DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2022/4**

Screening of potential sand resource areas for the planned energy island in the central Danish North Sea

Report for the Danish Energy Agency

Niels Nørgaard-Pedersen, Verner B. Ernstsen
& Thomas G. Vangkilde-Pedersen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

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G E U S

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1. Introduction

The Danish Energy Agency has asked GEUS to perform a desktop study in order to clarify the possibilities for dredging of larger amounts of sand for the planned energy island in the Danish North Sea. The results will form the basis for further investigation of potential sand resources in the areas, to prepare an application to the Danish Environmental Protection Agency (EPA) for fill sand extraction in a dedicated 'Specific purpose construction area' (Bygherreområde).

2. Scope of investigation

There is a need to find suitable sand resources as close as possible to the planned 10 GW energy island, as transport costs and total time used for dredging vessel transits increase considerable with distance to the energy island. The investigation area also includes the area that is currently designated to the windfarm installations. On basis of cost/benefit analyses, it can be decided later if it is advantageous to extract sand from that area.

The screening focuses on locating suitable sand resource areas, and it also includes a description of remaining areas not suitable for sand extraction.

2.1 Sand quality and amounts

Quality requirements given by the Danish Energy Agency state that the desired material to be investigated must be composed of well-graded friction material, and a good resource consists primarily of sand (0.0625 mm-2 mm). Parts of the resource can also be coarser gravelly sand.

There is a need for about 17 mill. m^3 sand for construction of the energy island. It is estimated that about 60 mill. m^3 sand shall be localised to consider unexpected circumstances in the localised dredging areas.

One primary extraction area will be identified as the best suitable, and one-two additional areas will be identified as alternatives.

3. Selection of screening area

As a first step of the investigation, the areal extent of the screening area was selected in cooperation with the Danish Energy Agency. GEUS' databases of seismic survey data and sediment cores as well as derived on-line maps of seabed conditions and location of potential marine resources formerly mapped by GEUS were crucial in this process. In addition, Natura 2000 areas (cf. Habitat Directive, HD) and new marine protected areas (cf. Marine Strategy Framework Directive, MSFD) were avoided.

The selected screening area is 4574 km^2 in size and located in the central part of the Danish North Sea sector with a minimum distance of about 55 km from the Danish west coast (Figure 3.1). The outer rim of the area is about 25-55 km from the centre of the planned energy island. The north-western notch, not included in the screening area, is currently in hearing as nature and environmental protection area (N138), i.e. marine protected area (MPA), in the first maritime spatial plan for Danish waters submitted in accordance with the EU directive for establishing a framework for maritime spatial planning (MSP).

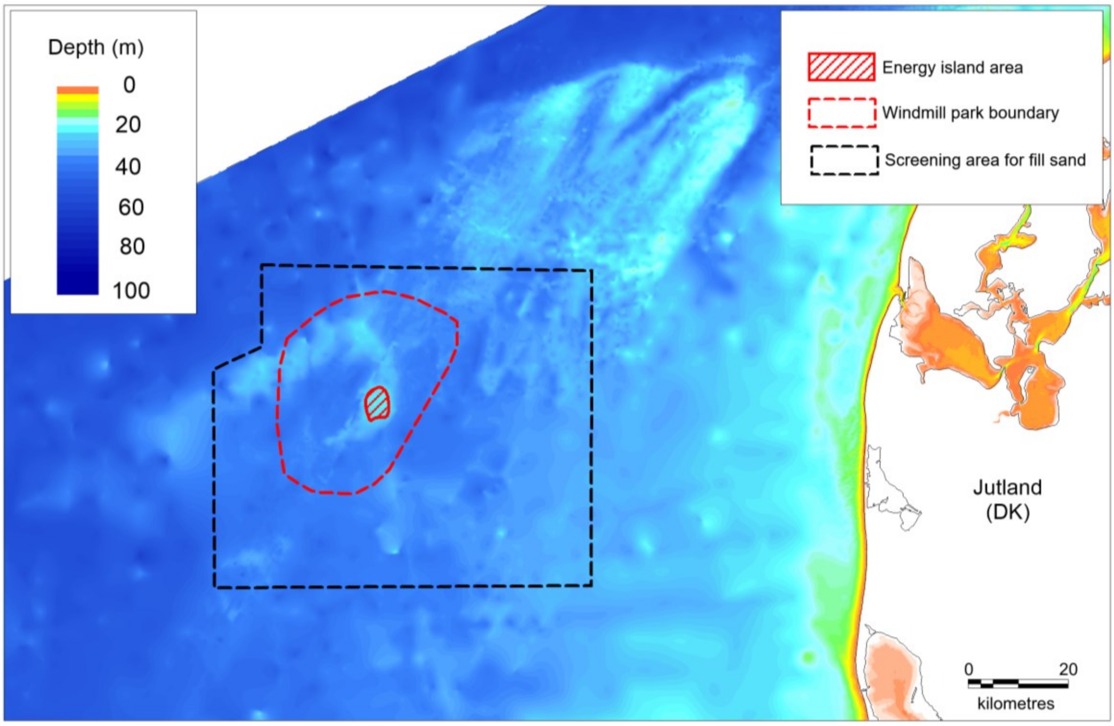


Figure 3.1. Screening area location in the central Danish North Sea.

4. Maritime spatial planning areas

The screening area does not contain marine protected areas or existing dredging areas. The nearest Natura 2000 habitat area N248 is situated at Lille Fiskerbanke ca. 10 km to the north of the screening area. Jyske Rev immediately to the northeast of the screening area, contains several gravel dredging areas, where active pebble and gravel aggregate dredging for concrete production takes place.

As part of Denmark's contribution to EU Directive 2014/89/EU "Establishing a framework for maritime spatial planning", a proposal for executive order on Denmark's maritime spatial plan has newly been presented and is currently in public consultation. The plan contains a digital sea planning map with different development zones and existing zonal use (Figure 4.1). The screening area for sand resources to the North Sea energy island is dominated by development zones for renewable energy and energy islands. It is intersected by two ship traffic corridors, one in the central part and one intersecting the south-easterly corner. The north-easterly corner is a development zone for natural resource extraction (ie. sand and gravel). It is stated concerning possible obstruction of ship corridors, that only plans may be adopted, or permission granted for land reclamation projects or infrastructure installations, if it does not make it impossible or significantly difficult to navigate. Permits etc. can be issued in special cases for activities and facilities for which development zones have not been determined.

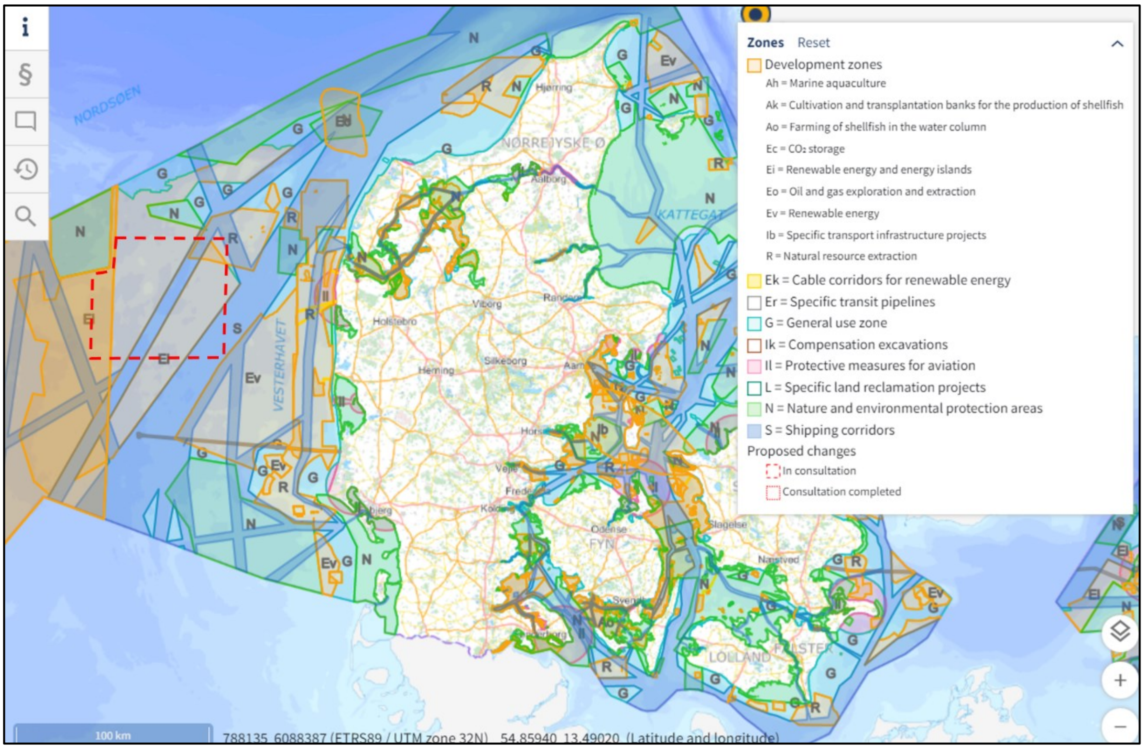


Figure 4.1. Maritime spatial plan for Denmark (source: [Danmarks Havplan](#)) with screening area polygon indicated by red dotted line.

5. Existing knowledge of seabed conditions

5.1 Bathymetry

The screening area is characterised by a relatively flat sea bed with depths in the range of 25-50 m (Figure 5.1). The most shallow parts <30 m are constituted by a half-circular ring of a large sand bar complex in the north-western part of the screening area. The eastern part of the area is generally <35 m in depth, whereas the south-western and central part generally is 40-45 m in depth. The largest depths of 45-50 m are found in the north-western corner.

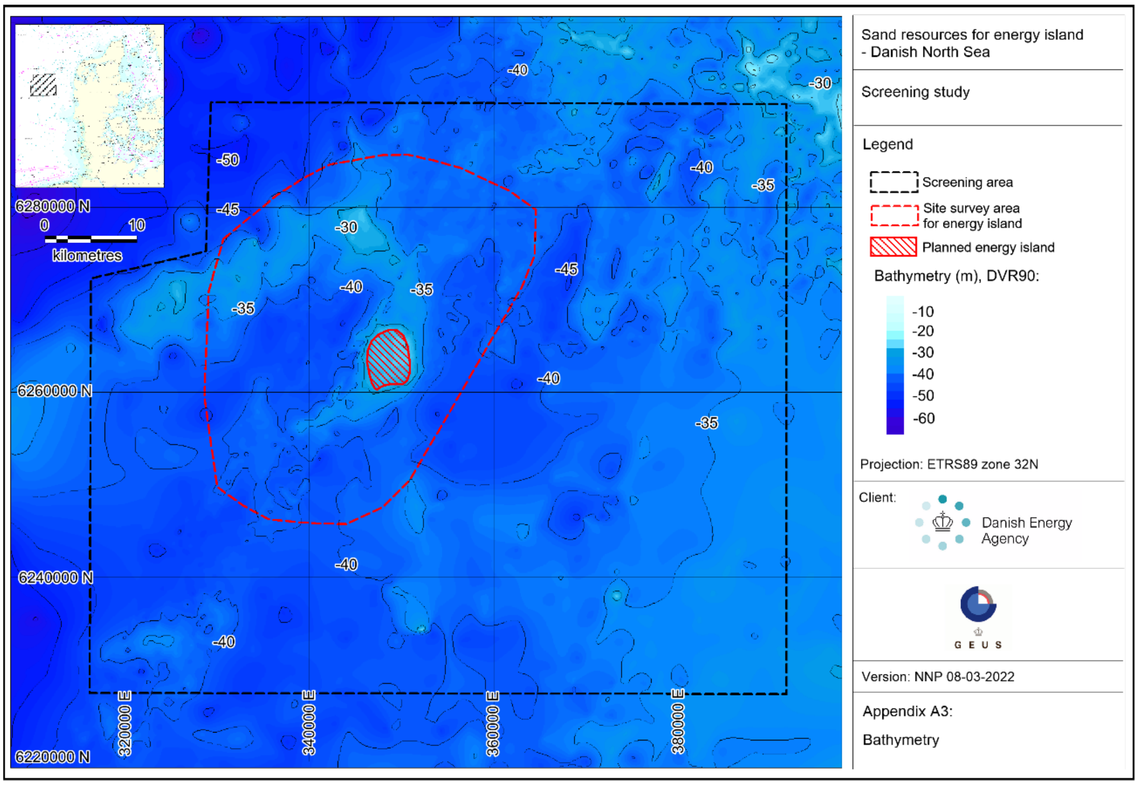


Figure 5.1. Bathymetry of screening area (Appendix A3).

5.2 Sub-surface geology

Marine sand bars are resting on late glacial (Weichselian) and possibly older glacial quaternary deposits, formed by subglacial and proglacial processes during previous glacial periods (Weichsel, Saale, and older). Base Quaternary (Miocene deposits) is generally found about 200-300 m below the seafloor in the area (Nielsen et al., 2008). However, the prequaternary deposits may be higher located around common salt diapir structures in the northern part of the area.

The glacial series are locally dissected by large buried channel systems, known from the quaternary sediment record in many parts of the North Sea (Huuse and Lykke-Andersen, 2000; Van der Vegt et al., 2012). Most studies indicate the former position of the last glacial maximum ice margin at about the northern boundary of the screening area (Ehlers et al., 2011; Hughes et al., 2016), where glacial till exposed at or near the sea floor occur extensively along an about 20-40 km wide east-westerly zone, from the Jutland coast towards Lille Fiskerbanke in the west. This implies that late Weichselian proglacial outwash channel systems may have had a more proximal (closer to ice sheet) location in the northern part of the screening area compared to the southern part. Following the retreat of the last glacial ice margin, the northern part of the area possibly was drowned by the late glacial Yoldia Sea, generally depositing glacio-marine silty layered deposits with scattered dropstones in landscape depressions. As effect of glacio-isostatic elevation, the area was followingly subaerially exposed. Between c. 9000 to 7000 yrs BP, the North Sea became connected to the English Channel and the screening area became progressively transgressed by the sea. Fully marine conditions in the North Sea basin were first established by c. 6.000 yrs BP (Graham et al., 2011). The redistribution of Pleistocene deposits since the onset of the marine transgression over the antecedent land surface is a key process in the distribution of the present-day seabed sediments. The screening area's present depth range of about 25-45 m implies that erosion and redeposition processes may have been most active in the early to mid-Holocene period when sea level was lower.

