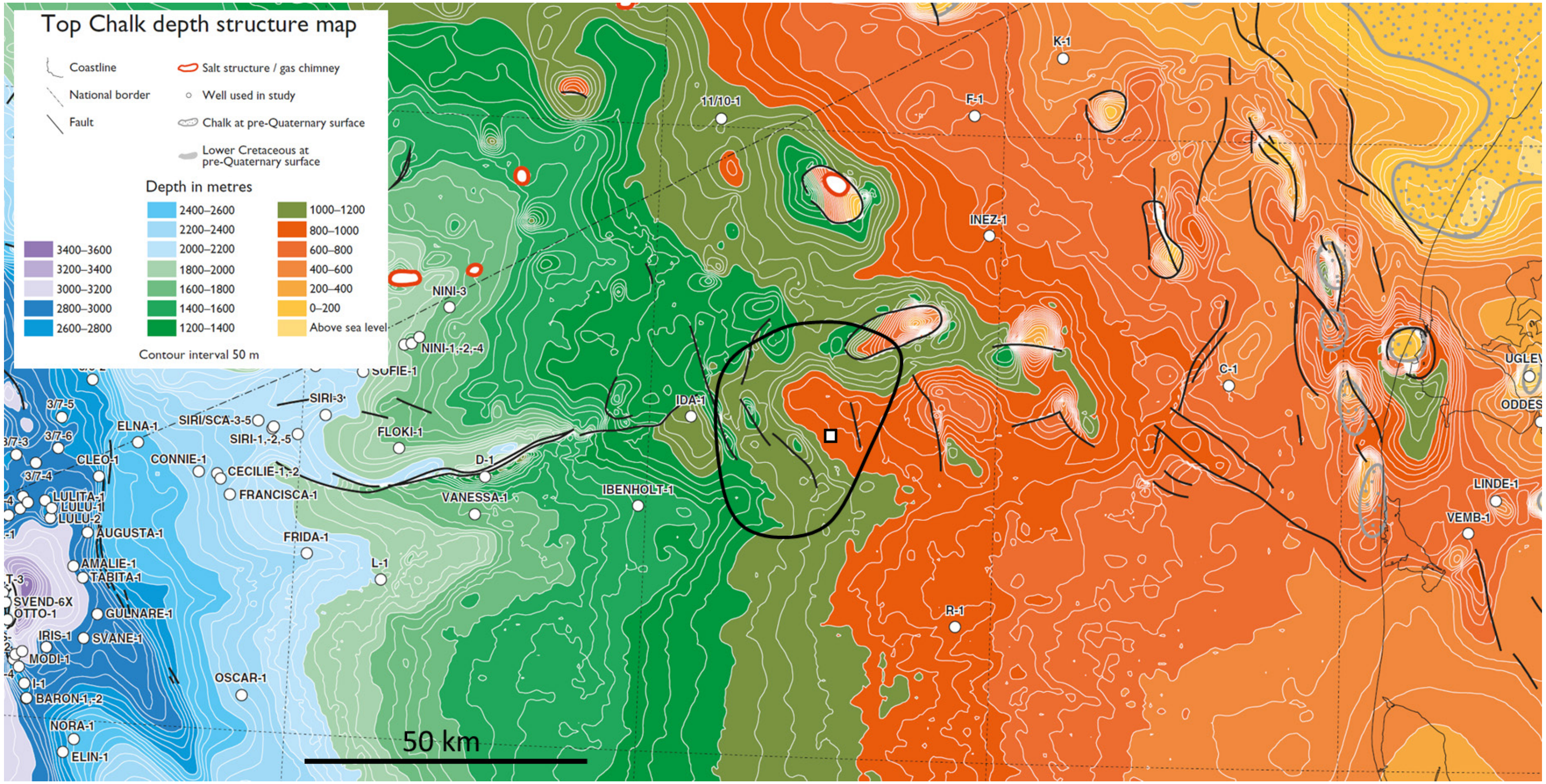


Figure 2. Depth-structure map of the Top Chalk surface (Vejbæk et al., 2007). Concentric highs and associated faults structures demarcate salt diapirs causing uplift of the overlying succession. Proposed energy island area (AOI) and surrounding area designated for windfarms shown with white square and black polygon, respectively.

2.1 The Cenozoic

During the earliest Paleocene, the North Sea Basin was filled by carbonate-rich mud (Fig. 3) which was a continuation of the sedimentation pattern that dominated the Late Cretaceous. This lithological development was in part a result of a low clastic input from the low-relief Fennoscandian Shield (Gabrielsen et al. 2010) and older Paleozoic massifs around the North Sea. During Late Paleocene-Eocene carbonate deposition ceased and was succeeded by deposition of delta systems and associated submarine fans in the marginal areas around the Shetland Platform while deposition of hemipelagic clays dominated most of the North Sea Basin. The incursion of clastic sediments from the Fennoscandian Shield was limited during this time (Schiøler et al. 2007; Nielsen et al. 2015) except for minor influx of glauconite-rich turbidites in the Late Paleocene – Early Eocene (Schiøler et al. 2007). West of Norway near Sognfjorden outbuilding of submarine fans occurred during the Late Paleocene – Eocene. Deltas continued to prograde from the Shetland Platform during the Oligocene (lower Lark Fm; Fig. 3) but a change in clastic input from Scandinavia commenced. Sediment supply to the west of Norway that characterised the Paleocene–Eocene time became restricted and the sediment was directed toward the south were a delta-shelf system developed in the eastern North Sea Basin south of present-day Norway (upper Lark Fm)(Schiøler et al. 2007). In the Northern North Sea adjacent to Scandinavia, deposition of almost pure clay took place, indicating very low input of coarse sediments to this area.

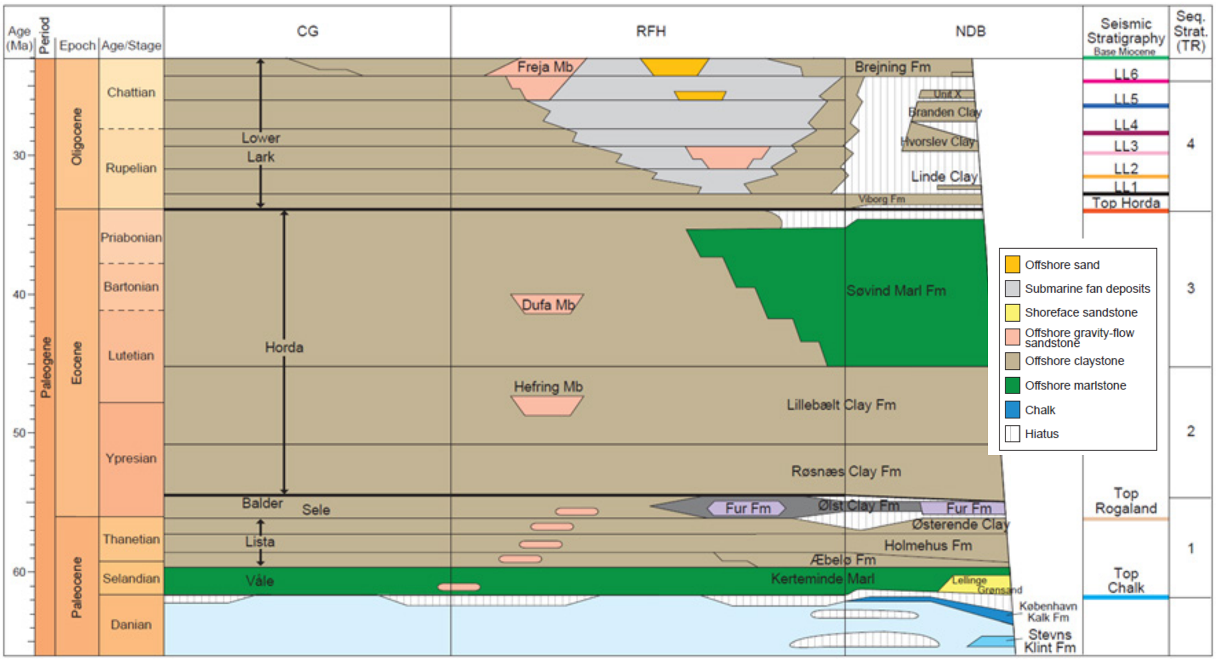


Figure 3. Paleogene lithostratigraphy and dinocyst zonation of the Danish sector. CC, Central Graben. RFH, Ringkøbing-Fyn High. NDB, Norwegian-Danish Basin (unpublished, GEUS).

In the Early Miocene distinct sand deposition characterised the northern North Sea that was sourced from the Shetland Platform (Eidvin et al. 2015). In the eastern North Sea Basin, marked progradation of a delta system commenced that was sourced from southern Norway and central Sweden (Fig. 4 and 5). During the Middle Miocene, marine mud deposition dominated the early phase of sedimentation but was succeeded by deposition of sand in the northern North Sea while deposition of marine mud continued in the eastern North Sea Basin. In the late Miocene, the eastern North Sea Basin was fully marine with water depths of more than 100 m (Rasmussen et al. 2005; 2010). The marine environment was predominated by hemipelagic settling of fine-grained sediments with some intercalation of distal tempestites (storm sand layers) which were composed of silt to fine-grained sand. These deposits are referred to as the Gram Formation (Fig. 4 and 6). During the latest ate Miocene, a fluviodeltaic depositional setting was established in the study area. The shoreline migrated towards the southwest across the Ringkøbing-Fyn High area and the Marbæk and Luna Formations were deposited (Fig. 5, 7 and 8). In the Pliocene, strong subsidence, resulted in resumed marine conditions in the Ringkøbing-Fyn High area. The strong subsidence that characterized the Pliocene, was the result of sediment load (Eridanos Delta) in the southern North Sea Basin (Overeem et al. 2001). During the latest part of the Pliocene, sediment supply from northeast (Fennoscandia) resulted in reestablishment of a fluviodeltaic system in the Ringkøbing-Fyn High area and during most of the late Pliocene and early Pleistocene, the area was land. A strong tilt of the pre-Quaternary and early Pleistocene succession occurred at 1.1 Ma before present (Rasmussen et al. 2005; Japsen et al. 2007; Ottesen et al. 2014).

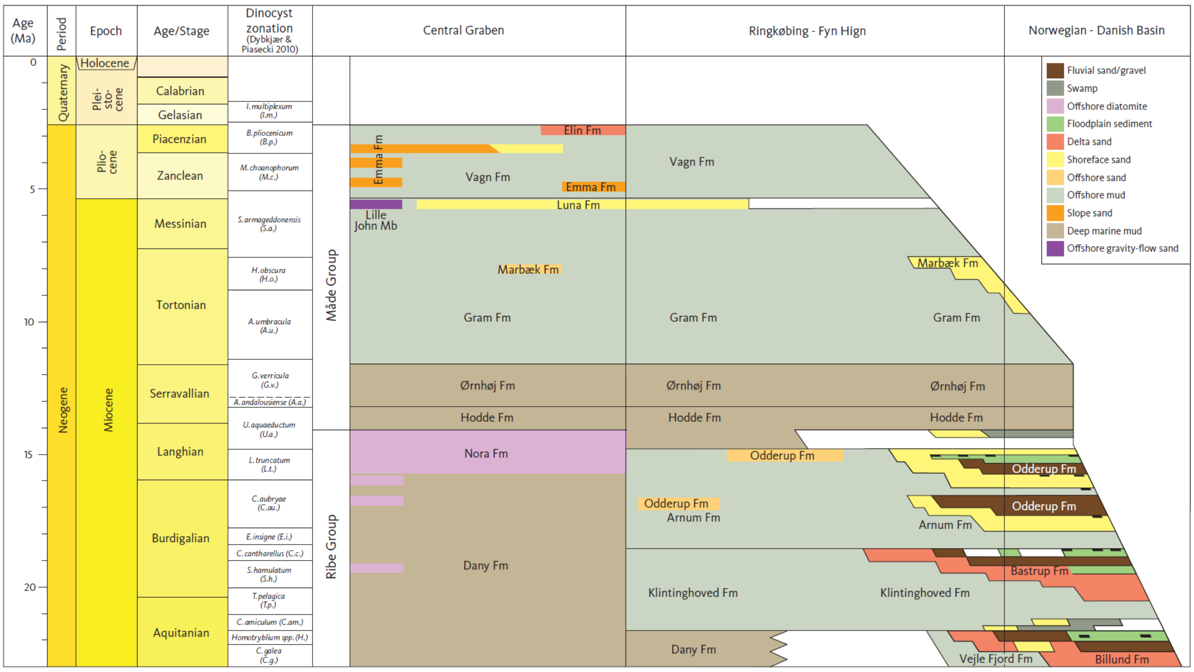


Figure 4. Neogene lithostratigraphy and dinocyst zonation of the Danish sector (unpublished, GEUS).

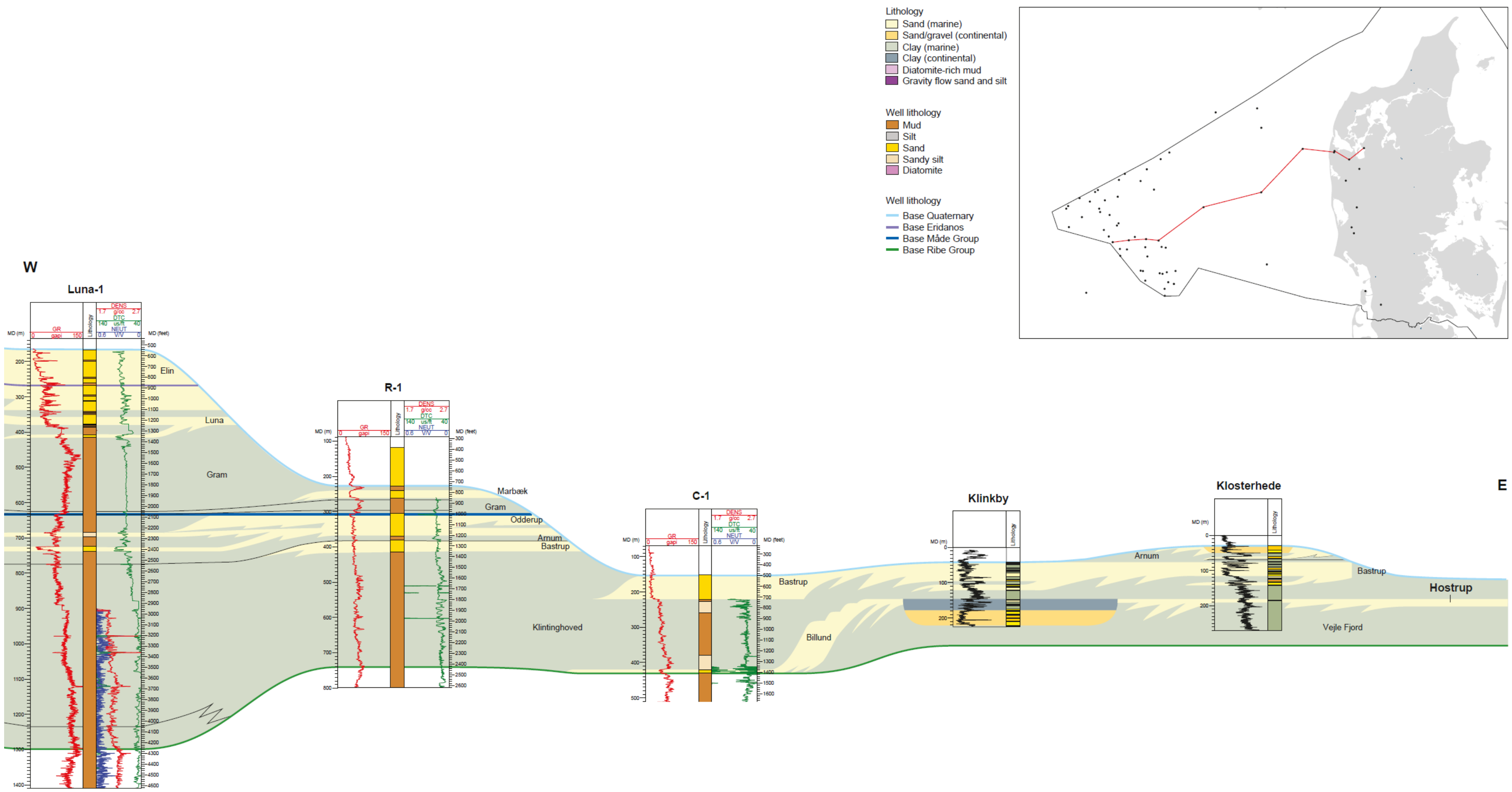


Figure 5. West – East correlation panel showing the onshore – offshore correlations of the Neogene succession. The Neogene geology of the study area correspond to Gram and Luna formations between the Luna-1 and R-1 wells (unpublished, GEUS).

Figure 6. Gram Formation: Dark brown clay which appears gray when oxidized. Centimeter thick fine-grained sands are commonly interbedded in the upper part of the formation. The sands are laminated and/or shows wave ripples and micro hummocky cross-stratified beds. The clay mineral association is composed of ca 40% kaolinite, 30% illite and minor smectite and chlorite (up to 20%).

Figure 7. Marbæk Fm: White fine- to medium-grain sand. Massive sand beds capped by wave ripples and hummocky cross-stratification are common (Rasmussen et al. 2010).

Figure 8. Miocene sand A) Luna Fm: Gray, mica-rich, fine- to coarse-grained sand. Clasts up to 6 mm in diameter are present. Both lignite and shells are common. B) and C) sand samples from the onshore Billund Formation (Rasmussen et al. 2010).

