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ENERGY ISLAND DANISH NORTH SEA GEOARCHAEOLOGICAL AND GEOLOGICAL DESK STUDY

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ENERGY ISLAND DANISH NORTH SEA
GEOARCHAEOLOGICAL AND GEOLOGICAL DESK STUDY

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CONTENTS

1. INTRODUCTION

Energinet has as part of the Energy Agreement June 2020 been instructed by the Danish Energy Agency (ENS (Energistyrelsen)) to carry out pre-investigations of the seabed for the project Energy Islands (Energiøer). The project comprises three 1 MW offshore wind farms (OWF's) and one energy island in the Danish North Sea plus two OWF's in the Baltic, near the island of Bornholm.

As part of the pre-investigations, Energinet must ensure that relevant museums carry out marine archaeological assessments of the project areas. In 2016, Energinet agreed on a Best Practice with the Palaces and Culture Agency (SLKS (Slots- og Kulturstyrelsen)) for Marine Archaeology on large offshore projects.

For the project areas in the Danish North Sea, Energinet has asked Rambøll to carry out a Geological Desk Study (DTS) to support the geoarchaeological assessments of the area according to the agreed Best Practice and to support Energinet's planned geoscience-focused surveys (geophysical, geotechnical etc.). The areas of investigation including the planned export cable routes are seen in Figure 1-1. The energy island and three OWF's are planned in area A and/or B whereas area C and D are the planned export cable corridors. The map also shows potential locations of the energy island and the designated OWF area (North Sea OWF area) supplied by ENS.

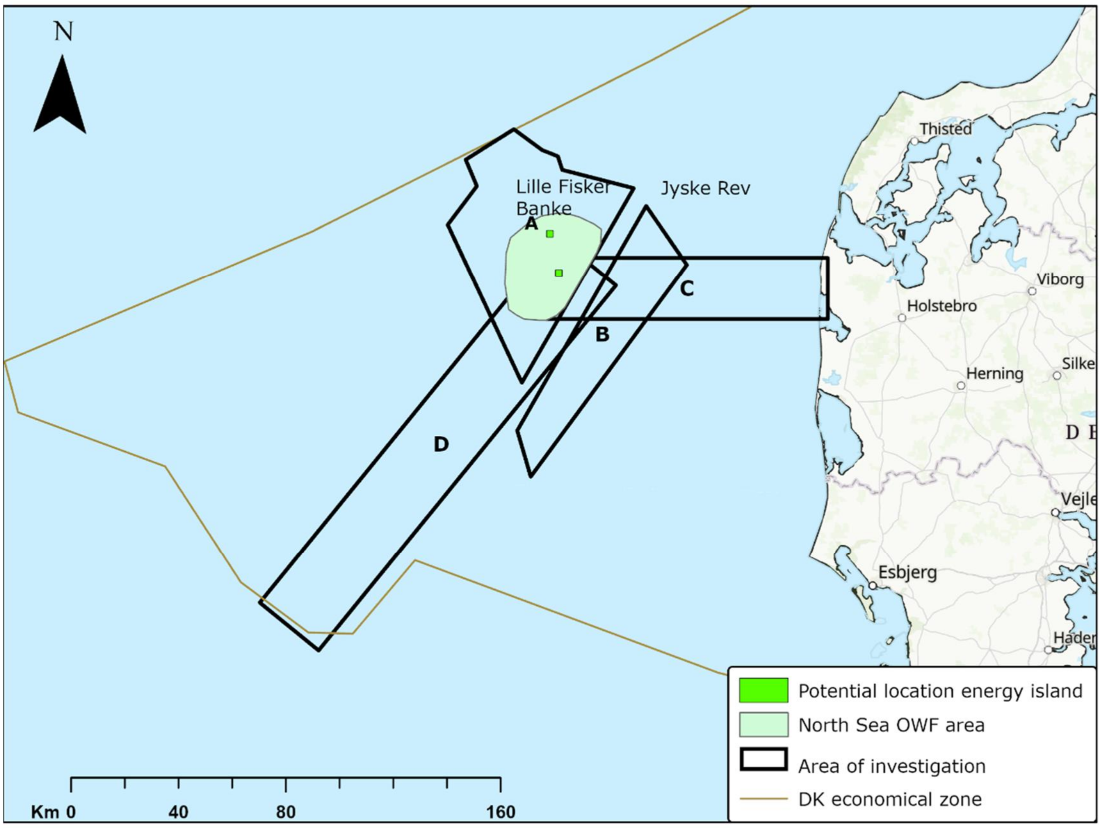

Figure 1-1 Overview of the gross areas for energy island and OWF's and planned export cable routes in the Danish Sector of the North Sea. The energy island and three OWF's are planned in area A and/or B whereas area C and D are the planned export cable corridors. The map also shows potential locations of the energy island and the designated OWF area (North Sea OWF area).

2. METHODOLOGY

A geological DTS is intended to accumulate, synthesize, and present information collected and extracted from existing data sources. It is used to help understand and communicate the physical conditions and associated constraints on project development. The data sources include public data sources and proprietary data from Ramboll and our client's files. This geological DTS has two purposes: to support Energinet’s planned geoscience-focused surveys (geophysical, geotechnical etc.), and to support geoarchaeological assessments of the area. Methodology for the geological DTS relevant for the preliminary seismo-stratigraphic interpretation is presented in section 2.1 and methodology for the geoarchaeological DTS relevant for marine archaeologist is presented in section 2.2.

2.1 Geological DTS relevant for the preliminary seismo-stratigraphic interpretation

As the primary purpose of this part of the geological DTS is setting up a conceptual geological model primarily indented for preliminary interpretations of the planned geoscience-focused surveys, particularly the planned seismic surveys, this part of the DTS focuses on:

- Regional geology
- Subsurface geology including examples of existing interpreted seismic sections
- Seafloor and subsurface sediment layering and characteristics

The above elements are synthesized into a conceptual geological model for the sub-surface geology relevant for the expected maximum installation depths including a conceptual geological profile.

The primary purpose of the Geological DTS is to form a geological basis for the planning, optimization, execution, and interpretation of the planned geophysical surveys of the site and cable route(s).

2.2 Geoarchaeological DTS relevant for the marine archaeologists

The applied methodology is similar to methods used internationally, e.g. /1/, /2/, /3/, /4/, which in general describe that a geoarchaeological study for preliminary assessments of the likelihood of encountering submerged Stone Age sites should as a minimum focus on the following items:

- Relative sea level fluctuations during relevant period of Late Glacial and especially Post Glacial
- Bathymetry
- Expected maximum installation depths
- Archaeological habitat and research model(s) for Stone Age settlers
- Geology in terms of expected geological setting, layering and erosional behaviour for the relevant geological layers on which the Stone Age people may have lived.

Energinet in 2016 agreed a Best Practice /5/ for large-scale marine projects with the Agency for Cultural Monuments and Palaces (SLKS (Slots- og Kulturstyrelsen)) – the authority in regards of cultural heritage issues in Denmark. The Best Practice also describes in general terms the methodology described in this chapter.

The primary purpose of the Geoarchaeological DTS is to form a geoarchaeological basis for the preparation of a so-called ‘Archaeological analysis’ as set out and defined in Energinet’s and SLKS’ joint Best Practice.

2.2.1 Relative sea level fluctuation curves

Relative sea level fluctuation curves are used for identification and assessment of the most relevant existing shoreline displacement curve(s), aka relative sea level (RSL) curve(s), if available, for the relevant marine area during Late Glacial and especially Post Glacial periods with special focus on the time slot for which the archaeological habitat and research model is relevant. Thus, sea level models and curves should be consulted if available and should be treated as a general guideline for presenting depth to age ratios and coastal environmental change.

2.2.2 Bathymetry

Bathymetry here means an existing Digital Terrain Model (DTM) of the seabed. Knowledge of bathymetry, seabed erosion and deposition in the area of investigation will be improved during the planned pre-investigations, however at the current stage, the present seabed terrain is the best available data source to estimate theoretical former land areas from.

2.2.3 Expected installation depths for turbines, substation(s), and cables

The final installation depths for the export cables will depend on various circumstances such as geology, engineering aspects, water depth, vessel traffic, trenching methods, crossing infrastructure, fishing, etc., and has not been finally defined yet; however, an expected burial depth of 1,5 m can be used as a starting point.

The expected foundation depth of the energy island is unknown but may be substantially dependent on the concept of design and construction and the local geological setting. The expected maximum foundation depths of wind turbines and offshore substations may extend down to 60m below seabed dependent on the local geological setting plus the foundation type

2.2.4 Archaeological habitat and research model(s) for Stone Age settlers

A survey and investigation strategy should include a model for prehistoric settlement practices, e.g. /5/, /6/. Thus, when assessing submerged Stone Age landscapes, focus for marine archaeologists are most likely the following parameters:

1. The sea level potential for pre-historic settlement; former dry land area making the area inhabitable; or inundated area during the archaeological period of interest making the area uninhabitable.
2. Habitat / Settlement model / Subsistence economy, including basic principles of human survival which dictate where people live, such as availability of fresh water and food procurement; well-known settlement patterns for the period enabling tracking through (paleo-)topographic models.

The habitat and settlement model used in this report is the internationally renowned ‘fishing site model’, e.g./1/, /5/, /6/, /7/, /8/ which argues that pre-historic sites exploiting marine resources were placed by the coast in immediate proximity to positions where these resources appear/pass in larger quantity. The concept of the fishing site model is to use topographical predictive modelling for mapping of prehistoric hunter-gatherer coastal settlements by tracing attractive coastal landscape elements such as coves, fjords, bays, indents, dire straits, river inlets/shores. Typical settlement positions for prehistoric hunters utilising marine resources according to the fishing site model are marked in Figure 2-1.

Other models for locating settlements exist in sketch form - and will possibly be detailed, verified, and made operational in the coming years. However, the ‘fishing site model’ is at present the best-tried topographic model for identifying archaeological interests on the seabed and has proven successful as remains of many coastal Stone Age settlements have been found using the concept of this model.

According to literature, e.g. /4/, /5/, focus in Danish waters is primarily on the archaeological period of the Stone Age called Mesolithic, c. 11,000-5,900 years before present (BP), where hunter-gatherers primarily lived close to the coasts finding food from the sea, see Table 2-1.

Findings according to the fishing site model are in Denmark primarily known to be of Late and Middle Mesolithic age, e.g. /6/, /8/, thus associated with the 'Kongemose culture' and the 'Ertebølle culture', c. 8,400 BP – c. 5,900 BP, see Table 2-1. However, recently a relic from a submerged prehistoric site was dated to c. 8,500 BP, thus the youngest part of the older 'Maglemose culture', /4/, /9/.

Table 2-1 Cultural, archaeological, climatic and geological periods, and approximate time intervals. compiled by Ramboll from various sources, e.g. /4/ and /8/.

Period	cal. ka BP (Thousand calendar years before present (BP))				
	>11	c. 11.0 – c. 8.4	c. 8.4 – c. 7.4	c. 7.4 – c. 5.9	< c. 5.9
Cultural	Ahrensburg	Maglemose	Kongemose	Ertebølle	NA
Archaeological	Paleolithic	Early Mesolithic	Mid Mesolithic	Late Mesolithic	Neolithic
Climatic	NA	Preboreal (c. 11.0-9.8) Boreal (c. 9.8-9.0) Atlantic (c. 9.0-8.4)	Atlantic	Atlantic	Subboreal Subatlantic

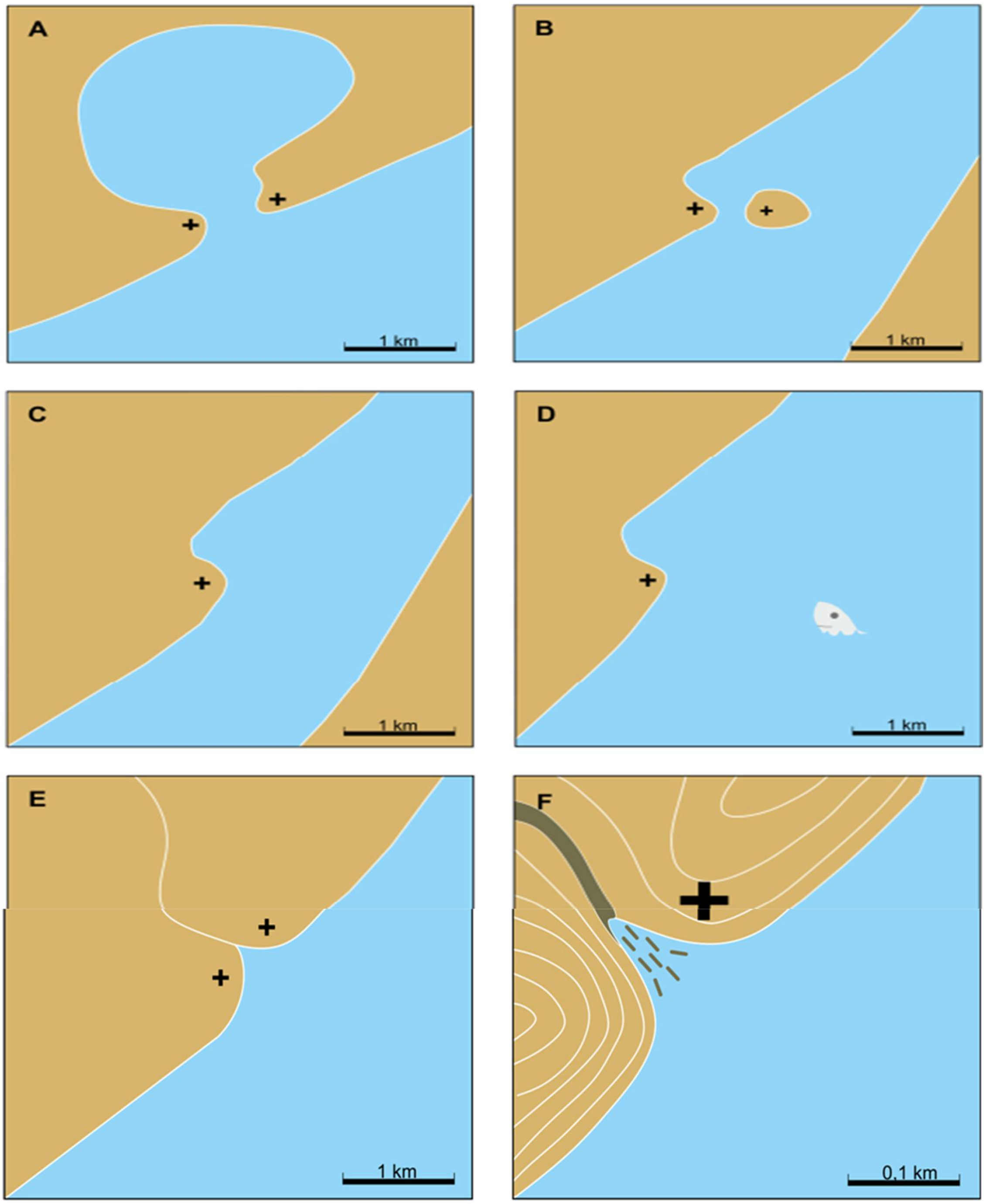

Figure 2-1 The principle of the 'fishing site model' where the placement of the x'es, and the sizes of the x'es mark the most attractive settlement areas for the Stone Age 'fisherman'. A: By the mouth of a cove or inlet, especially when the mouth is narrow, and channel like with a large 'hinterland' on both sides. The greatest probability is thought to be immediately adjacent to the channel. B: By a channel between a small island and a larger land area. Here the probability is thought to be greatest on the land side. C and D: By a projecting headland. Here the probability is considered greatest if the projecting headland is in sheltered waters. E and F: At the mouth of a watercourse. Here the probability is thought to be greatest where the settlement could be located on relatively flat terrain. After /7/, /8/.

2.2.5 Geology

The description of geological history and setting is also relevant for the geoarchaeological study. Of particular interest is the depositional and erosional history during Late Glacial and Post Glacial (Holocene).

2.2.6 Summary of the expected outcome of the applied methodology

The above-mentioned integrated assessments are carried out to preliminary evaluate if, when, and where former dry land areas, e.g. coastal zones attractive for former Stone Age settlements, in theory are expected to be crossed within the installation depths.

3. DATA

The data sources include public data sources and proprietary data from Ramboll and Energinet.

3.1 Bathymetry

Several databases contain lists of depths to seabed (bathymetry), and/or bathymetric models, such as for instance the European (EU) funded 'EMODnet Bathymetry'. In this report, EMODnet is applied.

According to the official webpage of EMODnet, /10/, bathymetric survey data and aggregated bathymetry data sets have been collated from public and research organisations. These have been processed, quality assured and used to produce regional Digital Terrain Models (DTM). Thereafter, these have been integrated into the EMODnet DTM (Digital Terrain Model) for European seas.

The EMODnet DTM has a grid size of 1/16 arcminute. Each grid cell has a variety of information, including x, y coordinates and average water depth in metres, which is applied in this report. For metadata, please refer to the website of EMODnet, /10/. Bathymetry based on EMODnet data is presented in a seabed map and used in the construction of paleoshoreline maps.
The relevant nautical map, "93-Nordsøen" provided by Energinet, has been consulted as well.

3.2 Geological and geophysical data

Data and reports from the following databases have been assessed in order to be able to describe shallow geology along the planned routes and OWF area:

- the national well / borehole database 'Jupiter' maintained by GEUS
- the marine raw materials database 'MARTA' maintained by GEUS, including overviews of various marine shallow geology surveys and reports thereof
- the national seabed sediment map developed and maintained by GEUS
- the national 'groundwater reports' database developed and maintained by GEUS

In Figure 3-1 is shown an overview of existing borehole data and grab samples and in Figure 3-2 is shown an overview of the reported geophysical survey lines in the investigation area.

From the Marta database is also downloaded marine survey reports and other geological reports covering the area of investigation. These are supplemented by geological reports from the groundwater reports database and geological reports and papers collected from GEUS, universities and academic databases.

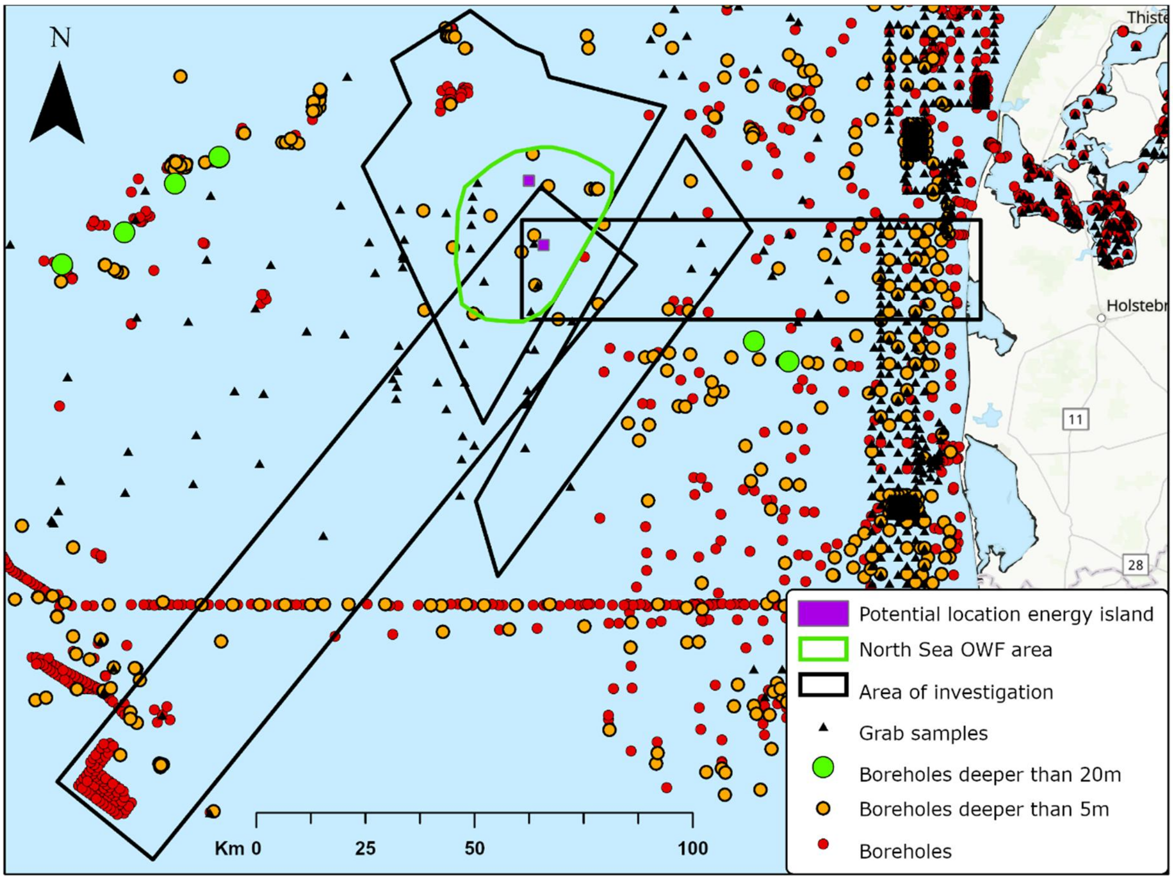

Figure 3-1: Overview of reported existing boreholes (typically vibrocores and seabed samples) and grab samples, based on the Marta database.