Jensen et al. (2011) presented a geological conceptual model for near-surface deposits of the Danish North Sea in relation to a study of Jyske Rev and Lille Fiskerbanke. In the model transect presented in Figure 5.2, the screening area may correspond to the central to south-easterly part of the profile. Recent studies of the central North Sea in the English and Norwegian sectors infer that large ice-dammed proglacial lake systems may have built up, as the Scandinavian and British ice sheets coalesced during the Last Glacial Maximum from ca. 26.000 yr BP to 19.000 yr BP (Hjelstuen et al., 2018; Emery et al., 2019). Such lake systems possibly also reached the Danish sector and may be part of the unit 'Weichselian proglacial silt and sand' in the model profile.

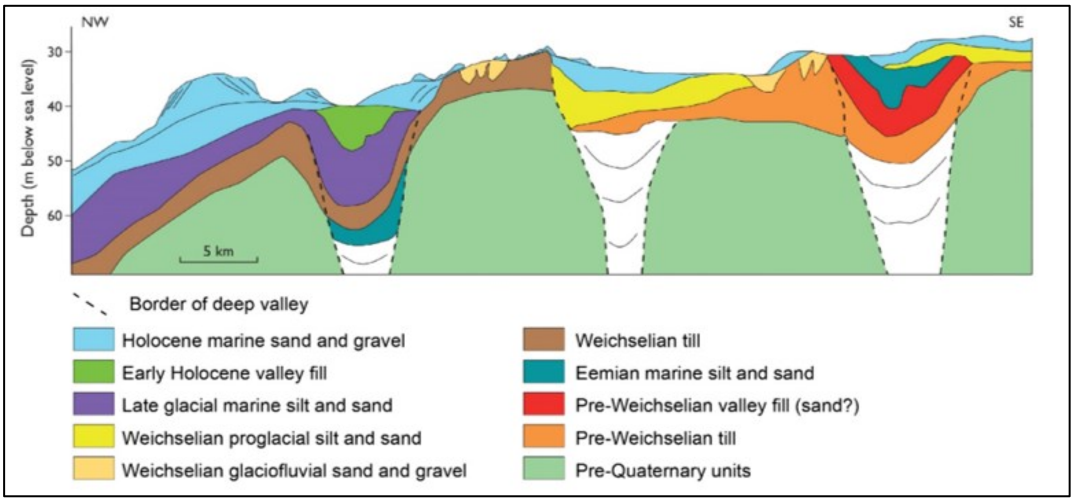


Figure 5.2. Profile of surface-near geological units in the Danish North Sea (Jensen et al., 2011).

5.3 Seabed sediments

Knowledge of the seabed surface sediments in the area is based on GEUS' surface sediment map (Figure 5.3) as well as results of a recent detailed mapping project for EPA (GEUS Rep. 2021/25) covering the central and western part of the screening area (Figure 5.4). The seabed surface sediment maps reflect the depositional and erosional history of the late quaternary period. In the screening area, sandy and gravelly sandy sediment dominate the seabed surface, and the distribution is both related to occurrences of Weichselian and older glacial outwash sediments, as well as modification by Holocene marine current and wave activity.

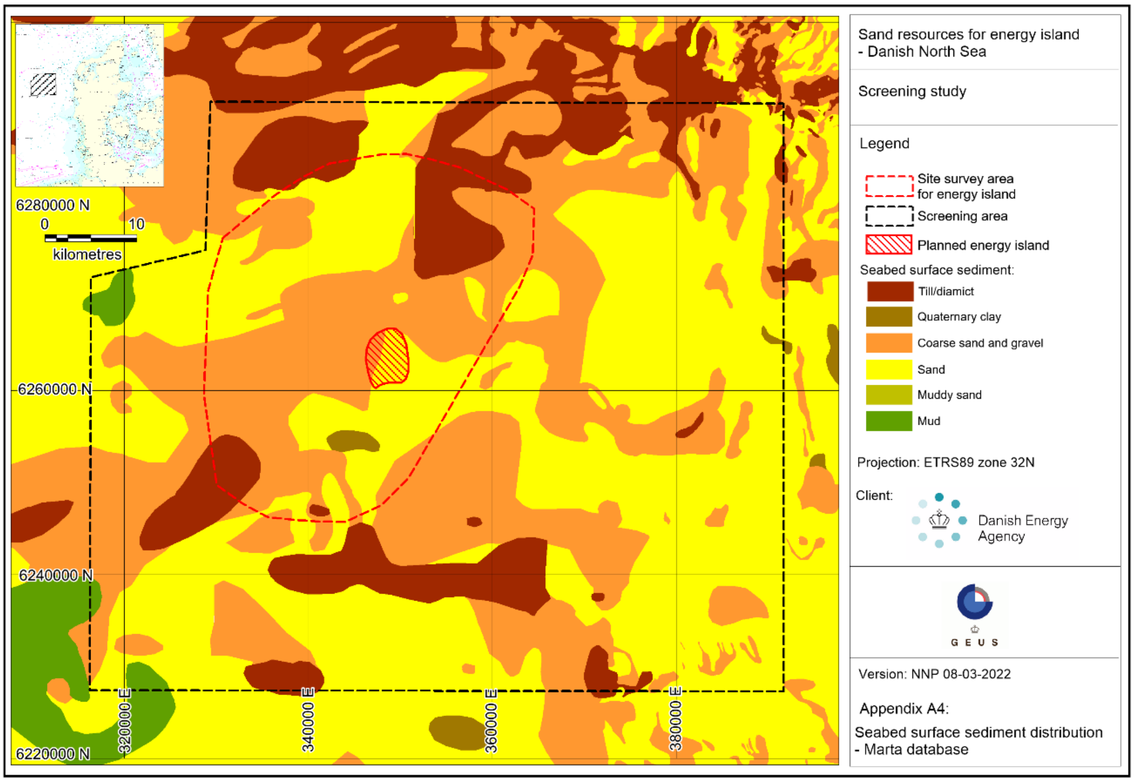


Figure 5.3. Seabed surface sediment map with demarcated screening area (Appendix A4).

Till/moraine with a scattered or more concentrated occurrence of larger stones on the sea floor is found in the central northern part of the screening area and along a stretch in the southern central and western part. The northern moraine areas are likely of late Weichselian origin, whereas the southern occurrences outside the Last Glacial Maximum ice sheet extent, more likely is of Saalian or older glacial origin. In the western deepest parts of the area, silty fine sand occurs.

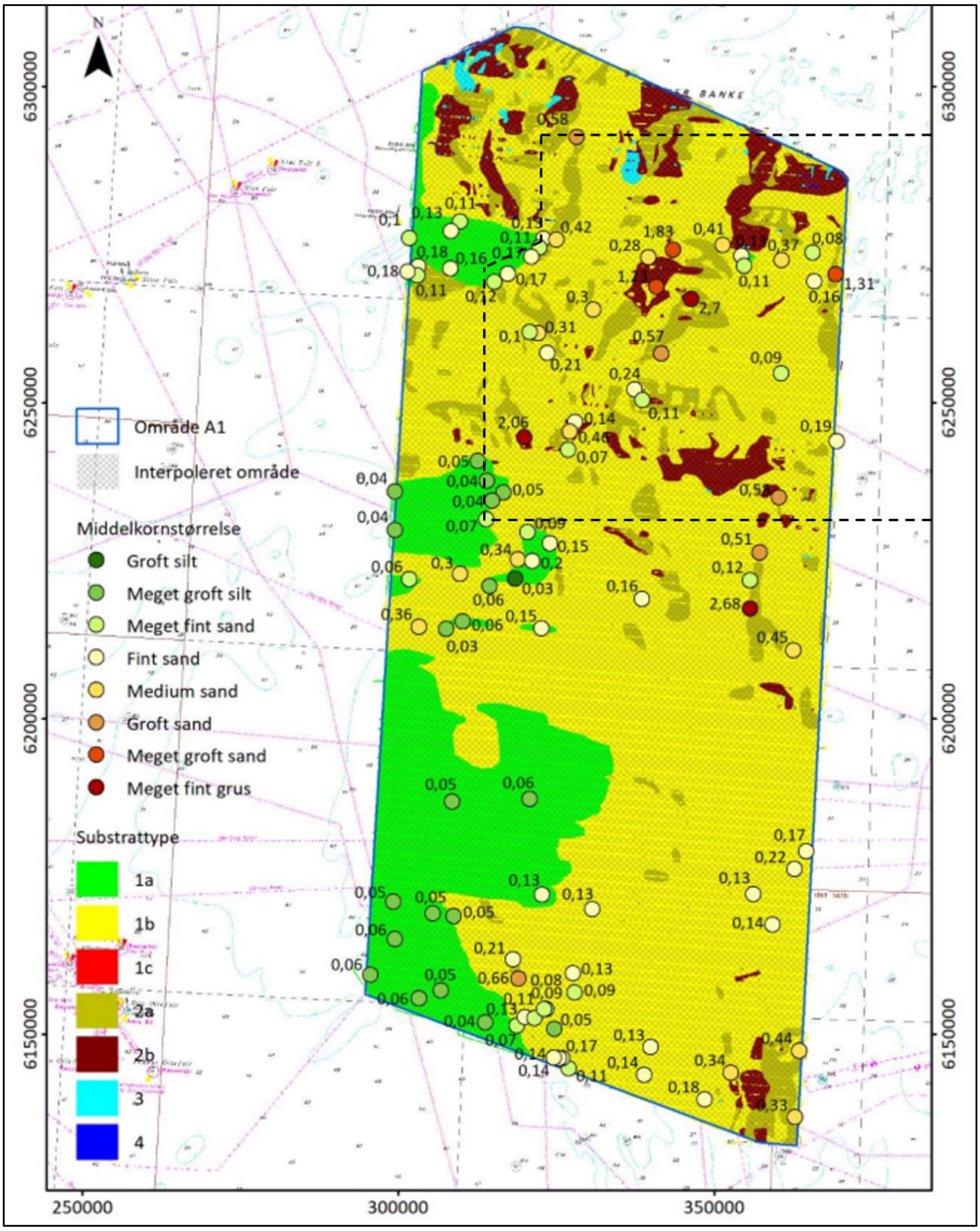


Figure 5.4.Seabed substrate types and sediment sample grain size data based on habitat mapping of a large area in the central Danish North Sea (GEUS Report 2021/25).The screening area for the present study is indicated by dashed line.

5.4 Sand and gravel resource areas

GEUS marine raw material database contains an overview of known resource areas of sand and gravel aggregates in Danish waters. The resource areas are classified based on raw material type, geological origin and data confidence (certainty). Almost all indicated resource areas in the screening area are classified as Speculative (low data confidence) (Figure 5.5). This is due to the open grid of sparker seismic data as well the relatively low number of sediment cores for verification of the resources. It is noteworthy that the resource mapping and classification is based on survey data gathered by GEUS in 2010-2012. The sparker seismic grid had a 10 km line distance in the western to central part of the area, and a 3 km x 10 km grid in the eastern part of the area. Additional sediment cores were collected in the southwestern part of the area in 2020, and the seismic grid in the western to central part of the area was densified to a 1.5 km grid by Innomar pinger data during an EPA habitat survey in 2019 carried out by GEUS and WSP. The new data has not yet been integrated in the resource mapping.

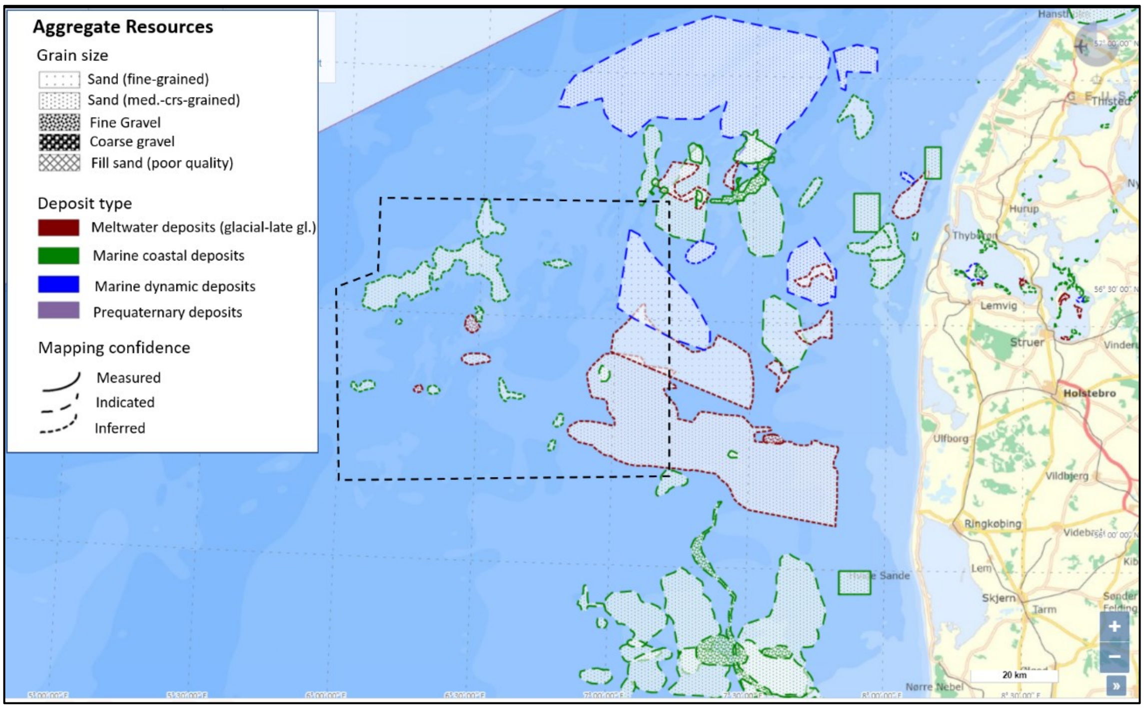


Figure 5.5. Existing marine aggregate resources in the Danish North Sea (GEUS' marine aggregate data base, MARTA).