2.2 The Quaternary

As part of the glaciated continental margin of North-West Europe, the North Sea has experienced multiple glacial and interglacial cycles with drastic variations in ice sheet and sea-level configurations. The stratigraphic nomenclature for the most recent glacial-interglacial cycles is shown in fig. 9.

Previous Quaternary studies show that the area around Lille Fiskerbanke is crossed by buried valleys that are principally related to erosion by pressurized glacial meltwater (Huuse & Lykke-Andersen, 2000; Prins et al. 2019) (Fig. 10). Similar valley systems are common on the Danish mainland, either as buried systems or open, topographic features, most conspicuously in connection with the tunnel valleys of the East Jutland fjord systems (Sandersen & Jørgensen, 2015) (Fig. 11). The sedimentary infill of buried valleys is best known from Danish onshore studies as these features contain major aquifers for groundwater extraction. Coarse grained material, e.g. sand and gravel, is a common lithology testifying to the high energy glacial processes by which the valleys were formed. Sandy-gravelly channel fills and morainal deposits may be interlayered by fine-grained clay-rich intervals representing pro-glacial lake conditions (e.g. issø-ler) or interglacial periods when the valleys became inundated by the sea. Organic-rich sediments in the form of peat deposits may have formed during glacial and de-glacial periods when large parts of the North Sea were land area (Cotterill et al. 2017; Coughlan et al. 2018). Compared to onshore sections, ground truthing, e.g. drilling and coring, of the North Sea valley systems is sparse but a similar heterogenic lithology may be expected. This heterogeneity is reflected in seismic data and models describing the Quaternary development of the eastern North Sea (Fig. 12).

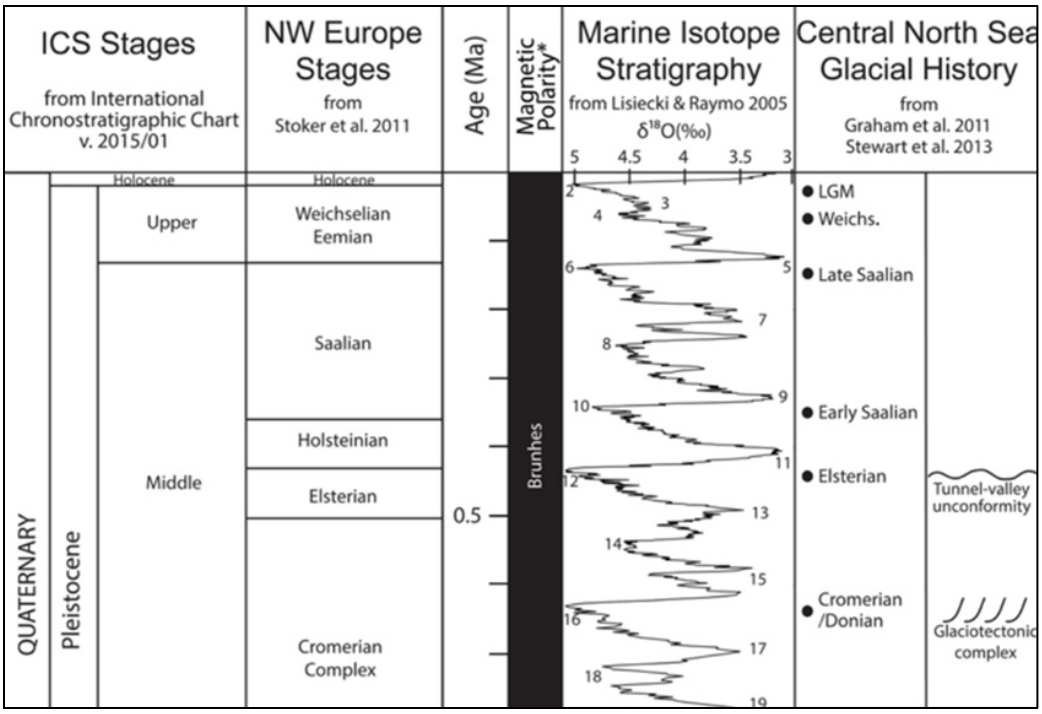


Figure 9. Stratigraphic scheme of the middle-late Quaternary in North-West Europe. Bendixen et al. 2017.

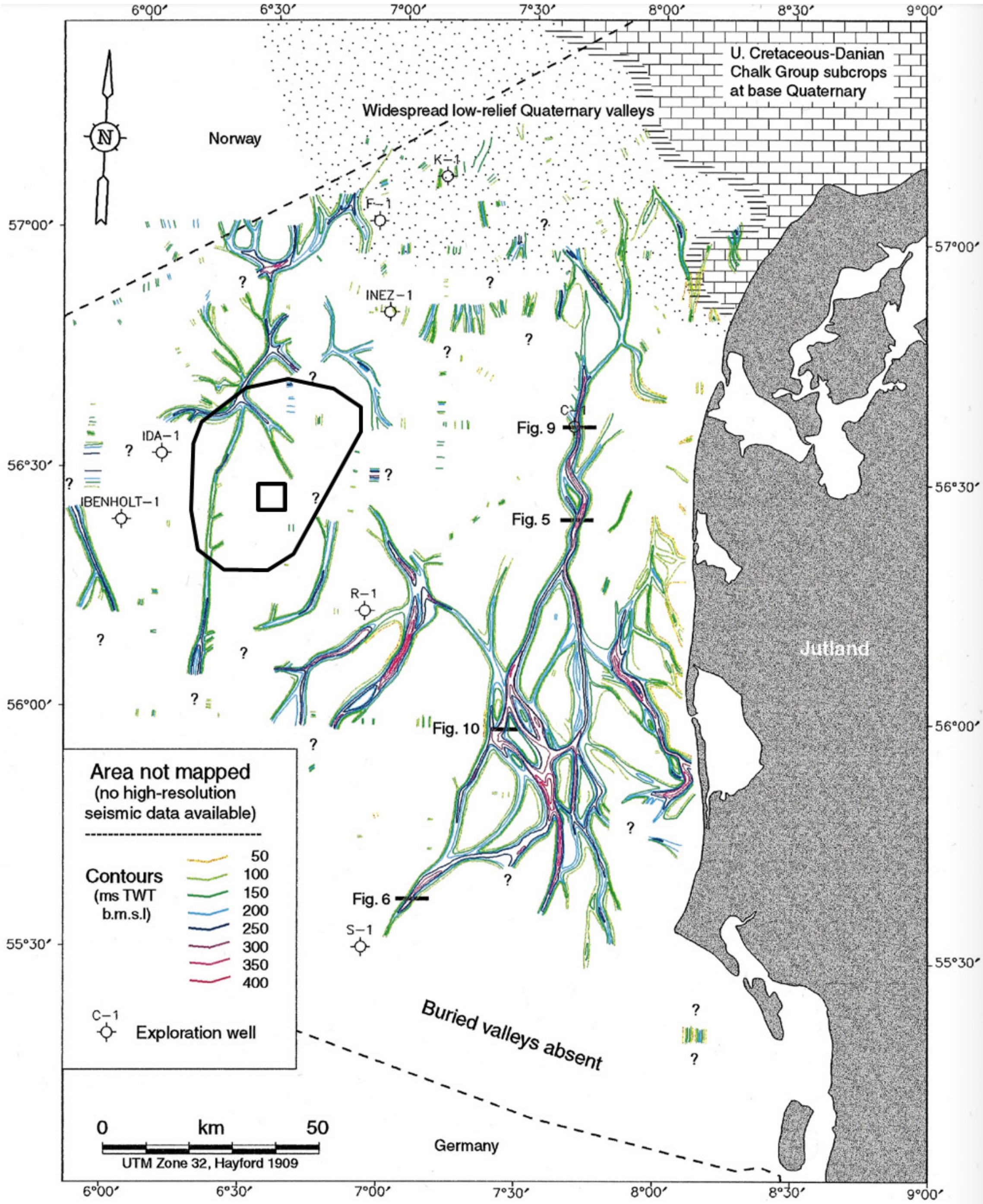


Figure 10. Distribution of tunnel valleys in the eastern North Sea. From Huuse & Løkke-Andersen (2000). Approximate location of proposed Energy island is marked by square.

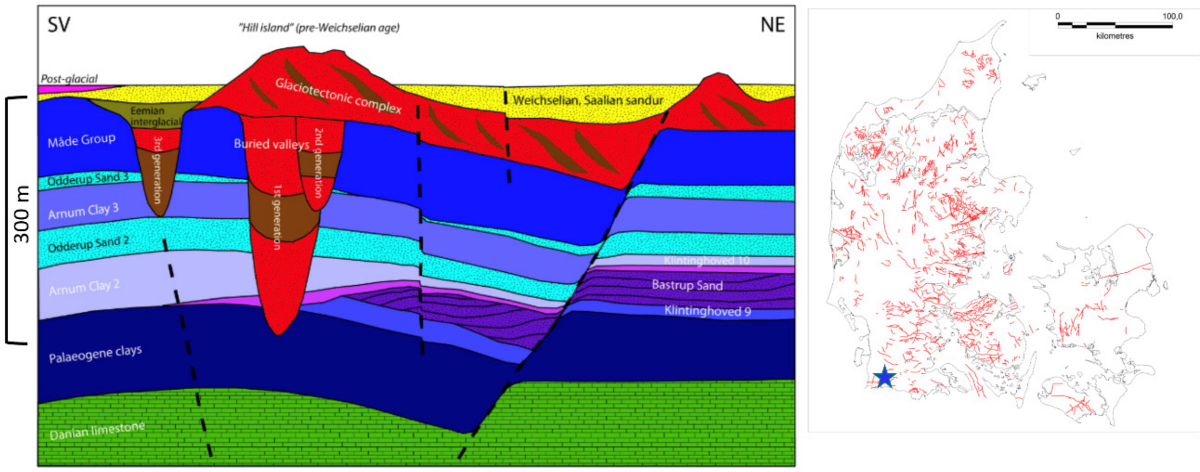


Figure 11. Model of buried valley system from the Tønder area (Jørgensen et al. 2014; Sandersen & Jørgensen, 2015).

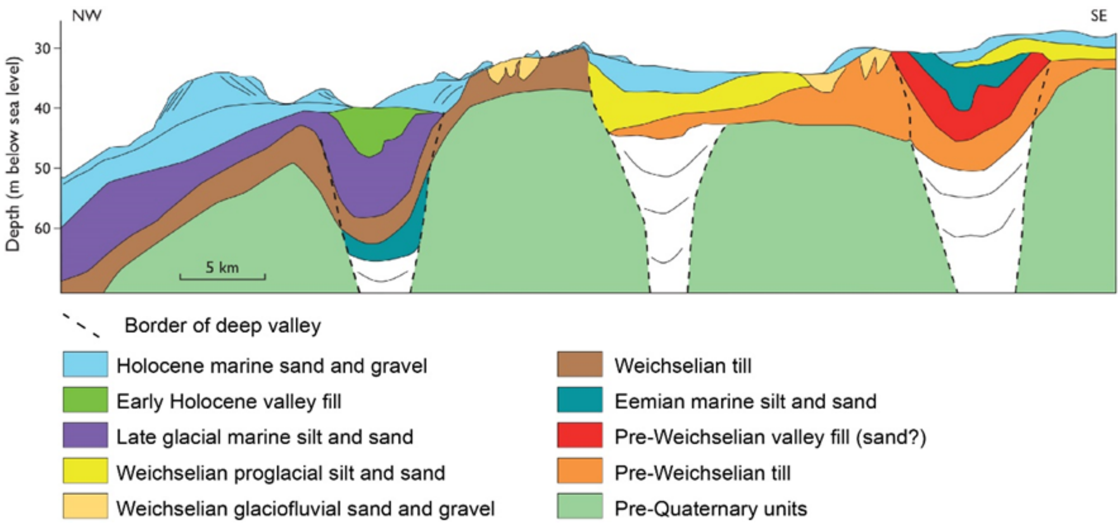


Figure 12. Geological model for the Quaternary of the northeast North Sea sector (Jensen et al. 2011).

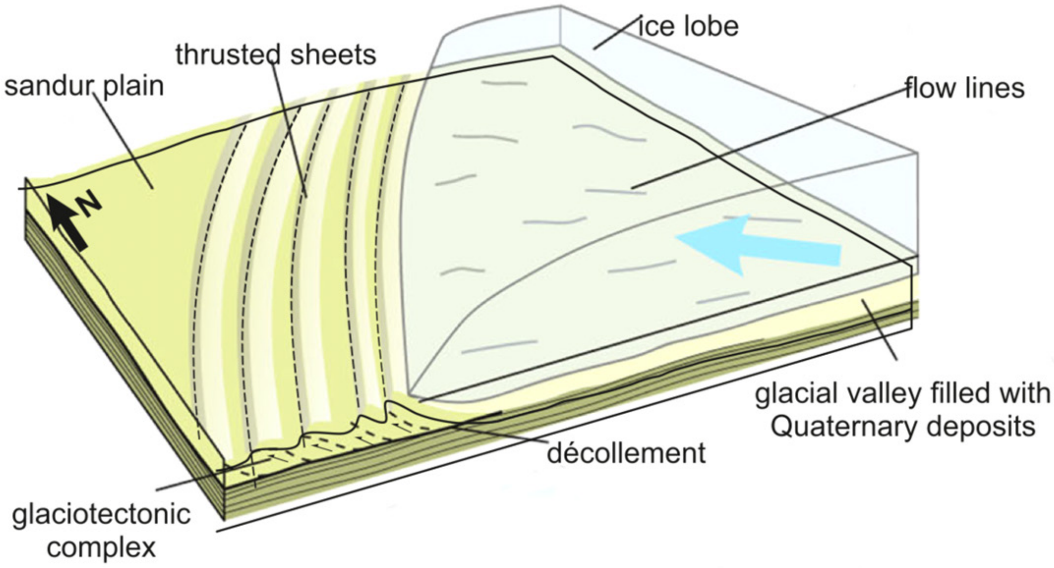


Figure 13. Glacio-tectonic model. Modified from Lohrberg et al. 2020.

The strata that make up the uppermost section of the North Sea is commonly disturbed by glaciotectonic processes (Fig. 13). These features of thrusting and deformation of near-surface sedimentary packages formed as glaciers moved across the region during the last glacial maximum (LGM) and during previous phases of ice sheet expansion, notably the Saale and Elster glaciations (Fig. 9)(Pedersen og Boldreel, 2017; Phillips et al. 2018). The deformation is often seen to converge onto a basal detachment surface (decollement) with the thrusted layers dipping towards the direction of ice flow (Fig. 13). If the subsurface sediments are coherent, glacio-tectonism can cause a repetitive stratigraphy through in a vertical section. Glacio-tectonic features are often linked with polythermal conditions along the glacial bed.

Deposits formed within ice-dammed lakes have been described from central North Sea, e.g. Dogger Bank area (Roberts et al. 2018). These ice marginal deposits imply extended periods with confluence between the British-Irish and Scandinavian ice sheets and relatively stable ice margins. The lake sedimentation stage ended as the glacial margins retreated, possibly resulting in major discharges of ice dammed meltwater (Fig. 14) (Hjelstuen et al. 2017). The distribution and evolution of pro-glacial lakes in the Danish North Sea sector is not well known.

The present-day positive topography of Lille Fiskerbanke is mainly formed by deposition of marine sediments since the early Holocene (about 9000 years Before Present) when the North Sea became inundated after the last sea level low-stand (Fig. 12) (Jensen et al. 2011; Sturt et al. 2013). In common with other shallow grounds in the southern North Sea region, e.g. Doggerbanke, Jydske Rev and Fladengrund, the accumulation of Lille Fiskerbanke occurred under the influence of marine currents and tidal forces causing focussed accumulation of sand-size material. The bank systems may have nucleated around topographic features remnant from the last ice age (Roberts et al. 2018).