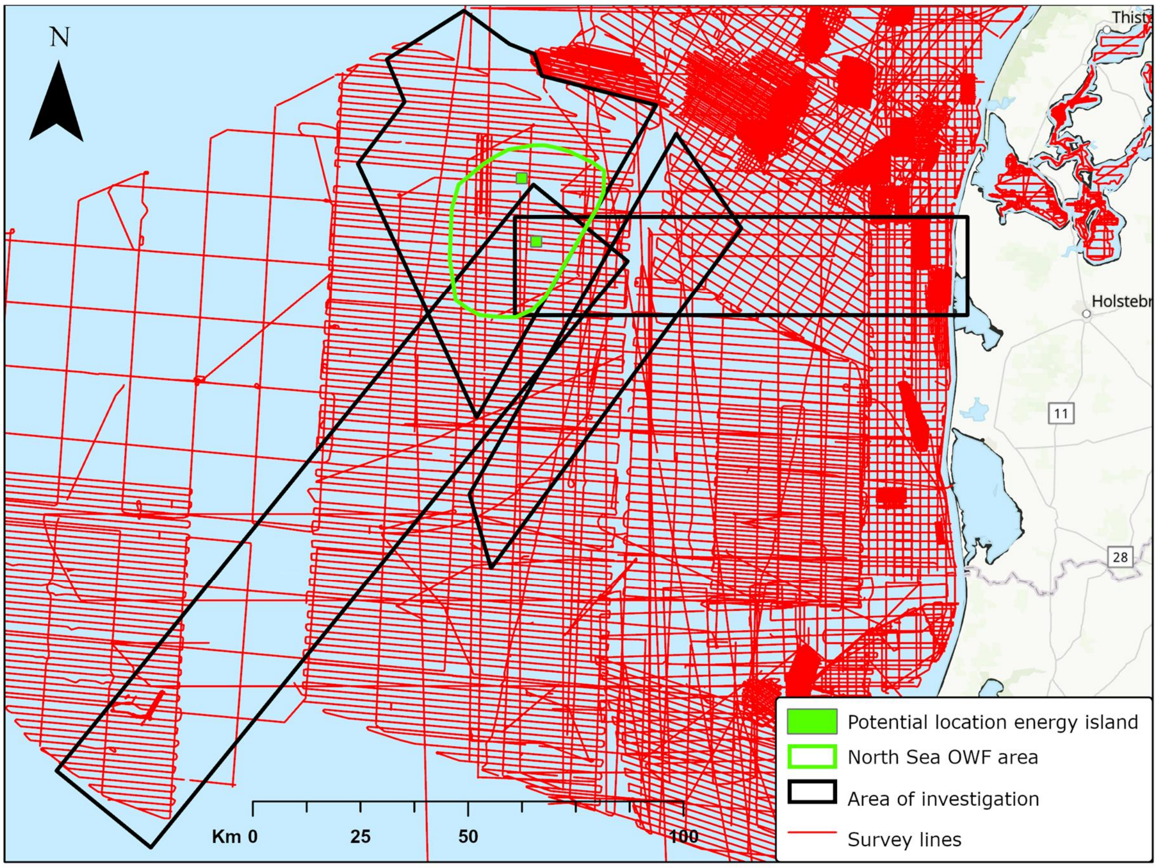

Figure 3-2: Overview of reported shallow seismic/geophysical survey lines in the area based on the Marta database.

3.3 Shore level displacement curves

In Denmark sea level fluctuations aka shore level displacements during Late Glacial and Post Glacial periods have evolved quite differently during the global sea level rise (eustasy) depending on the geography. These differences in shore level displacements are mainly due to geographical differences in uplift (isostasy), but at times also possible local barriers/thresholds impeding the general sea level rise until that local threshold eventually was inundated. The latter is particularly relevant for inner Danish waters. Relevant shore level displacement curves have been collected from the literature.

4. RESULTS - GEOLOGICAL MODEL FOR SEISMIC INTERPRETATION

The bathymetry of the project area is presented in section 5.1.

4.1 Geological setting

This section first describes the general geological setting in the Danish part of the North Sea, followed by a description of the pre-Quaternary and Quaternary sedimentary deposits in the project area.

4.1.1 Pre-Quaternary history

In the Danish part of the North Sea Basin, the Pre-Quaternary surface varies between sediments from the Upper Cretaceous Chalk towards the northeast, and Paleogene and Neogene sedimentary units towards the central part, Figure 4-1. In the region where the energy island is situated the Pre-Quaternary sediments are from the Miocene, possibly with local thin cover of sediments from the Pliocene. In the cable route towards East the Pre-Quaternary sediments are also from the Miocene whereas the sediments in the southern part of the cable route towards the Southwest are from the Pliocene.

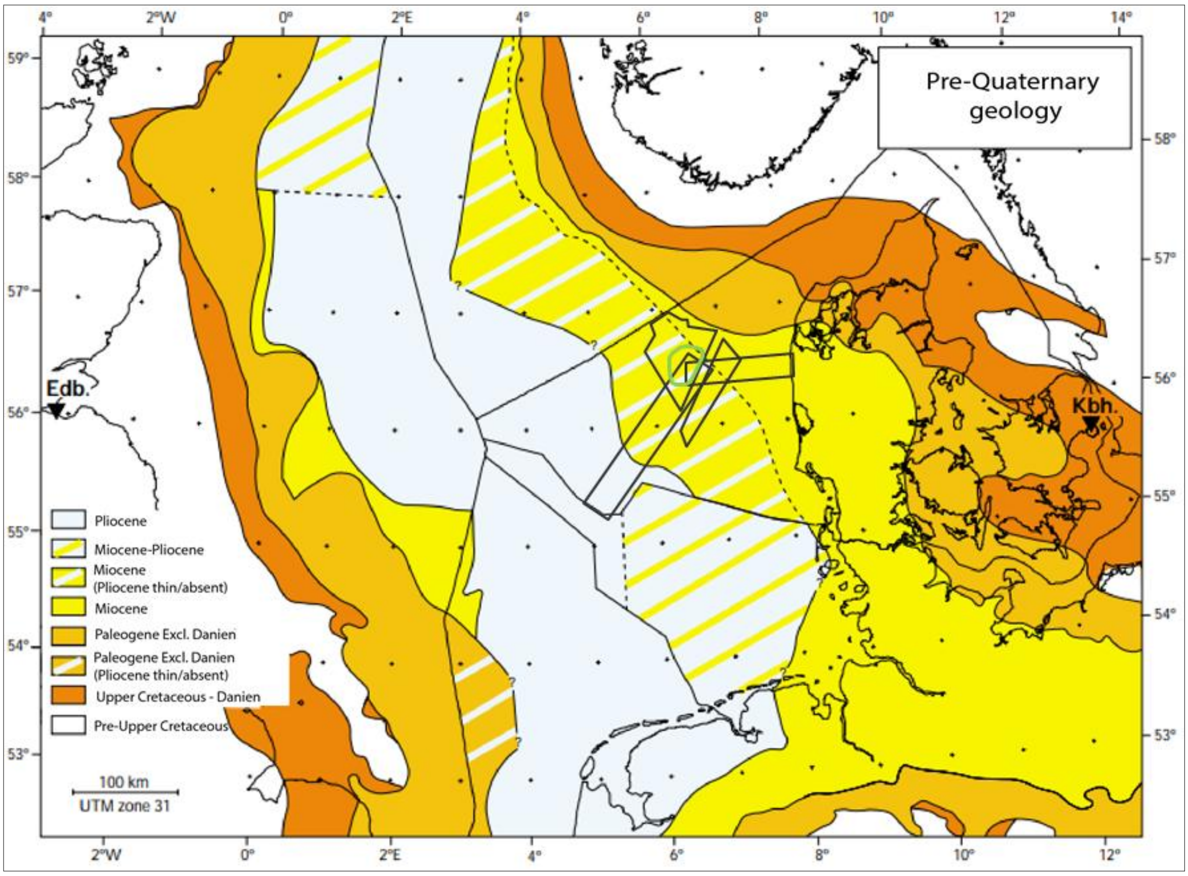

Figure 4-1: Pre-Quaternary geology in the North Sea Basin /11//23/. Investigation area marked with black polygons; North Sea OWF area marked with green polygon.

In the period from Oligocene in the Paleogene Period to early Pliocene the North Sea Basin was filled with sediments from deltas, which where build out from the Scandinavian Shield.

The Paleogene end Neogene sediments superimpose Cretaceous chalk. A top chalk depth structure map showing the westwards dipping chalk surface is seen in Figure 4-2.

In greater depths there are thick layers of Zechstein salt which has led to halokinesis and formation of salt diapir structures. The salt diapir structures affect the overlying strata including the Cretaceous chalk. In the northernmost part of the project area a few salt diapir structures with surrounding marginal depressions are seen in Figure 4-2. In the salt diapir structures the salt has lifted the younger strata whereas the younger strata have subsided in the marginal depressions due to removal of salt. A number of salt diapir structures are also seen in the southernmost part of the southern cable route. The salt tectonism has been active since the Cretaceous and is still ongoing. There are typically faults associated with the salt tectonism. These faults can to some degree be active today.

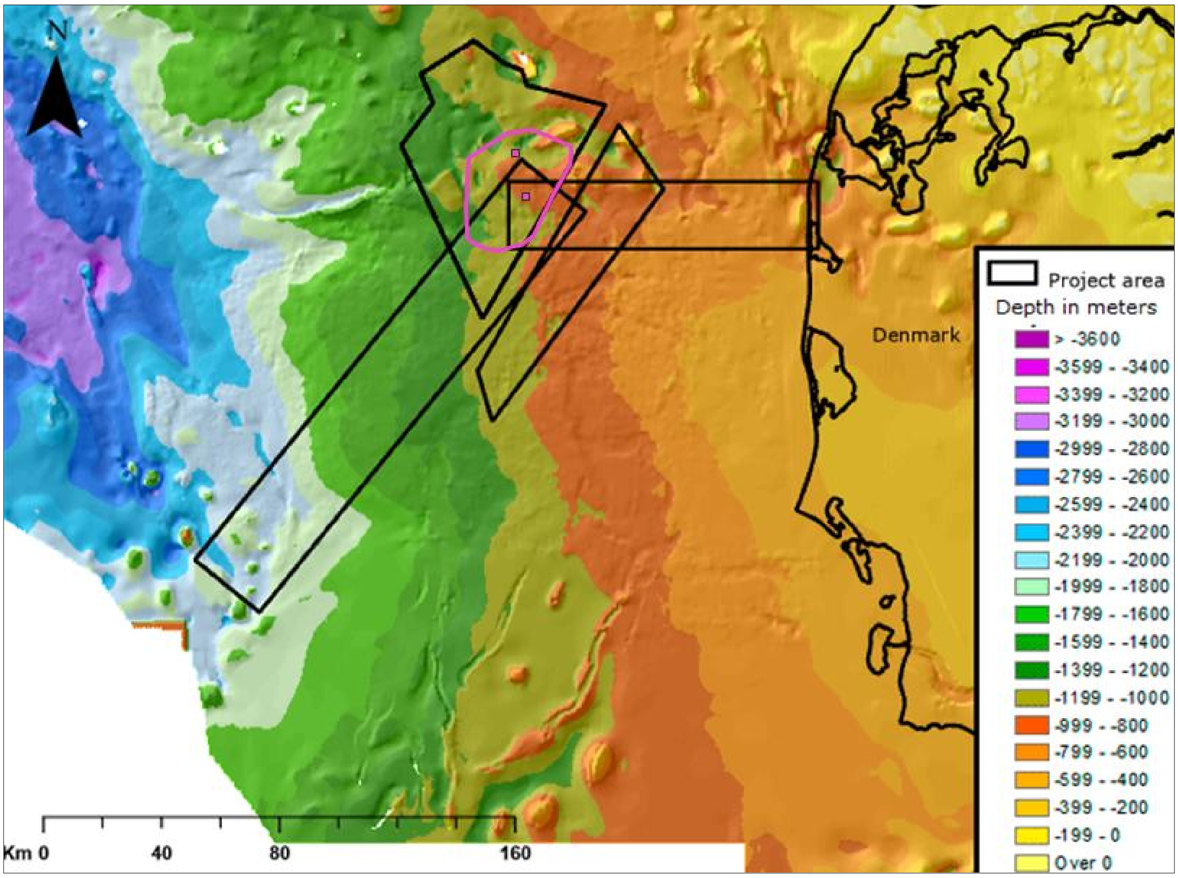

Figure 4-2: Top chalk depth structure map, depth in meters /12/.The map shows indirectly the presence of salt structures in the northernmost part of the project area and in the southernmost part of the southern cable route. The salt structures are local highs, some of them with surrounding marginal depressions. Purple polygon and dots represent North Sea OWF area and potential locations of energy island respectively.

During the Pliocene and the Pleistocene, the margins of the North Sea were uplifted, and large volumes of sediments were eroded and transported towards the central parts of the basin. The top Pre-Quaternary surface is therefore an erosional surface. Buried paleo-valleys are a characteristic of the Pre-Quaternary surface in the project area as well as for large parts of the North Sea. Figure 4-3 shows a net of buried Quaternary valleys which are cut deep into the Pre-Quaternary sediments.

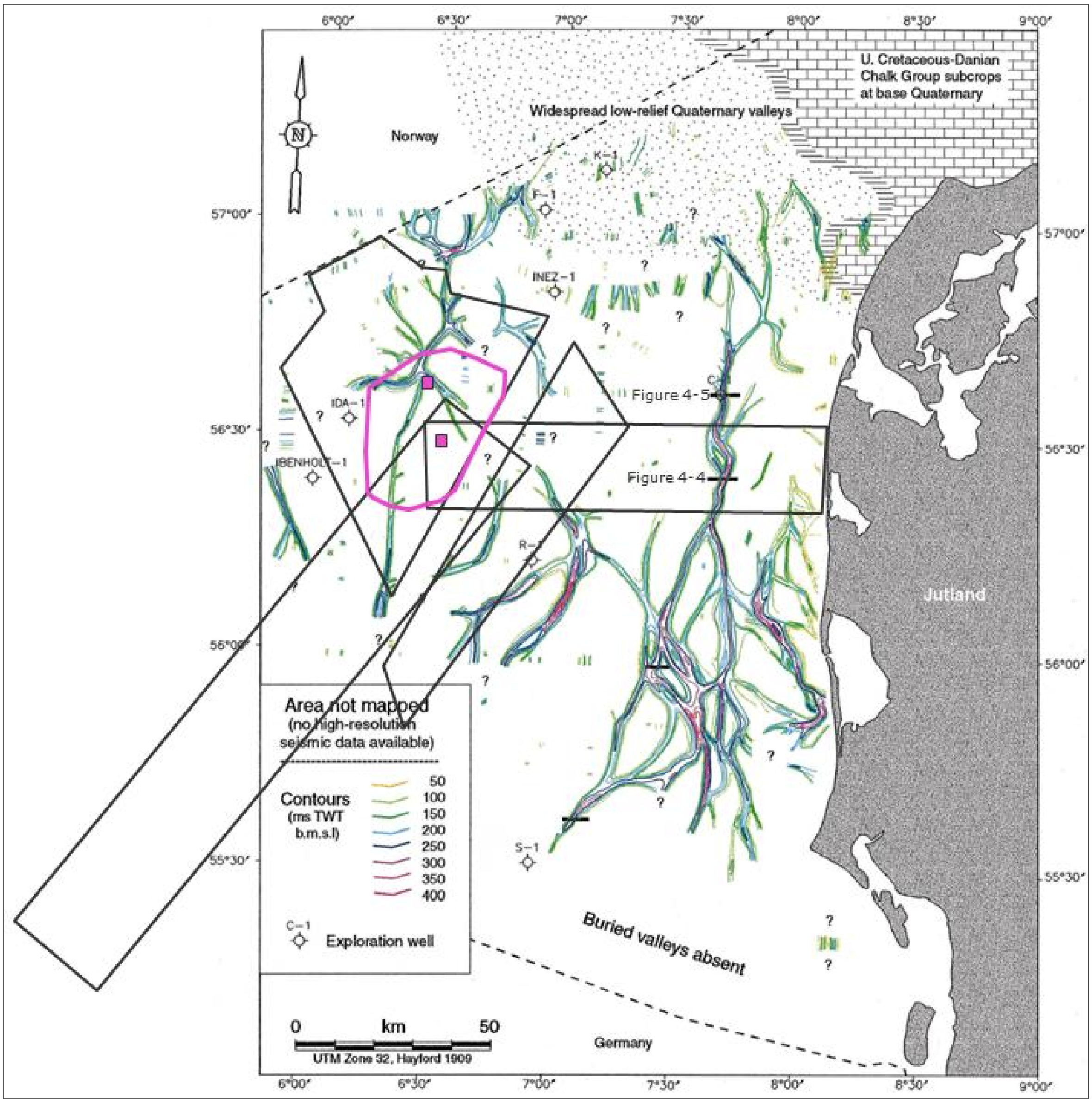

Figure 4-3: Buried Quaternary valleys in the eastern part of the North Sea, modified from /14/. The area of investigation is shown with black polygons. Purple polygon and dots represent North Sea OWF area and potential locations of energy island respectively.

Such valleys or larger channels are related to the glaciations and weak zones in the Pre-Quaternary sediments. The channels are reused by the ice sheets moving and later filled with glacial, interglacial, and Late Glacial sediments. The thickest Quaternary deposits in the area are registered in the paleo-valleys in the Pre-Quaternary surface and are sometimes, but not always, related to depressions in the present-day bottom relief. Several deep buried valleys are situated in the areas planned for energy island and OWF's and in the eastern export cable corridor, Figure 4-3. In the southern export cable corridor buried valleys have not been mapped in /14/.

Figure 4-4 shows an interpreted high resolution multichannel seismic profile across a buried Quaternary valley, located in the eastern cable corridor, Figure 4-3, /14/. The profile shows a typical infill sequence consisting of a lower, seismically disrupted/chaotic unit, followed by a seismically well-layered unit displaying onlap fill. It is seen that the flanks of this valley can be followed almost to the sea floor.

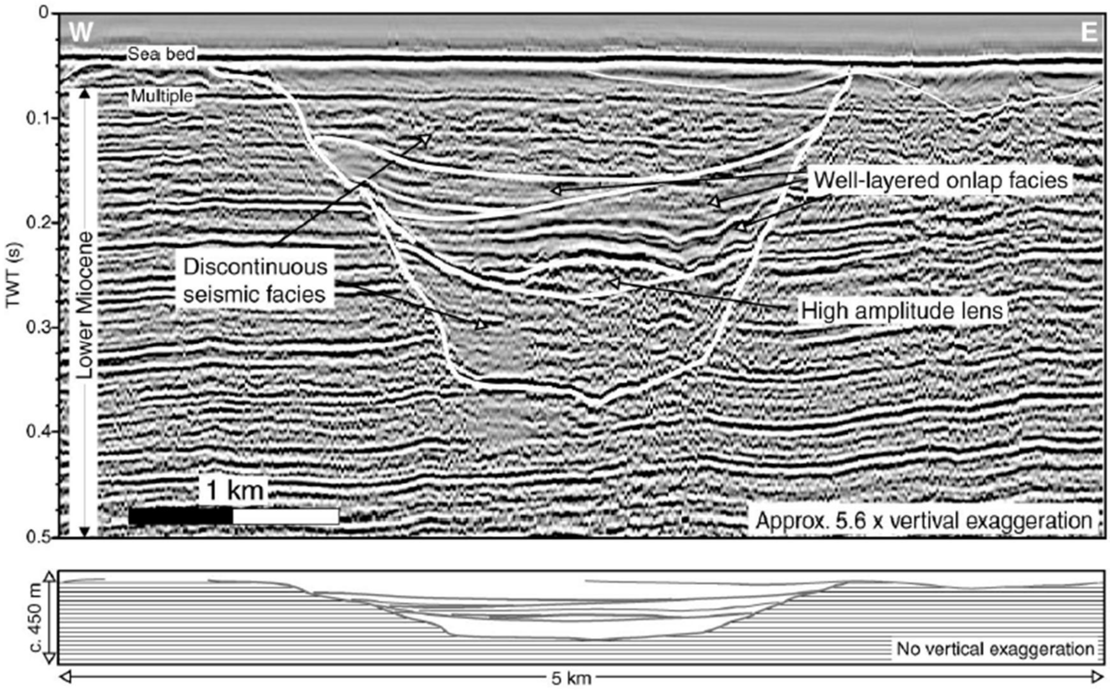

Figure 4-4: Interpreted high resolution seismic profile across a buried Quaternary valley, showing a typical infill sequence, for location see Figure 4-3, /14/.

To the north of the eastern export cable corridor the deep exploration well C-1 penetrates a minor branch of the same major valley seen in Figure 4-4. A seismic profile including the C-1 well is seen in Figure 4-5.

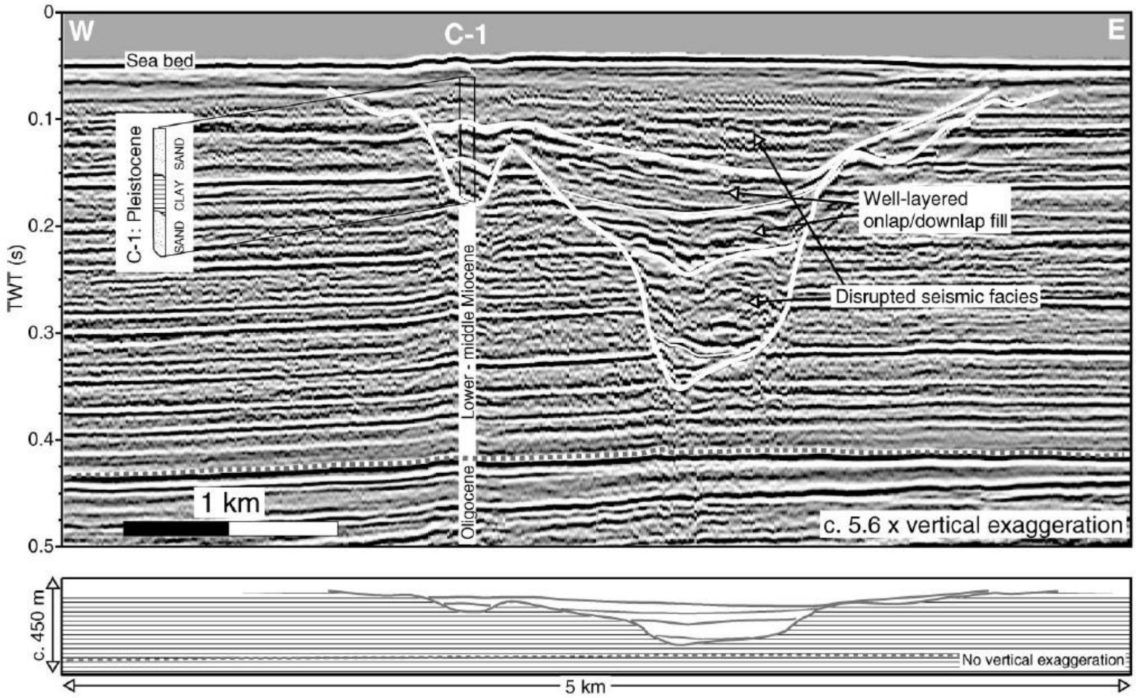

Figure 4-5: Interpreted high resolution seismic profile across a buried Quaternary valley, showing a typical infill sequence, for location see Figure 4-3, /14/.