6. Methods

6.1 Available data

Single channel Sparker data from GEUS' marine aggregate mapping campaigns in 2010 and 2012 for EPA were reprocessed and used for interpretation of geological units and the extent and thickness of potential sand resource units. In addition, newer Innomar sub-bottom profiler (SBP) data recorded in 2019 during an EPA habitat survey carried out by GEUS and WSP and covering the western to central screening was integrated in order to obtain a higher resolution mapping of the subsurface geology. Figure 6.1 shows the distribution of seismic lines and sediment cores in the area.

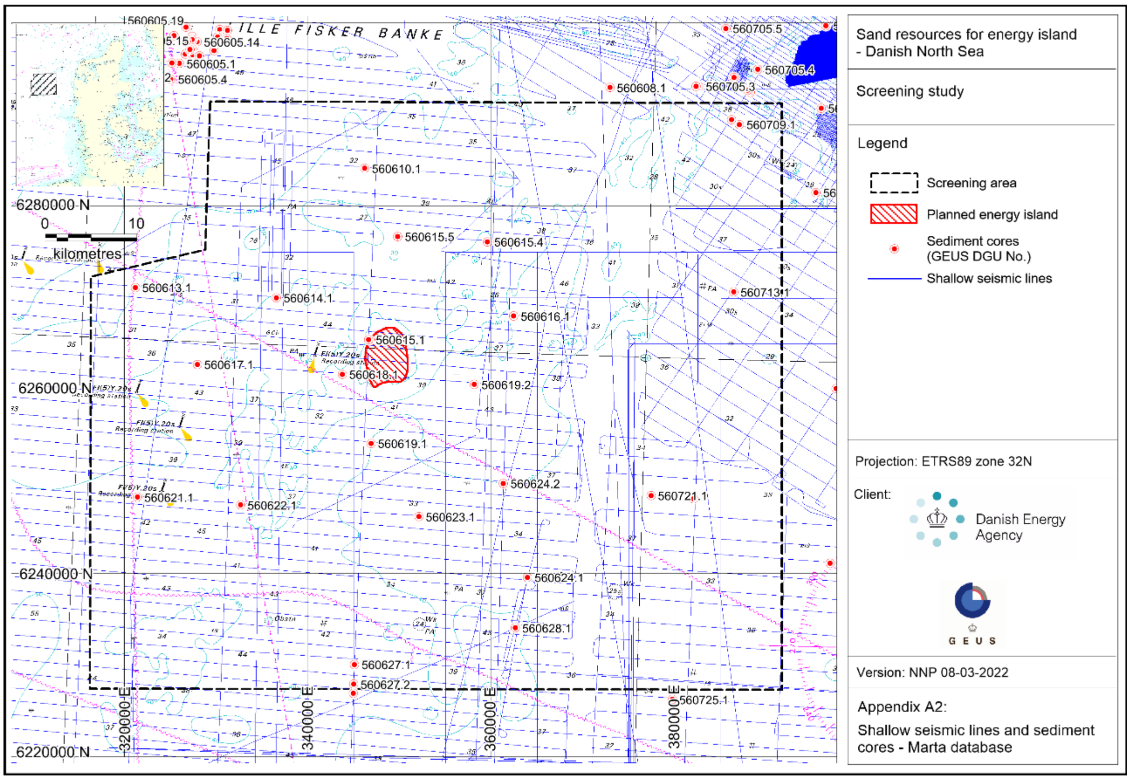


Figure 6.1. Existing seismic lines, sediment cores and mapped aggregate resource areas (Appendix A2).

The vertical penetration of the Sparker data is typically in the range of 50-100 ms (40-80 m subbottom depth). The higher frequency SBP data have a much lower vertical penetration, about 5-40 ms (3-30 m sub-bottom depth), depending on lithological characteristics. On the other hand, the higher frequency SBP data can resolve few decimetre thick seabed layers close to the seafloor. Due to the character of single channel seismic data, multiples at relatively shallow depths will typically obscure the data quality below the first seabed multiple.

All available sediment cores within the screening area were included in an analysis of potential resource quality and as ground truthing for the interpretation of the seismic profiles.

Information on seabed surface lithology (clayey, silty, sandy, gravelly, stony) was based on existing GEUS map products which mainly are derived from side scan sonar mapping with ROV and sediment sample verification points from the above survey campaigns. In addition, seabed lithology data from the 2019-2020 EPA habitat survey were integrated.

6.2 Seismic data

In the western and central part of the screening area, the EW/NS orientated 2010 Sparker line grid has a line distance of about 10 km x 20 km (Figure 6.1). This very open grid was supplemented by 2019 Innomar sub-bottom profiler data along E-W orientated lines with a mutual distance of about 1.5 km. The Innomar data set has hitherto not been integrated in the geological mapping of the North Sea area.

In the eastern part of the screening area, the NW-SE/SW-NE orientated 2010 Sparker grid is about 2.5 km x 5 km. In the southwestern part of the area, the EW/NS orientated Sparker grid from 2012 is about 2.5 km x 10 km.

Between above mentioned two regions, a longitudinal area of about 5-7 km width and about 30 km in length occurs with only very scarse data.

The quality of the original pre-processed single channel sparker data (sgy format) is of highly variable quality due to common rough sea conditions on the North Sea. Typically, it can be observed that better quality data are obtained along courses with the wave propagation from behind. Wave conditions may thus cause that air bubbles occur in the water column directly below the sparker, taking energy out of the acoustic signal, and thereby periodically increasing the noise to signal ratio. Moreover, with increasing wave hights, raw seismic data will be similarly wavy. The Innomar data are somewhat less affected by sea conditions, as the influence of ship movements on the recorded data to a large degree is compensated by a motion sensor mounted on top of the pole along the ship.

In order to increase the quality of the raw seismic data, processing of single line Sparker and Innomar data sets were performed according to procedures described in the following sections.

6.2.1 Processing of sparker data

Sparker data in sgy format were imported to the software Geosuite Allworks and processing was performed according to the following procedure:

- Infinite Impulse Response (Bandpass) filter, low cut-off at 200 Hz, high cut-off 2000 Hz
- Median Filter

- Constant gain of 4 dB
- Trace equalisation from the seabed with a Root Mean Squared (RMS) scaling base
- Normalisation
- Automated Gain Control (AGC)
- Trace mixing of adjacent traces with a weighting of 50, 100, 50 for the previous, current and next shot respectively
- Tracing of seabed
- Muting of the water column
- A time varied gain from the seabed, with 0 dB at the seabed and 20 dB at the end of trace (150 ms TWTT)
- Swell filter over 15 traces

After processing, the sparker data sets were exported in SEGY format and imported in IHS Kingdom (seismic interpretation and visualisation software) for a seismic stratigraphic analysis. The depth axis (Y-axis) of the seismic profiles is shown in two-way travel time (TWT). Unless indicated, the corresponding vertical depth in meter is based on a constant sediment sound velocity of 1600 m/s, ie. an interval of 10 ms corresponds to about 8 m. The uncertainty of this simple time/distance relationship becomes more pronounced with depth.

6.2.2 Processing of sub-bottom profiler data

Innomar data in raw format were converted to SEGY format by Innomar SESConvert64 software. Data were then imported to the software Geosuite Allworks and processing were performed according to the following procedure:

- Median Filter
- Application of a constant gain at 5 dB
- Tracing of seabed
- Trace equalisation from seabed with a Root Mean Squared (RMS) scaling base
- Muting of the water column
- A time varied gain from the seabed, with 0 dB at the seabed and 20 dB at the end of trace (100 ms TWTT)
- Swell filter over 15 traces
- Swell filter over 100 traces

After processing, Innomar data sets were correspondingly exported in SEGY format and imported in IHS Kingdom (seismic interpretation and visualisation software) for a seismic stratigraphic analysis. Vertical depth in meter is based on a constant sediment velocity of 1600 m/s, i.e. an interval of 10 ms corresponds to about 8 m.

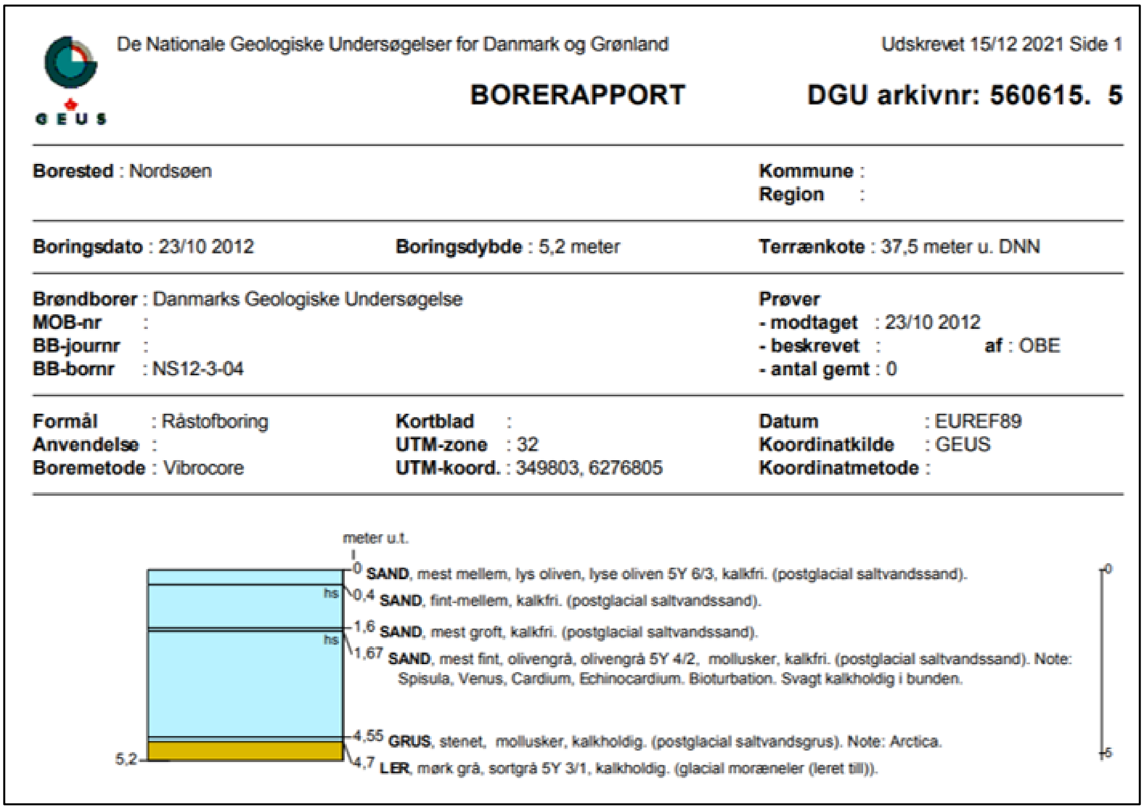
6.3 Sediment cores

All available sediment cores from GEUS' marine raw material database within the screening area were included in an analysis of potential resource quality and as ground truthing for the interpretation of the seismic profiles. Figure 6.1 gives an overview of core location in relation to seismic lines. Table 6-1 gives a summary of core location, potential resource thickness and dominant grain size, as well as a link to the sediment core log description. Two examples of core descriptions are shown in Figure 6.2 and Figure 6.3.

Table 6-1. Overview and evaluation of resource potential of existing sediment cores in the screening area.

DGU No.	X UTM32 EUREF89	Y UTM32 EUREF89	Water depth (m)	Core length (m)	Est. resource thickness (m)	Resource grain size	Core description link
560624.3	373976	6237732	36	5.90	1.10	unsorted sand	Link
560624.4	372021	6237540	36	6.00	>6.00	f-m sand	Link
560624.5	368298	6237815	36	3.10	>3.10	unsorted sand	Link
560624.6	374976	6238724	37	2.00	>2.00	f-m sand	Link
560721.3	377580	6238544	36	5.60	1.20	f sand	Link
560721.4	382304	6238248	36	5.70	4.60	f sand	Link
560722.6	391763	6237574	32	5.00	>5.0	f sand	Link
560722.7	398051	6237102	32	5.20	>5.20	f sand	Link
560721.5	380103	6248371	34	1.65	>1.65	f sand	Link
560721.6	386501	6247921	34	1.75	-	no resource (clay)	Link
560717.3	381737	6250267	34	4.25	0.91	f sand	Link
560717.4	378591	6250519	34	4.14	2.24	f sand	Link
560725.2	377061	6234571	36	5.20	2.90	f-m sand	Link
560725.3	384376	6234051	35	3.35	>3.35	f sand, m-c at base	Link
560725.4	387266	6231862	35	5.87	-	no resource (silty fine sand)	Link
560725.5	380132	6232365	35	3.94	1.02	f-m sand	Link
560725.6	387853	6229805	35	5.90	-	no resource (silty fine sand)	Link
560725.7	389719	6229661	30	5.94	0.78	unsorted sand	Link
560725.8	387045	6227869	34	5.66	0.59	unsorted sand	Link
560725.9	382891	6228163	35	4.60	1.66	f sand	Link
560725.10	381214	6226253	34	5.66	-	no resource (silty fine sand)	Link
560628.4	373234	6226891	36	0.60	-	no resource (sandy till, gravel on top)	Link
560628.5	371384	6226940	36	1.51	-	no resource (clayey til, sand on top)	Link
560725.1	379714	6226348	34.8	5.40	1.20	f sand	Link
560721.1	377392	6248580	34	5.39	2.15	f sand	Link
560615.2	361164	6276157	41.3	5.90	2.75	f sand, m-c at top	Link
560615.3	360685	6276152	42.5	5.87	-	no resource (clay)	Link
560615.4	359547	6276214	42.5	5.05	-	no resource (silty fine sand)	Link
560615.5	349803	6276805	37.5	5.20	4.70	f-m sand	Link
560616.1	362422	6268134	41	5.54	1.03	m sand	Link
560614.1	336596	6270112	39.6	5.65	-	no resource (clay layer, sand at top)	Link
560613.1	321193	6271258	42.2	5.85	>5.85	f-m sand	Link
560617.1	327954	6262874	40.8	5.87	3.96	m-c sand, fine at base	Link
560618.1	343760	6261796	43.5	5.70	-	no resource (clay layer, sand at top)	Link
560619.2	358147	6260680	44	2.47	1.02	f sand	Link