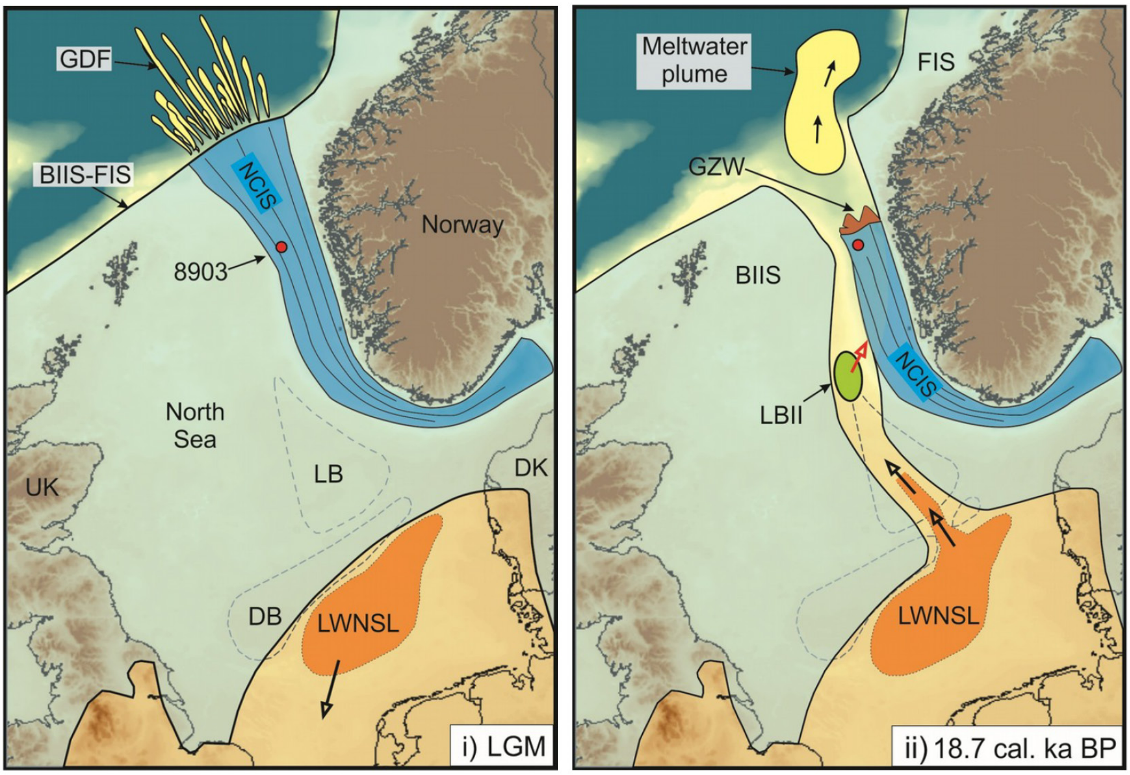


Figure 14. Map from Hjelstuen et al. (2017) illustrating an LGM lake development in the central North Sea (i) followed by catastrophic drainage toward the Norwegian Channel as the FIS and BIIS retreated (ii). DB: Dogger Banke. LB: Ling Bank. LWNS: Late Weichselian, North Sea Lake. FIS, Fennoscandian Ice Sheet. BIIS, British-Irish Ice Sheet.

3. Data and Methods

3.1. Seismic data and interpretation

The different data types were evaluated with respect to penetration depth, quality and resolution. The data were grouped in three categories: (1) Data derived from hydrocarbon exploration with deep penetration and a typical resolution of 20-30 m (Table 1). (2) Regional high-resolution (HR) data providing information on the Cenozoic section, e.g. to Top Chalk level, with a resolution of 5-15 m (Table 2). (3) Ultra-high-resolution (UHR) shallow seismic surveys restricted to the shallow water area around Lille Fiskerbanke (Table 3). The UHR data resolve changes in sedimentary strata with a resolution of about 0.5-2.0 m to depths of ~200 ms twt. Location of seismic lines is shown on Fig. 19 (all data) and Fig. 26 (HR and UHR only).

A comparison between the three types of seismic data (Fig. 15) demonstrates the differences in acoustic frequency content, corresponding to seismic resolution, and the capability/limitations of seismic interpretation of the shallow section.

Seismic interpretation and mapping were carried out using the Petrel software platform (2020). The seismic analyses were performed based on seismic-stratigraphic mapping principles that recognises reflection patterns/facies, depositional geometries/ and amplitude variations (Fig. 16). Seismic facies analysis involves more than 100 parameters but with the following 9 key elements (Xu & Haq, 2022): Spatial position, External form, Internal configuration, Continuity, Smoothness, Amplitude, Frequency, Neatness, Wave pattern.

The UHR seismic data was supplied in conventional two-way travel time (twt) in milliseconds (ms) and a depth-converted version (m). The seismic interpretation was performed on the twt data version in order to be stratigraphically compatible with the regional seismic surveys. A borehole-to-seismic correlation was carried out using the depth-converted UHR seismic profiles, which required re-interpretion of seismic horizons close to the borehole positions.

Survey name	Depth of penetration [Two-way-time (ms)]	Reflector characteristics And Signal to Noise ratio	Dominant frequency range (Hertz)
RTD81K-RTD-81	-7002	Good S/N with moderate reflector continuity.	10-30
DKR13	-9002	Good S/N with moderate reflector continuity.	5-20
NP85N	-7002	Fair S/N with average reflector continuity.	8-60
DCS-RE96	-7002	Good S/N with moderate reflector continuity.	8-50
AG9801-3D	-4047.5	Good S/N with moderate reflector continuity.	30-58

Table 1. Hydrocarbon industry surveys used in the study.

Survey name	Depth of penetration [Two-way-time (ms)]	Reflector characteristics	Dominant frequency range (Hertz)
Gribben-1997	-800.25	Good S/N with moderate reflector continuity.	40-85
Gribben-1998	-2047.5	Good S/N with moderate reflector continuity.	40-80
Danna-1994	1999.5	Fair S/N with average reflector continuity.	60-110
Danna-1995	-1999.5	Good S/N with moderate reflector continuity.	60-100
Danna-1996	-2047.5	Good S/N with moderate reflector continuity.	50-100

Table 2. High-resolution seismic surveys used in the study.

Survey name	Depth of penetration [Two-way-time (ms)]	Reflector characteristics	Dominant frequency range (Hertz)
ENN-MMT-2021	-224.95	Very high S/N with average reflector continuity due to enhancement of subtle geological features.	170-550

Table 3. Ultra-High-resolution site survey, involving 6 selected lines, used in the study.

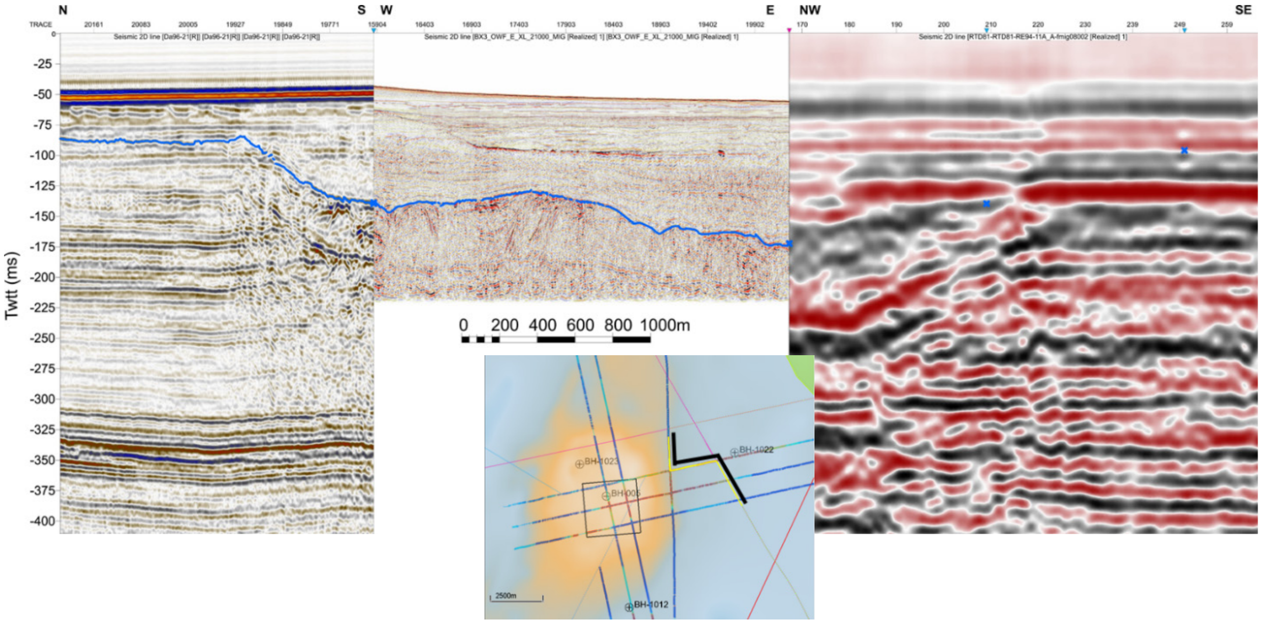


Figure 15. A composite section displaying difference in data resolution between HR (Dana-96), UHR (ENN-MMT-21) and Exploration (RTD81-RE94) data shown from left to right. The section crosses a buried valley located just east of the proposed Energi Island. The scattering of the seismic signal below the valley is attributed to the heterogenic and energy-absorbing sedimentary infill, e.g. coarse clastic deposits

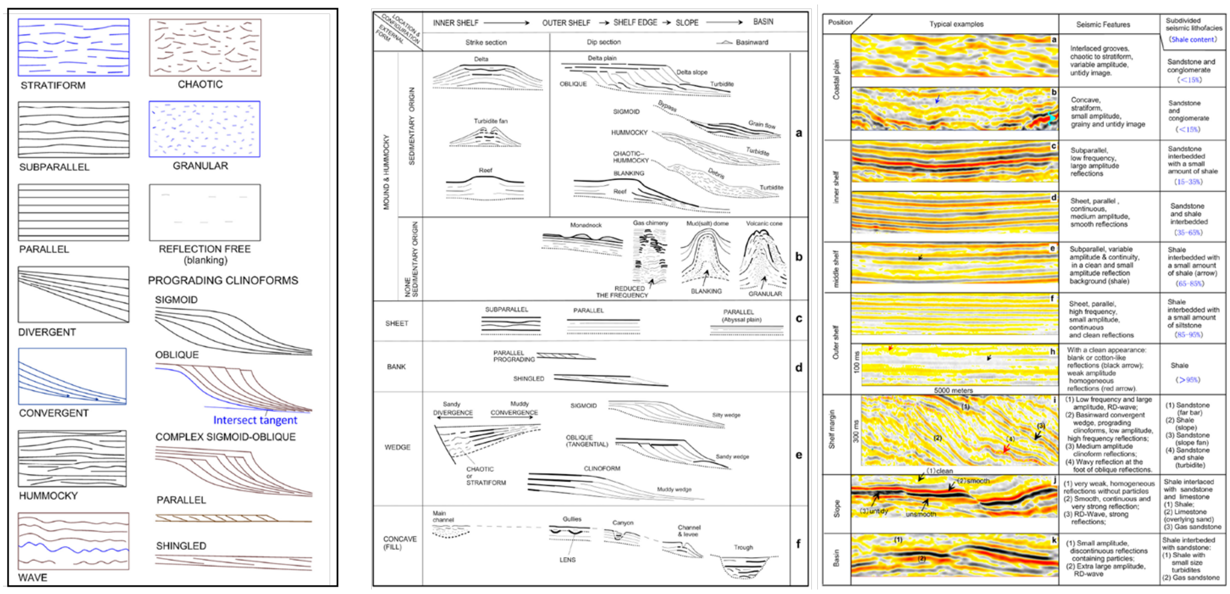


Figure 16. Seismic reflection configurations and facies. From Xu & Haq 2022 (and references therein.

3.2. Well biostratigraphy

In the present study the resting cysts of the microscopic marine algae called dinoflagellates (in the following referred to as “dinocysts”) in 3 ditch cuttings samples from the Ibenholt-1 and 7 ditch cuttings samples from the Ida-1 well have been analysed. The dinocyst species have been used for dating and correlating the studied successions. In addition, a study of the assemblages of sedimentary organic particles, a palynofacies study, have been performed on the same samples in order to interpret variations in the depositional environment. The depths of the studied samples are as follows;

Ibenholt-1: 900´-930´, 1050´-1080´, 1200´-1230´.

Ida-1: 160-170 m, 210-220 m, 260-270 m, 310-320 m, 350-360 m, 395-398 m, 419-428 m.

The locations of the samples in the wells are shown in the distribution charts (Appendix A1 and A2).

Processing: Approximately 20 grams of sample material from each sample was processed using standard palynological preparation methods, including treatment with HCl, HF, neutralization, heavy liquid separation, brief oxidation with KOH and sieving on 20 µm nylon mesh. The organic residues were mounted on glass slides and studied using a normal light microscope.

For the palynostratigraphy a minimum of 200 dinocysts have been counted and referred to species or (if not possible) genus. Furthermore, two full slides were scanned in order to record rare taxa. Based on the dinocyst content and the recorded first occurrences (LO´s) and last occurrences (LO´s) the samples have been referred to dinocyst zones following the zonation defined by Dybkjær & Piasecki (2010).

The palynofacies study included identifying and counting a minimum of 200 sedimentary organic particles and referring them to either of the main categories. This was followed by identifying and counting a minimum of 300 palynomorphs. See further the detailed description of the palynofacies-methods in Dybkjær et al. (2019).

4. Results

4.1. Lower Cenozoic succession

The lower Cenozoic stratigraphy is represented by three exploration boreholes, Ibenholt-1, Ida-1 and Inez-1, that are located in the vicinity to the proposed Energy Island (Figs. 1 and 17). The North Sea lithostratigraphic sub-divison entails the Rogaland Group, Stronsay Group and Westray Group (Deegan & Scull, 1977; Knox & Holloway, 1992). The Rogaland Group comprise a series of lithological formations and members of the lower Paleocene – lower Eocene interval with a combined thickness between 80 (Ibenholt-1) to 40 m (Ida-1)(Fig. 17; Schiøler et al. 2007). Individual formations, including the clay-rich Lista Fm and Sele Fm, are too thin (<20 m) to be resolved by the conventional seismic data acquired for hydrocarbon exploration. The Stronsay Group is represented by the Horda Formation which comprises the Røsnæs Clay and Lillebælt Clay formations in the onshore Danish sector. Based on the nearby well data this interval thins to < 10 m in the study area (Fig. 17).

The lower Cenozoic succession in the area of interest is dominated volumetrically by the Westray Group, or corresponding Lark Formation (Knox & Holloway, 1992), with well site thicknesses between 850 and 600 m (Fig. 17). The Lark Fm comprises 4 major muddy sediment packages, L1-L4, that on regional seismic data display progradation toward south-west (Danielsen et al. 1997; Schiøler et al. 2007). The upper Lark Fm (L4) contains discrete sand beds and thin sandy intervals. The well biostratigraphy indicate a Late Eocene to Middle Miocene age for the Lark Fm, but with most of the basin infill assigned to the Oligocene-Early Miocene.

Figure 18 shows a single-line correlation of major seismic reflectors between Ibenholt-1 and the Lille Fiskebanke area based on a composite seismic section (Dana-96). The seismic stratigraphy suggests that most of the lower Cenozoic succession below the AOI, encompassing the horizons a-c, represents L1 to L4 of the Lark Fm, (~Oligocene – Middle Miocene). A tentative estimate based on a seismic velocity of 2500 m s^{-1} indicate a thickness of around 850 of the Top Chalk to Base Gram Fm interval at the Energy Island position.

For Rogaland Group formations, analogue lithologies exist in the Danish onshore sector (e.g. Ølst Fm). However, this is not the case for the prograding systems of the Lark Fm.