Well C-1 provides information about the sedimentology and stratigraphy of the valley fill /14/. The base of the valley occurs c. 115 m below seabed. The interval 25-80 m is assigned to the Late Pleistocene, whereas the interval from 89 to 115 m lacks index fossils and a “Plio-Pleistocene” age is suggested. Below the base of the valley, C-1 penetrates Middle Miocene strata. Based on descriptions of cuttings from C-1, the valley fill can be divided into three sedimentary unit, to units of unconsolidated sand divided by a clay unit, see insert in Figure 4-5. Each sedimentary unit seems to correspond to a distinct seismic unit /14/.

There is only limited access to data from the other deep exploration wells shown in Figure 4-3. For example, the available data from exploration well IDA-1, c. 5 km west of North Sea OWF area only provide the information that 71 to 1,139 meters below sea-bed is Tertiary, 1139 to 1,577 meters below sea-bed is Cretaceous, etc.

4.1.2 Quaternary history

During the Quaternary period the western part of Jutland and nearby offshore areas was covered by ice streams a number of times during the Elsterian as well as the Saalian glaciation. Remnants from the old glacial landscape from the Saalian glaciation, are found as large moraine plateaus (“Bakkeøer”) on the outwash plain west of the Last Glacial Maximum (LGM) of the last ice age, the Weichselian. The ice streams and their meltwater with associated debris eroded the Pre-Quaternary surface and deposited glacial till and glaciogenic (deglaciation and meltwater) sediments. The glaciers also caused glaciotectonic deformation of older glacial/glaciogenic deposits and the Pre-Quaternary deposits.

The Saalian glaciation was followed by a warm period, the Eemian interglacial. The climate was warmer and more humid than today, and coastal areas in Denmark was flooded by the Eemian Sea. The sea level rose and flooded the low-land areas and deposited clay-rich sediments with high organic content.

During the last ice age, the Weichselian, only the eastern and northern part of Denmark was covered by the Fennoscandian ice sheet, see Figure 4-6, which shows the maximum extension of the Weichselian ice sheet in western Jutland and the Danish part of the North Sea. The major part of the area of investigation was ice-free and covered by proglacial river plains and/or Saalian moraine plateaus. In the proglacial river plains glaciofluvial sand and gravel was deposited. However, the northernmost parts of area of investigation were likely covered by the Weichselian Fennoscandian ice sheet at the glacial maximum c. 18,000. Impacts from the Weichselian ice sheet in this area are probably represented by glacial till and in glaciotectonic disturbances in the glaciofluvial sediments near the glacier margin. Glacial deformations are offshore observed in proximal glacial sediments near the maximum extend of ice sheets in the Weichselian glaciation and in Weichselian meltwater sediments deposited between the old moraine plateaus (“Bakkeøer”) from the Saalian glaciation.

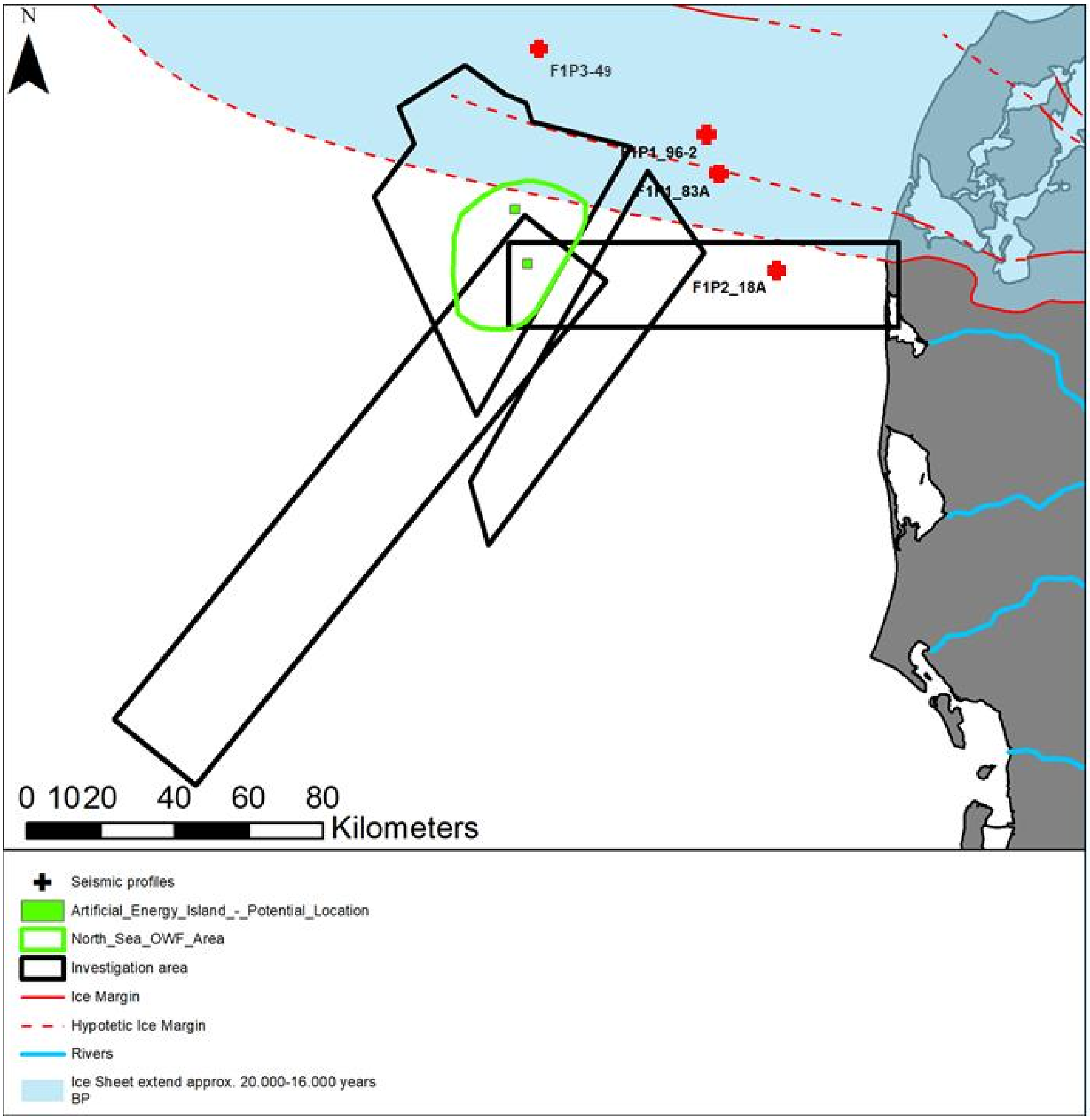

Figure 4-6: Maximum extent of the Fennoscandian ice sheet in the Danish part of the North Sea during the Late Weichselian. Crosses marks the approximately location of the seismic profiles shown on Figure 4-8 (F1P2-18A), Figure 4-9 (F1P1-83A),Figure 4-10 (F1P1-96-2), and Figure 4-11 (F1P3-49), /13/ and /15/. No illustrative seismic profiles have been found for the North Sea OWS area and nearest surrounding areas.

The peak of the Weichselian glaciation occurred approximately 18,000 years BP. Deglaciation of the Danish area began approximately 16,000 years BP. The geological history of the Danish area during and after deglaciation was controlled by the interplay between deglaciation, uplift of the Earth's crust due to the reduced load from the melting ice sheet and rise in global sea level due to the release of water from the ice sheets.

During the decline of the glaciers, increased melting of the ice sheets released large volumes of water causing global sea level to rise and deglaciated areas were covered by a flooding, the younger Yoldia Sea, Figure 4-7.

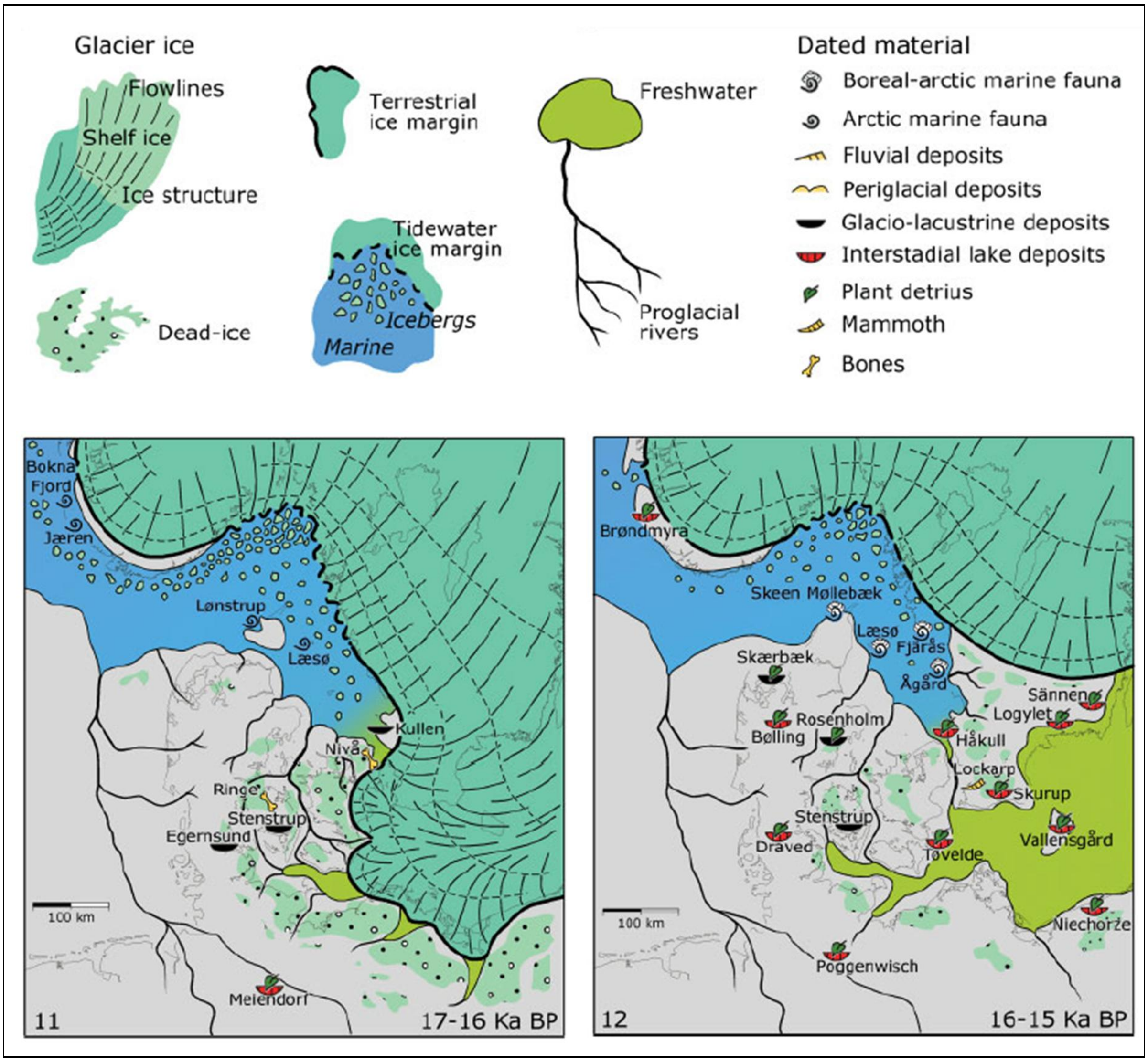

Figure 4-7: Paleogeographic maps showing the configuration of land (grey), ice (blueish-green), sea (blue) and lake (green) at two different times during deglaciation, /16/.

The left map in Figure 4-7 shows the situation 17-16,000 years BP where the Yoldia Sea covered most of the present Kattegat and Skagerrak, with higher shorelines than the present-day shorelines in the north, and lower shorelines than the present-day shorelines in the south. The present Denmark, a large part of the North Sea Basin and the energy island investigation area were dry land at that time. The right map shows the situation 16-15,000 years BP where the glaciers further declined, and a large lake covered most of the present Baltic Sea area. The North Sea area was characterized by regression from deglaciation to c. 11,000 BP and most of the present day Southern North Sea was dry land.

From 11,000 to 6,000 years BP a continued global transgression effected the area, and the North Sea Basin was slowly inundated and the area around the investigation area gradually changed from being a land area to a marine area, where the old glacial landscape was eroded and transformed to first an archipelago with former hills forming islands in the open sea. The whole area was covered by sea around 7,000 years BP. The flooded sediments were now exposed to erosion and with time covered by marine sand. Relative sea level changes during the Late Glacial and Holocene are discussed in chapter 5.

4.2 Lithologies

4.2.1 Pre-Quaternary sediments

The Pre-Quaternary sediments comprise different geological lithologies from the Miocene, and in the southern export cable corridor from the Pliocene, primarily consisting of sand and clay. The Miocene deposits are covering the underlying Paleogene sediments and Cretaceous chalk deposits. In the areas with salt structures the older deposits are lifted to near the seabed by salt diapirism.

4.2.2 Glacial sediments

Quaternary sediments cover the floor of the North Sea Basin almost completely. The sedimentary cover comprises glacial deposits from the Saalian and older glaciations, marine deposits from the Eemian interglacial period, Late Glacial meltwater deposits from the last ice age, the Weichselian and in the northernmost part of the project area also glacial deposits from the Weichselian.

The thickest Quaternary deposits are registered in paleo-valleys in the Pre-Quaternary surface. Figure 4-8 shows a deep buried valley (green reflector) filled with Quaternary deposits. Outside the buried valleys the thickness of the Quaternary sediments generally does not exceed 10-20 meter.

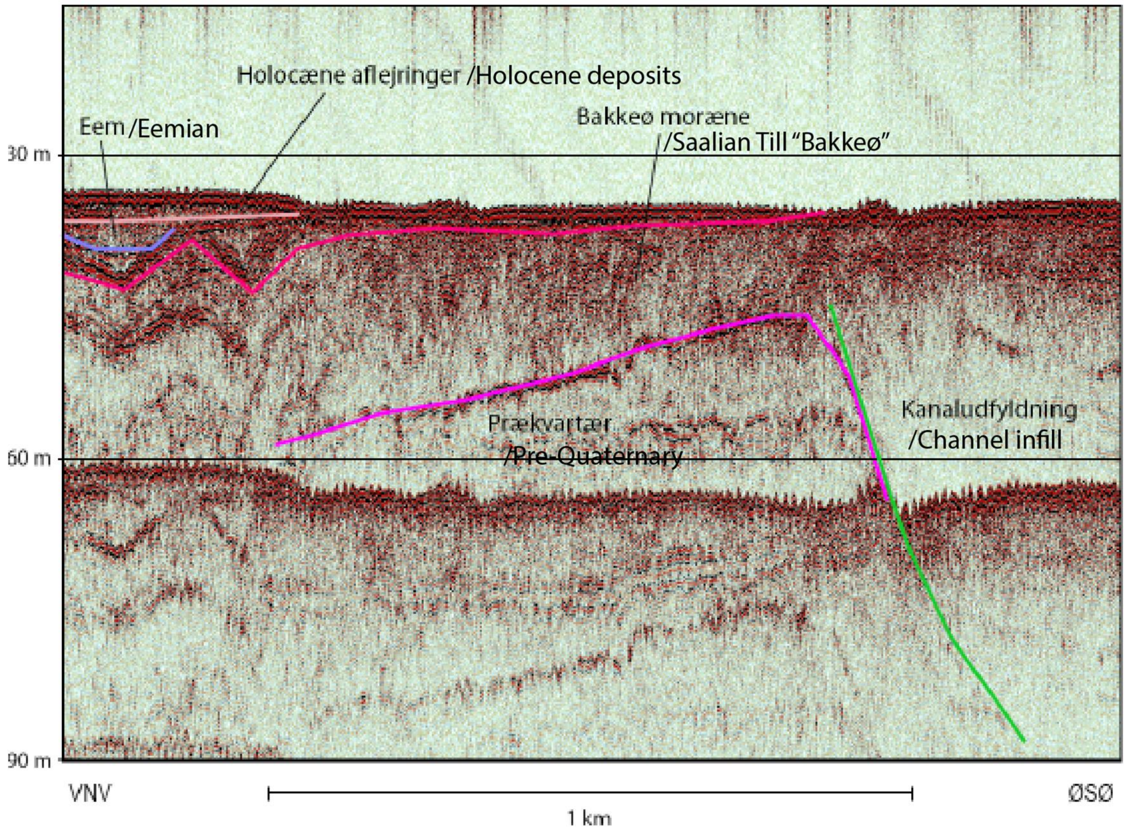

Figure 4-8: Seismic profile F1P2_18A shows Saalian glacial till above Pre-Quaternary sediments. The till is superimposed by Saalian meltwater deposits, Eemian and Holocene deposits. To the right a buried valley cut deep into the Pre-Quaternary. The profile is located in the eastern export cable corridor, south of the Weichselian ice sheets maximum extend, /13/ see Figure 4-6 for location.

The oldest Pleistocene sequence in the area consists of glacial sediments of Elsterian and Saalian age. The deposits are dominated by glacial till and meltwater deposits, interglacial clay deposits from the Eemian interglacial and meltwater sediments from the last ice age, the Weichselian.

Figure 4-8 shows the old Saalian glacial landscape dominated by glacial till above the Pre-Quaternary sediments.

Most of the tills are deposited below glaciers, and the sediment is consequently normally pre-consolidated and hard, with high strength due to the pressure from the overlying ice. The tills consist of poorly sorted mixtures of grain sizes ranging from clay to boulders. When tills crop out in the sea floor or are covered by only a thin veneer of marine sediments, boulders and stones are often spread over the sea floor.

Prior to marine inundation during the following Eemian interglacial, small channels were eroded into the Saalian meltwater plain and freshwater sediments sand, mud and peat were deposited, the lilac reflector on Figure 4-8 shows a small Eemian channels eroded into the older Saalian landscape. Once the area was inundated, marine mud and clay was deposited, the thickness of the Eemian deposits varies from 0-10 meters.

Figure 4-9 shows a relatively thin layer of Quaternary sediments above the Pre-Quaternary units. In this profile the Eemian marine deposits are represented by a characteristic transparent seismic unit.

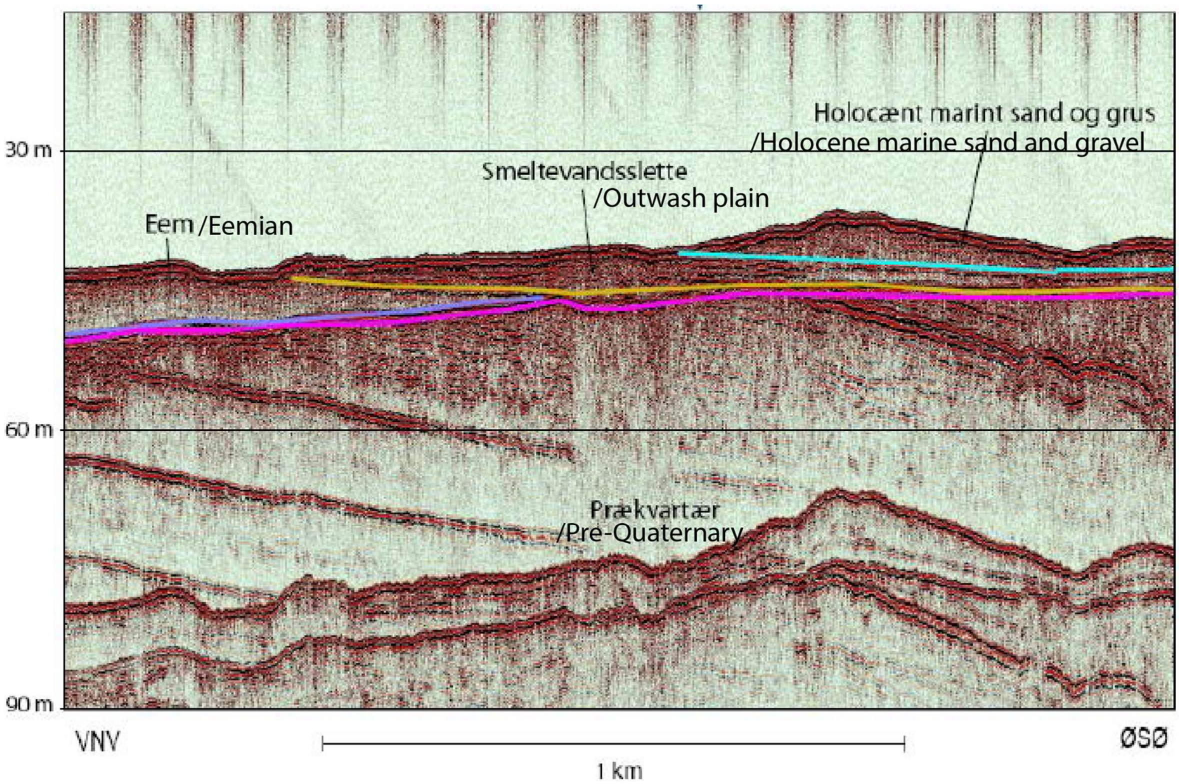

Figure 4-9: Seismic profile F1P1_83A shows a relatively thin quaternary unit above the Pre-Quaternary layers, /13/. The profile is located near the last glacial maximum (LGM), north of the area of investigation. Light blue line indicates the base of the Holocene marine sand and gravel. Orange line marks the base of the Weichselian meltwater sediments. Lilac line shows the base of the Eemian deposits and violet line shows the base of the Quaternary sediments, the Pre-Quaternary surface. The seismic profile is located north of the project area, see Figure 4-6 for location.