560619.1	346883	6254255	40.6	5.82	2.48	f sand, gravelly at base	Link
560615.1	346633	6265572	32.4	5.40	3.45	fine gravel and sand	Link
560623.1	352100	6246279	38	5.40	5.40	f sand, gravelly at base	Link
560622.1	332675	6247556	47.1	5.00	>5.00	f sand, gravelly intermediate layer	Link
560621.1	321426	6248396	42.1	5.35	1.14	m sand	Link
560624.1	363924	6239643	36.8	3.57	>3.57	variable size sand layers	Link
560628.1	362601	6234155	38.7	4.33	>4.33	m-c sand, gravelly intermediate layer	Link
560624.2	361310	6249887	42	5.27	-	no resource (silt)	Link
560610.1	346212	6284245	35	5.84	5.51	f sand, silt layer in intermediate part	Link
560709.1	387032	6289017	41	2.25	>2.25	f sand	Link
560710.3	395928	6290800	36	2.64	>2.64	m-c sand	Link
560709.2	386165	6289562	41	2.37	1.23	f sand, gravelly at top	Link
560710.4	395377	6281600	43	2.68	2.30	f sand	Link
560713.1	386391	6270762	41	4.00	>4.00	f-m sand	Link
560718.1	397582	6260215	42	3.10	-	no resource (clay with sandy top)	Link
560710.6	398084	6289551	30	3.90	2.07	f sand	Link
560710.7	398787	6288284	27	4.80	>4.80	f-m sand	Link
560710.9	396191	6289813	30	5.60	2.64	m sand, gravelly intermediate part	Link
560710.10	396634	6288048	28	5.57	4.52	f-m sand, gravellly at base	Link
560710.11	396999	6290279	29	2.13	-	no resource (clay with sandy/gravelly top)	Link
560710.12	396510	6289969	30	4.94	3.44	fine gravel / fine sand	Link



De Nationale Geologiske Undersøgelser for Danmark og Grønland
Udskrevet 15/12 2021 Side 1

BORERAPPORT **DGU arkivnr: 560615. 5**

Borested : Nordsøen
Kommune :
Region :

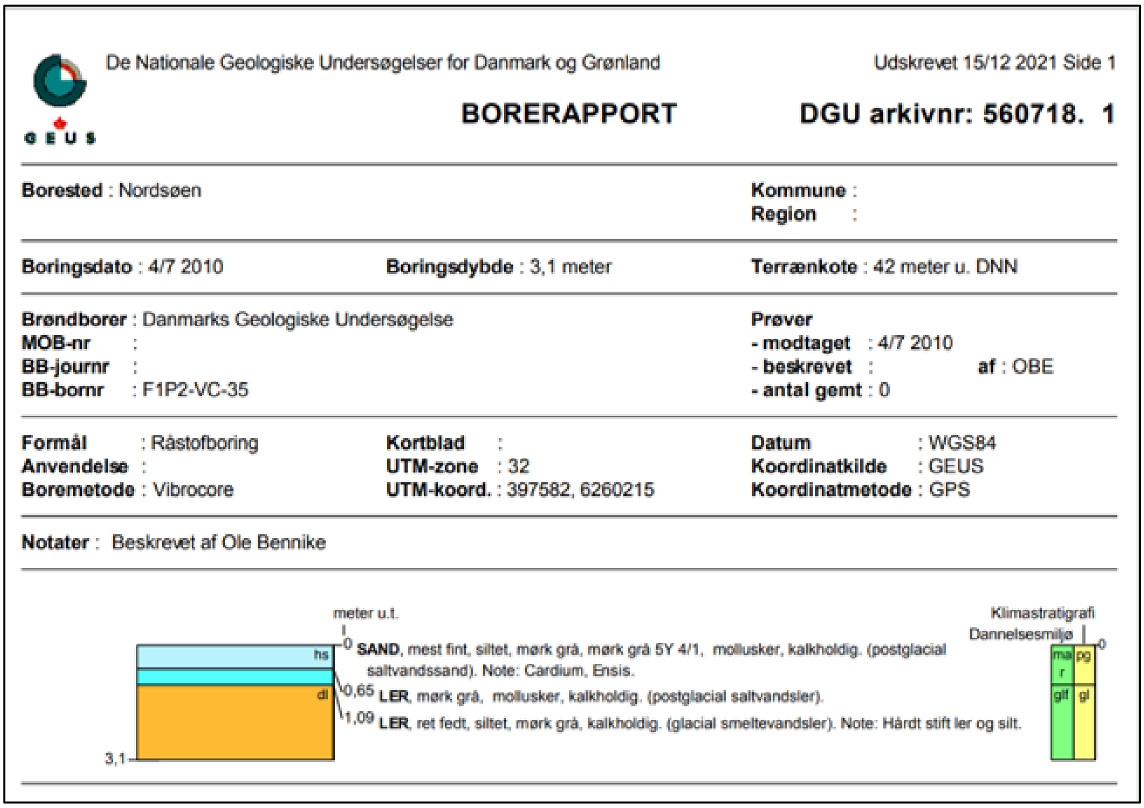
Boringsdato : 23/10 2012 **Boringsdybde** : 5,2 meter **Terrænkote** : 37,5 meter u. DNN

Brøndborer : Danmarks Geologiske Undersøgelse
MOB-nr :
BB-journr :
BB-bornr : NS12-3-04

Prøver
- modtaget : 23/10 2012
- beskrevet : **af** : OBE
- antal gemt : 0

Formål : Råstofboring
Anvendelse :
Boremetode : Vibrocore
Kortblad :
UTM-zone : 32
UTM-koord. : 349803, 6276805
Datum : EUREF89
Koordinatkilde : GEUS
Koordinatmetode :

Figure 6.2. Example of core description (core No. 560615.5) showing a section of 5.7 m fine-medium grained marine sand on top of clay (glacial till).



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Udskrevet 15/12 2021 Side 1

BORERAPPORT **DGU arkivnr: 560718. 1**

Borested : Nordsøen
Kommune :
Region :

Boringsdato : 4/7 2010 **Boringsdybde** : 3,1 meter **Terrænkote** : 42 meter u. DNN

Brøndborer : Danmarks Geologiske Undersøgelse
MOB-nr :
BB-journr :
BB-bornr : F1P2-VC-35

Prøver
- modtaget : 4/7 2010
- beskrevet : **af** : OBE
- antal gemt : 0

Formål : Råstofboring
Anvendelse :
Boremetode : Vibrocore
Kortblad :
UTM-zone : 32
UTM-koord. : 397582, 6260215
Datum : WGS84
Koordinatkilde : GEUS
Koordinatmetode : GPS

Notater : Beskrevet af Ole Bennike

Figure 6.3. Example of core description (core No. 560718.1) showing a section of 0.65 m marine sand on top of two clay unit. This site was classified as not having a resource potential.

7. Results

7.1 Interpretation of seismic profiles

The seabed and boundaries between main surface-near seismic units were traced on the available seismic profiles. Interpretation of deeper penetration but lower resolution sparker data and lower penetrating but higher resolution Innomar data took place in the same Kingdom seismic interpretation project. Results from available sediment cores along seismic lines were integrated in the interpretation of seismic unit stratigraphic and lithological character.

Six seismic units were identified and geologically interpreted, representing deposits ranging from Weichselian or older subglacial till or buried valleys, to late glacial meltwater and lacustrine deposits, and to Holocene shallow marine and more open marine deposits (Table 7-1).

Table 7-1. Identified seismic units and interpretation of lithology, environment and age.

Unit	Seismic reflection pattern	Lithology	Depositional environment	Age
1	Massive-weak parallel reflection	Sand	Open marine	Late Holocene
2	Weak parallel reflection	Clay/silt/sand + organic	Shallow marine + brackish-fluvial	Early Holocene
3	Distinct fine parallel reflections	Clay/silt/sand	Lacustrine	Late glacial
4	High amplitude reflection pattern with discontinuous and undulating reflection	Sand/gravel/silt/clay	Proglacial meltwater	Weichselian
5	Infill of large channels/valleys. Variable reflection pattern	Variable	Subglacial	Weichselian or older
6	Massive-chaotic reflections	Till (clay-boulders)	Subglacial	Weichselian or older

In general, it was possible to identify the distinct erosional base of Holocene marine deposits, which are considered to be the main potential sand resource. However, at sites with >8-10 m thick Holocene deposits of sandy character, the base of the unit was getting increasing indistinct and difficult to trace on high frequency Innomar data. Hereby, data from sparker cross-lines was used as well as lateral extrapolation of reflections along lines where the sand units were less thick.

In the eastern part of the screening area, mainly characterised by high reflective meltwater deposits, only sparker data was used. In that area, a distinct reflector identified as top of glacial deposits/base of weichselian meltwater deposits was mapped out. Due to limited numbers of sediment cores, it was not possible to separate distinct sand, gravelley or clayey/silty subunits in the meltwater unit. Moreover, the base of potential marine sandy deposits superimposed on the meltwater deposits was mapped out.

Sparker and Innomar seismic examples with focus on potential sand deposit units as well as areas characterised by sediment units that cannot be considered to have resource potential are shown in the following Figure 7.1, Figure 7.2, Figure 7.3, and Figure 7.4.

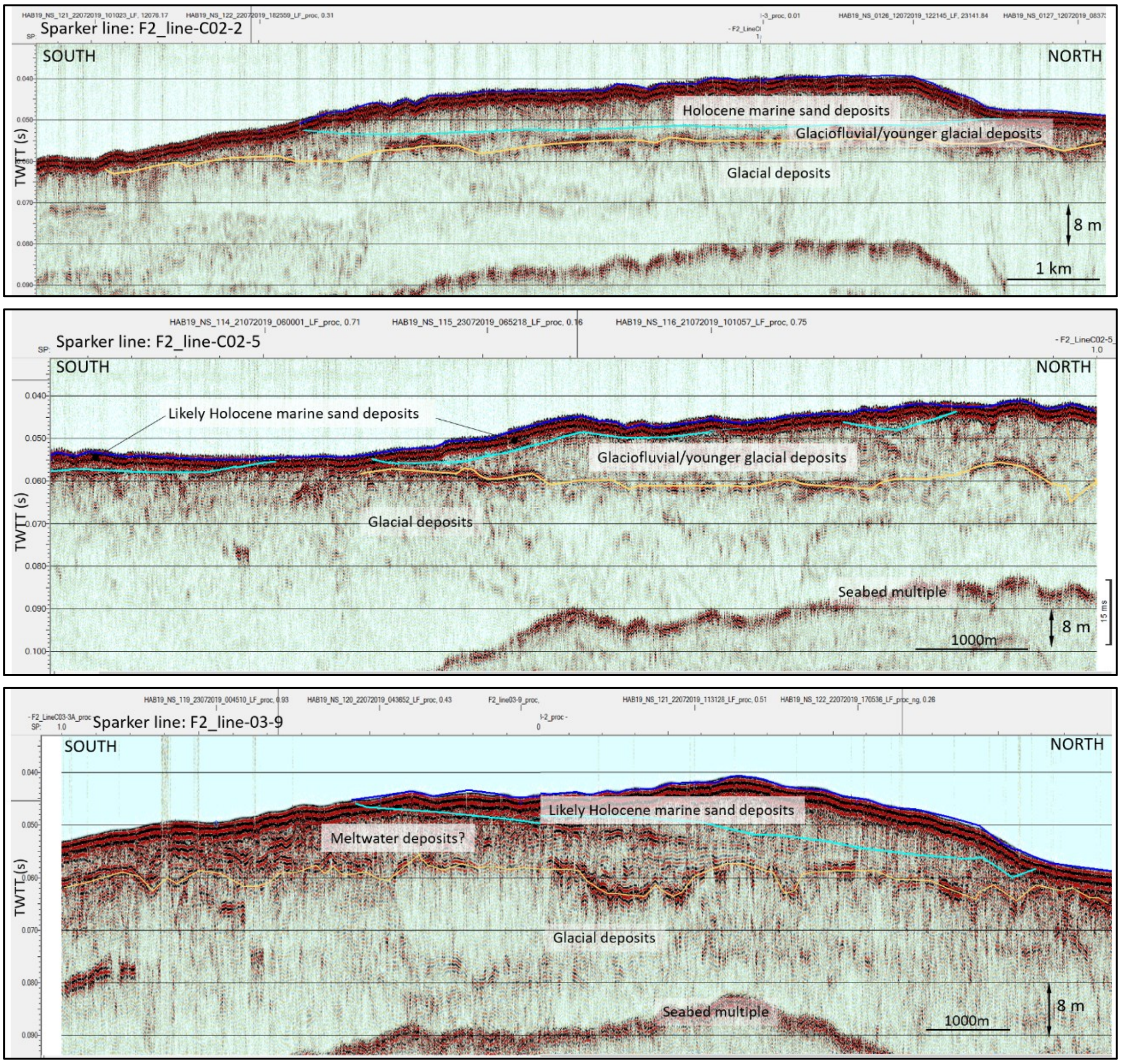

Figure 7.1. Examples of interpreted Sparker seismic sections from the northern and central part of the screening area. Glacial deposits, glaciofluvial or younger glacial deposits, and Holocene marine sand deposits (potential resource) were identified.