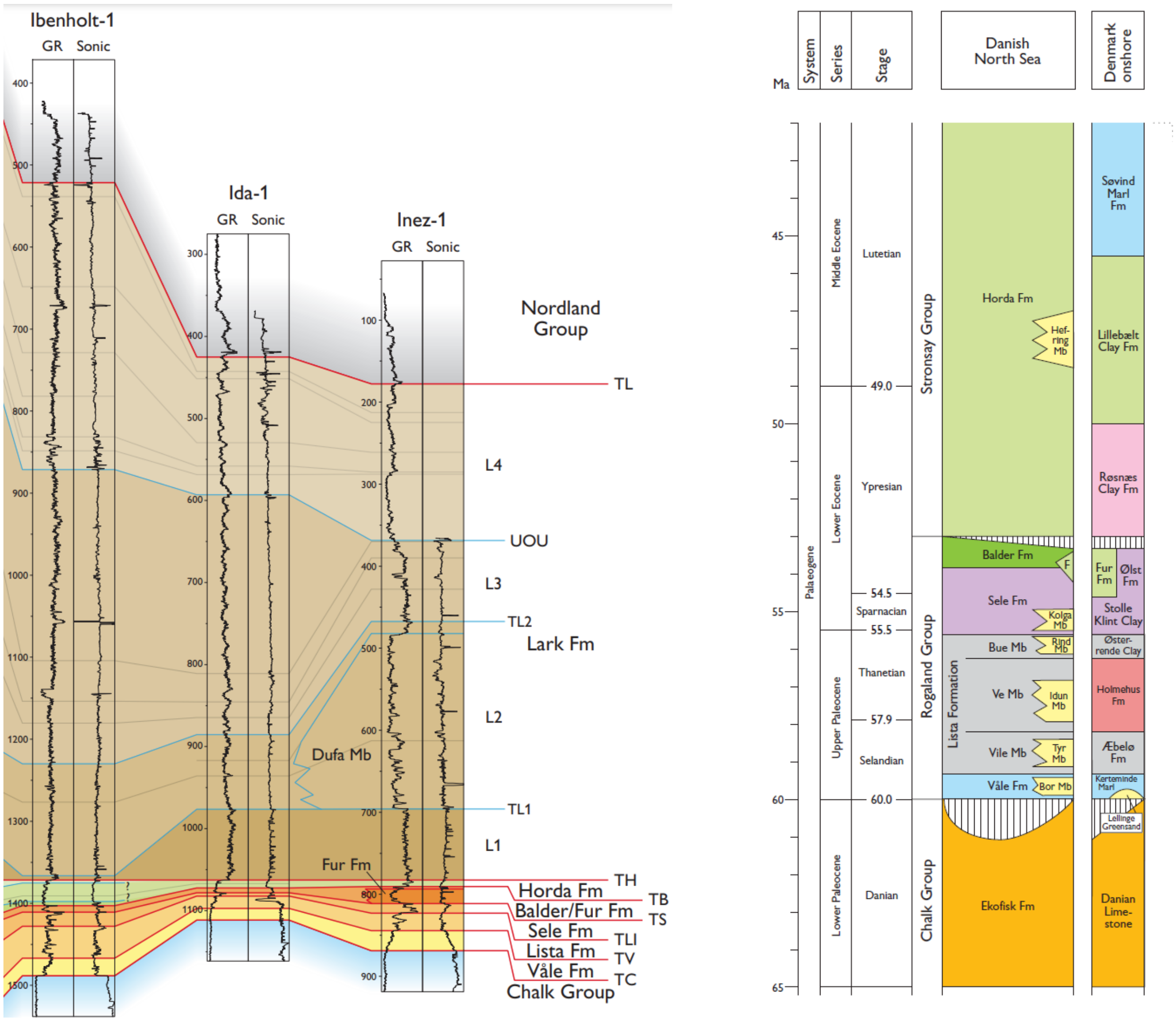
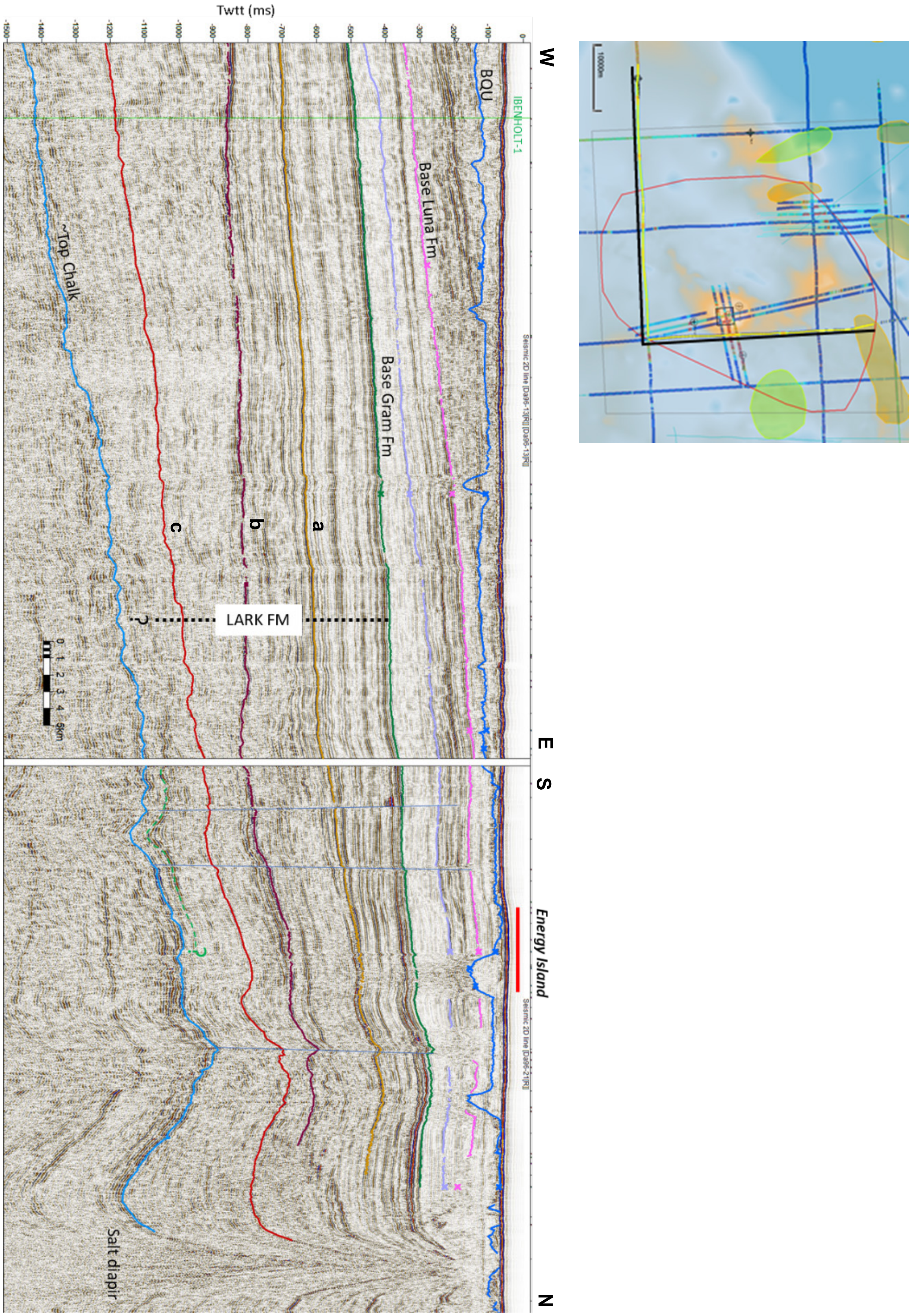


Figure 17. Left panel: Seismic log ties between three boreholes from the eastern North Sea. Right panel: Stratigraphic scheme for the Rogaland Group. From Schiøler et al. (2007).

Figure 18 (overleaf). Seismic correlation between Ibenholt-1 and the Energy Island area. BQU: Base Quaternary Unconformity. Deep-seated faults are marked. The poorly resolved strata package overlying Top Chalk is possibly the Rogaland Group (green punctuated horizon).


Twtt (ms)
W
E
S
N
IBENHOLT-1
BQU
Base Luna Fm
Base Gram Fm
~Top Chalk
a
b
c
LARK FM
Energy Island
Salt diapir

4.2. Miocene succession

4.2.1. Seismic stratigraphy and well tie

The study is based on multi-channel seismic industrial data of different vintages (1980 – 2013)(Fig. 19) including selected lines from the high-resolution Dana-96 survey. Cuttings from Ida-1 and Ibenholt-1 have been described sedimentologically (Fig. 20). Based on the regional understanding of the geology (Rasmussen et al. 2005), biostratigraphy/palyno-facies and cutting description 4 units have been mapped.

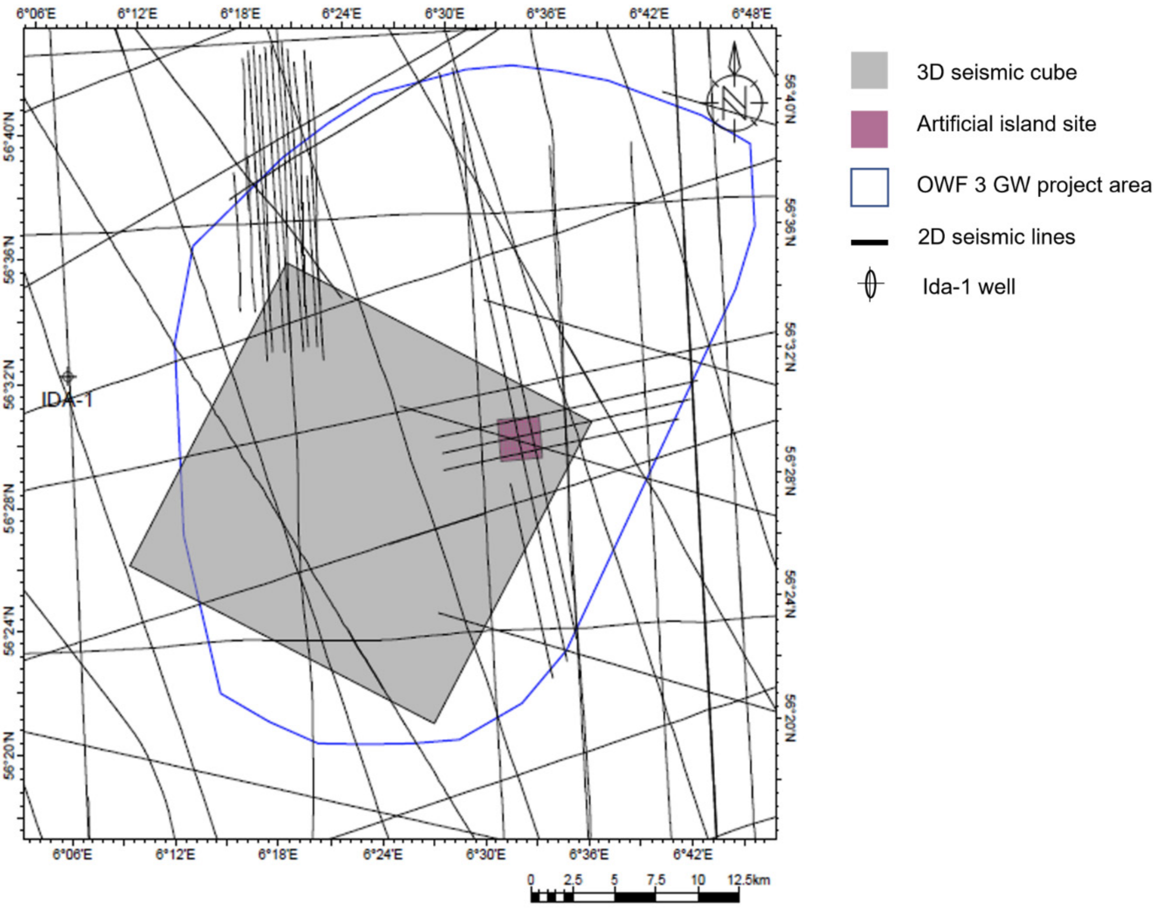


Figure 19. Distribution of seismic data lines for this study. Regular grid over the energy island site (purple box) are URH data (Table 3).

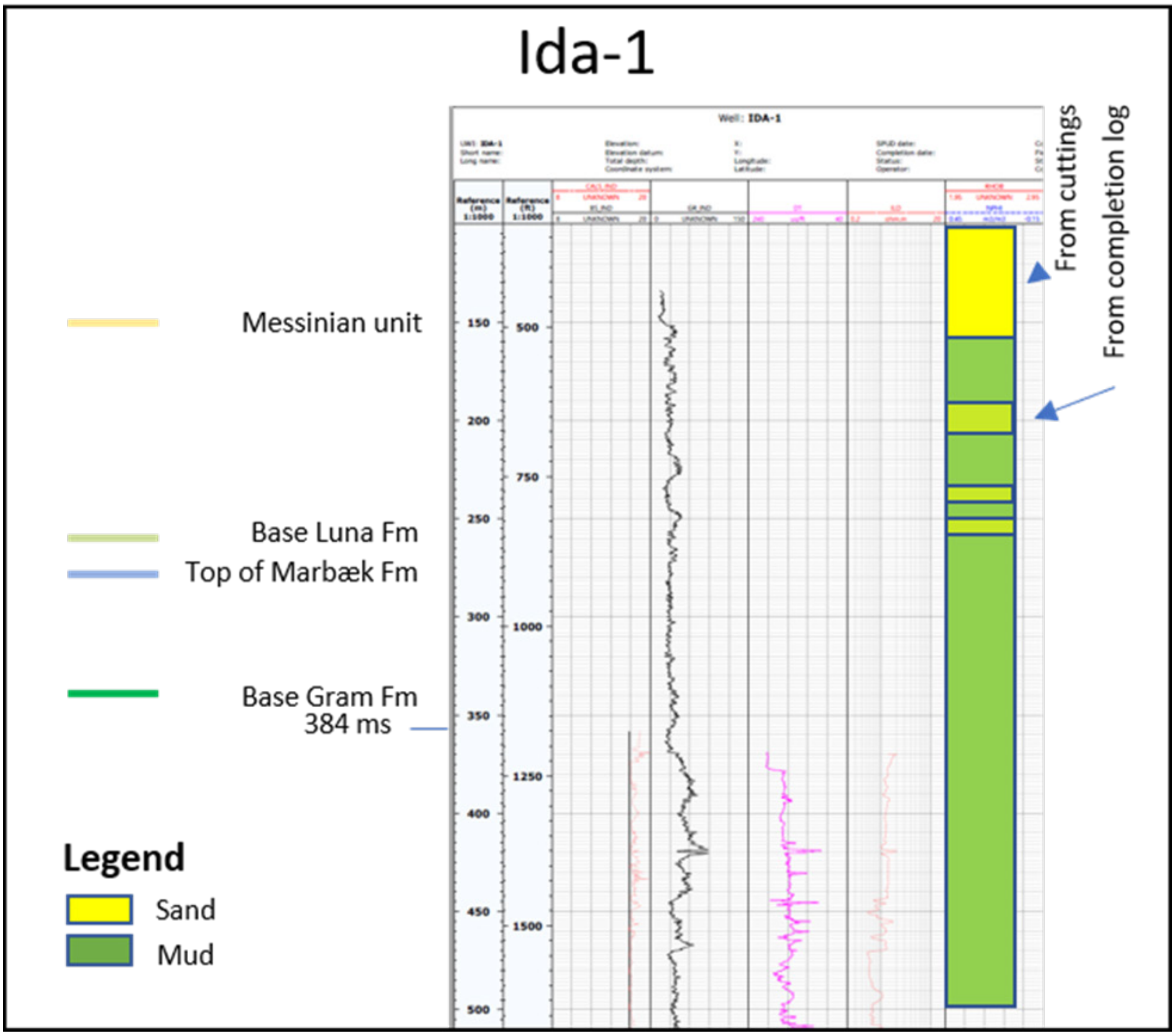


Figure 20. Lithology of the Ida-1 well, based partly on completion report and partly on cuttings descriptions. Positions of the mapped seismic surfaces are indicated.

In order to reveal the geology of the Miocene succession 4 surfaces have been mapped Figs. 21 and 22). The 4 surfaces are: the base Gram Formation, Top Marbæk Formation, base of the Luna Formation and a surface just below the base Lille John Member (Fig. 4). The upper Miocene marker horizons, Base Luna Fm and Top Marbæk Fm, were carried from the well-tied deep seismic data to the UHR shallow seismic profiles (Ch. 4.3).

Base Gram Formation: The surface is characterized by a high amplitude and continuous reflection. The reflection amplitude is locally extremely high due to presence of gas. The surface separates prodeltaic mud and sand from fully marine mud. The surface forms an overall westward dipping monocline with a maximum at 190 ms in the north-eastern part which dipping to a minimum of 450 ms towards the southwest (Fig. 22). Minor domal features are recognized in the north-eastern part of the study area and N–S faults dissected the surface, especially in the north-western portion of the area.

Top Marbæk Formation: Is a moderate to low amplitude reflection which shows a more continuous pattern in the western part of the study area. In the eastern part, a more fractured and low amplitude reflector characterizes the boundary. The surface is truncated by quaternary incision in the easternmost portion of the area. The boundary forms an overall westward dipping monocline with a maximum at 200 ms in the northeastern part which is dipping to a minimum of 340 ms towards the southwest (Fig. 23). The surface is dissected by N–S striking faults, especially in the northwestern portion of the area.

Base Luna Fm: The surface is a moderate, continuous reflection which is easily mappable in the entire area except near the boundary towards the Quaternary. The surface is only present in the western part of the study area and is not found in the focus area for the energy island. The boundary forms an overall westward dipping monocline with a maximum at 160 ms in the northeastern part which is dipping to a minimum of 260 ms towards the southwest (Fig. 24). The surface is dissected by N–S striking faults.

Intra Luna Formation (Messinian): The surface is a moderate, continuous reflection only recognized locally in the extreme westernmost part of the study area (not shown due to limited extent).

All units between the four surfaces are characterized by a parallel to sub-parallel reflection pattern. Some amplitude variations are recognized. Locally, downlap towards the west is recognized and locally, an undulating reflection pattern is seen.

The distribution of the units below the pre-Quaternary surface is shown in figure 25. The north-eastern portion is dominated by the mud-dominated Gram Formation while the southwestern part is alternating between Gram Fm and the sand-rich Luna and possibly Marbæk formations.

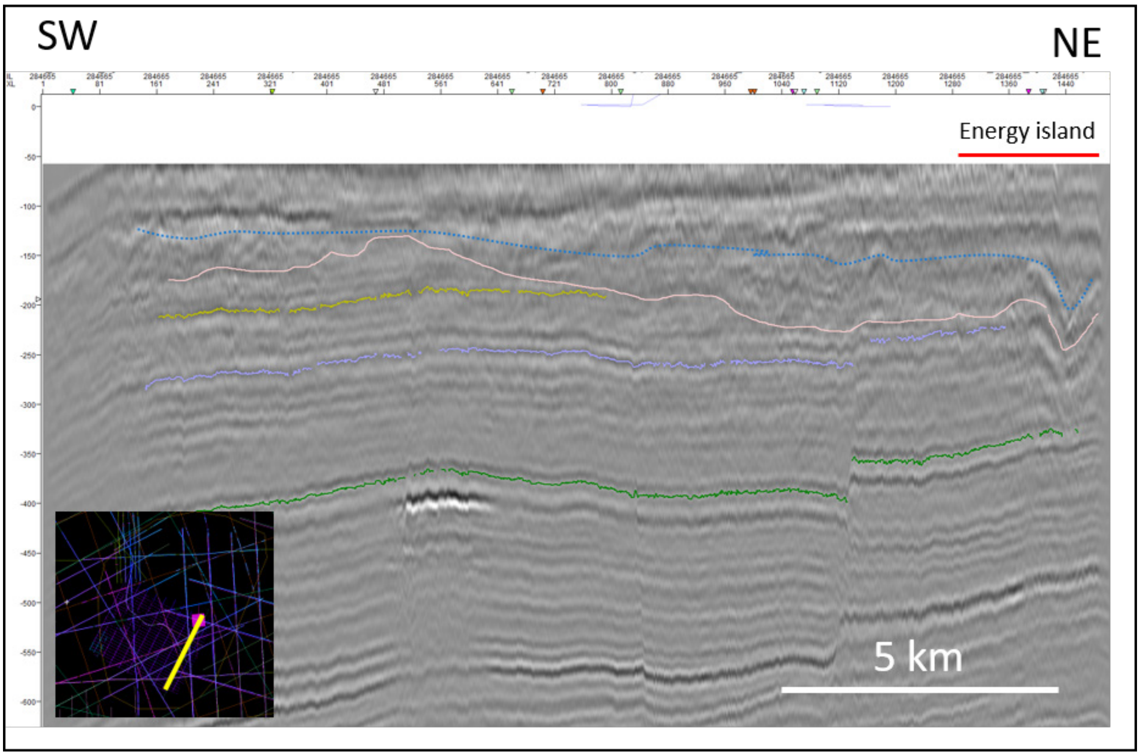


Figure 21. NNE-SSW striking seismic line from the AG9801-3D survey across the area of interest. The extent of the energy island is marked with a red bar above the seismic section. The approximate position of the Base Quaternary Unconformity is marked by punctuated blue line (based on tie to UHR data, Ch. 4.3). Pink marker denotes an erosional feature, possibly a glacio-tectonic decollement surface, which deepens toward north-east. The yellow marker represents the upper Miocene Messinian (intra Luna) boundary. The blue and green markers represent top Marbæk and base Gram respectively.