In addition to the older tills from the Saalian and older glaciations and marine sediments from the Eemian interglacial period, sorted glacial deposits are also found, Figure 4-9, Figure 4-10. The sorted deposits mainly comprise sand/gravels deposited by meltwater in increasing distance from the melting ice-front, leaning to typical fining upwards successions.

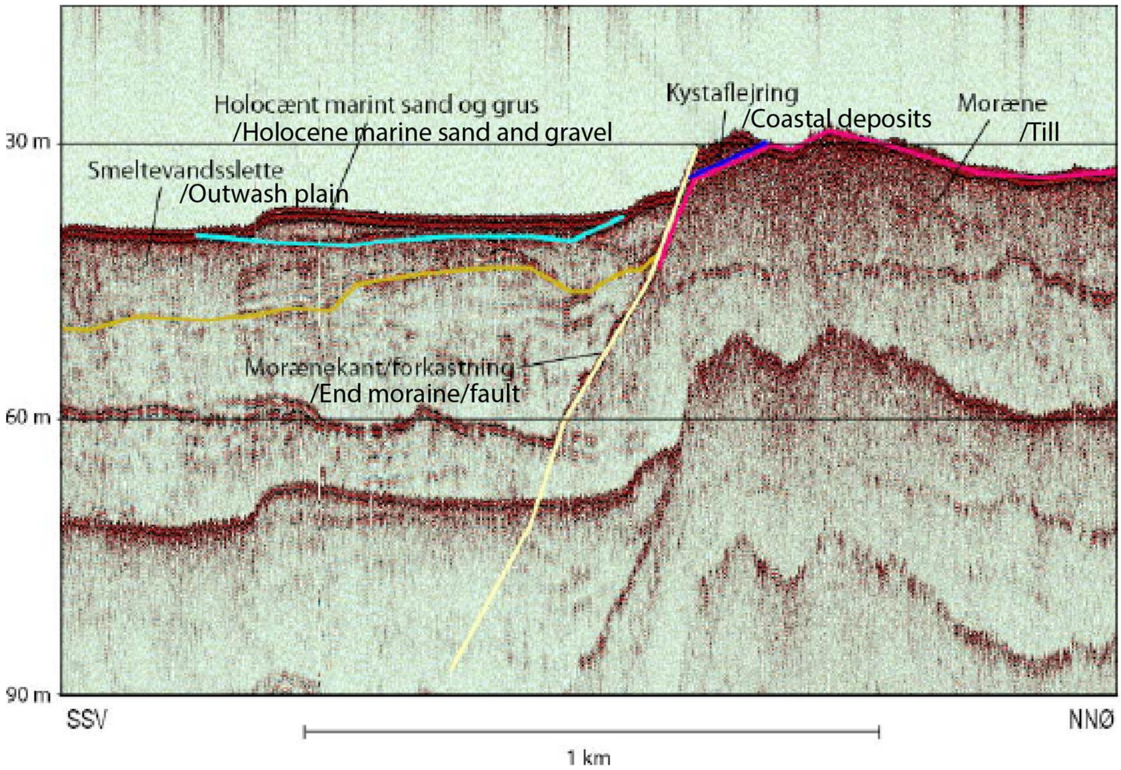

Figure 4-10: Seismic profile F1P1_96-2 shows the meltwater plain deposits south of the main stationary line of the Weichselian glaciation LGM /13/. Light yellow line shows an end moraine/fault. Light blue line indicates the base of the Holocene marine sand and gravel. Orange line marks the base of the Weichselian meltwater sediments. Blue line marks base of coastal sediments, and red line marks the base of glacial sediments deposited during the last ice age. The seismic profile is located north of the project area, see Figure 4-6 for location.

In the northernmost part of the project area ice marginal deposits from the Weichselian icesheet can be expected. Figure 4-11 shows an ice marginal complex north of the project area. The complex includes marginal moraine comprising glacial till, outwash plain with meltwater deposits and an area with glaciotectonic disturbances. Glaciotectonic disturbances may also be found in the older (Saale and older) landscapes/strata in the investigation area.

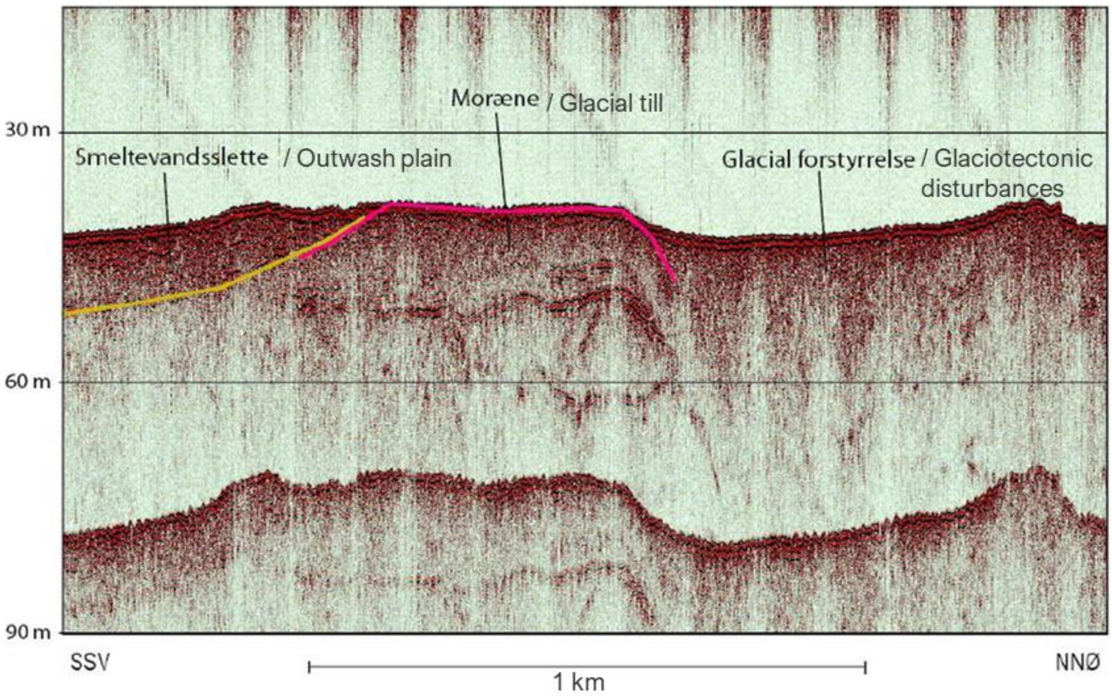

Figure 4-11: Seismic profile F1P1-49 shows an ice marginal complex north of the project area. A marginal moraine comprising glacial till is to the south (left) followed by an outwash plain with meltwater deposits. "Up ice" (right) glaciotectonic disturbances are seen /13/. The seismic profile is located north of the project area, see Figure 4-6 for location.

4.2.3 Late Glacial and Holocene sediments

The Late Glacial and Holocene deposits are mainly sand and gravelly sand deposited by the Jutland coastal current. The sandy sediments are deposited in open sea with influence of strong currents at the seabed, and giant sand waves are located on water depts between 30 and 20 meters.

In shallow and sheltered areas, the Holocene (Littorina Sea to present) marine sediments consist typically of clay and mud with a high organic content and high-water content. However, recent marine sand and gravel deposits are typical sediments of the coastal zones, and therefore the dominant sediment type in the project area.

4.3 Seabed sediments

Distribution of the seabed soil types within and encompassing the project area is shown on Figure 4-12.

According to the GEUS seabed sediment map the seabed is dominated by sediments such as Post Glacial, Late Glacial, and glacial sandy to gravelly sediments (yellow-orange). In the areas planned for energy island and OWF's, especially in the northern part, and more locally in the eastern cable route mounds of glacial till are outcropping the seabed surface (dark brown/brown). In the northernmost part of the project area these tills may been of Weichselian or older age while they are of Saalian or older age in other subareas. The seabed surface sediments vary from combinations of fine-coarse sand, with areas of silty sand and areas of more gravelly composition (Jyske Rev Sand). In parts of the southern export cable corridor the marine sand is muddy and mud and sandy mud also occur in this part of the project area.

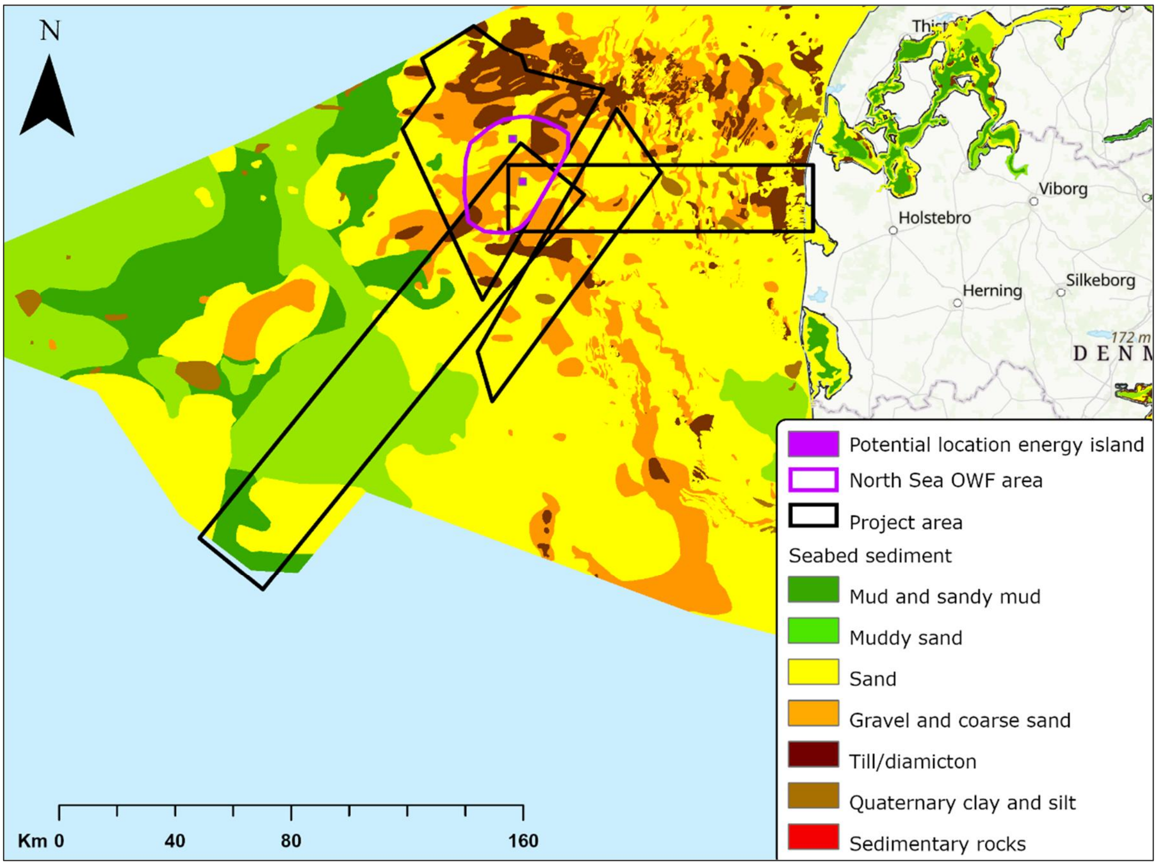

Figure 4-12: Distributions of seabed soil types in and around the investigation area, /17/ .

The seabed in the North Sea is exposed to erosion and sediment transportation. The presence of glacial till in the project area, indicates active erosion or transportation.

A preliminary mapping of sand and gravel resources covering the North Sea OWF area and neighboring areas was performed in 2012 /18/. The mapping shows delimited areas with a resource of an exploitable thickness, Figure 4-13. Most of the resource is interpreted as Holocene marine but some of the deposits contain, in addition to Holocene deposits, also Late Glacial meltwater deposits /18/. However, it should be noted that the amount of data is modest. Figure 3-1 shows the limited number of boreholes in the area. None of the more than 5 m deep boreholes in the area are more than 7 m deep. Figure 4-14 shows four shallow boreholes (vibrocores) from the North Sea OWF area.

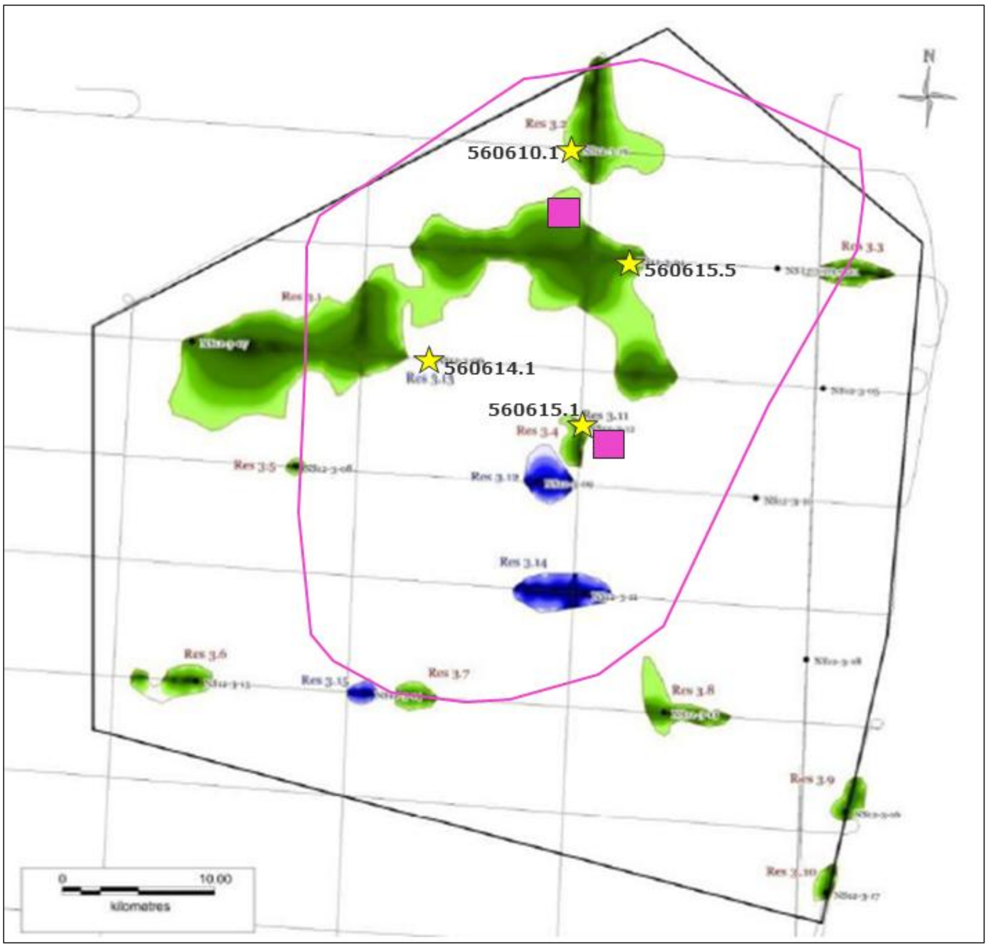

Figure 4-13: Results of preliminary mapping of sand and gravel resources /18/. Green colours indicate Holocene marine sand and gravel with thicknesses from <1 m (light green) to 8-9 m (darkest green). Blue colours indicate resource of both Late Glacial and Holocene origin. Pink polygon and dots represent North Sea OWF area and potential locations of energy island respectively. Yellow stars mark shallow boreholes (vibrocores) shown in Figure 4-14.

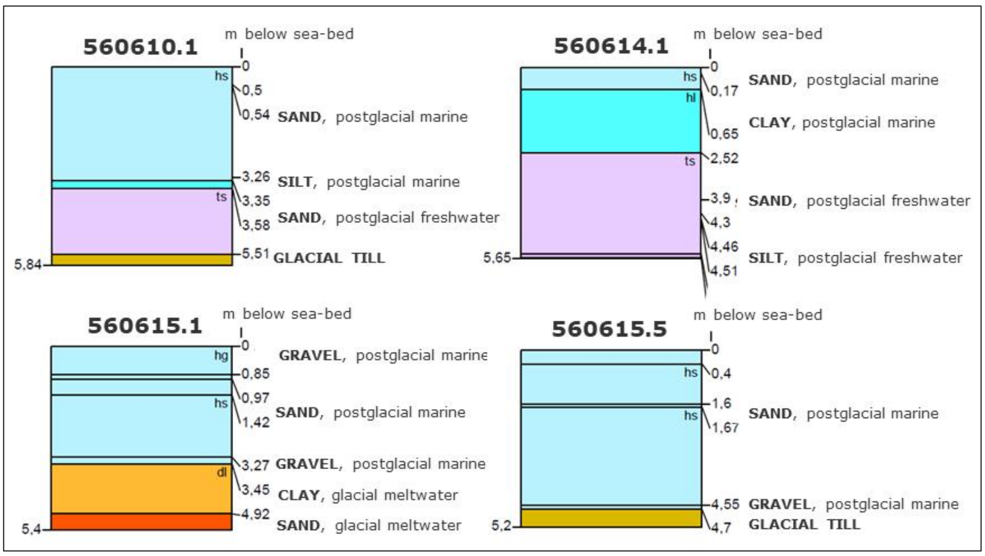

Figure 4-14: Typical examples of vibrocores from the North Sea OWF area. For location see Figure 4-13.

4.4 Subsurface geology and stratigraphy

Based in the combined results from the earlier investigations in the area, a schematic diagram of the identified sub-seabed geological units, representative for the project area is created and shown in Figure 4-15 and Figure 4-16. This geological model is developed from the above described formations and based on the information from /13/.

The conceptual model in Figure 4-15 does not represent a specific section through the project area but seeks to represent all the geological units of the area and their geometry.

It can be concluded that in large areas the seabed, and the upper geological layers in the project area exhibits marine Post Glacial sandy sediments.

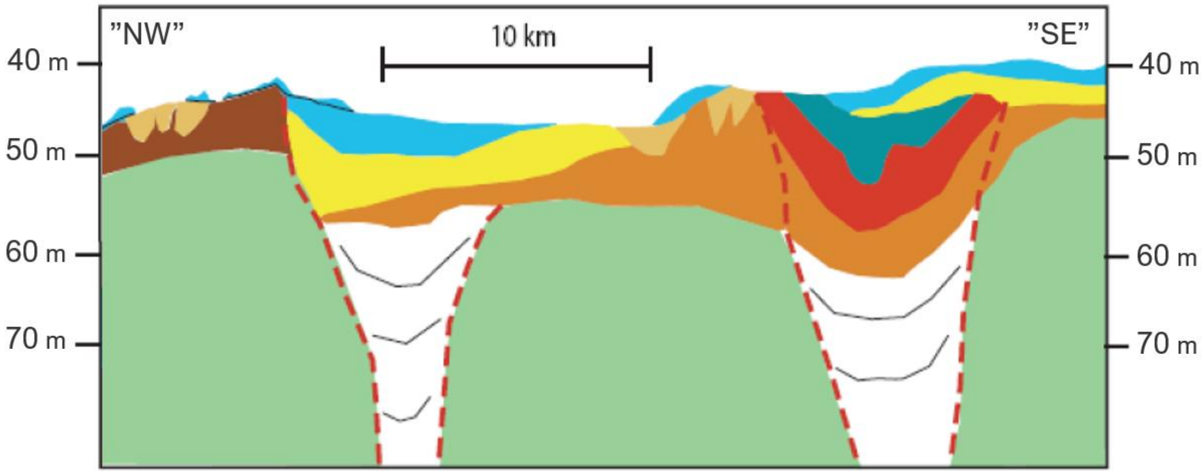

Figure 4-15: Geological conceptual geological model. The colours on conceptual geological model correspond to the stratigraphic model shown on Figure 4-16, modified from /13/.

Below the Post Glacial deposits, and in places directly below seafloor sandy glaciofluvial (Weichselian) meltwater deposits overlay the older Saalian glacial sediments. Local and perhaps also more widespread deposits of marine Eemian clay are found between the older glacial till deposits and the younger meltwater sediments deposited under the last glacial and deglaciation period. In the northern part of the project area Weichselian deposits also include glacial till and ice margins with increased frequency of glaciotectonic disturbances might be found in this area.

The Quaternary succession is generally less than 20 m thick outside buried valleys. A large number of buried valleys cut deep into the Pre-Quaternary sediments. The Quaternary can thus be hundreds of meters thick in the buried valleys. There is only limited knowledge on the lithology of valley fill. Seismic data indicate a complex fill in many cases.

Figure 4-16 summarises all soil types that are likely to occur inside the project area from seabed and down to foundation relevant depths, i.e. several tens of meters below seabed, /13/.