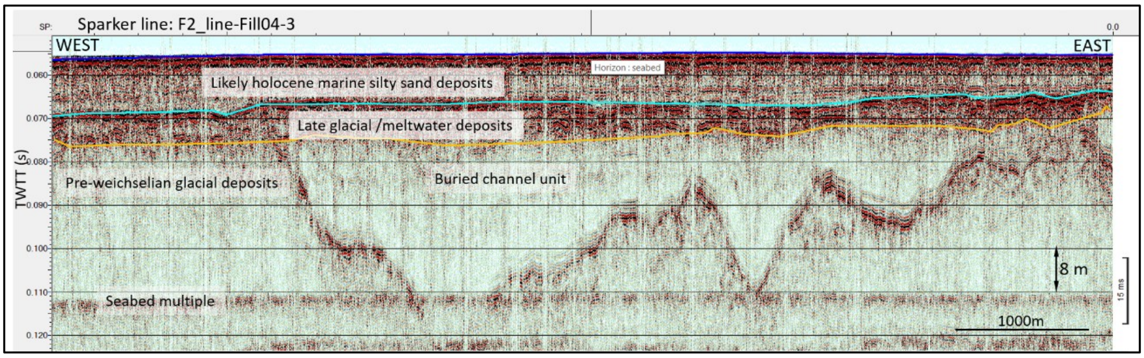

Figure 7.2. Example of Sparker seismic section from the southern part of the screening area which is characterised by a thick Holocene cover of possible silty fine-grained sand (considered not to have resource value).

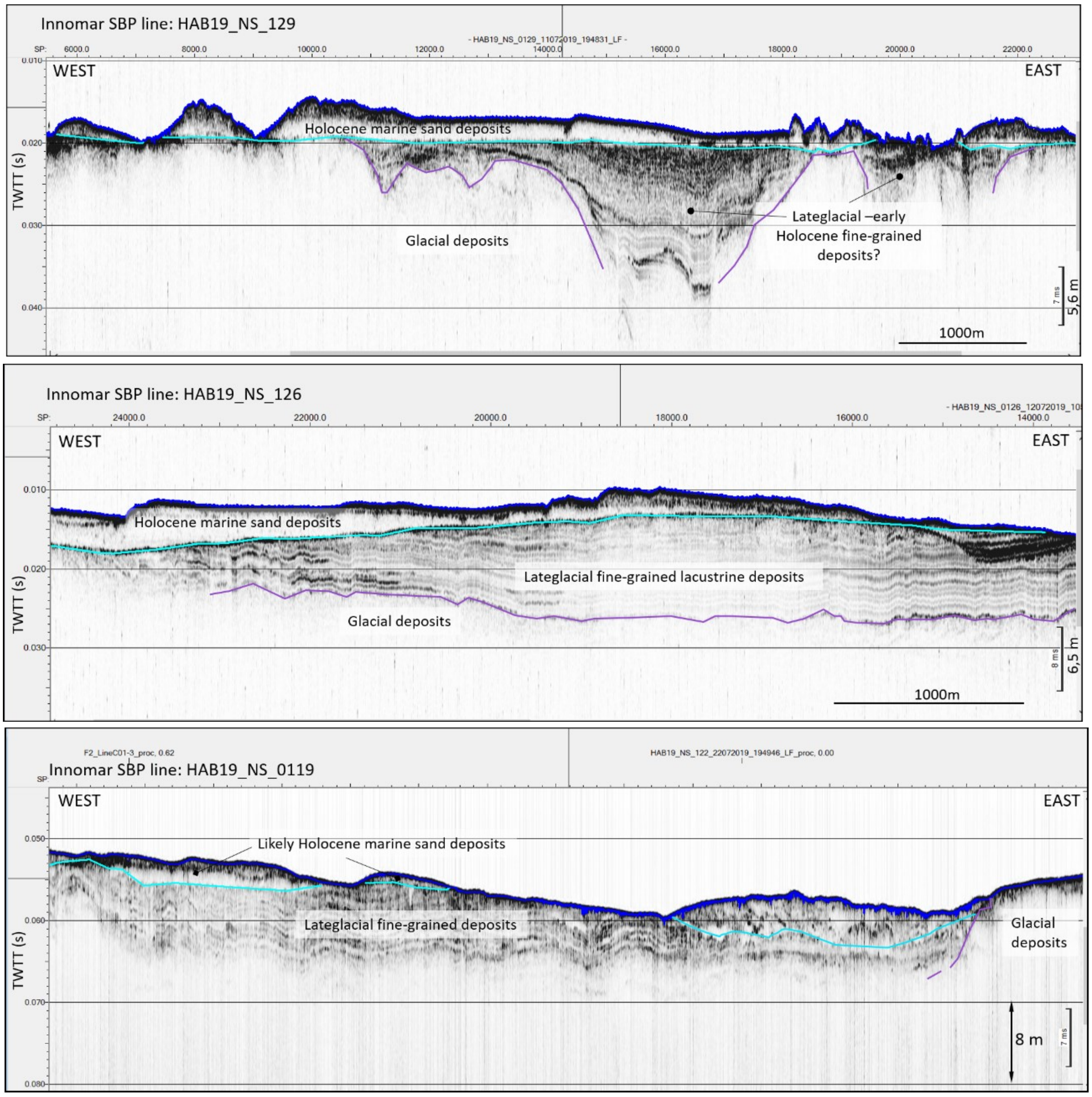

Figure 7.3. Example of high-resolution Innomar seismic profiles showing finely layered late-glacial clay-silt deposits (possibly lacustrine), superimposed by up to c. 5 m thick more massive appearing Holocene marine sand deposits.

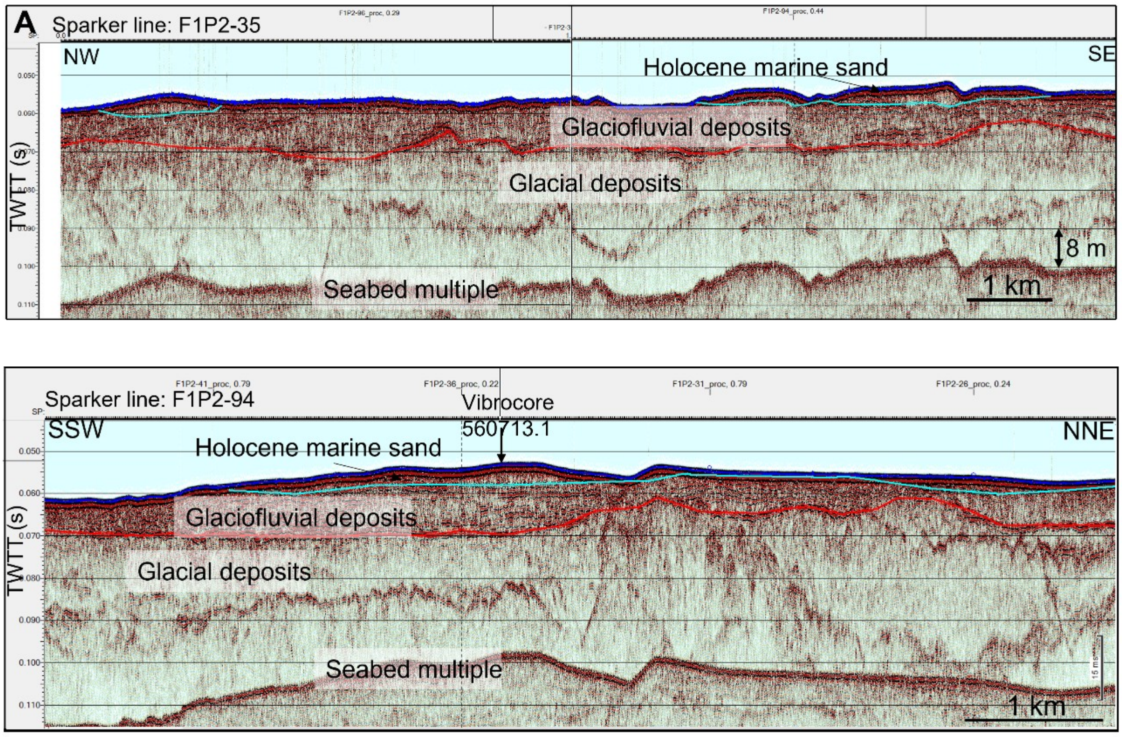

Figure 7.4. Sparker seismic profiles from the northeastern part of the screening area, characterised by an ubiquitous unit of glaciofluvial deposits and only locally a thin cover of Holocene marine sand deposits.

7.2 Geological conceptual model

A conceptual model of the upper c. 30 m of the subsurface geology of the screening area was established on basis of interpretation of seismic profiles verified by a limited number of sediment cores (Figure 5.5). The schematic geological cross section shows a high-lying glacial surface locally with in-filled valleys. On top of this, a c. 5-10 m thick composite unit of proglacial meltwater sediments is found. Most of the unit was possibly deposited in shifting braided river systems and meltwater lakes during the last glacial Weichselian period. The meltwater sediment unit which shows variable seismic reflection patterns, possibly varies a lot with respect to grain size composition both vertically as well as laterally. Due to very limited number of sediment cores for verification of composition, it has not been possible to subdivide the unit. In parts of the screening area, a distinct finely layered unit dominated by clay and silt can be observed between the meltwater sediment unit and overlying marine Holocene sediments. The fine laminated character of the sediment and absence of marine shells suggest that the unit represents late glacial lacustrine sediments of possible larger dammed lake systems that existed in the North Sea during the late part of the Weichselian. Holocene marine sandy sediments are found as a thin sediment cover over large parts of the area. However, in the northern part of the area, large marine bar form structures with a thickness of up to 5-8 m occur. The grain size of the sand in the bar formsis typically fine-medium grained, with a tendency to be more fine-grained in the lower part of the bar forms. The southwestern part of the screening area is characterised by an infilled larger depression, and here Holocene sediments reach a thickness of 10-15 m. There are no sediment cores from that area, but surface sediment mapping with HAPS/grab sampling indicates that the sediments are silty fine sand, and therefore do not have resource potential.

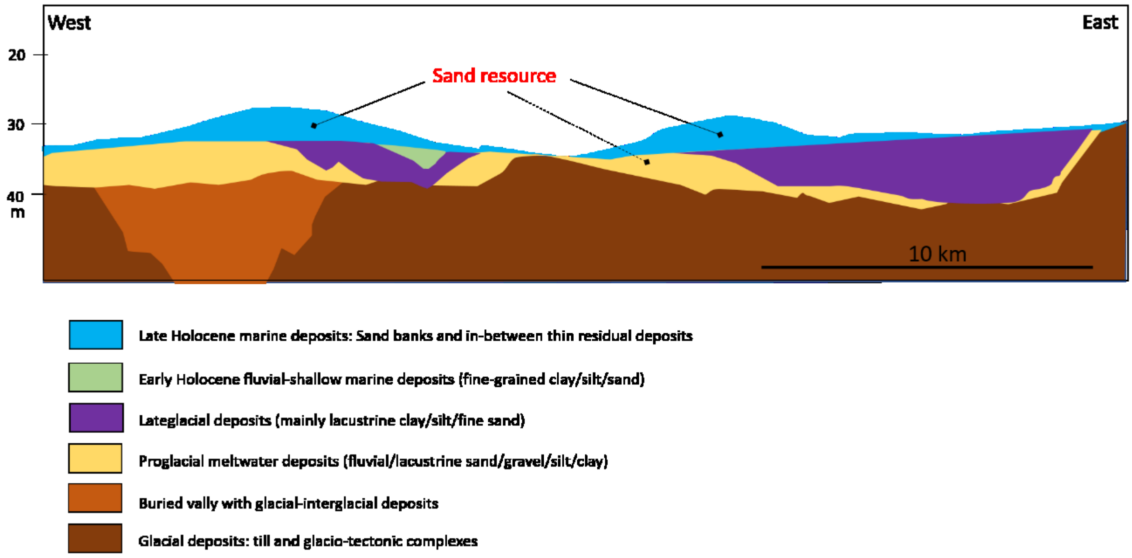

Figure 7.5. Geological conceptual model for surface near geological units and sand resource type.

7.3 Identification of sand resource areas

On basis of seismic mapping, thickness data of potential sand resource units along seismic lines were produced (Holocene unit and eastern area Meltwater unit). The thickness data are shown in map form in Figure 7.6 and Figure 7.7.

Sediment core data from the Holocene marine sand bar forms in the northern part of the screening area confirm that the sand grain sizes are fine to medium grained. There are no sediment core data from the thick Holocene sediment infilled depression in the southern part of the area, but surface sediment sampling as well as the seismic character indicate that the unit is too fine-grained to have resource potential.

There is limited sediment core data from the large meltwater sediment unit identified in the eastern part of the screening area. It is therefore not possible to subdivide the unit into specific resource areas. Local areas with a 2-4 m thick Holocene sand cover were identified on top of the meltwater sediment unit in the north-eastern part of the screening area. These local Holocene sand occurrences together with the underlying meltwater sediments are suggested as a resource of material with potential more widespread composition as the possible more homogeneous Holocene resource areas north and west of the planned energy island area.

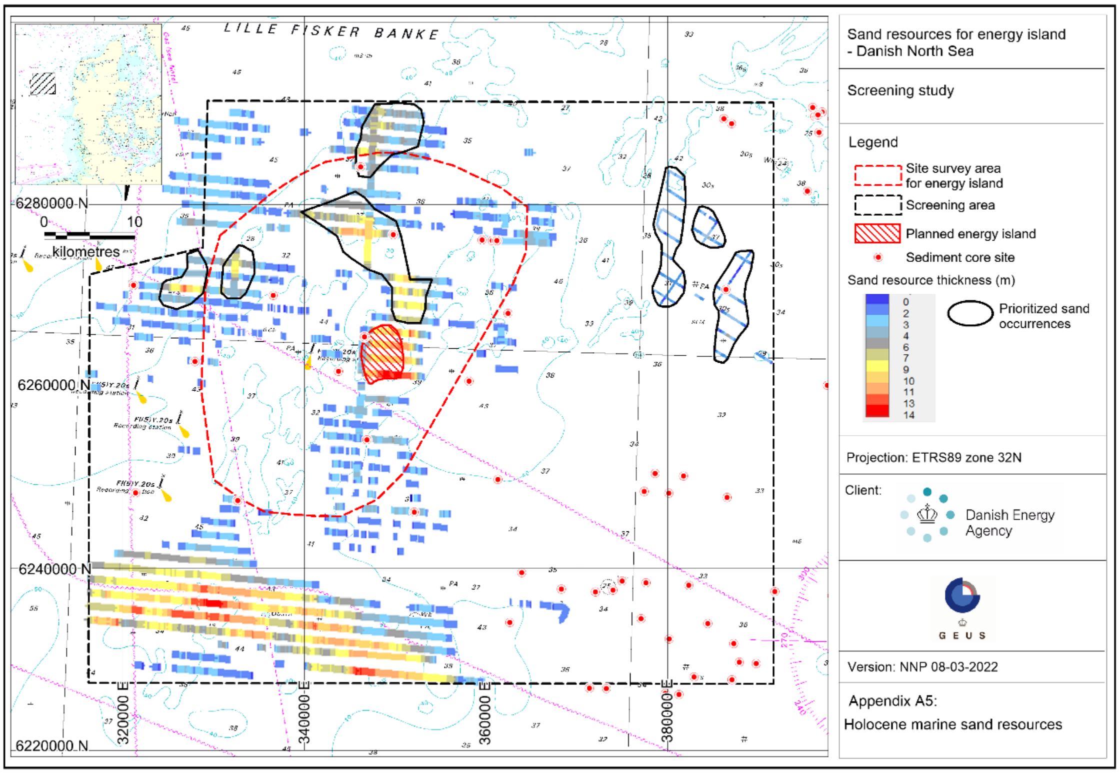

Figure 7.6. mapped thickness of Holocene marine sand resources along seismic lines (Appendix A5).