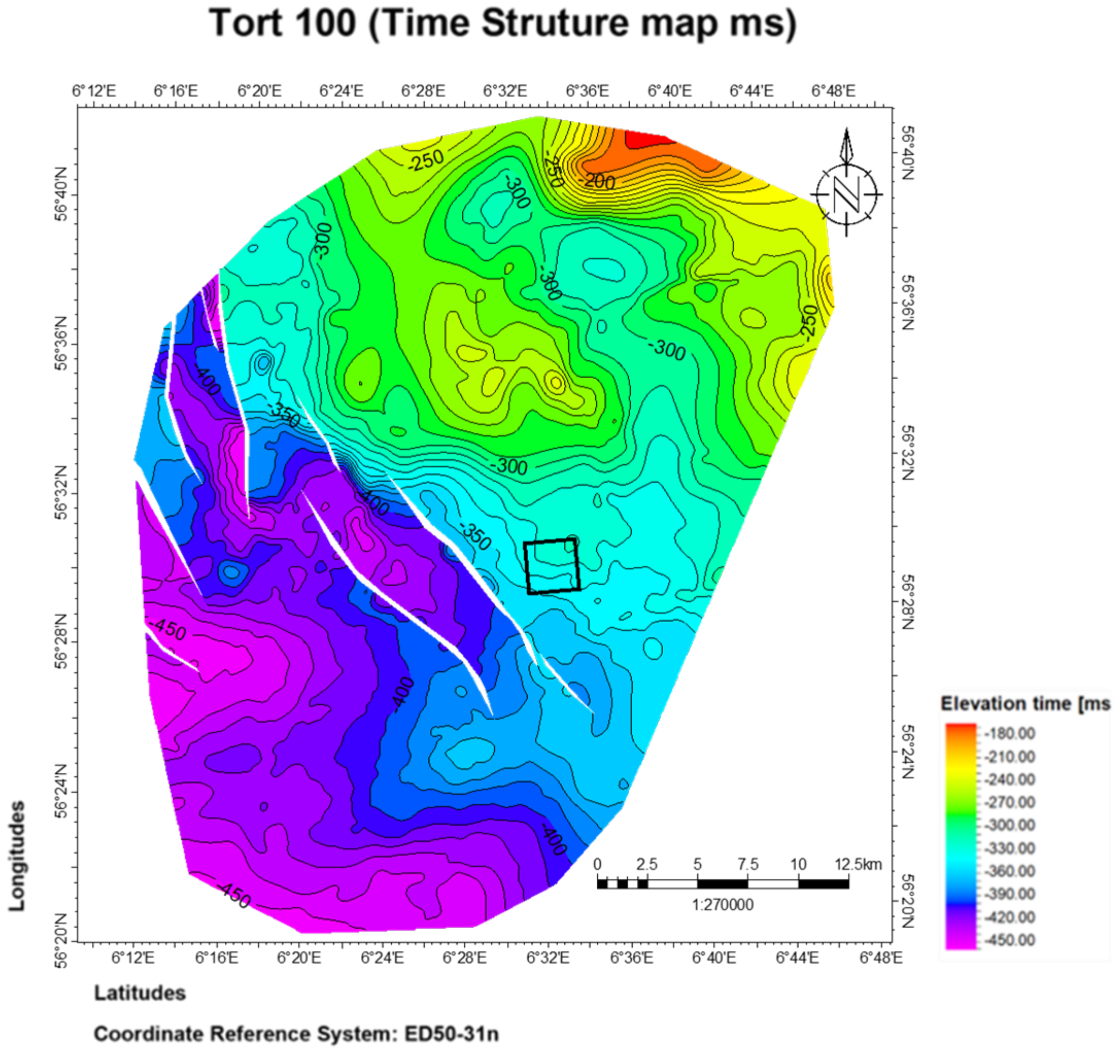


Figure 22. Time-structure map of the base Gram Formation. The surface is dipping towards the SW. Note the presence of NW – SE and NNW – SSE trending faults in the central portion of the study area.

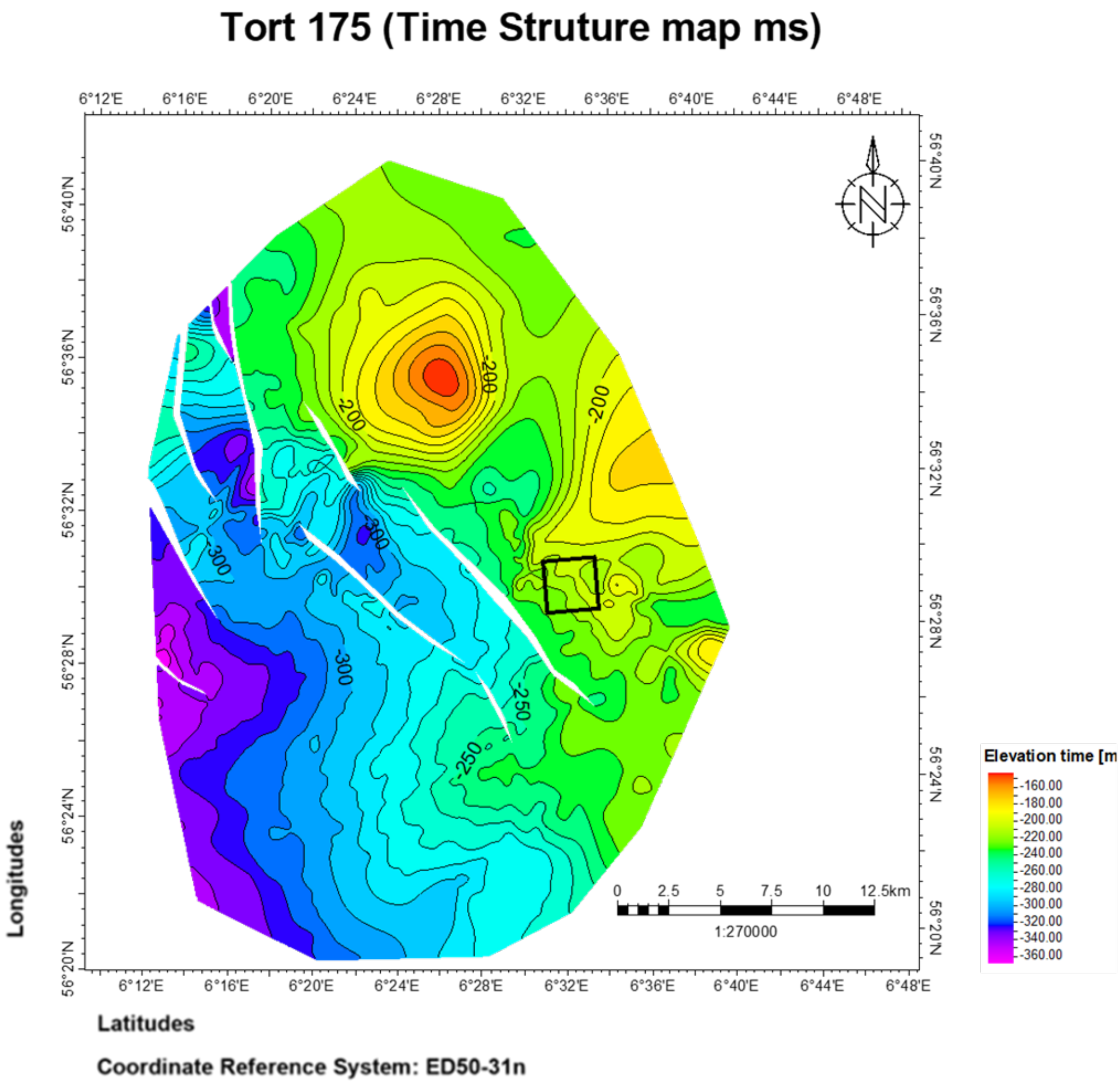


Figure 23. Time-structure map of the top Marbæk Formation. Note that the extent of the formation towards the east is more westerly than compared to the Base Gram Formation. This is due to truncation.

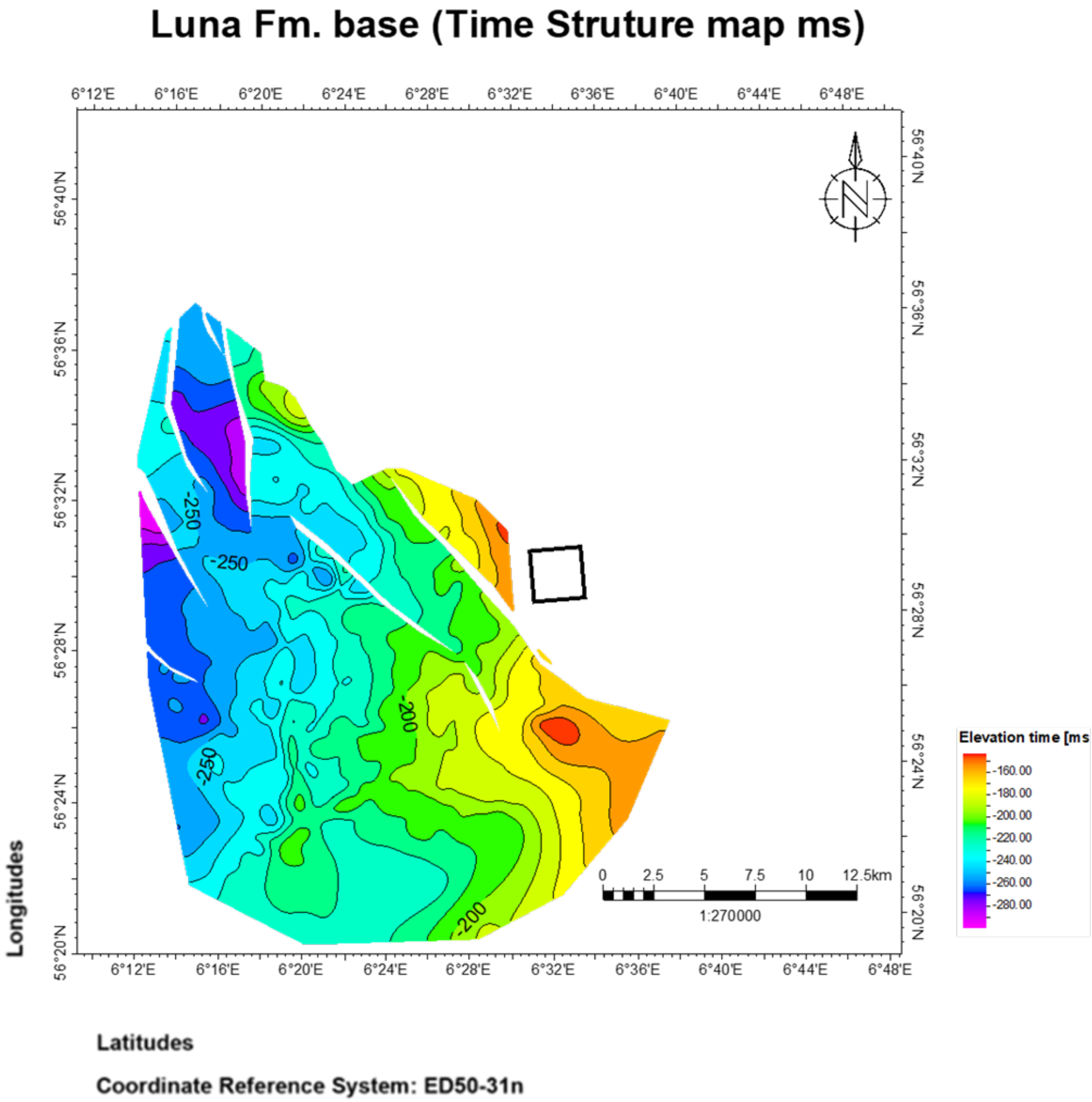


Figure 24. Time-structure map of the base Luna Formation. Note that the extent of the formation towards the east is more westerly than compared to the Base Gram Formation. This is due to truncation.

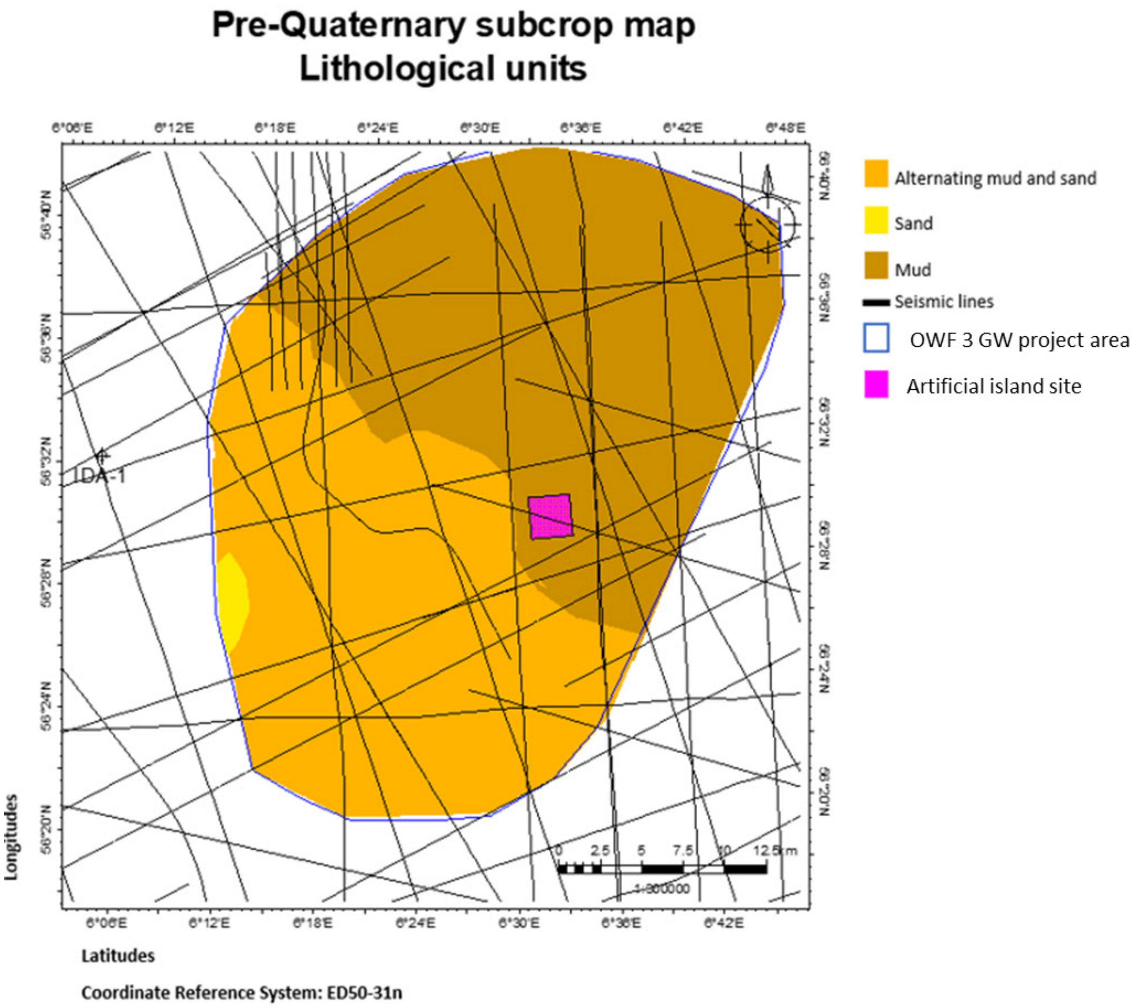


Figure 25. Pre-Quaternary subcrop map showing lithological units. The northeastern portion of the area is dominated by the mud-rich Gram Formation. The southwestern part is more sandy, especially in the extreme western part, sand dominates.

4.2.2. Biostratigraphy and depositional environment

IDA-1; DINOCYST STRATIGRAPHY

419-428 m: The last occurrences of *Caligodinium amiculum*, *Dinopterygidium cladoides* and *Hystrichokolpoma cinctum* in this sample combined with the absence of *Homotryblium* spp. and of *Chiropteridium galea* refer this sample to the *Caligodinium amiculum* Zone of late Aquitanian age (Appendix A1). The *C. amiculum* Zone is found in the Klintinghoved Formation.