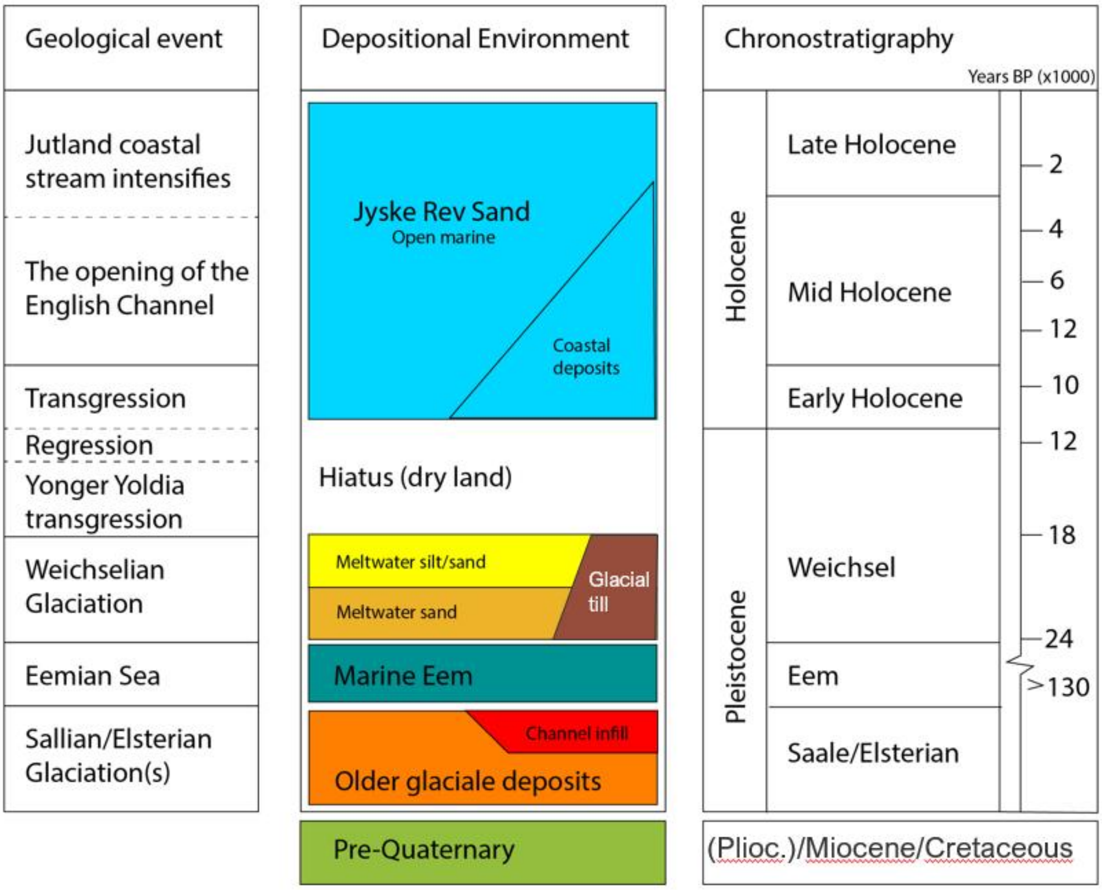

Figure 4-16: Stratigraphic model, modified from /13/.

5. RESULTS - GEOARCHAEOLOGY

5.1 Seafloor morphology (bathymetry)

In Figure 5-1 is shown the general bathymetry in the area of investigation based on EMODnet, /10/.

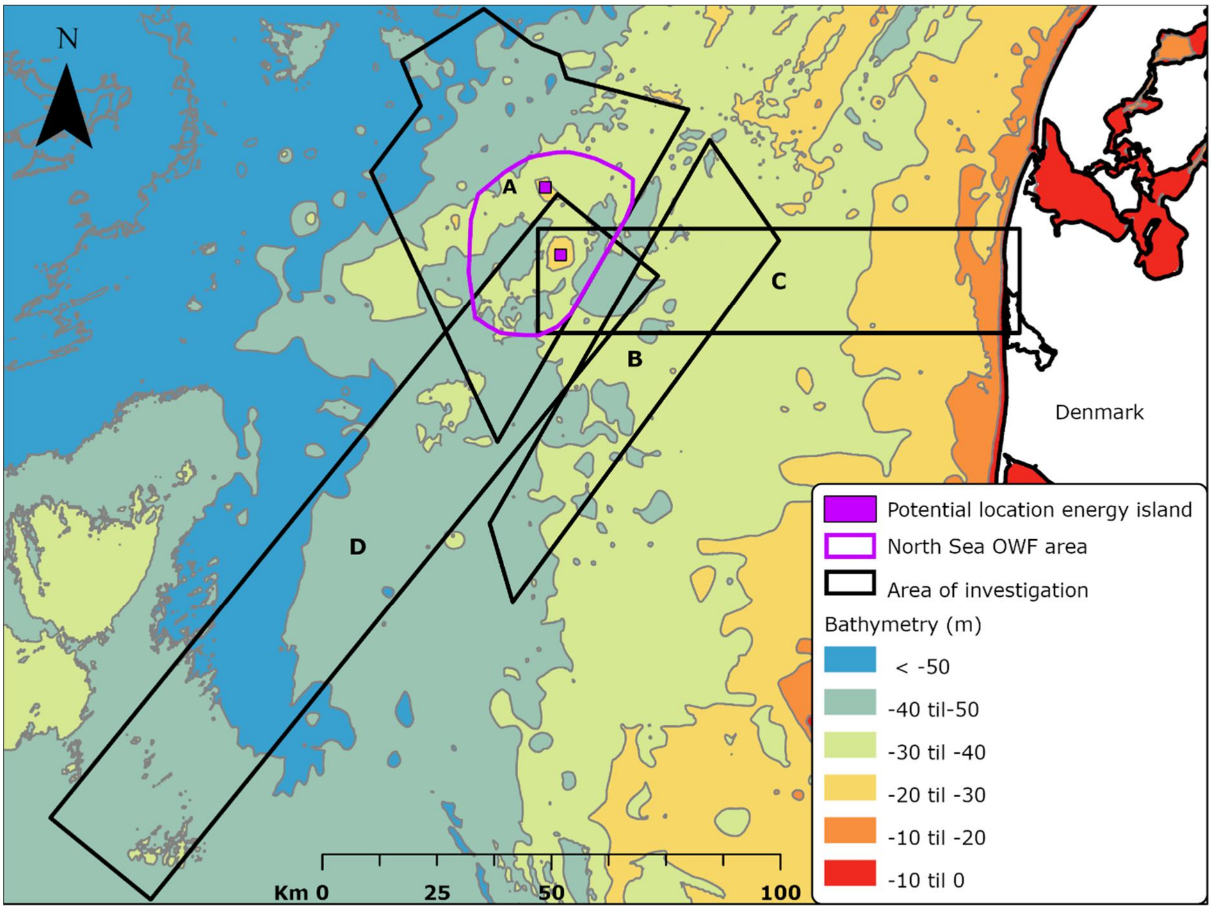

Figure 5-1: General bathymetry based on EMODnet data, /10/.

In the areas of potential location of energy island and OWF's (area A and B) the water depth is only less than 30 m in smaller sub-areas in area A. Area A also includes sub-areas with a water depth of more than 50 m whereas the water depth in area B varies between 30 and 50 m. Water depth in area C, the eastern cable route, is less than 30 m and shallowing towards the coast in the east. In area D, the southwestern cable route, water depth is between 40 and 50 m in most of the area. However, this cable route crosses a wide channel with a water depth of more than 50 m and the route also includes sub-areas with water depths of less than 40 m.

5.2 Shore level displacement curves

5.2.1 Existing shore level displacement curves

In Denmark sea level shore level displacements during Late Glacial and Post Glacial periods have evolved quite differently during the global (eustatic) sea level rise, mainly depending on geographical differences in (isostatic) uplift.

The magnitude of Late Glacial and Post Glacial isostatic uplift decreases from the northern parts of

Denmark (and Scandinavia) towards the south/south-west, i.e. isostatic uplift has had less effect, the farther away from the centre of the Weichselian ice sheet. This has had a significant impact on local relative coastline changes as illustrated by a map of Denmark showing the isobases for the highest registered shoreline of the Littorina Sea in Denmark, Figure 5-2. The isobases for instance illustrate that the highest shoreline in the northernmost part of Jutland is situated >12m above the present sea level.

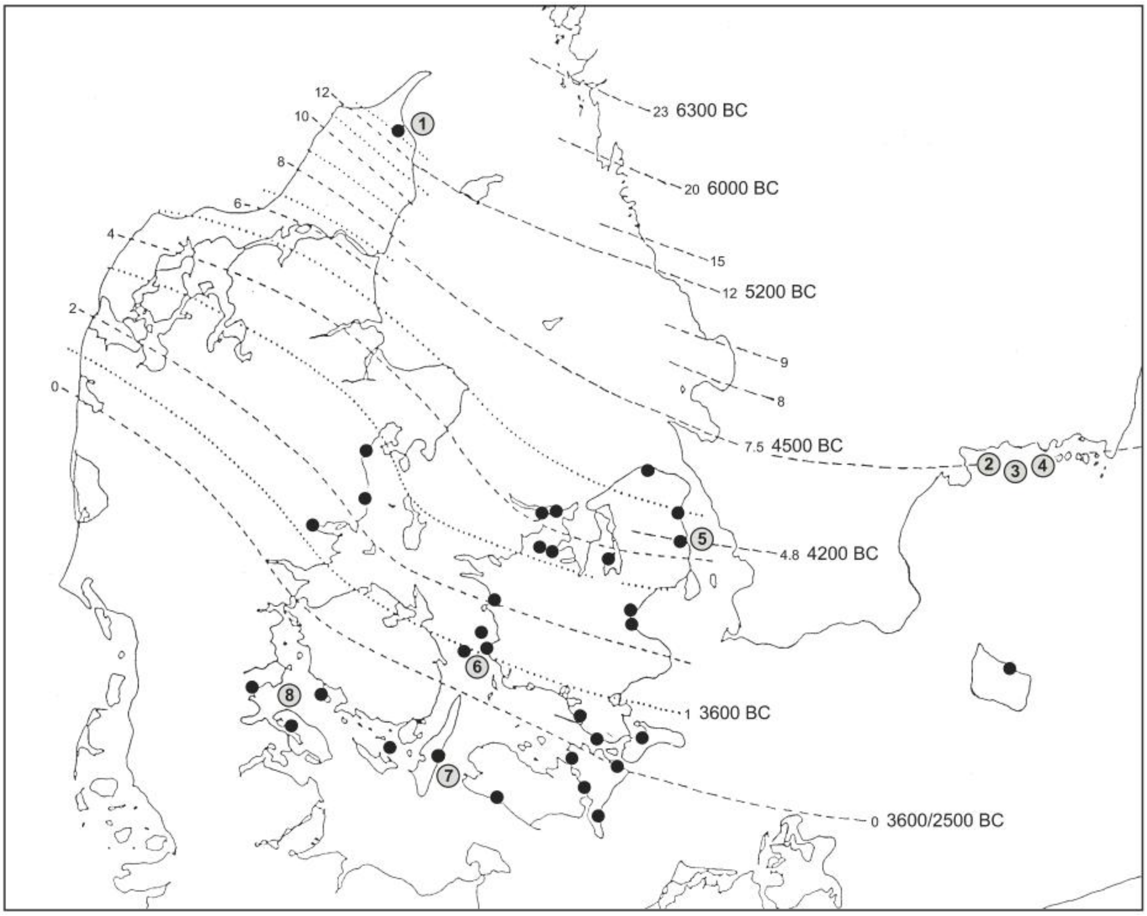

Figure 5-2 Isobases for the highest shore lines of the Littorina Sea in Denmark. The highest shorelines are diachronic, approximate ages are shown. The circles with number 1-8 indicate the geographies of shoreline displacement curves /19/.

There are a lot of dated material representing shorelines in the Scandinavian area. The resulting existing shoreline displacement curves are typically established by way of numerous radiocarbon dates for tree stumps or other organic components during archaeological and geological investigations both on- and offshore.

Based on such data Påsse and Andersson have in an empirical model calculated shoreline displacement curves throughout the Scandinavian area /20/. The accuracy of these calculated shore-levels is in general high when compared with data and manual interpretations, and they can be used carefully along the highest coastline of the isobars in Figure 5-2.

The most relevant curves will help identify periods and levels of regression and transgression during the Late Glacial and Post Glacial periods for the relevant area. Furthermore – in connection with a habitat model - it will assist in establishing the 'time slot' for, for example, potential coastal zones and hence the archaeological periods where coastal settlements may have occurred.

Multiple shore level displacement curves have been found for the North Sea area and are displayed in Figure 5-3:

- “Storebælt” displacement curve described in Påsse and Andersson 2005 /20/, which follow the 1 m isobar, as shown in Figure 5-2. The curve has for instance been applied to the geoarchaeological study of the VHN area /21/ and the geoarchaeological study for the THOR area /22/.

- “Germany, North Sea” displacement curve described in Påsse and Andersson 2005 /20/, which correlate to an area off the coast of Germany. The curve has for instance been applied to the geoarchaeological study of the VHS area /23/ and to the Baltic Pipe Norwegian Tie-In /24/.

- An updated displacement curve for the above-mentioned Baltic Pipe Norwegian Tie-in route /25/. This curve is based on new and existing dated samples, including AMS (C14) dated sediments/samples from the Baltic Pipe project.

In addition to the above existing curves, a 4th potentially relevant ‘curve’ – the GIA-Thor curve for the Thor OWF located in the eastern export cable corridor of the present project – is also presented in Figure 5-3. However, the quote mark around ‘curve’ indicates that this curve is not a reconstruction of an existing curve. Instead it is Ramboll’s representation in /22/ of so-called Glacio Isostatic Adjustment (GIA) variation isolines deducted from a new book called “Sea-level change in Mesolithic southern Scandinavia – long-and short-term effect on society and the environment”, /4/.

In that book numerous so-called sea-level index points (SLIPs), which are new and existing C14 dated sediments and samples covering southern Scandinavia focusing on Denmark, including the North Sea, have been compiled and analysed into a model. Based on these SLIPs isostatic uplift variations have been analysed within the study area, and 8 Glacio Isostatic Adjustment (GIA) variations maps – representing relative sea levels - have been modelled for 500-year intervals from the period 8,000-7,500 BC to 4,500-4,000 BC (before Christ). The values for the GIA 1 m isolines centred at the Thor site have been digitized in /22/, see Figure 5-3.

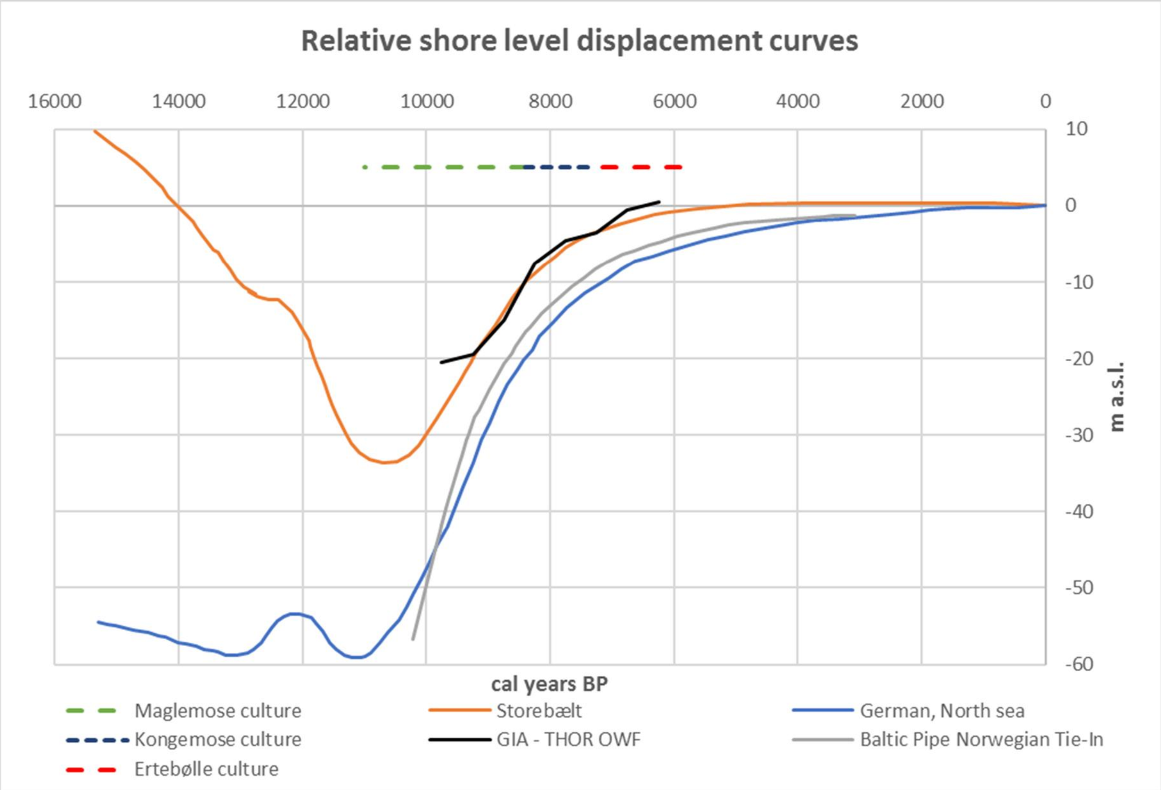

Figure 5-3 RSL curves for the North Sea. The orange curve is the Storebælt RSL /20/, the blue curve is the German – North Sea RSL /20/, grey curve is the updated Baltic Pipe Norwegian Tie-in RSL /25/, while the black curve is the approximated GIA-Thor RSL /4/. The dotted line shows the temporal extend of the different Mesolithic cultures.

5.2.2 The most relevant shore level displacement curves

The area of investigation is large and crosses isobases of Figure 5-2. Area A and B extend from the 1 m isobase and to the south. The zero isobase is only approx. one third to the south in these areas, and the southern export cable route extends further south. To cover the project area, it is therefore necessary to add isobases from previous research /26/ to include the location of the -1 m isobase.

The zero isobase represents the line where the land has been vertically stable. The isobases around the zero line either express down- or uplift. The numbers related to the isobases represent mm/year down (minus) or uplift (plus).

In accordance with VHN project /21/ and THOR project /22/ it is concluded that the Storebælt curve is the most relevant sea level curve for areas near the +1 m isobase, i.e. at the northern margin of the project area. By using the isobase displacement values it is possible from the Storebælt curve to construct sea level curves for isobase 0 and -1, hereby covering the full project area except the southern export cable corridor. To cover the area of the southern export cable corridor it is necessary to use the German North Sea Curve, Figure 5-4.

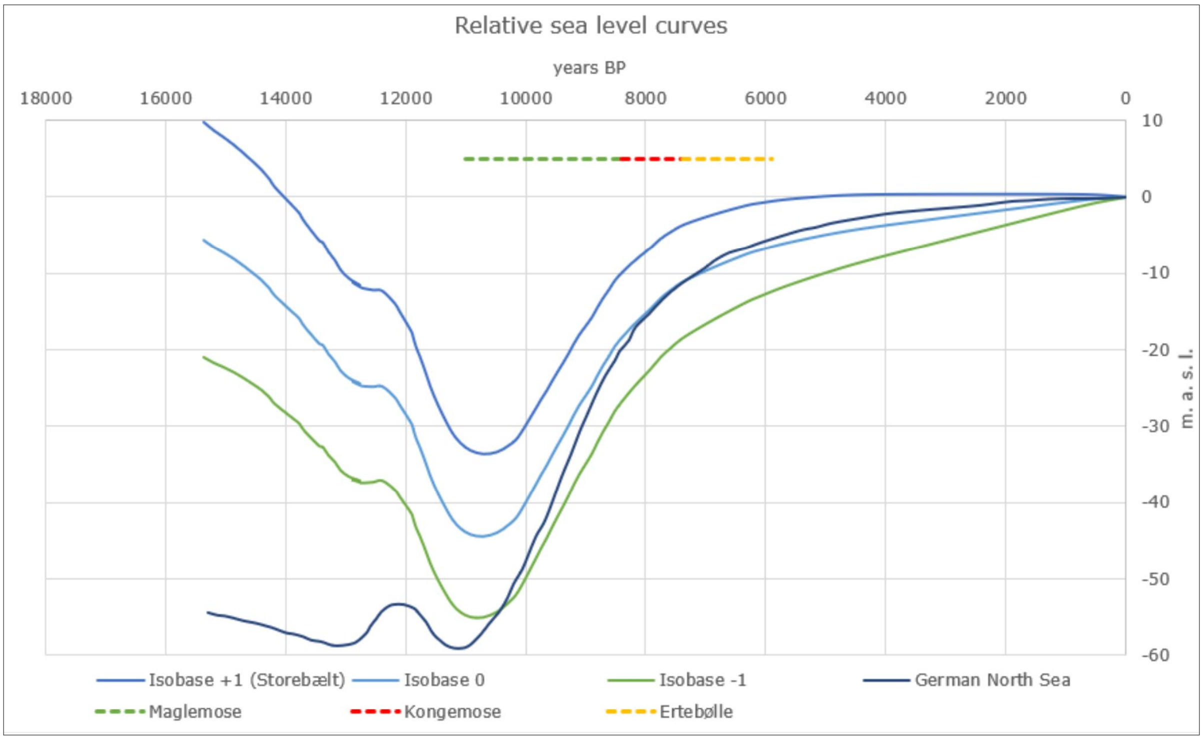

Figure 5-4: Most relevant shore level displacement curves for isobase +1 (Storebælt), German North Sea and along isobases 0 and -1.