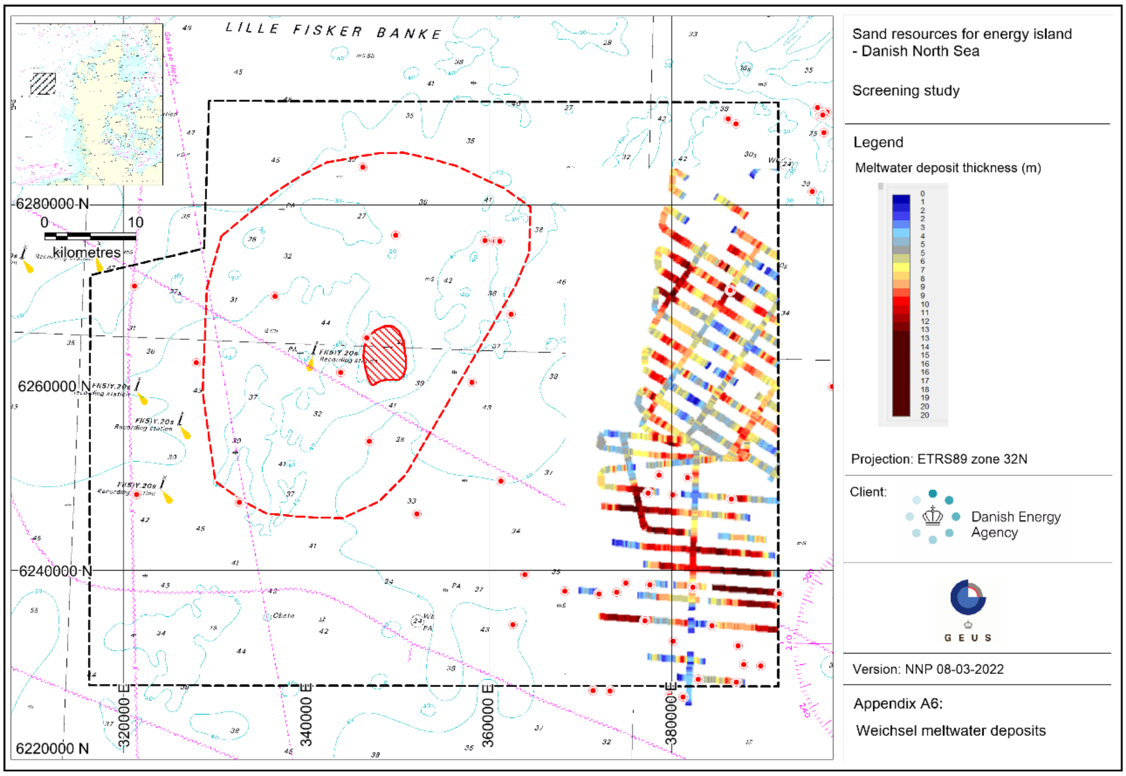

Figure 7.7. Mapped thickness of meltwater deposits (potential sand resource) along seismic lines in eastern part of screening area (Appendix A6).

7.4 Surficial sediments and non-resource areas

In order to get an overview of the variability of sediment units close to the sea floor, an overview map was produced (Figure 7.8). The map shows areas dominated by glacial till, eastern meltwater unit, undifferentiated late glacial clay/silt/sand, fine grained Holocene marine unit, Holocene marine sand unit, and an area which is considered to have insufficient data for interpretation. It must be emphasized that over large parts of the area with no indicated Holocene sediment cover, there is likely to be a thin (<1m) marine reworked top unit.

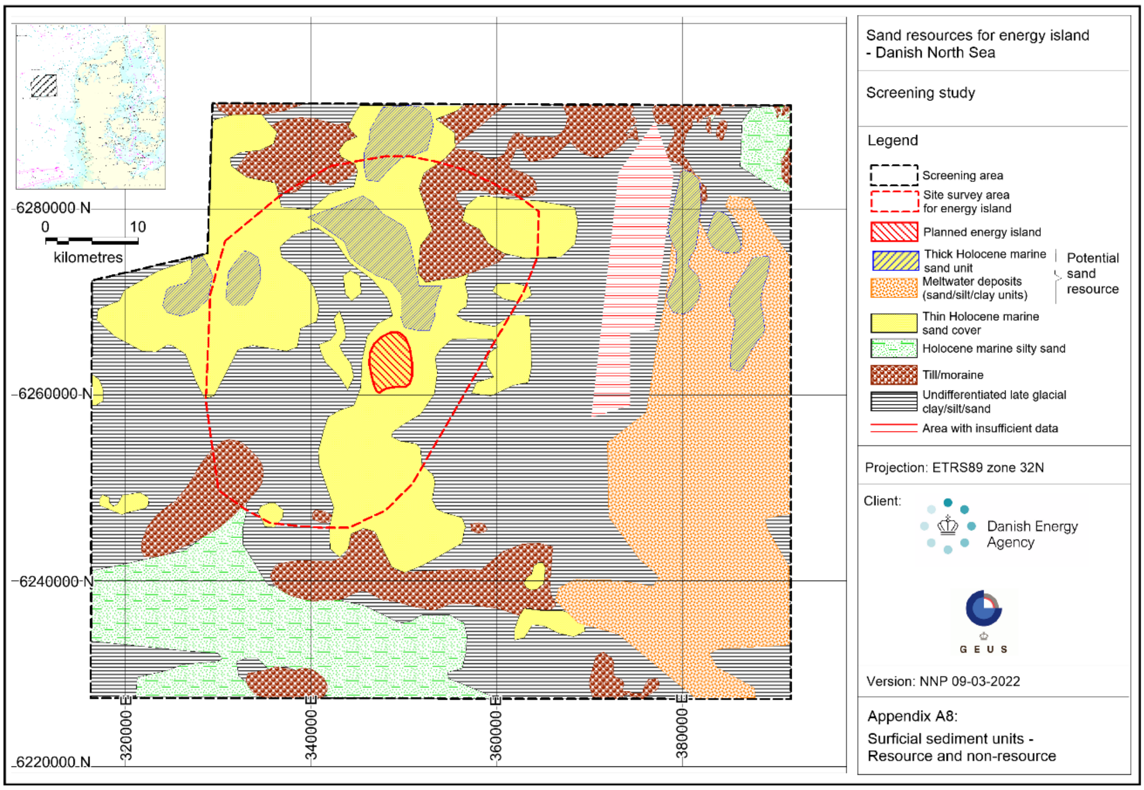

Figure 7.8. Overview of sediment units close to the sea floor.

8. Selection of potential sand resource survey areas

Three potential sand resource survey areas A, B, and C were selected on basis of the overall mapping results (Figure 8.1). The characteristics of each area are given in Table 8-1. Polygon coordinates for the proposed sand resource survey areas are given in Table 8-2, Table 8-3, and Table 8-4.

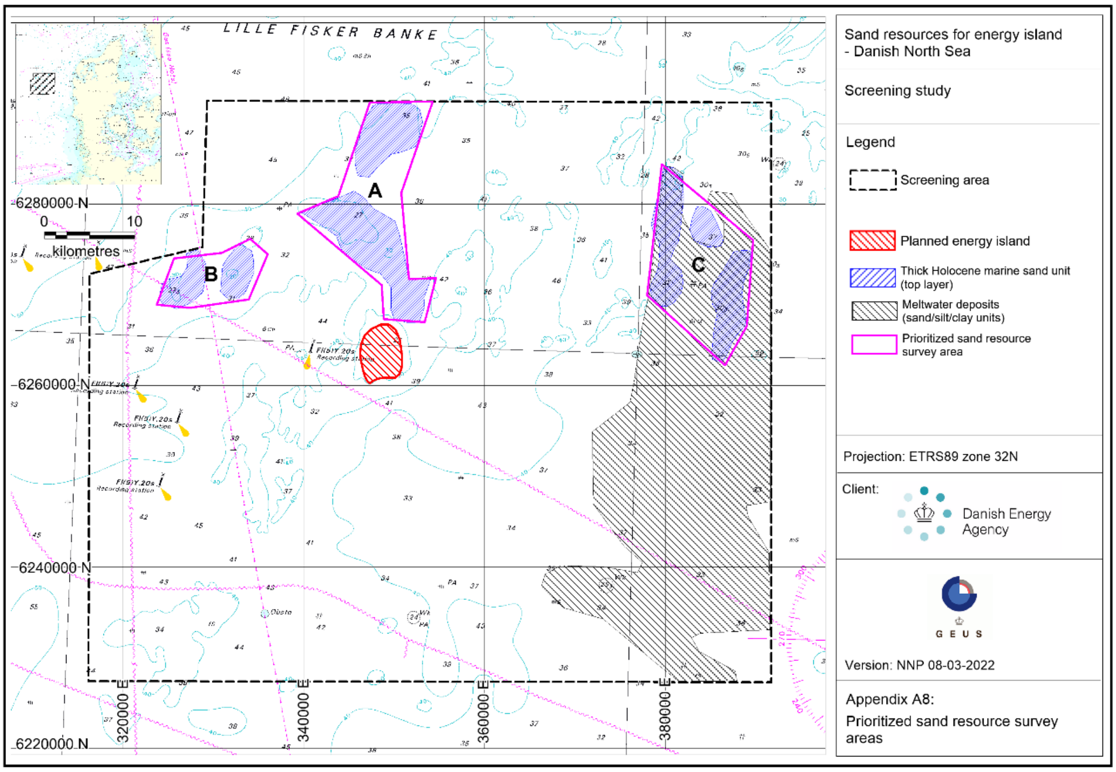

Figure 8.1. Potential sand resource survey areas A, B, and C. Appendix A8.

Table 8-1. Characteristics of potential sand resource survey areas

Sand resource survey area	Area (km2)	Max. thickness (m)	Volume (mill. m3) by 1 m dredging	Grain size	Deposit type
A	168.7	10	169	Fine-medium sand	Marine sand
B	59.3	10	59	Fine-medium sand	Marine sand
C	159.8	15	160	Fine-medium sand/ potential coarser sand and gravel	Marine sand/ Meltwater deposits

Table 8-2. Polygon coordinates for proposed survey area A.

	X (UTM32 N)	Y (UTM32N)	Longitude E	Latitude N
A1	347315	6291216	006° 30.219'	56° 44.394'
A2	354259	6291303	006° 37.021'	56° 44.574'
A3	350787	6281235	006° 33.969'	56° 39.086'
A4	351625	6271759	006° 35.114'	56° 33.999'
A5	354606	6271862	006° 38.019'	56° 34.110'
A6	353391	6267002	006° 36.998'	56° 31.470'
A7	348878	6267349	006° 32.589'	56° 31.571'
A8	348617	6271081	006° 32.204'	56° 33.576'
A9	339331	6278979	006° 22.854'	56° 37.644'
A10	343844	6280888	006° 27.194'	56° 38.764'

Table 8-3. Polygon coordinates for proposed survey area B.

	X (UTM32 N)	Y (UTM32N)	Longitude E	Latitude N
B1	325705	6274032	006° 09.745'	56° 34.689'
B2	330999	6274640	006° 14.886'	56° 35.132'
B3	334123	6276202	006° 17.874'	56° 36.040'
B4	336033	6274466	006° 19.804'	56° 35.146'
B5	333950	6269519	006° 17.962'	56° 32.438'
B6	327438	6268566	006° 11.653'	56° 31.784'
B7	323795	6268911	006° 08.090'	56° 31.889'

Table 8-4. Polygon coordinates for proposed survey area C.

	X (UTM32 N)	Y (UTM32N)	Longitude E	Latitude N
C1	379561	6284413	007° 02.019'	56° 41.296'
C2	389629	6276012	007° 12.092'	56° 36.919'
C3	388950	6266561	007° 11.671'	56° 31.817'
C4	386541	6262238	007° 09.436'	56° 29.453'
C5	377955	6269959	007° 00.857'	56° 33.484'

9. Requirements for approval of raw material extraction areas

EPA is responsible for the management of offshore aggregate extraction allowances and approval of prior investigation programmes. Five types of areas exist:

- Common areas (Fællesområder)
- Potential common areas (Potentielle fællesområder, previously called 'Overgangsområder')
- Auction areas (Auktionsområder)
- Reservation areas (Reservationsområder)
- Specific purpose construction areas (Bygherreområder)

For energy island construction in the central Danish North Sea, it is envisaged that filling sand extraction will take place from a 'specific purpose construction area'.

The procedures listed below are a prerequisite for getting a permission from EPA to extract sand and gravel from a dedicated offshore area:

- Application for offshore raw material prospection (addressed to EPA and Danish Geodata Agency)
    - The application describes the investigation area and methods to be used following statutory requirement specifications from EPA. It shall be attached an environmental impact assessment (EIA) report on the expected effects of the planned investigations on the environment.