395-398 m: The last occurrence of *Cordosphaeridium cantharellus* in this sample refer the sample to the *Cordosphaeridium cantharellus* Zone of mid-Burdigalian age (Appendix A1). This zone is known to occur within the Arnum Formation.

350-360 m: The interval represented by this cuttings sample seems to comprise an unconformity. The last occurrence of *Exochosphaeridium insigne* in this sample indicate that part of the interval (below the unconformity) should be referred to the *Exochosphaeridium insigne* Zone of late Burdigalian age. This zone is known to occur within the Arnum Formation. The first occurrences of both *Achomosphaera andalousiense* and *Gramocysta verricula* indicate the presence of the *Gramocysta verricula* Zone of Serravallian to earliest Tortonian age in the interval above the unconformity. The *G. verricula* Zone is known to occur within the Ørnhøj Formation. The presence of an unconformity is strongly supported by the fact that none of the index species of the dinocyst zones in between the *E. insigne* Zone and the *G. verricula* Zone, e.g. *Cousteaudinium aubryae*, *Labyrinthodinium truncatum*, *Unipontidinium aquaductum* and *Cannosphaeropsis passio* (Appendix A1), have been recorded.

310-160 m: The common occurrence of *Impagidinium* "*densiverrucosum*" in the sample at 320-310 m refer this sample to the *Hystrichosphaeropsis obscura* Zone of late Tortonian age (Appendix A1). The last occurrence of *Hystrichosphaeropsis obscura* in the same sample support this. The abundant occurrences of *Achomosphaera andalousiense andalousiense* and *Achomosphaera* sp. Head 1996 in the samples above, including the uppermost sample from 170-160 m, indicate that these samples also should be referred to the *H. obscura* Zone although the index taxa *H. obscura* and *L. truncatum* are not present. In the Nora-1 well the LO´s of *H. obscura* and *L. truncatum* were also recorded too low (Dybkjær et al. 2021). The *H. obscura* Zone is known to occur within the Gram and Marbæk formations.

Palynofacies

The organic particles are dominated by palynomorphs indicating a low-energy depositional environment. The rich and diverse dinocyst assemblages in the lower four samples indicate a fully marine setting. The distinct increase in cuticle and membranes, in freshwater algae and in bisaccate pollen in the upper three samples combined with a distinct decrease in dinocysts strongly indicate an upwards prograding trend.

IBENHOLT-1; DINOCYST STRATIGRAPHY

1230´-900´: The presence of *Impagidinium* "*densiverrucosum*" in the sample at 1230´-1200´refers this sample to the *Hystrichosphaeropsis obscura* Zone of late Tortonian age (Appendix A2). The presence of *Cleistosphaeridium placacantha* in the sample at 930´-900´ indicates that this sample also should be referred to the *H. obscura* Zone and thus that all three samples within the interval from 1230´-900´ belongs to this zone. The *H. obscura* Zone is known to occur within the Gram and Marbæk formations.

Palynofacies

The organic particles are dominated by palynomorphs indicating a low-energy depositional environment. The moderately rich and diverse dinocyst assemblage in the lowermost sample indicate a fully marine setting although the abundance of freshwater algae (*Mougeotia latevirens*) and of bisaccate pollen indicate rather strong influence from land areas. The distinct increase in wood particles, cuticle and membranes in the upper samples combined with a decrease in dinocysts strongly indicate an upwards prograding trend.

DEPOSITIONAL ENVIRONMENT

The biostratigraphic study indicates a fully marine to pro-deltaic depositional setting. This is consistent with the dominantly parallel seismic reflection pattern recognized in the study. The domal structures and faults found in the area are all due to movements of salt structures. These were particularly active at the Oligocene-Miocene boundary and during the late Quaternary. The overall dip towards the SW is due to late Quaternary tilting of the marginal areas of the North Sea (Japsen et al. 2007).

4.3. Quaternary succession

The thickness of Quaternary deposits is generally thin, e.g. below 50 meters, in the eastern North Sea sector except at the location of tunnel valleys where infills on the scale of several hundreds of meters are observed (Huuse & Lykke-Andersen, 2000; Nielsen et al. 2008).

The Base Quaternary Unconformity (BQU) was interpreted using the available HR and UHR seismic data, which provides a local recognition of buried valley features in and around the AOI (Fig. 26 & 27). Industry seismic data is of insufficient resolution for detailed mapping of the buried valley systems (Fig. 15). Moreover, the presence of seabed multiples forming “ghost” reflections in the upper 100 ms interval hampers interpretation of the BQU on the HR data (Fig. 27). It is noted that the tunnel valley below the proposed Energy Island has not been identified or mapped in previous studies (compare with Fig. 10).

Seismic horizons representing Base Luna Fm (pink) and Base Gram Fm (dark green), including an internal seismic marker (pale blue) (Fig. 27), were carried over from industry seismic profiles that was used to map the Miocene (Ch. 4.2.1).

QUATERNARY UNITS

Five sedimentary units were recognized above BQU comprising three phases of valley infill overlain by two aggradational to progradational sediment packages (Fig. 28). Examples of depositional geometries and detailed seismic facies are shown Fig. 31 and 32. Correlation between borehole data and depth-converted seismic profiles show that the bounding seismic horizons in general match the lithological boundaries (Fig. 29 &

30). Borehole-seismic correlations were established for BH-005, BH-1012 and BH-1022 where the available data could support a direct seismic tie.

Unit 1, Bank (top = seabed)

Mounded geometry, weak to transparent reflections. Lithology recorded as sand; partly laminated with varying amounts of shells. The unit may be subdivided into:

1A: Thin semi-continuous top layer below strong seabed reflection.

1B: Progradational interval with shingled to sigmoidal geometries.

1C: Sheeted interval; occasional reflective sediment lenses/channels along the base.

Interpretation: early Holocene transgression (1C); late Holocene, open marine environment influenced by strong tidal currents and storm waves (1A and 1B).

Unit 2, Channelized unit (top = green horizon)

Stratified conformable succession of medium reflectivity. Lithology recorded as mainly clay; silty, medium-high plasticity, laminated. May be subdivided into:

2A: Uneven, discontinuous, low amplitude reflections; laterally developed into semi-transparent facies. Abundant incised channel features; occasional high-amplitude infills

2B: Parallel, semi-continuous reflections filling into low-relief depression with depositional onlap onto topographic highs/flanks or mounded-hummocky relief of Unit 3. Occasional small channels are observed.

Interpretation: Possibly components of a glacial lake system (e.g. Hjelstuen et al. 2017). Discrete amplitude reversals may reflect organic-rich channel infills.

Unit 3; Valley infill – upper interval (top = purple horizon)

Heterogenic character with marked erosion along base. Lithology is recorded as mainly sand; fine-medium, sorted, occasional presence of gravel and shell fragments.

3A: Semi-continuous reflections, commonly with uneven, divergent-convergent spacing; onlapping and covering the valley flanks. This sub-unit, expressed in seismic sections below the western AOI (Fig. 32), does not appear to be covered by boreholes.

3B: Discontinuous to semi-continuous reflections forming irregular convex – lenticular geometries; often stacked. The seismic facies is often chaotic to transparent. Common internal erosion surfaces, aggrading channels and small-scale clinoform progradation. Presence of seafloor “ghost” reflection may complicate interpretation.

Interpretation: Pro-glacial and sub-glacial deposits, influenced by meltwater (3A), overlying ice-contact deposits, e.g. moraines (3B). Clay-rich sediments, e.g. glacial-marine, within the stratified sections of 3A cannot be ruled out (Fig. 32).

Unit 4; Valley infill – middle interval (top = red horizon).

Weak seismic character, often with a chaotic to transparent facies. Distinctly hummocky surface with an erosive character. Vaguely defined layering along the valley flanks that tend to dip into the central parts. Disturbed and deformed by glacio-tectonic activity.

The lithology is recorded as clay rich; high plasticity, partly laminated, calcareous, occasionally bioturbated. May also display a heterogenic character, with intercalated clayey and silt-sandy layers (BH-1012, Fig. 30).

Interpretation: Marine interglacial deposits; Eemian or Holstein?

Unit 5 Valley infill – lower interval (top green horizon).

Generally weak seismic character, often transparent in the upper part, but with tracible continuous reflections in the lower part that onlap the lower valley flanks with dips up to 7°. A stratified section (or sub-unit?) onlapping the BQU, is observed within the deepest part of the tunnel valley at depths below 140 ms.

The lithology in the upper part is recorded as mainly sand; fine-medium, clayey, gravelly and generally poorly sorted. However, the stratified interval forming the basal part of unit 5 is apparently not penetrated by boreholes (Fig. 31).

Interpretation (upper part only): Sub-glacial diamict, flow till?

EVIDENCE OF GLACIAL EROSION

The UHR seismic show evidence of planar erosion at the base of Unit 3 (Fig. 31). This truncation event may be related to ice flow during Saale, although it cannot be ruled out that the AOI was overrun by ice during the LGM (Fig. 34).

COMPARISON BETWEEN NORTHERN AND SOUTHERN BANK

As noted by Owen et al. 2020, the geology below Lille Fiskebanke show large differences between the southern and northern bank segments. Most notable are the dips in subsurface stratal planes to near vertical positions below the northern fringe of the bank system (Fig. 33). These structural features are presumably related to the salt dome activity north-east of the area but may be superimposed by glacial-tectonic processes. The area influenced by sub-surface salt is encompassed by fault zones that delineate transitions between disturbed and undisturbed sedimentary sections (Fig. 33).

The northern bank area is underlain by buried valleys with at least two separate elements observed on the available data (Fig. 26). These valleys appear to be smaller and shallower (generally <70 m) than the valley system below the EIA. It is possible that the northern component valleys are connected to a larger tunnel valley network observed on HR data about 10 km farther east.

The channelized sedimentary sequence (unit 2) appear to show a more limited distribution toward the northern segment of Lille Fiskebanke.

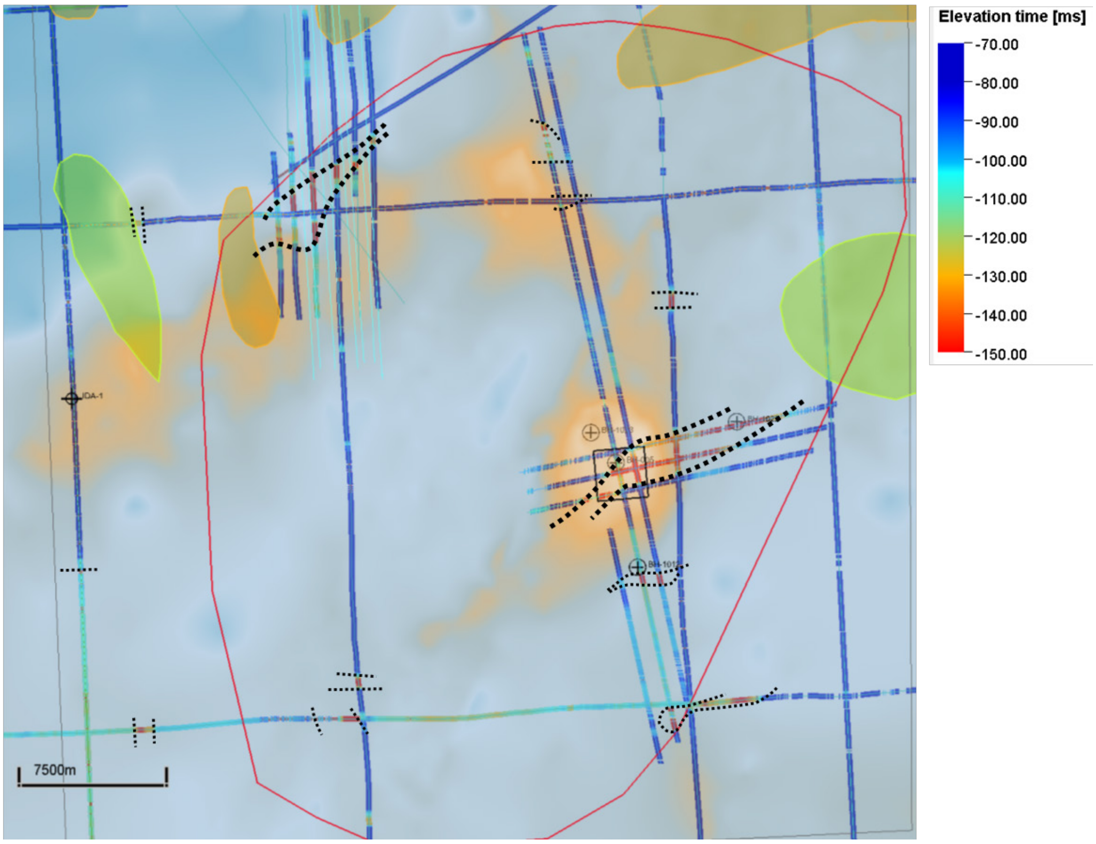
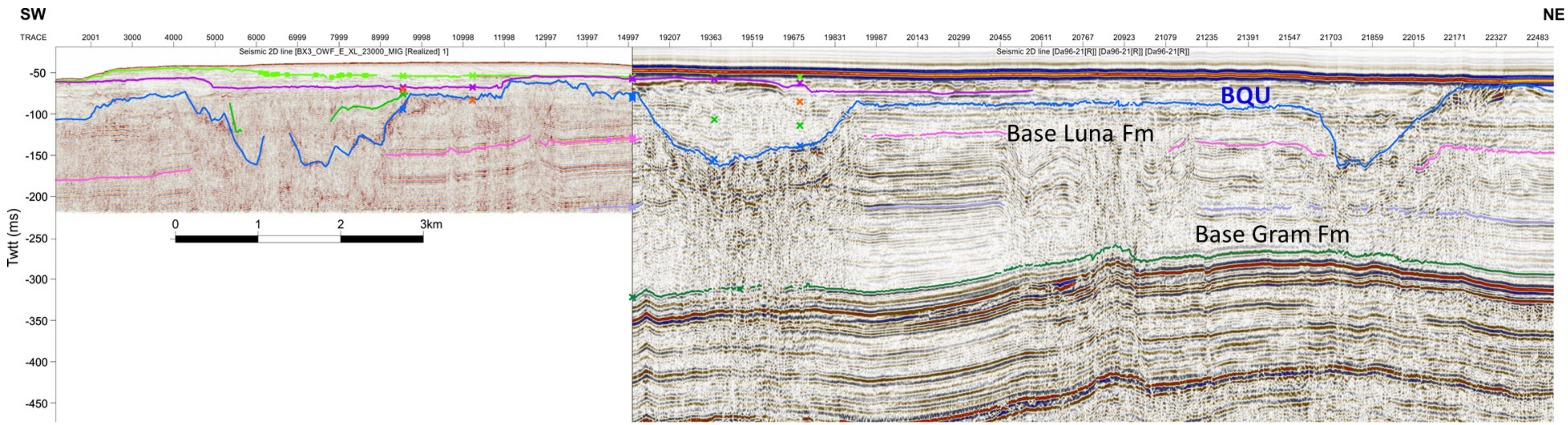


Figure 26. Map showing HR and UHR seismic lines with colour coding representing depth to Base Quaternary Unconformity. Flanks of buried valley features are indicated by punctuated curves. Proposed Energy Island location (box) and wind farm area (red polygon) is indicated. Position of salt diapirs illustrated by green ellipsoids. Background colouration is Emodnet bathymetry.



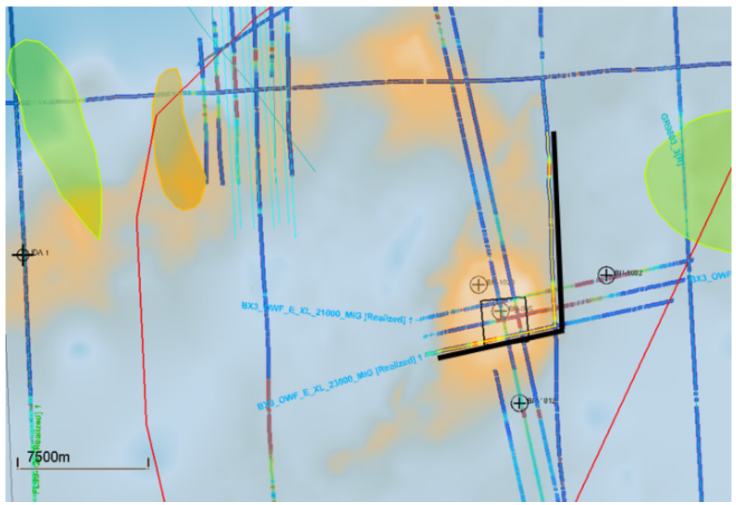


Figure 27. Composite profile demonstrating seismic-stratigraphic ties between UHR and HR seismic data.