5.3 Shorelines

Five theoretical spatial shorelines have been constructed covering:

- onset of the Maglemose Culture at 11000 BP,
- Mid Maglemose Culture at 10000 BP
- Late Maglemose Culture at 9000 BP
- Onset of Kongemose Culture at 8400 BP
- Onset of Ertebølle Culture at 7400 BP

The shorelines have been constructed by "cutting" the sea bottom topography (bathymetry) with the different shorelines from the above list along the relevant isobases. Shore lines are constructed for isobase 1 (Storebælt), 0, -1 and German North Sea sea-level curve. To create a continuous shoreline for the different archaeological periods, the different isobase shorelines are connected with straight dotted lines (Figure 5-5).

The paleo shorelines are theoretical as they are based on the assumption that the current seabed corresponds to a potential former dry land surface before the Post Glacial marine transgression and does not take into account later potential erosion or sedimentation. This is, of course, a simplification. As shown in Figure 4-13 there are sub-areas with thick Holocene marine deposits and there has most certainly been erosion in sub-areas during and after the marine transgression.

The continuous shorelines for the different time periods are shown in Figure 5-5. The figure also shows the project areas and the bathymetry. In general, the only area that has not, at some point in archaeological time, been landlocked, is the north western part of the area planned for energy island and OWF's, subarea A. At the onset of Maglemose Culture this area was submerged, and the rest of the project areas was land. At 10000 BP, still Maglemose, the sea-level rise resulted in submerging of the southern part of the corridor towards Germany. By the end of Maglemose, most of the project area was submerged, except the south eastern most area of subarea B and the eastern most part of the corridor towards Denmark, subarea C. At the onset of Kongemose Culture and later all the project area was submerged except the coastal areas at the eastern most corridor to Denmark, subarea C.

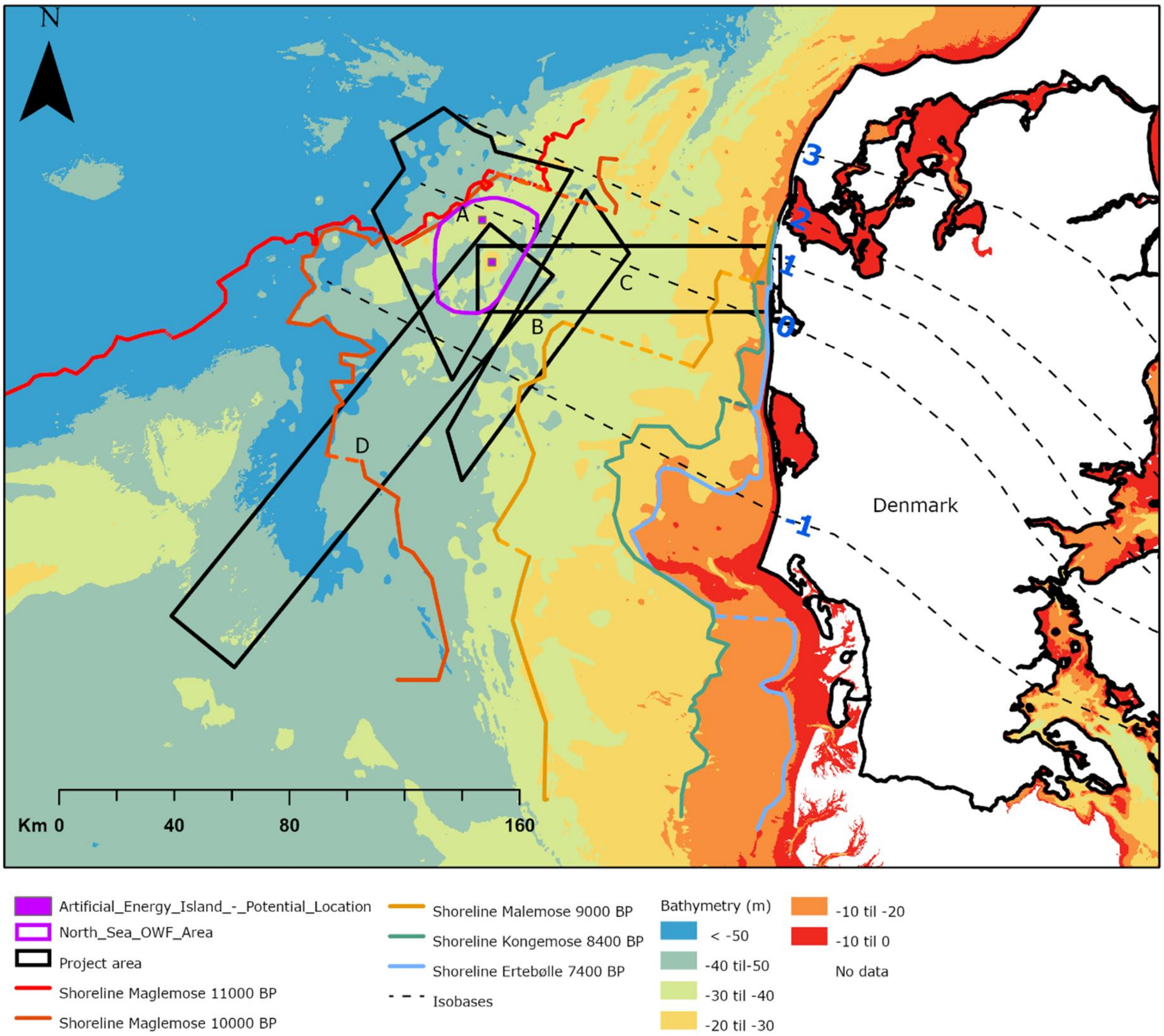

Figure 5-5: Theoretical paleo shorelines, Early Maglemose, Mid Maglemose, Late Maglemose, Early Kongemose and Early Ertebølle Cultures. The paleo shorelines are theoretical as they are based on the assumption that the current seabed corresponds to a potential former dry land surface before the Post Glacial marine transgression and does not take into account later potential erosion or sedimentation See text for further explanation.

The paleo shorelines are also shown in more simple maps in Appendix 1. Each map is based on a specific isobase and is therefore only valid in areas around this isobase. Maps are shown for isobases +1, zero and -1 and for the same five time slices shown in Figure 5-5.

5.4 Fjords, rivers, and other paleo coastal fishing spots

This section describes results related to the "fishing site model" described in section 2.2. Based on the location of the project area and the bathymetry it is possible to locate areas where the bathymetry indicates a paleo landscape including river systems and fjords. These systems will evolve from rivers to bays, lagoons, and fjords to ocean as the sea level rises.

The river system/fjord areas are preliminary shown in Figure 5-6 and related only to bathymetric structures within the project subareas A-D.

As the paleo coastlines as described in the previous section are theoretical and preliminary, these designated possible fishing spot areas are also theoretical and preliminary. More precise designations can be made when a top Late Glacial/Post Glacial land surface has been mapped from detailed seismic investigations also addressing postglacial marine erosion and deposition.

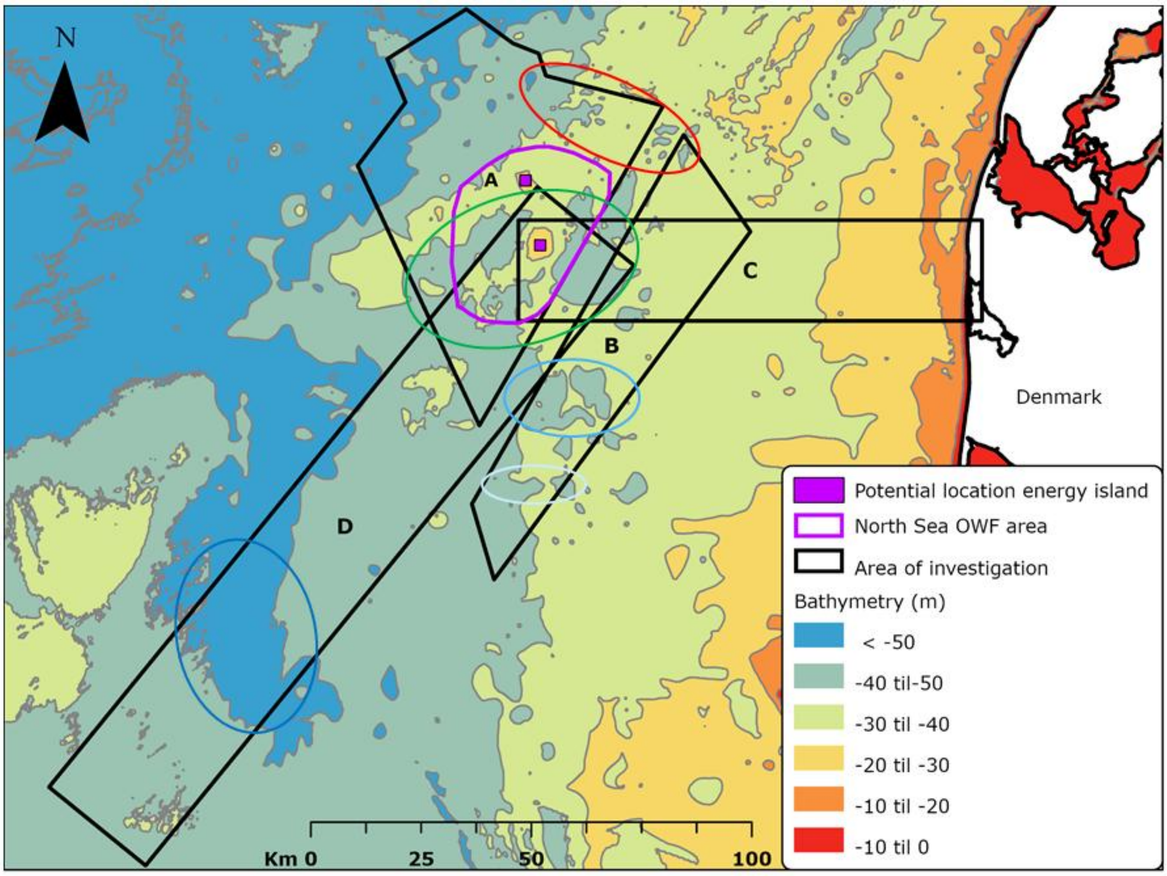

Figure 5-6: Theoretical enhanced probability for sites of archaeological interest, based on the "fishing site model".

5.4.1 Subarea A

The seabed in subarea A is located appr. 20-50 m bsl. The bathymetry (figure 4-3) shows a depression marked with a red oval in the northern part of subarea A, 30-50 m bsl. This area probably represents a river/fjord area. There is a large variation in the bathymetry, indicating that the paleo landscape could have included several river outlets and, as the sea-level rose, several lagoons, bays, and minor fjords constituting favourable fishing sites.

In the southern part of subarea A is a larger bathymetrical depression, 30-50 m bsl., shown with a green oval in figure 4-3. Similar to the above, this area also shows a large bathymetrical variation indicating a paleo landscape with several favourable fishing sites in bays, lagoons, and small fjords and in the river system on land.

Potential archaeological findings in these two areas will relate to early-mid Maglemose Culture, either as landlocked findings or coastal zone findings.

5.4.2 Subarea B

In the southern part of subarea B are 2 depressions, 30-50 m bsl., shown with blue and light blue. The bathymetrical variation is less pronounced and thereby representing a system with less variation resulting in a lower occurrence of lagoons and bays etc. Potential archaeological findings will relate to early-mid Maglemose Culture where the area was either landlocked or coastal.

The upper north part of the subarea intersects the system described in subarea A and marked with a red oval. The area was landlocked or coastal during Late Maglemose Culture, and potential findings will be related to this period.

5.4.3 Subarea C

In the part of the subarea C, the Danish cable corridor, that does not superimpose area A and B there are no larger bathymetrical depressions that could indicate rivers, fjords or similar, except in the coastal area of the present shoreline, 10-30 m bsl. This area is marked with a purple oval. Here it can be expected to find archaeological remains from Late Maglemose, Kongemose and Ertebølle Cultures.

To the west, subarea C intersects the area marked with a green oval and which is described above under subarea A.

5.4.4 Subarea D

The German cable corridor, subarea D, shows in the southern part, 40 to more than 50 m bsl., bathymetric features that indicate a large paleo river system including both large and small structures with potential fishing sites such as bays, lagoons and river outlets etc. The area is marked with a dark blue oval. The area was land/coastal area during early Maglemose Culture only (figure 4-3).

The northern part of subarea D intersects subareas A, B and C and the potential areas of archaeological findings are described above.

5.5 Preliminary conclusions in regards of potential Stone Age landscapes

In general, most of the project area has at some point in archaeological time been land. At the onset of Maglemose Culture the area was, apart from a small area to the north west, landlocked. At 10000 BP, still Maglemose Culture, the sea-level rise resulted in submerging of the southern part of the corridor towards Germany. By the end of Maglemose Culture, most of the project area was submerged, except the south eastern most area of the project area and the eastern most part of the corridor towards Denmark. At the onset of Kongemose Culture and later, all the project area was submerged except the coastal areas at the eastern most corridor to Denmark.

6 areas with potential paleo river, lagoon, bay, and fjord environments have been located theoretically. These will, according to the “fishing site model”, have increased probability for archaeological findings.

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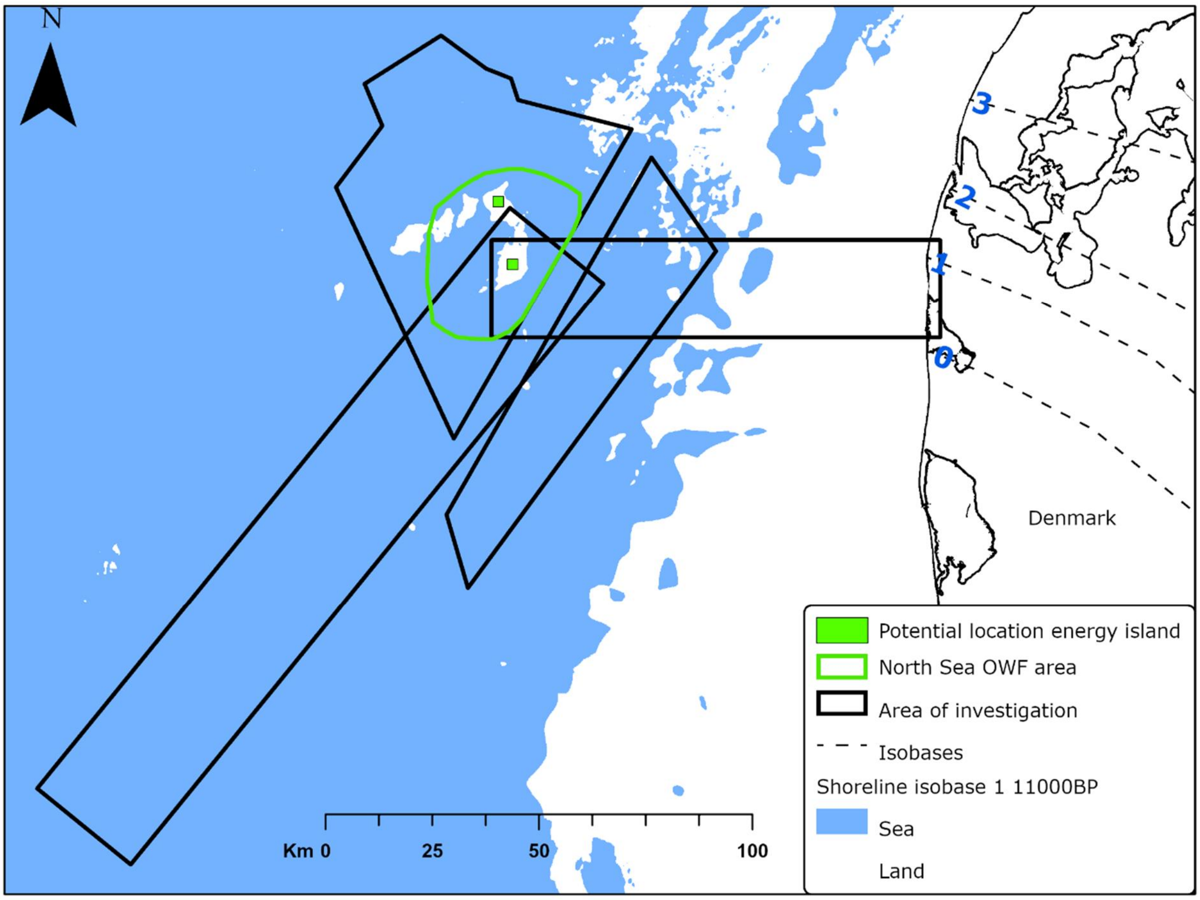
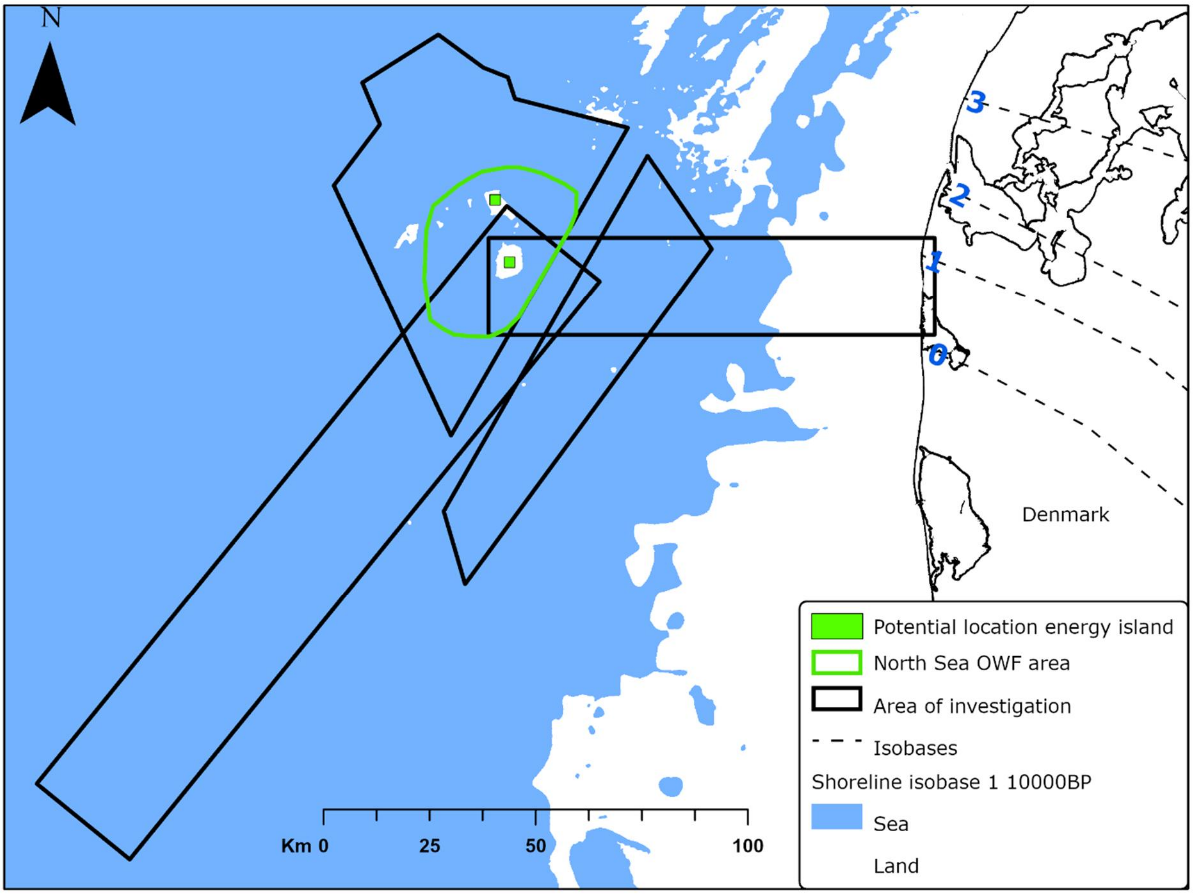
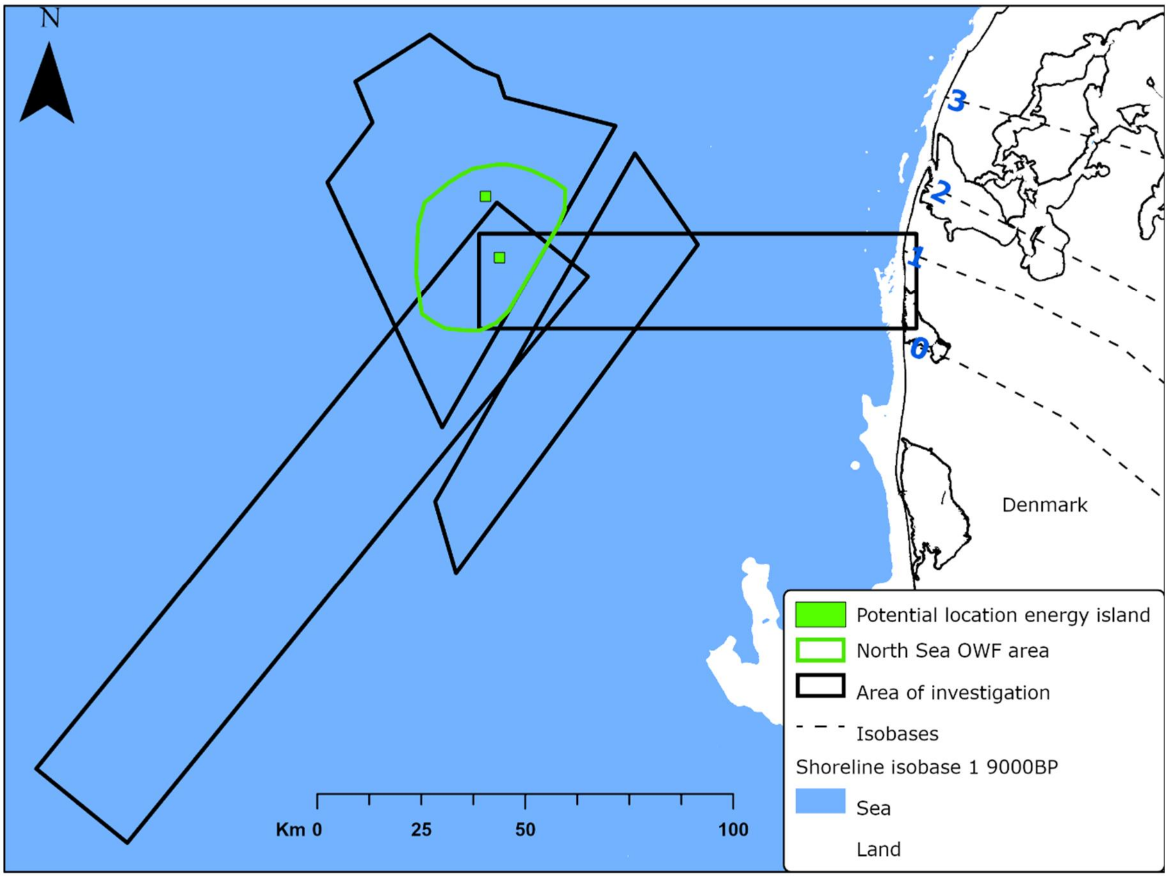
APPENDIX 1
PALEOGEOGRAPHIC MAPS