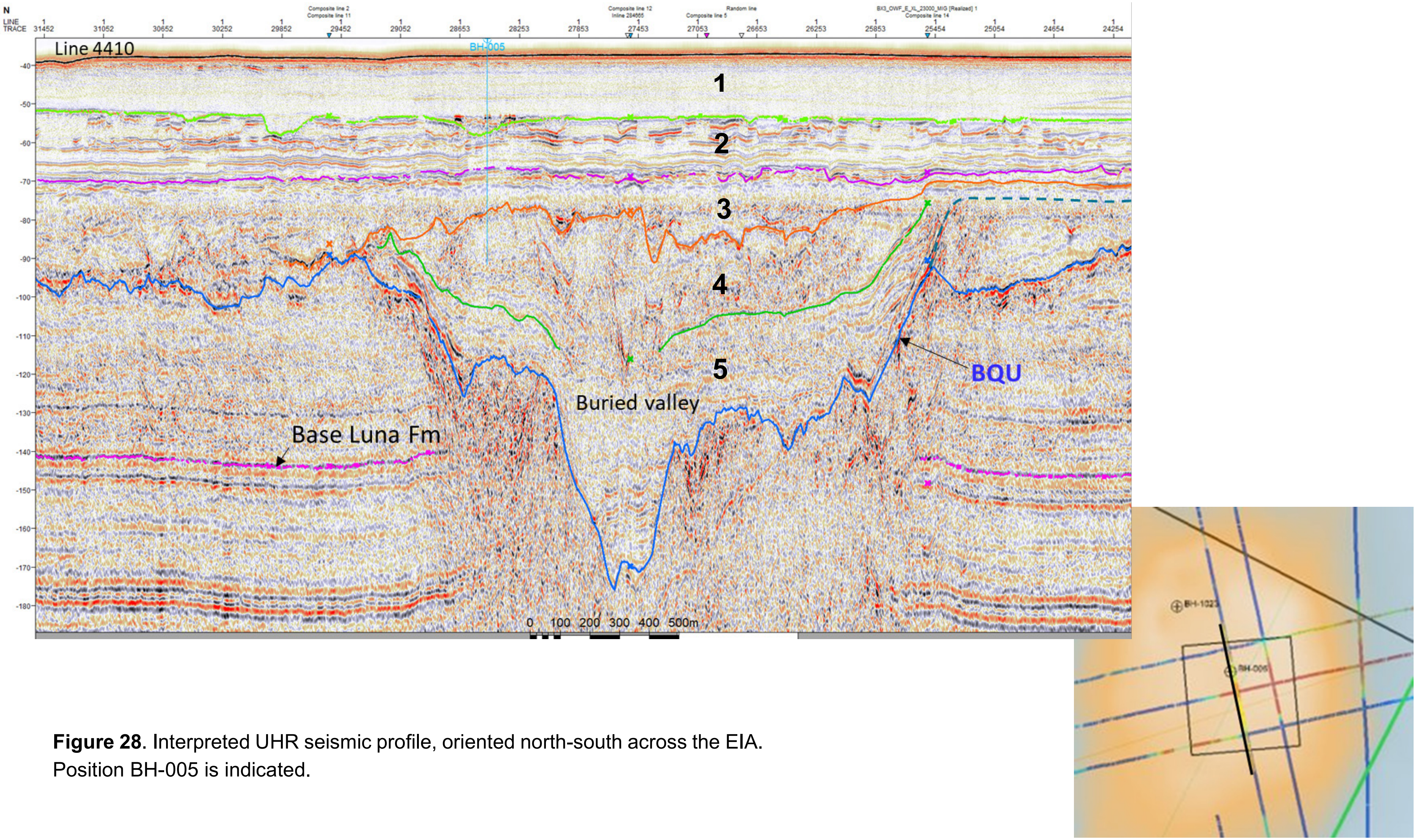


Figure 28. Interpreted UHR seismic profile, oriented north-south across the EIA. Position BH-005 is indicated.

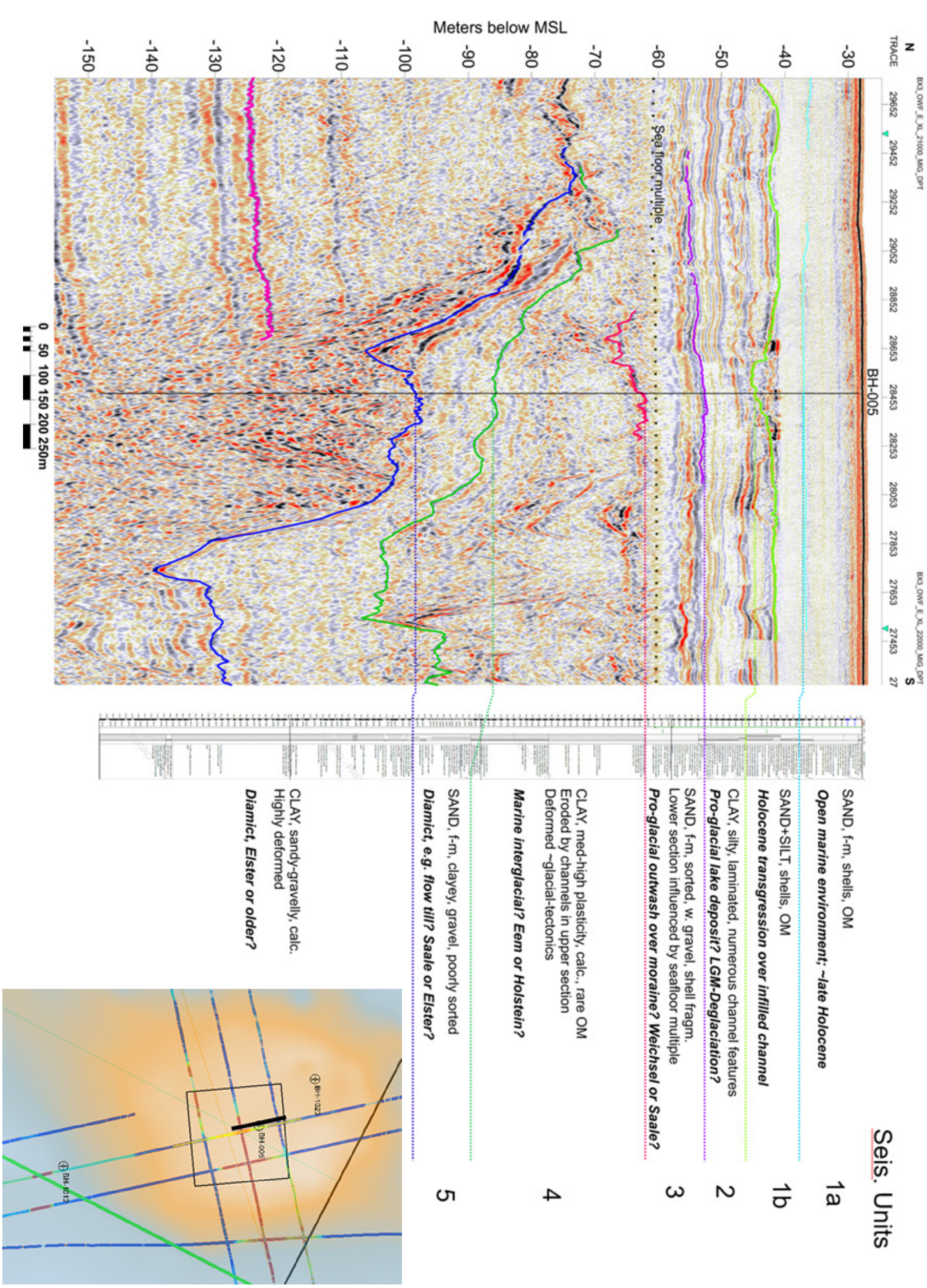


Figure 29. Seismic-borehole correlation (BH-005) with interpretation of depositional units.

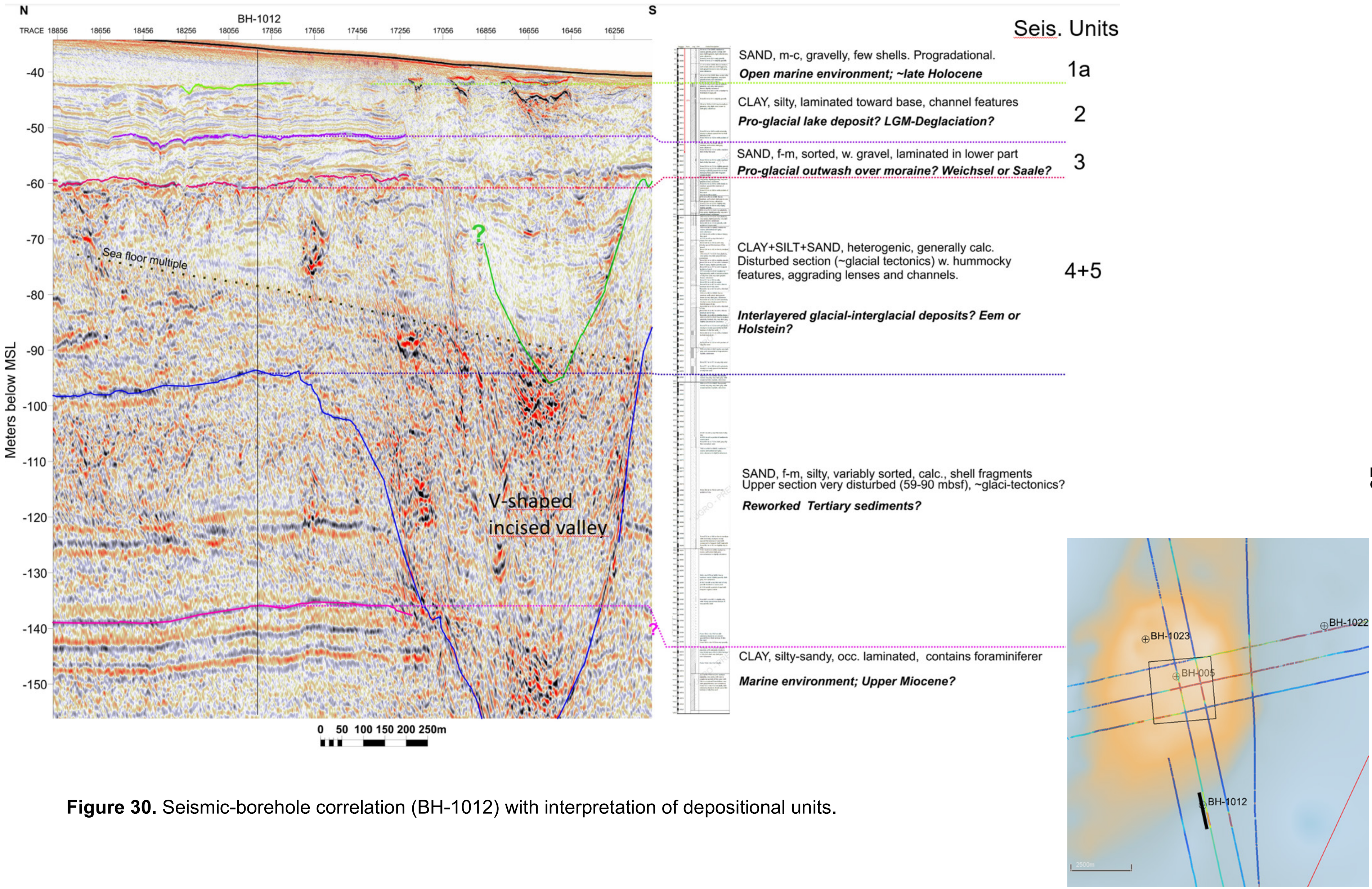
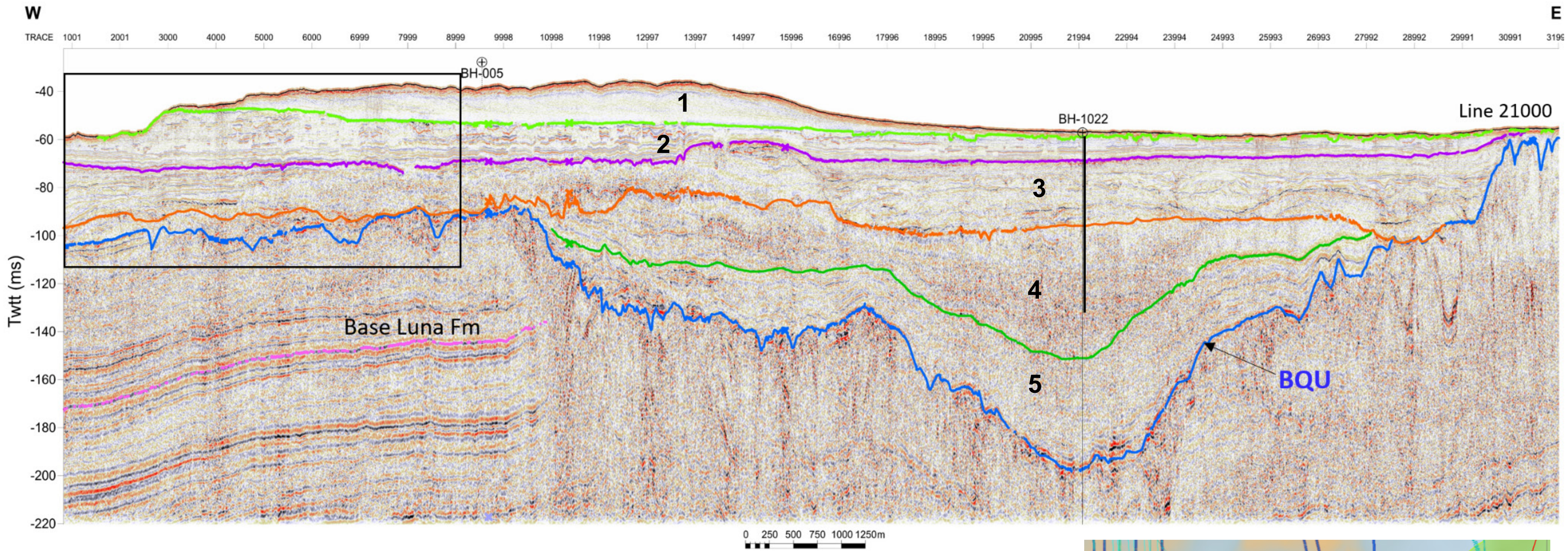


Figure 30. Seismic-borehole correlation (BH-1012) with interpretation of depositional units.



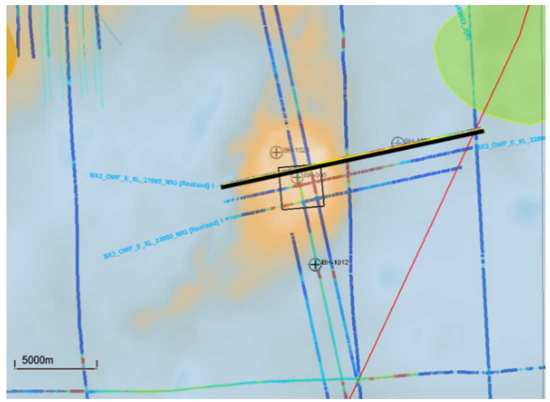


Figure 31. East-west seismic section slicing the buried valley at an oblique angle. Position of BH-1022 is shown. Box highlights detail shown in Fig. 32.