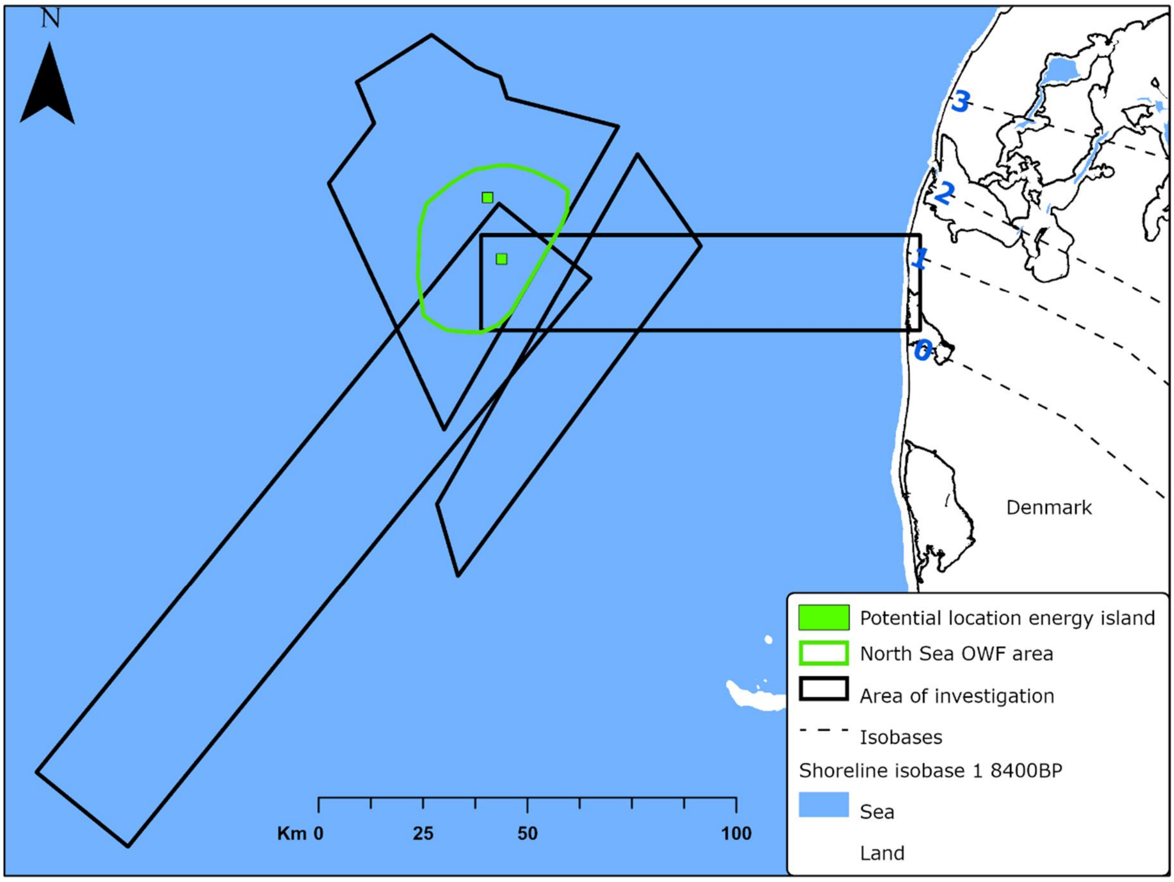
1-A: Theoretical paleogeographic map 11,000 BP for shoreline isobase +1 m. To be used in the northernmost part of the project area. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



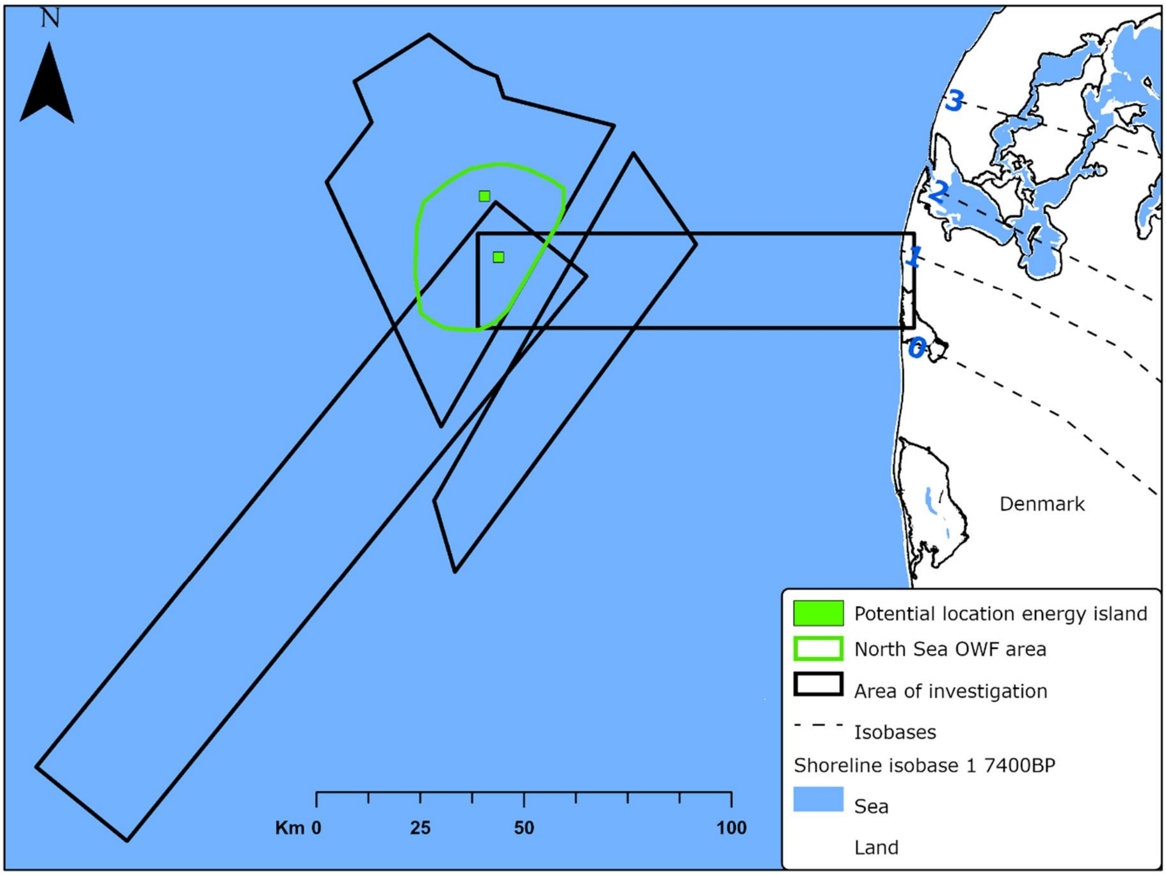
1-B: Theoretical paleogeographic map 10,000 BP for shoreline isobase +1 m. To be used in the northernmost part of the project area. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



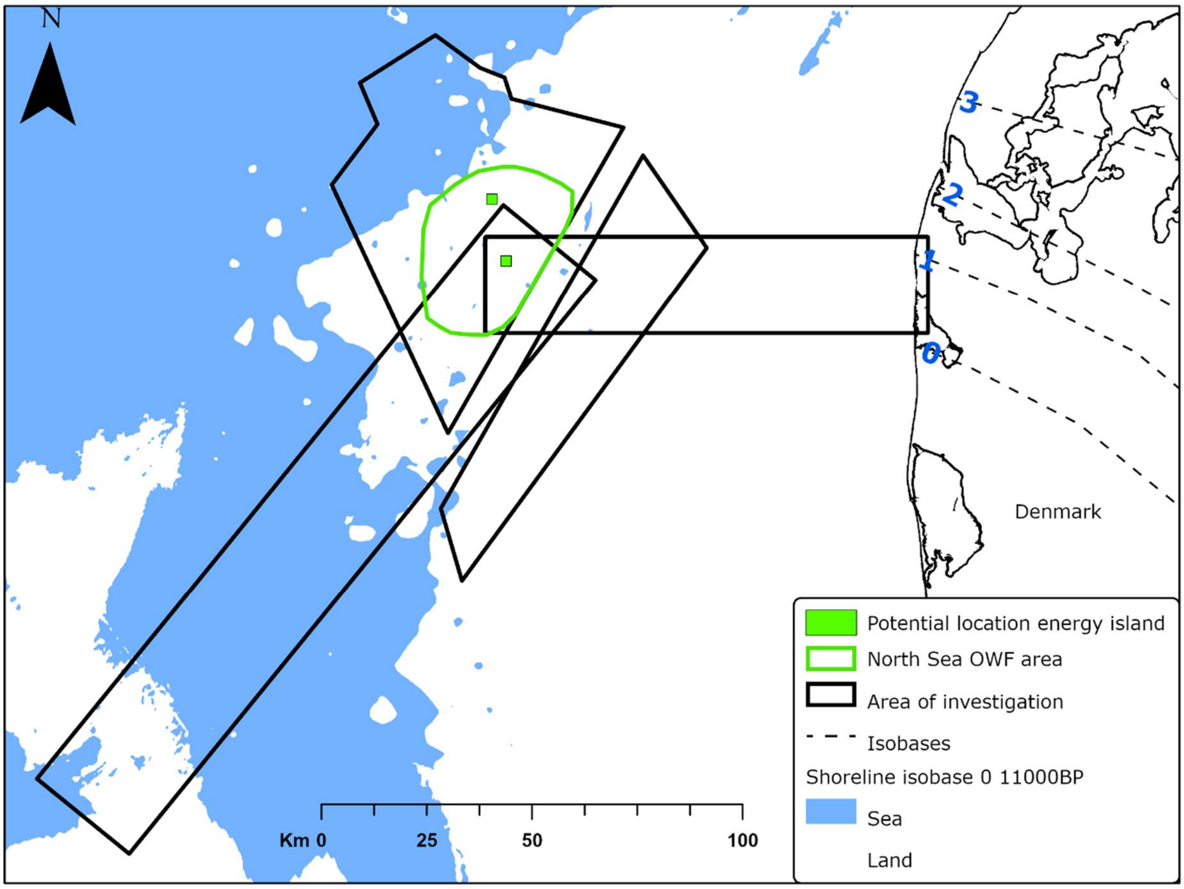
1-C: Theoretical paleogeographic map 9,000 BP for shoreline isobase +1 m. To be used in the northernmost part of the project area. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



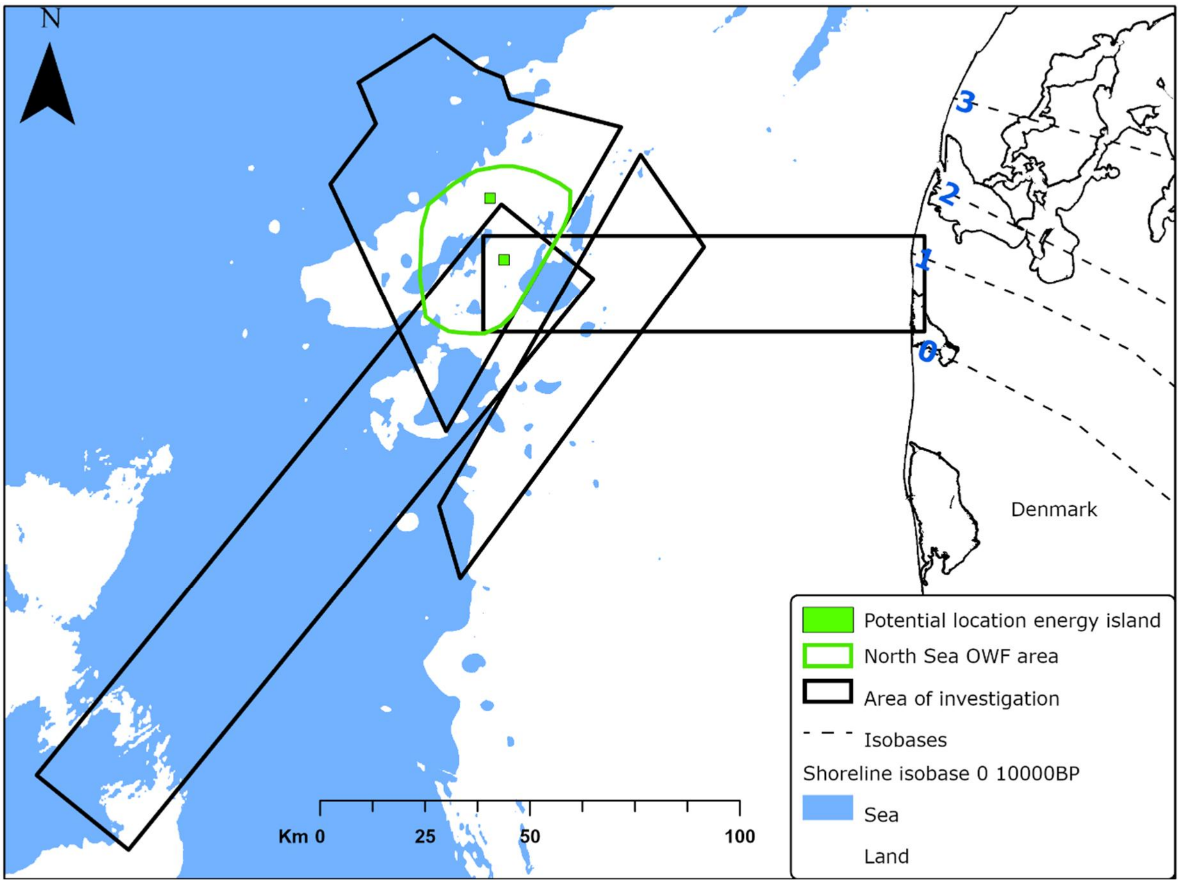
1-D: Theoretical paleogeographic map 8,400 BP for shoreline isobase +1 m. To be used in the northernmost part of the project area. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



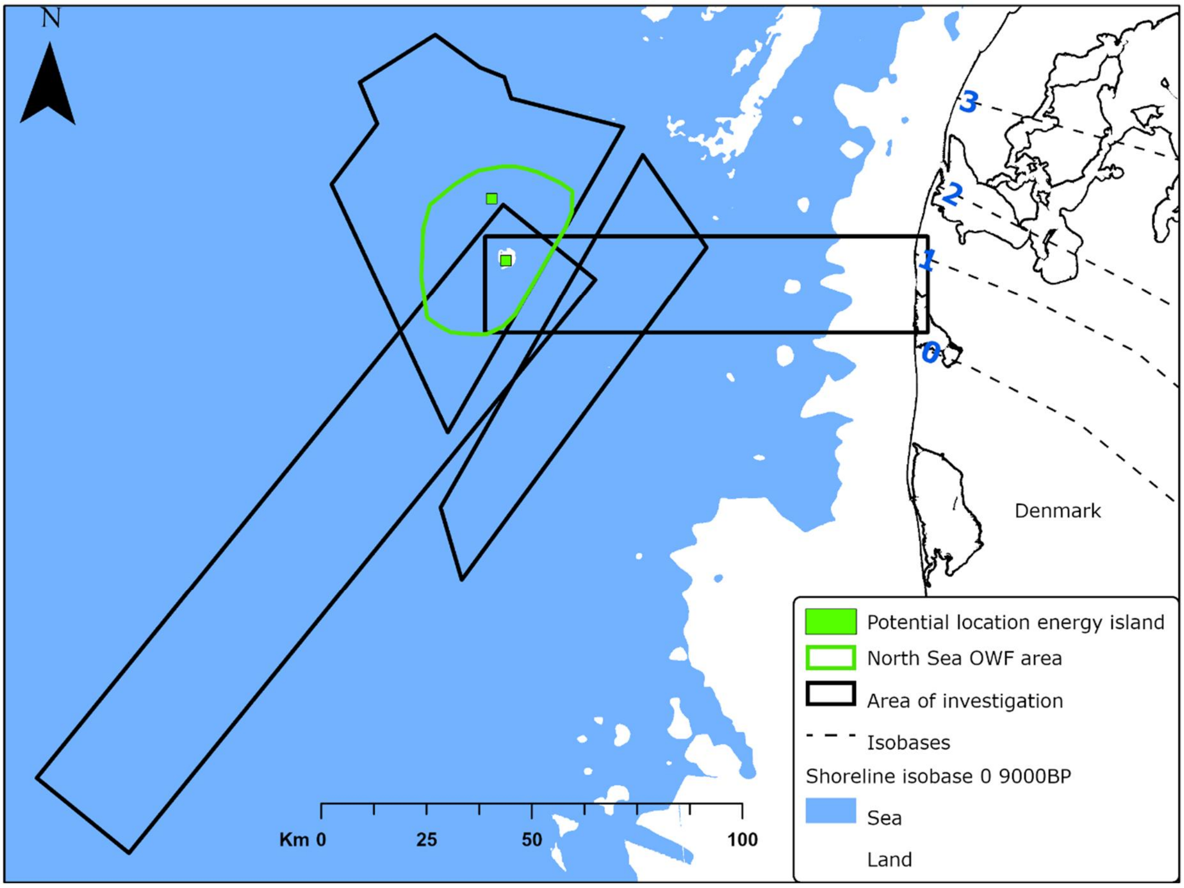
1-E: Theoretical paleogeographic map 7,400 BP for shoreline isobase +1 m. To be used in the northernmost part of the project area. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



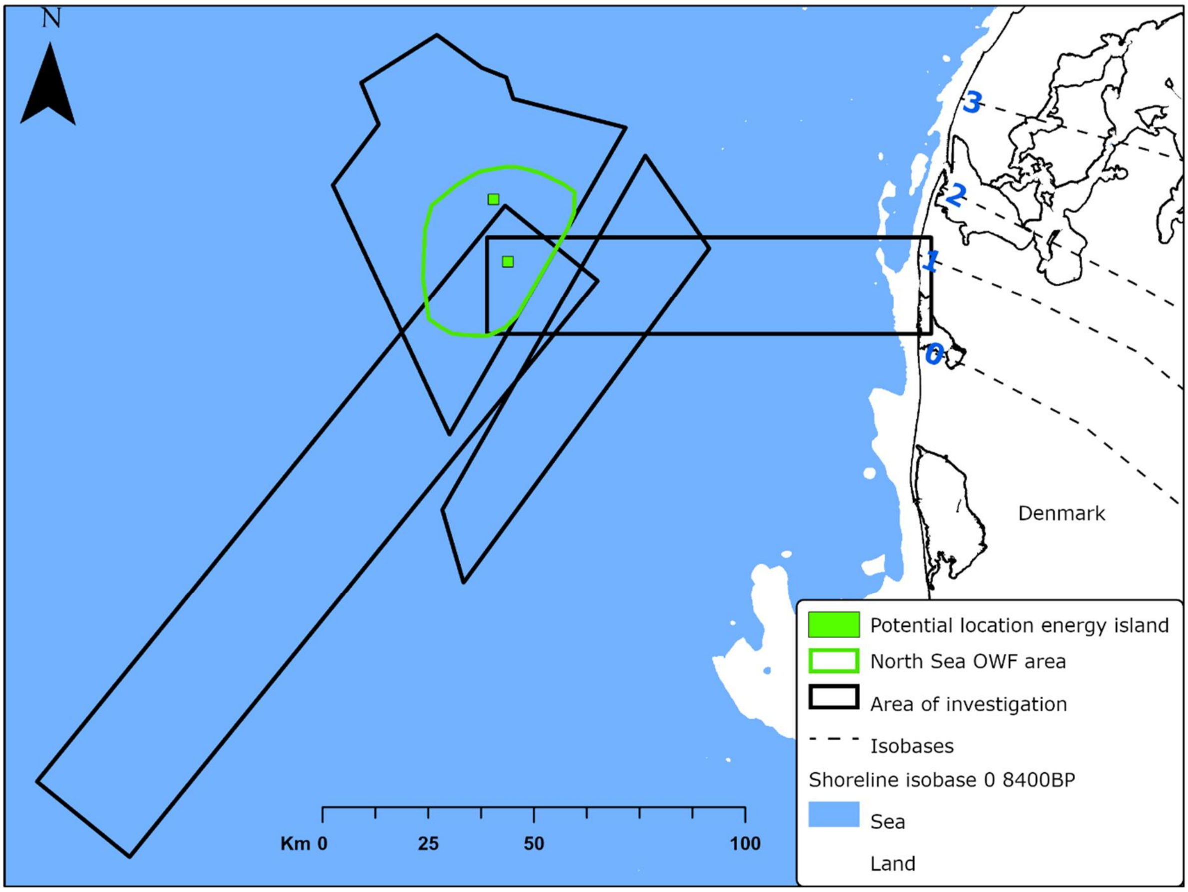
1-F: Theoretical paleogeographic map 11,000 BP for shoreline isobase 0 m. To be used in the central part of the areas planned for energy island and OWF’s. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



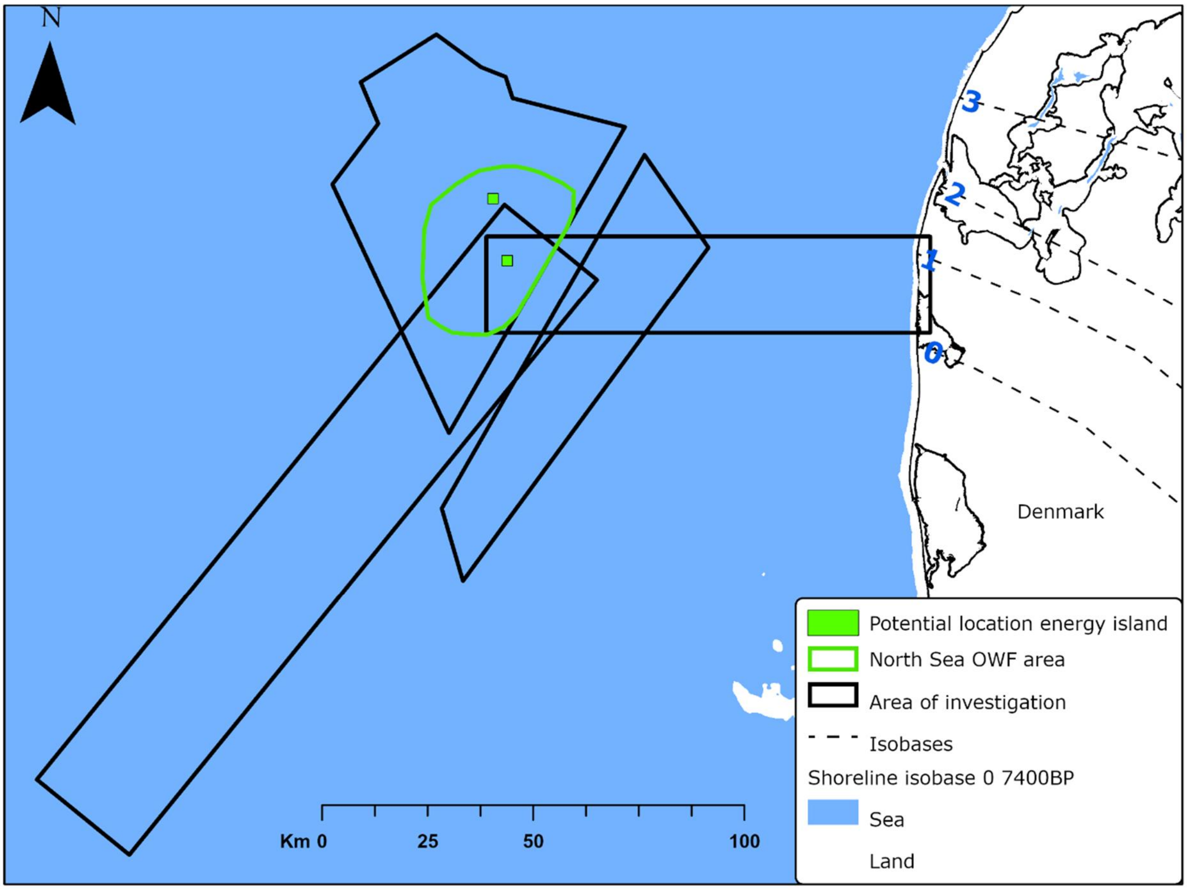
1-G: Theoretical paleogeographic map 10,000 BP for shoreline isobase 0 m. To be used in the central part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



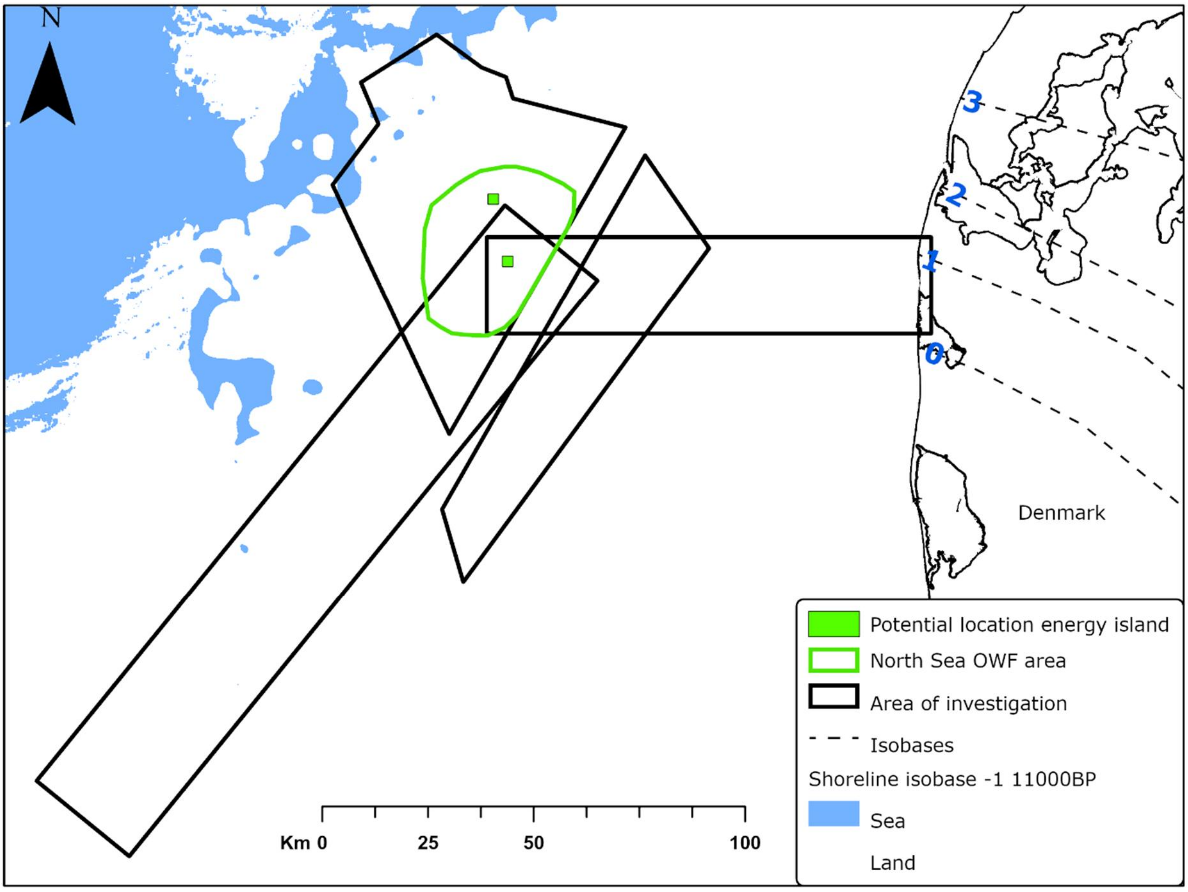
1-H: Theoretical paleogeographic map 9,000 BP for shoreline isobase 0 m. To be used in the central part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



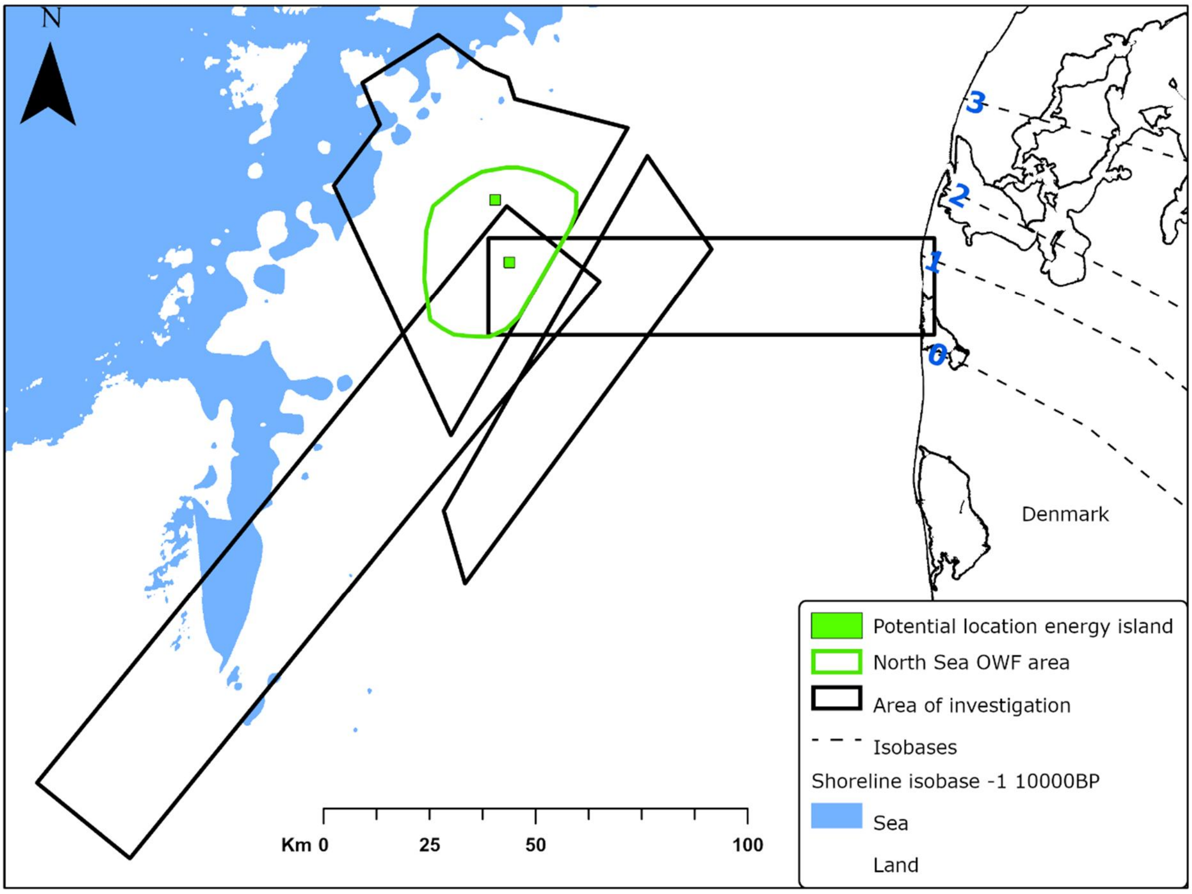
1-I: Theoretical paleogeographic map 8,400 BP for shoreline isobase 0 m. To be used in the central part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



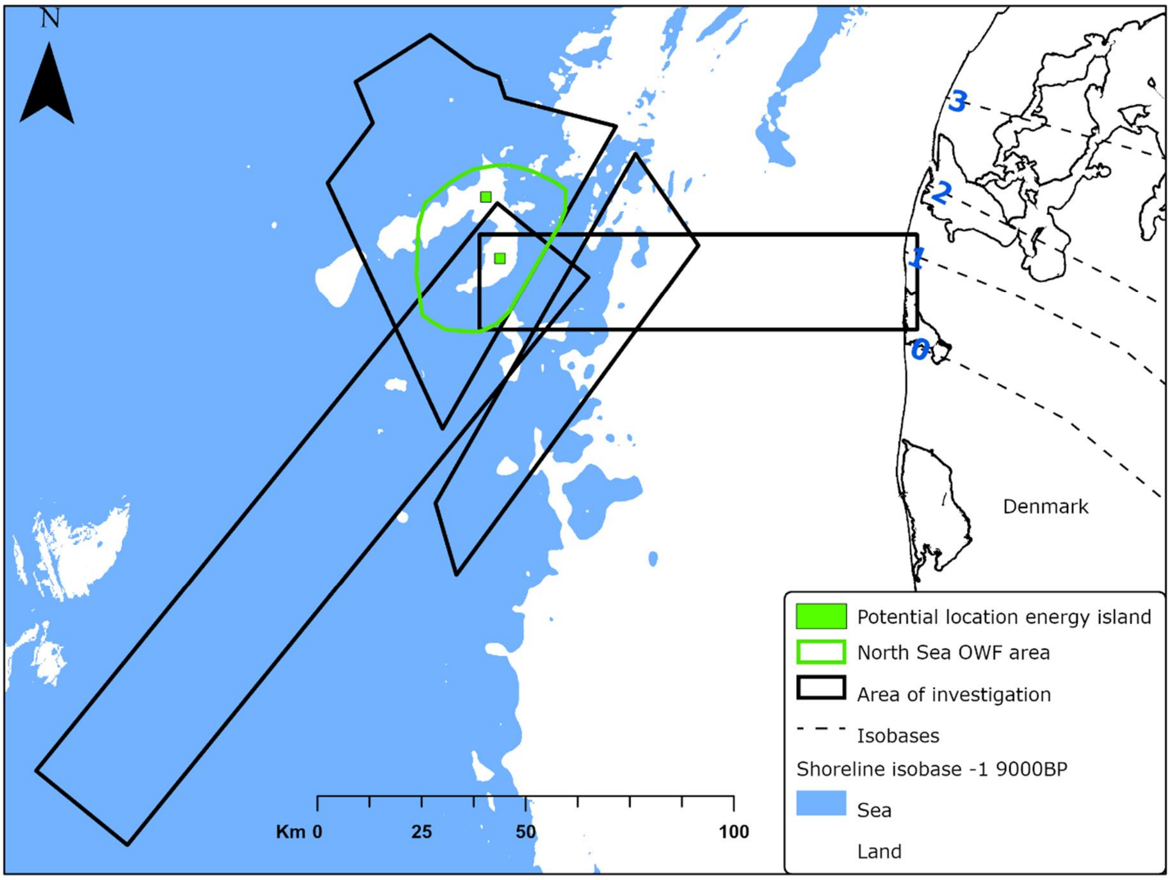
1-J: Theoretical paleogeographic map 7,400 BP for shoreline isobase 0 m. To be used in the central part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



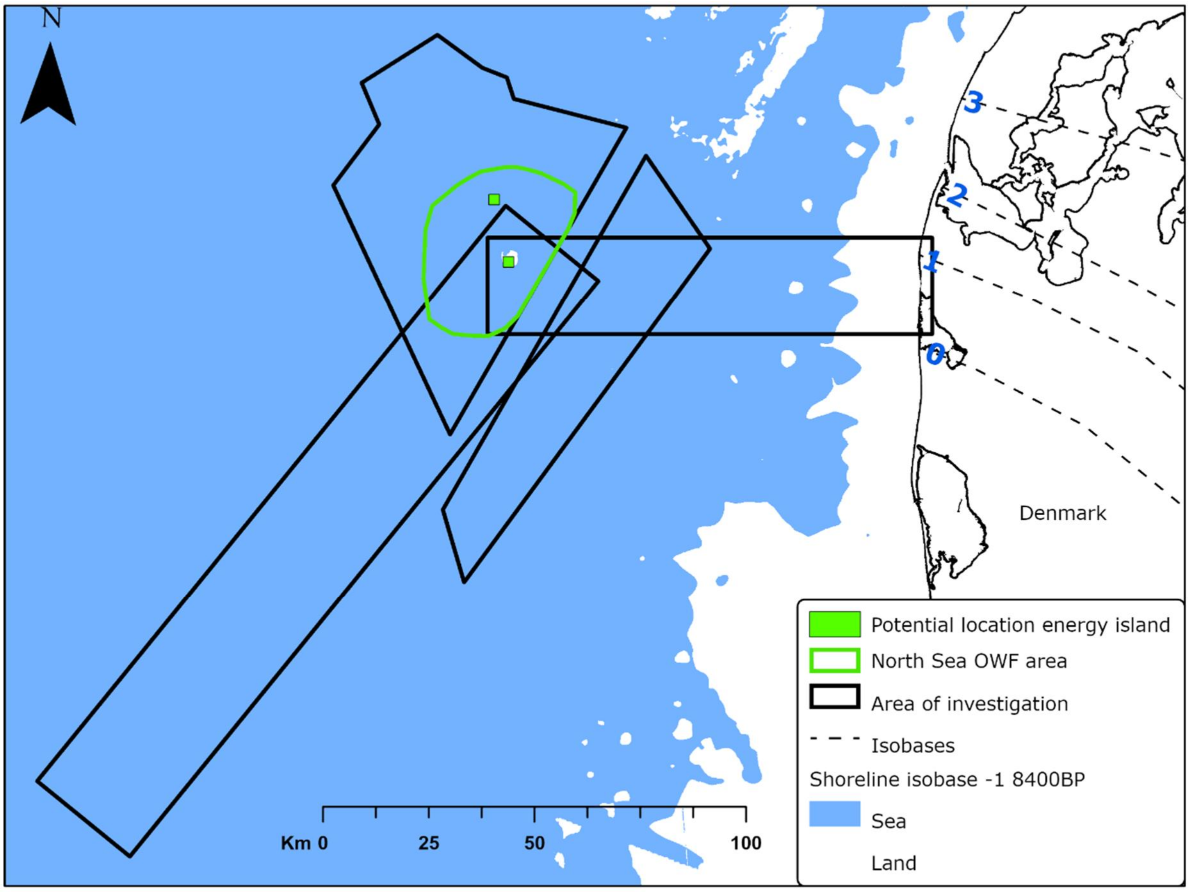
1-K: Theoretical paleogeographic map 11,000 BP for shoreline isobase -1 m. To be used in the southern part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



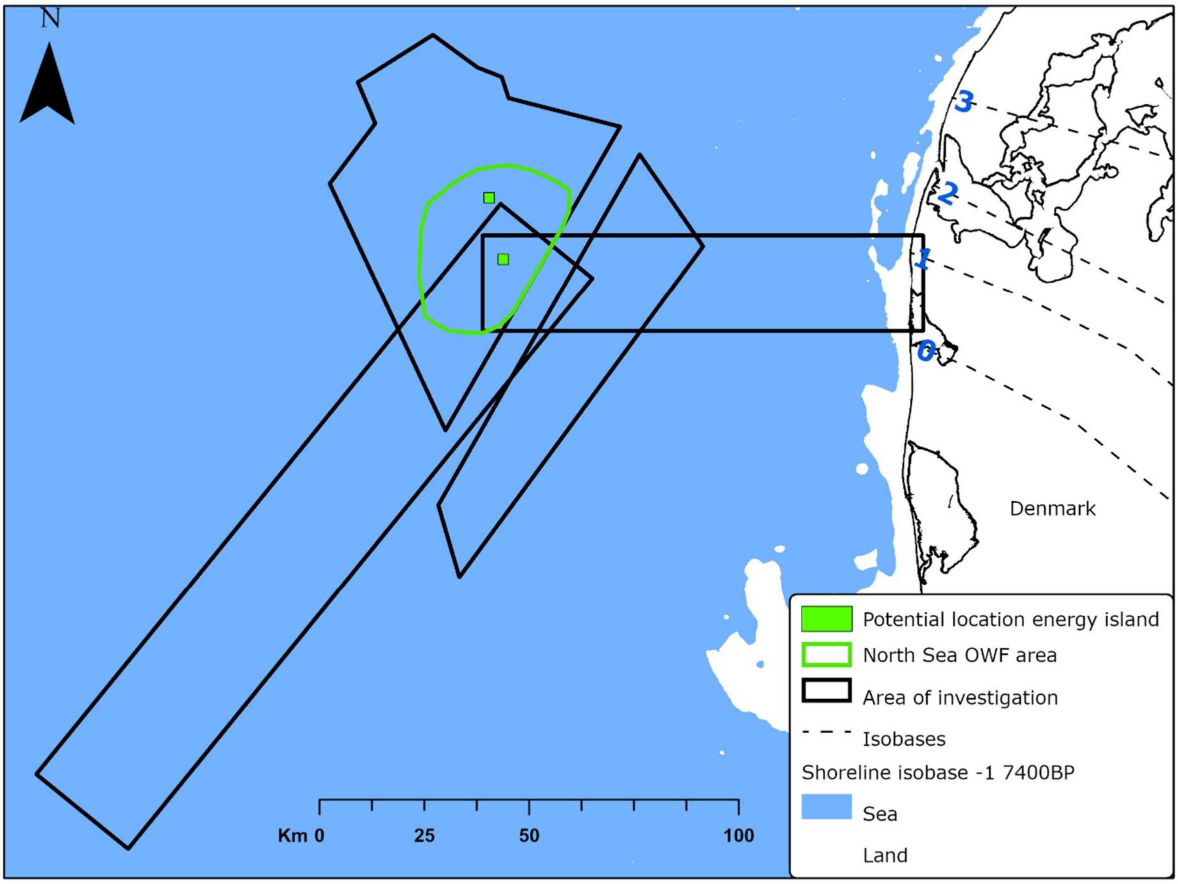
1-L: Theoretical paleogeographic map 10,000 BP for shoreline isobase -1 m. To be used in the southern part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



1-M: Theoretical paleogeographic map 9,000 BP for shoreline isobase -1 m. To be used in the southern part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



1-N: Theoretical paleogeographic map 8,400 BP for shoreline isobase -1 m. To be used in the southern part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.



1-O: Theoretical paleogeographic map 7,400 BP for shoreline isobase -1 m. To be used in the southern part of the areas planned for energy island and OWF's. Note that the shoreline calculations are based on present day bathymetry and thus ignore effects of erosion and deposition during and after transgression.