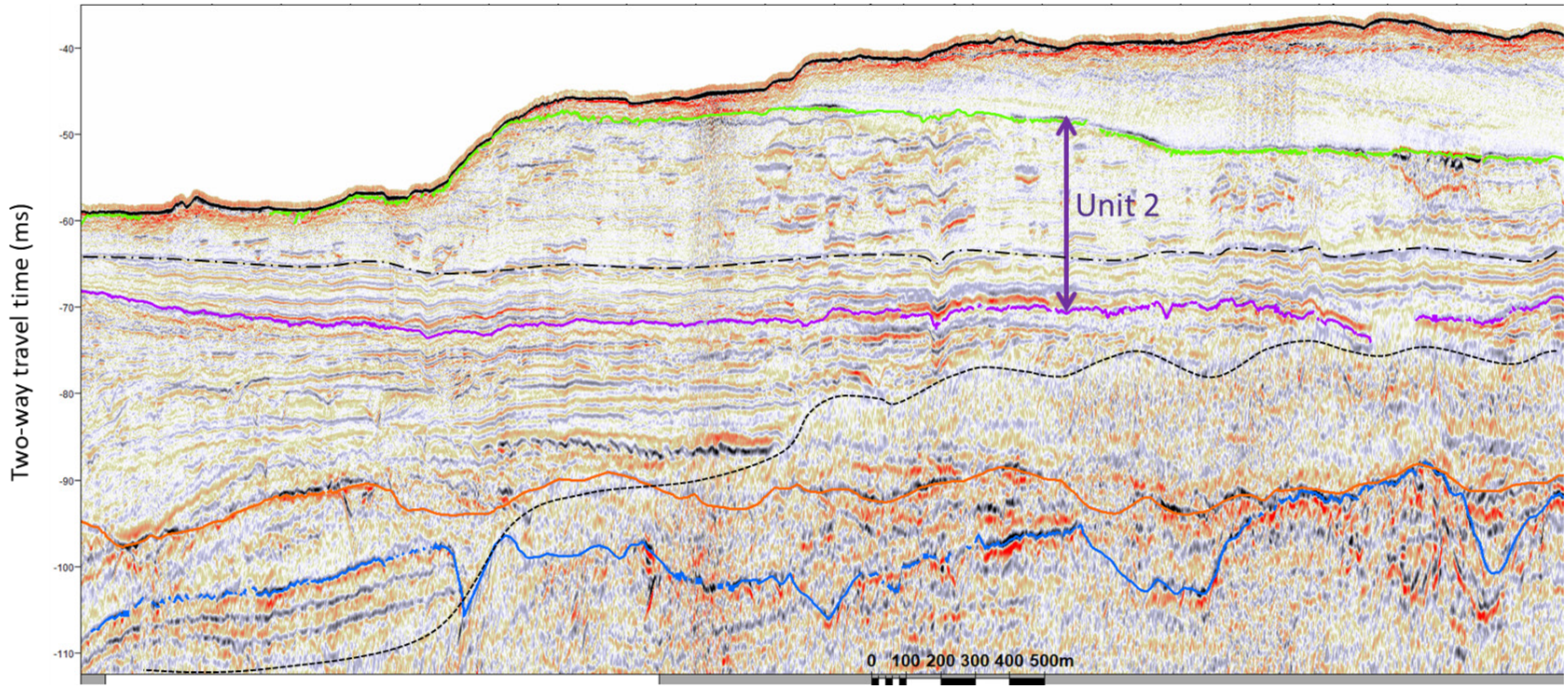
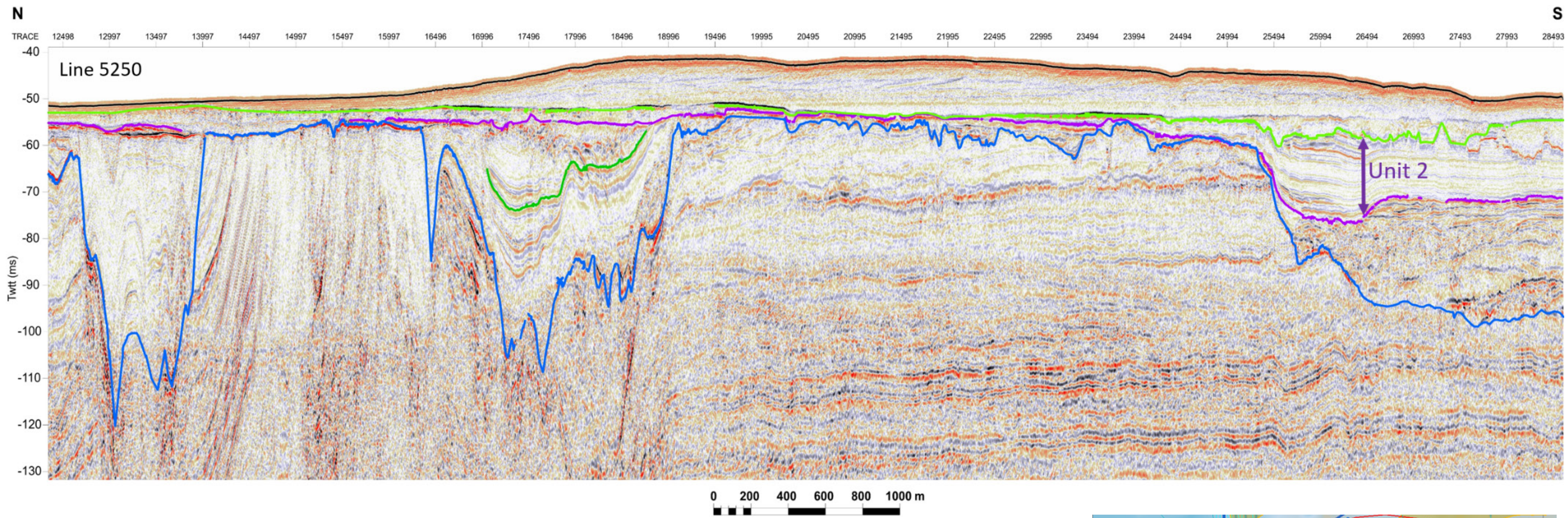


Figure 32. Detail showing western section of the Holocene bank formation that has developed around a remnant topography of Unit 2 representing channelized fine-grained sediments, possibly formed in a pro-glacial lake environment (see position in Fig. 32). Unit 2 can be subdivided into 2a and 2b (see text). Fine punctuated line traces a seabed mulitiple.



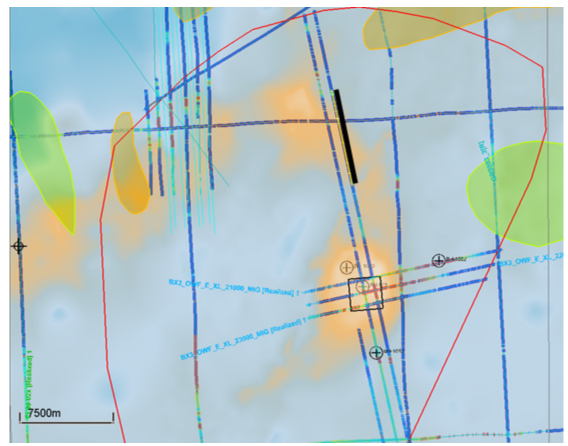


Figure 33. North-west seismic section capturing the northern part of Lille Fiskebanke were the sub-surface is complexed by tectonic deformation which presumably is mainly related to vertical salt movements (compare with HR profile in Fig. 18). Unit 2 appear to be absent along the northern flank of the bank system.

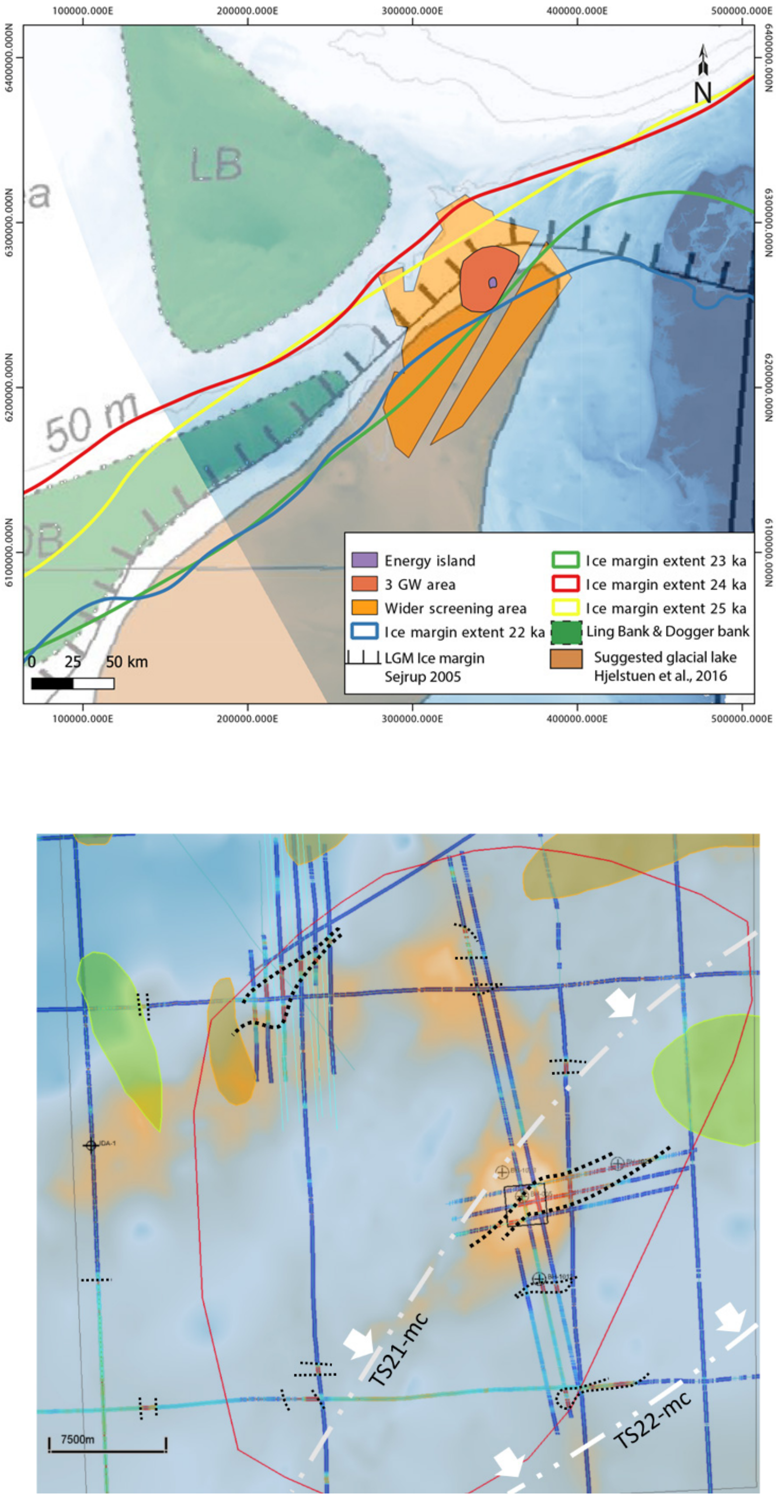


Figure 34. Location of proposed Energy Island in relation to proposed LGM ice margin scenarios and late glacial lake system (Hjelstuen et al. 2017; Prins et al. 2019).

5. Executive Summary

SEISMIC DATA

Data of different vintages, qualities, depth range and resolutions are available in the area around the proposed Energy Island. Recognizing the data limitations and qualities for individual survey is important for the seismic-stratigraphic interpretation and understanding how shallow geological features are connected with the deeper stratigraphic section.

PALEOGENE TO NEOGENE SUCCESSION

The lower Cenozoic succession below the area of interest (AOI) consists mainly of clay-dominated lithologies with occasional sand intervals. These sediments, ascribed to the Lark Formation (L1-L4 ~Oligocene – Middle Miocene), were generated by major depositional wedges prograding from the Fennoscandian region toward southwest into the North Sea basin.

Based on near-by well information deposits of Paleocene to Eocene age are likely limited to <80 m. Individual formations and members of the Rogaland Group, may exists below the AOI, but would be too thin to be recognized on the existing seismic data.

The Lower Miocene interval (upper Lark Fm; unit L4) may contain flood plain intervals associated with sea-level low stands where development of coal seams cannot be ruled out.

The AOI is underlain by Upper Miocene formations delimited by the Base Gram Fm horizon and upward by an erosional contact to younger Pleistocene and Holocene deposits (Base Quaternary Unconformity: BQU). The youngest Miocene sediments belong to the Luna Formation displaying sandy to silty sediments deposited in a near-shore marine environment. Transition from generally sandy sediments of the Luna and Marbæk formations to clay-rich strata of the Gram Fm is inferred in a north-east direction. Borehole 1012 appear to penetrate the base of the Luna Fm, recovering >50 m Upper Miocene sediments.

QUATERNARY SUCCESSION

Buried tunnel valleys with complex infills have been interpreted on available high-resolution seismic data and selected ultra-high-resolution survey lines (ENN-MMT-2021). The topology of the valley systems, defined by the BQU, can be traced on individual line segments but more data is required for a full spatial recognition that can accommodate gridded maps.

The AOI is underlain by a tunnel valley extending west to south-west with depths of up to 130 m and widths of 1.5 - 2.5 km. The valley geometry exhibits a broad U-shape with a central V-shaped incision. Overlying and infilling the valley, 5 main seismic units are recognized above the BQU, some of which can be further subdivided. The seismic units have been correlated to lithological information extracted from geotechnical boreholes intersected by seismic survey lines.

The shallow bank (unit 1) of the AOI is a convex, asymmetric sand body up to 17 m thick, likely deposited over different stages of the Holocene (last 11.500 years). The sand body is constructed by an early phase of horizontal aggradation over pre-existing topography followed by progradation toward east-southeast.

The bank has accumulated over a channelized unit (unit 2) of laminated clay, up to 20 m thick, possibly formed in a pro-glacial lake environment developed during the last ice age. This deposit is apparently limited to the southern parts of Lille Fiskebanke.

Valley infilling deposits (units 3-5) show large variations in seismic character and lithological properties associated with deposition in a proximal glacial setting. A marked planar erosional event is observed at the base of Unit 3, likely formed by ice advance during Saale or possibly Weichsel?

The tunnel valley infill (Unit 4) contains a package of at least 30 m of soft clays, presumably marine interglacial sediments representing either Eem (115-130 kyr BP) or Holstein (418-386 kyr BP).

The existing boreholes drilled to 120 m provide a good coverage of the shallow geological strata. However, the deepest valley section that extends below the central part of the proposed Energy Island contains an interval of about 50 m of stratified deposits that remain untested.

TECTONIC ELEMENTS AND GLACIAL INFLUENCE

Several tectonic elements are observed within the AOI. South and west of the proposed Energy Island location a series of fault-bounded depressions, aligned north-northwest, are expressed on time-structure maps of the Upper Miocene. The faulting is likely related to deep salt movements activated during major glacial episodes (ice sheet loading). The north-eastern part of the study area is influenced by a major salt diapir that has penetrated and uplifted the Cenozoic succession.

Glacial-tectonic disturbances, e.g. thrust sheets, are abundant across the area implying multiple generations of ice moving across the region. Prominent deformation features oriented east-west are generally linked with Pre-Weichselian ice ages (Saale, Elster). However, the position of the ice margin during the Last Glacial Maximum is not well known. The AOI on Lille Fiskerbanke was positioned proximal to the ice margin of the Weichsel glaciation and according to published models it was overrun by ice during Last Glacial Maximum. This has implications for understanding the loading-compaction history of the sedimentary succession.

6. Options and Recommendations

- The lower Cenozoic interval may be tested by performing a study of near-by wells; Ibenholt-1 and Ida-1, involving cuttings and well log data. Based on this well information that can be seismic-stratigraphically tied to the AOI, analogue successions from onshore DK sections may be identified and analyzed, e.g. Rogaland Group formations. The combined data sets will provide input to a geological model for the Energy Island area, which avoids a deep drilling to Top Chalk level.
- For testing the upper Cenozoic below the proposed Energy Island, in particular the potential presence of intercalated sandstone-mudstone facies and coal intervals, we recommend drilling a high-quality borehole that penetrates the Arnum Fm below the Base Gram Fm horizon, with an estimated target depth of 350-400 mbsf.
- We recommend further investigations that can clarify the age, distribution and character of soft marine clays that form part of the buried valley infill. In this respect, the stratified deposits located within the deepest part of the valley system have not been tested which will require additional coring to about 140 mbsf.
- Upper Miocene strata drilled at some of the sites (e.g. BH-1012) should be subject to further biostratigraphic and sedimentological analyses.
- To supplement the existing data base, further seismic acquisition may be considered that is bespoke to the lower Cenozoic interval (Top Chalk – Middle Miocene), aimed optimizing resolution above Top Chalk level. This may be gathered in a relatively coarse grid with focus on tying Ibenholt-1 and Ida-1 to the AOI.
- The potential influence of earthquake-related geohazards should be evaluated, especially considering the presence of tectonic faults within <3 km of the AOI.
- Finally, we recommend that all borehole and seismic data will be made available for research that can elaborate understandings and insights on the Danish North Sea geology and its applications for resources, marine habitats and green energy transition.

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APPENDICES

A1: Biostratigraphic range chart for Ida-1

A2: Biostratigraphic range chart for Ibenholt-1

Well Name : Ida-1

Interval : 100m - 500m
Scale : 1:2500
Chart date: 07 April 2022 Karen Dybkjær

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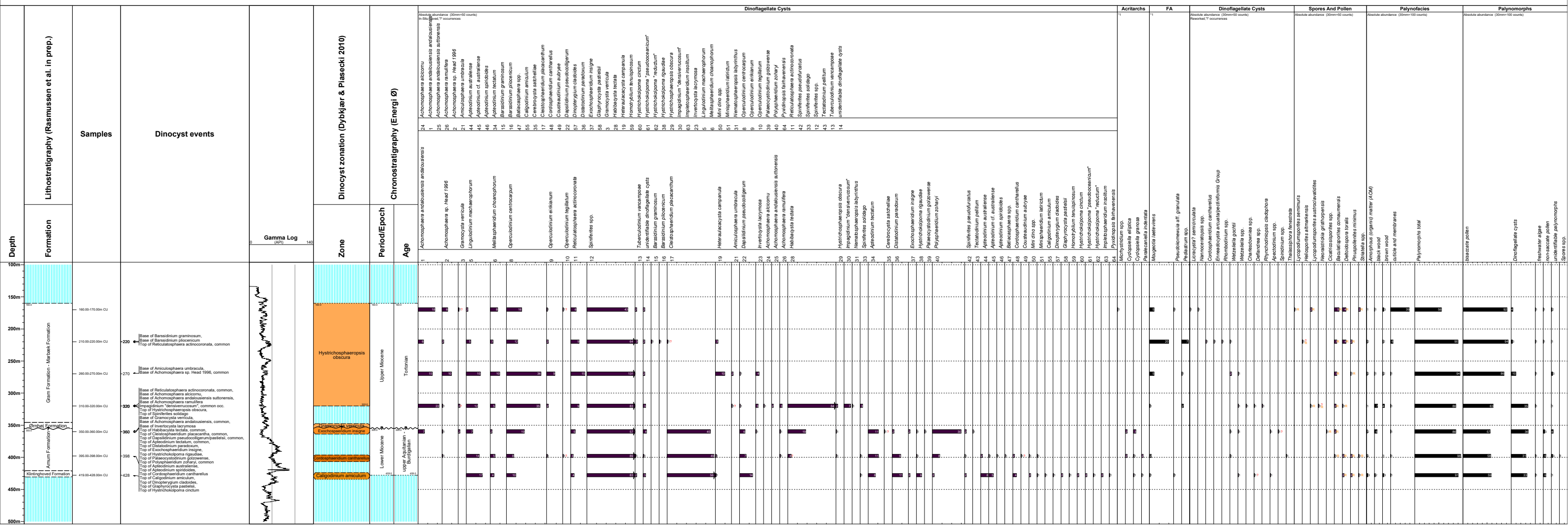

Well Name : Ibenholt-1
Interval : 800' - 1400'
Scale : 1:2500
Chart date: 07 April 2022 **Karen Dybkjær**

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