- Offshore survey (application area incl. 500 m surrounding zone)

  After approval by EPA (including a public hearing phase), the raw material survey can be carried out. The survey can take place in two steps with a first phase IA regional survey followed by a detailed phase IB covering a selected part of the gross area, and with maximum 100 m between seismic lines. The survey typically includes:

    - Seismic survey (Sparker/SBP, Side scan sonar, Echosounder, Magnetometer)
    - Vibrocoring incl. core description and lab analyses (optional)
    - ROV point investigations (seabed substrates, habitat types, biology with benthic flora and fauna)

- Raw material mapping including:
    - Bathymetry (based on single or multibeam echosounder)
    - Side scan sonar mosaic
    - Seabed substrate types
    - Archaeological screening of man-made features and artefacts
    - Resource mapping (areal extension and volume)
    - Environmental evaluation of habitat types and expected effects of aggregate dredging on benthic life, fish stocks, bird life and marine mammals

- Application for permission of aggregate extraction (to EPA) including survey reports and proof of raw data delivery to GEUS and side scan sonar data to museum responsible for offshore archaeological findings

- After expiration of permit: final survey of seabed surface character
  - Side scan sonar and bathymetry survey
  - ROV survey typical including re-visit to previous ROV sites
  - Summary report to EPA

10. Conclusions and recommendations

An area with a distance of c. 50 km from the planned energy island in the Danish North Sea was screened in order to clarify the possibilities for dredging of larger amounts of sand for energy island construction.

The study shows that large potential sand resources of the suitable grain size composition may be found in large marine sand bar structures to the north and northwest of the energy island area. The largest and closest area to the energy island (area A) can at this step be considered to be the primary potential resource area. To the northeast, potential marine sand resources of limited thickness are found on top of a very large area dominated by thick melt-water deposits, which potentially can be a resource of coarser sand and gravel. Sediment core data describing the grain size variability in the potential resource areas are very limited and further sediment coring is recommended before a dedicated seismic mapping programme of sand resource distribution can be undertaken.

It is recommended to further investigate the identified potential sand resource areas by:

- Performing a dedicated sediment coring programme with sites selected based on existing seismic data. This corresponds to a phase 1A geological/geophysical resource investigation according to the requirement specification by EPA.

- Selecting of 2-3 seismic survey areas where a larger number of sediment core sites has verified sand resources of suitable composition.

- Execution of detail-seismic survey in selected resource areas This corresponds to a phase 1B geological/geophysical resource investigation according to the requirement specification by EPA.

- Collecting of additional sediment cores in selected sub-areas, which can be expected to be included in future dredging areas. The final verification step is necessary in order to get a comprehensive view of grain size variability and consistent differences to be used in the planning of the future dredging programme.

11. References

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Appendices

A1 – Screening area

A2 – Seismic lines and sediment core positions

A3 – Bathymetry

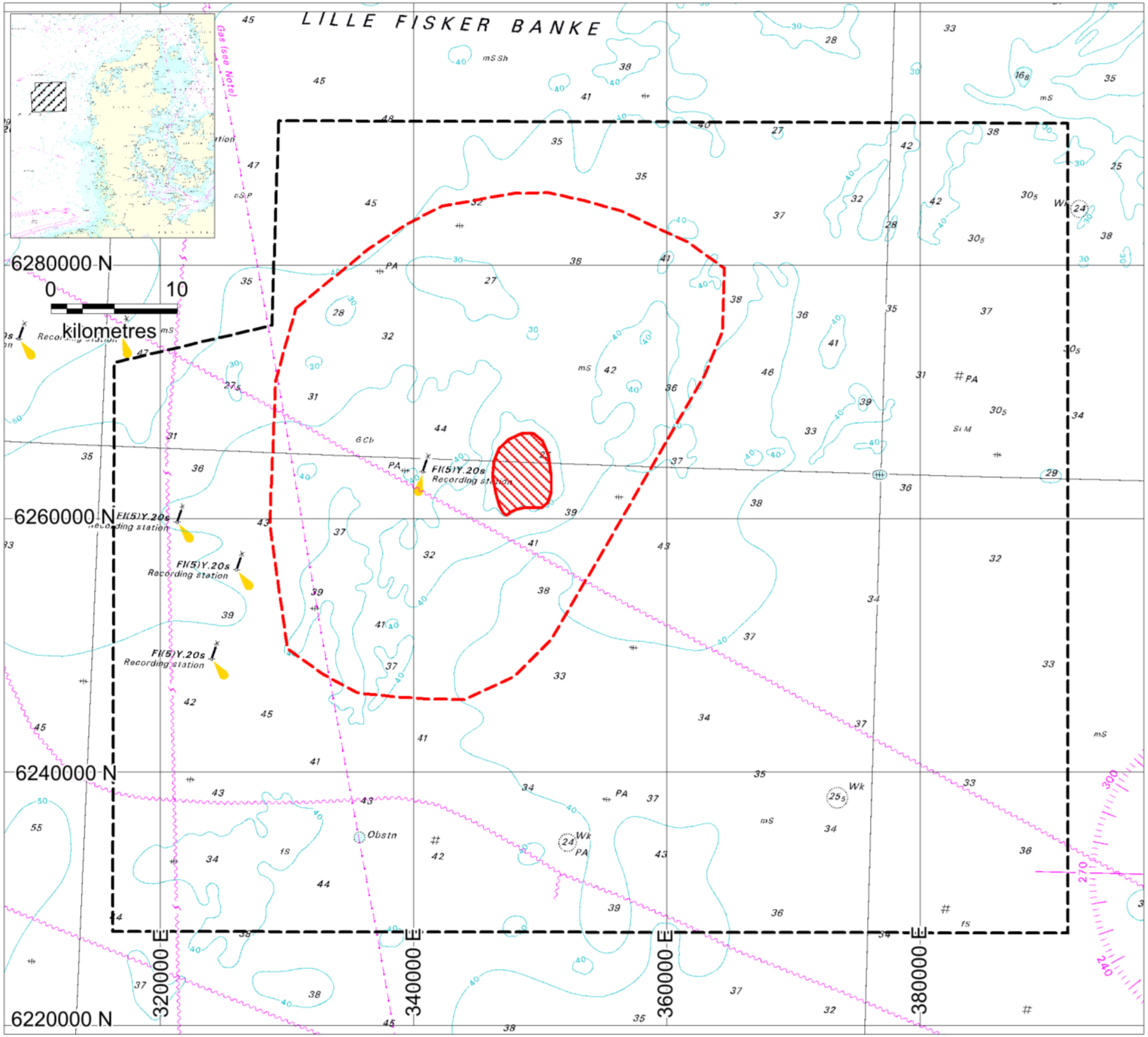
A4 – Seabed surface sediments

A5 – Holocene marine sand occurrence

A6 – Meltwater deposit occurrence

A7 – Surficial sediment units/non-resources

A8 – Prioritized potential survey areas



Sand resources for energy island
- Danish North Sea

Screening study

Legend

Screening area

Site survey area
for energy island

Planned energy island

Projection: ETRS89 zone 32N

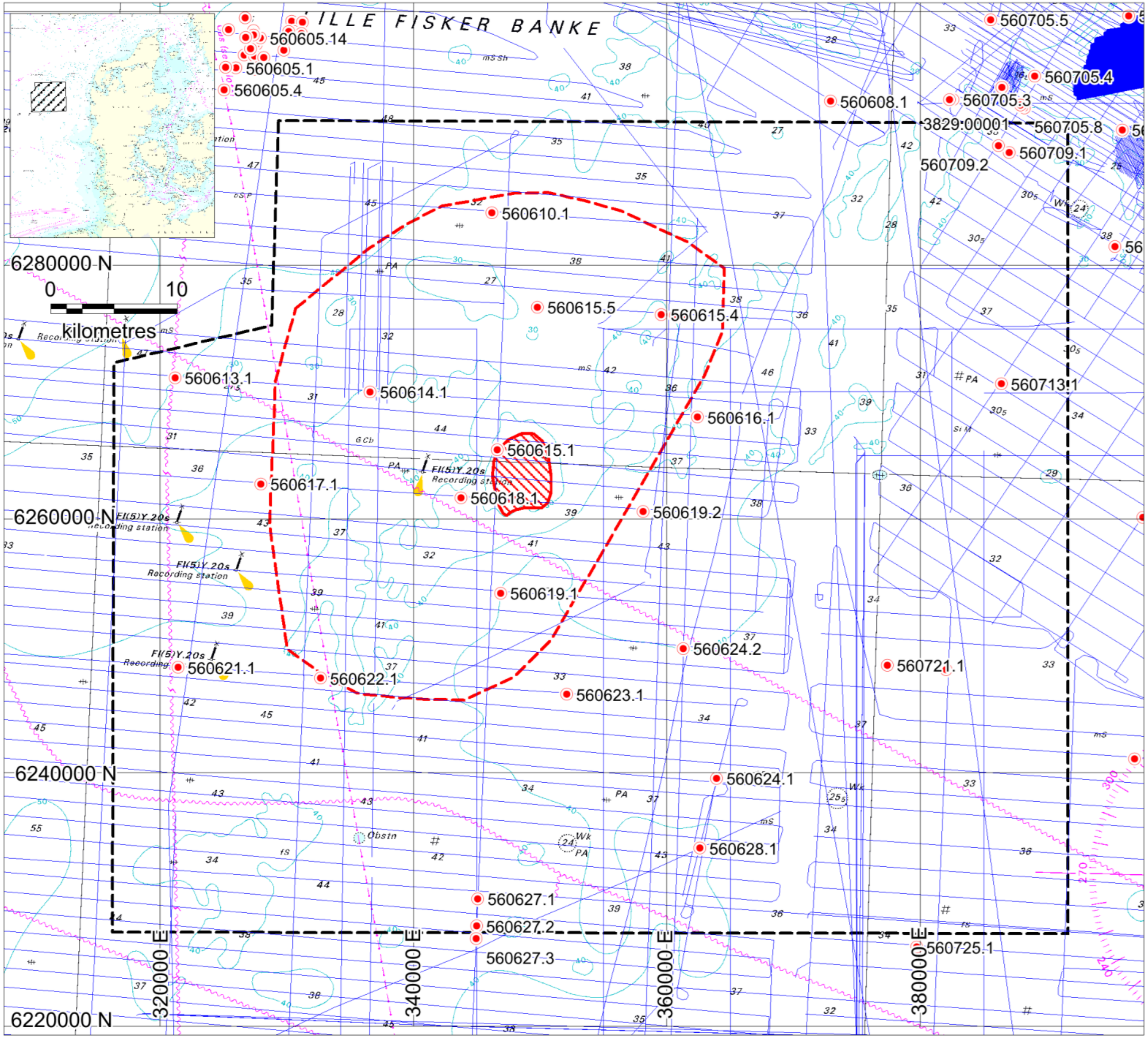
Client: Danish Energy Agency

GEUS

Version: NNP 08-03-2022

Appendix A1:

Screening area



Sand resources for energy island - Danish North Sea

Screening study

Legend

- Site survey area for energy island
- Screening area
- Planned energy island
- Sediment cores (GEUS DGU No.)
- Shallow seismic lines

Projection: ETRS89 zone 32N

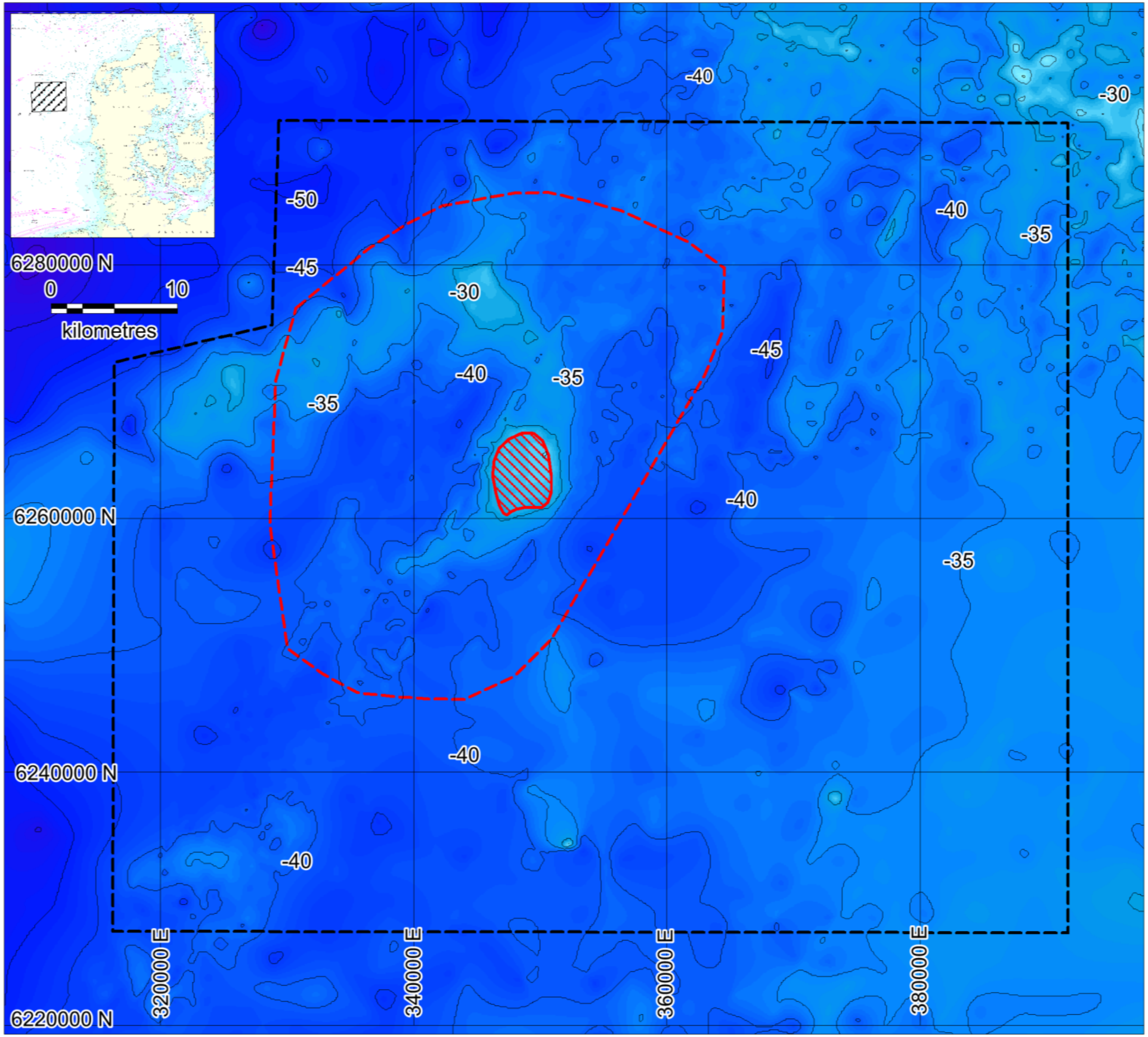
Client: Danish Energy Agency

GEUS

Version: NNP 08-03-2022

Appendix A1:

Shallow seismic lines and sediment cores - Marta database



Sand resources for energy island
- Danish North Sea

Screening study

Legend

Screening area

Site survey area for energy island

Planned energy island

Bathymetry (m), DVR90:

-10
-20
-30
-40
-50
-60

Projection: ETRS89 zone 32N

Client:

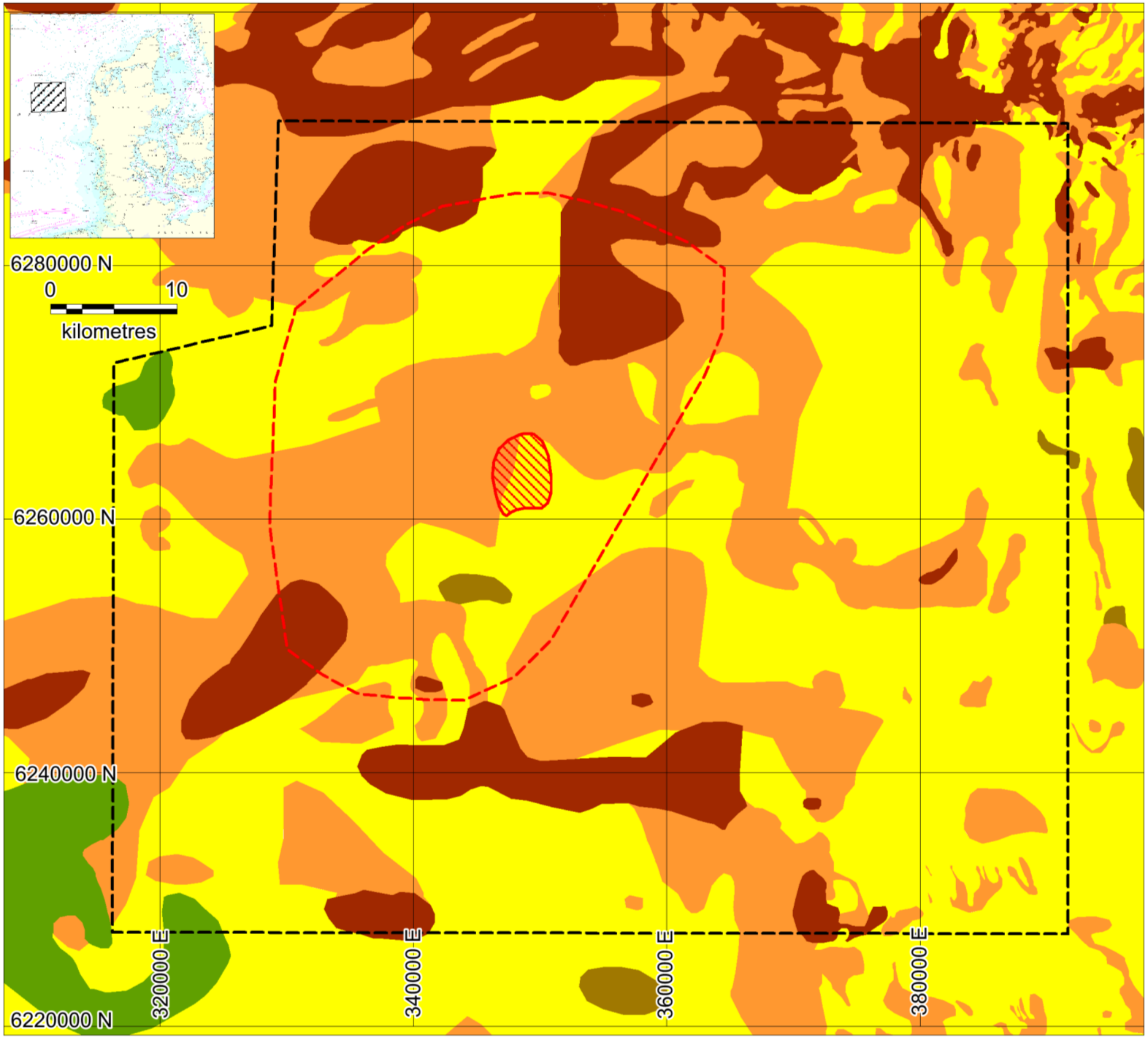
Danish Energy Agency

G E U S

Version: NNP 08-03-2022

Appendix A3:

Bathymetry



Sand resources for energy island
- Danish North Sea

Screening study

Legend

Site survey area for energy island
Screening area
Planned energy island

Seabed surface sediment:
Till/diamict
Quaternary clay
Coarse sand and gravel
Sand
Muddy sand
Mud

Projection: ETRS89 zone 32N

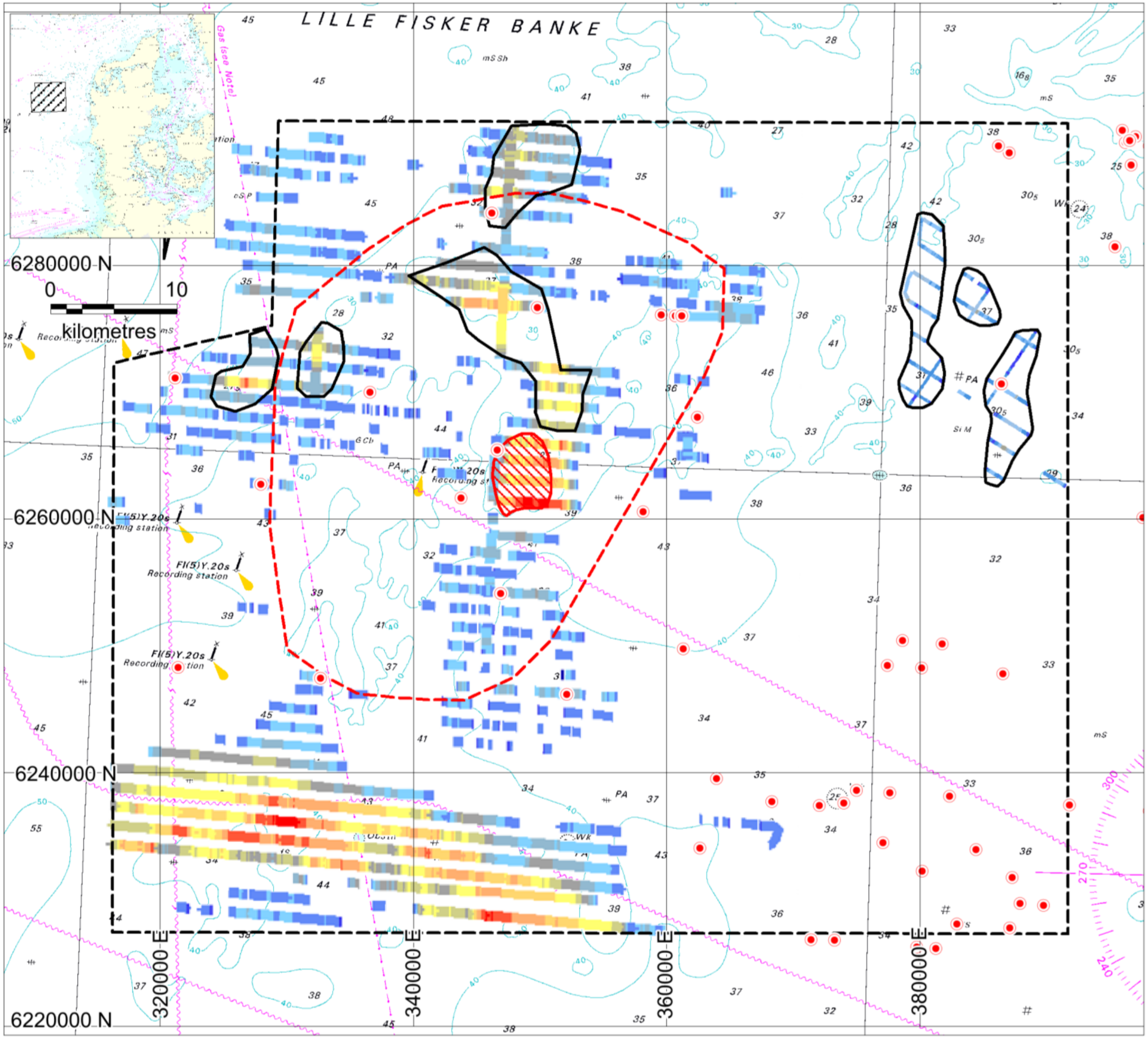
Client: Danish Energy Agency

GEUS

Version: NNP 08-03-2022

Appendix A4:

Seabed surface sediment distribution
- Marta database



Sand resources for energy island - Danish North Sea

Screening study

Legend

- Site survey area for energy island
- Screening area
- Planned energy island
- Sediment core site
- Prioritized sand occurrences

Sand resource thickness (m)

0, 2, 3, 4, 6, 7, 9, 10, 11, 13, 14

Projection: ETRS89 zone 32N

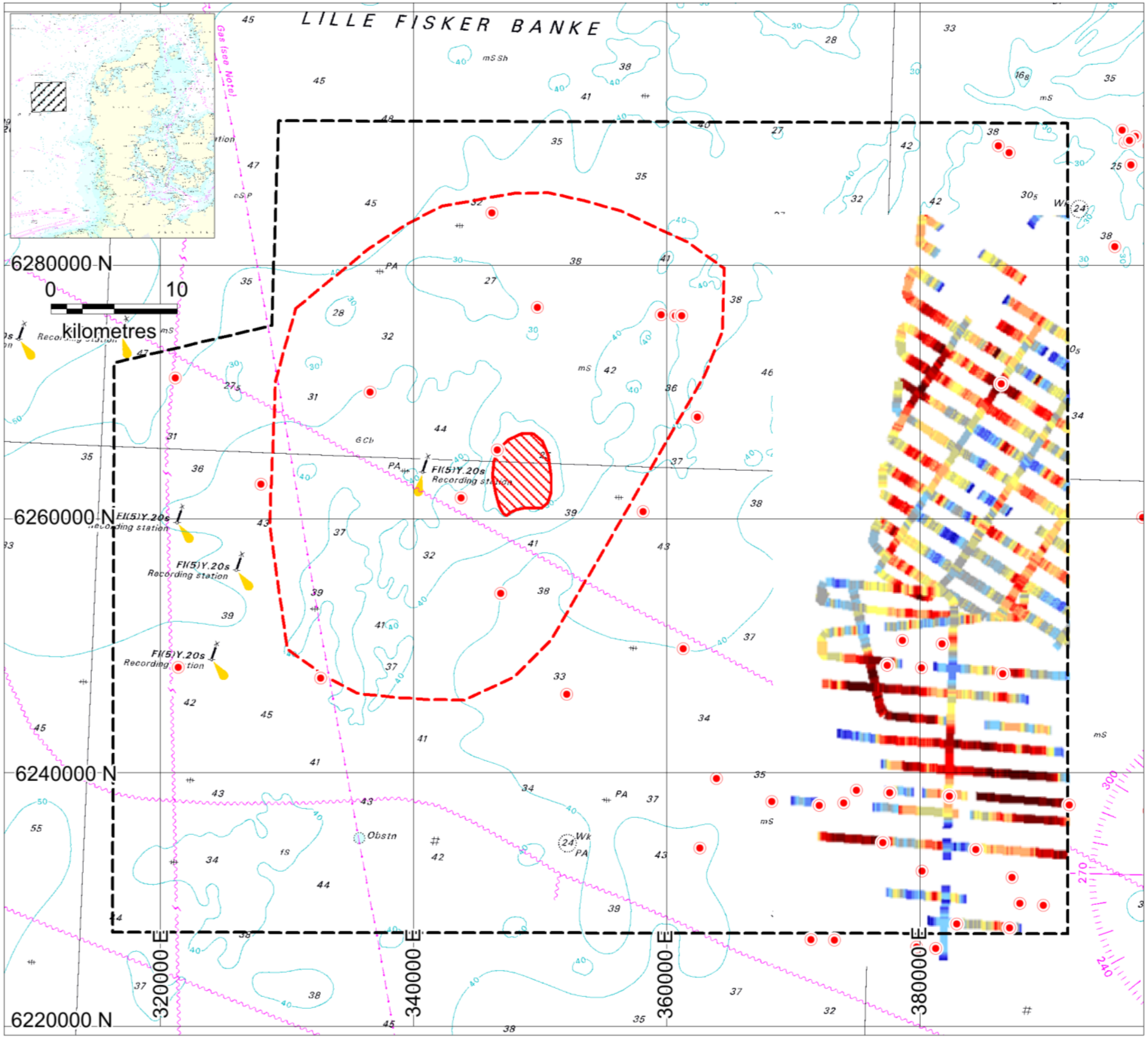
Client: Danish Energy Agency

GEUS

Version: NNP 08-03-2022

Appendix A5:

Holocene marine sand resources

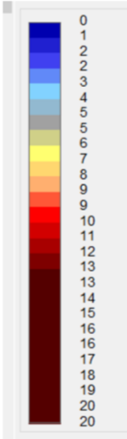


Sand resources for energy island - Danish North Sea

Screening study

Legend

Meltwater deposit thickness (m)



Projection: ETRS89 zone 32N

Client:

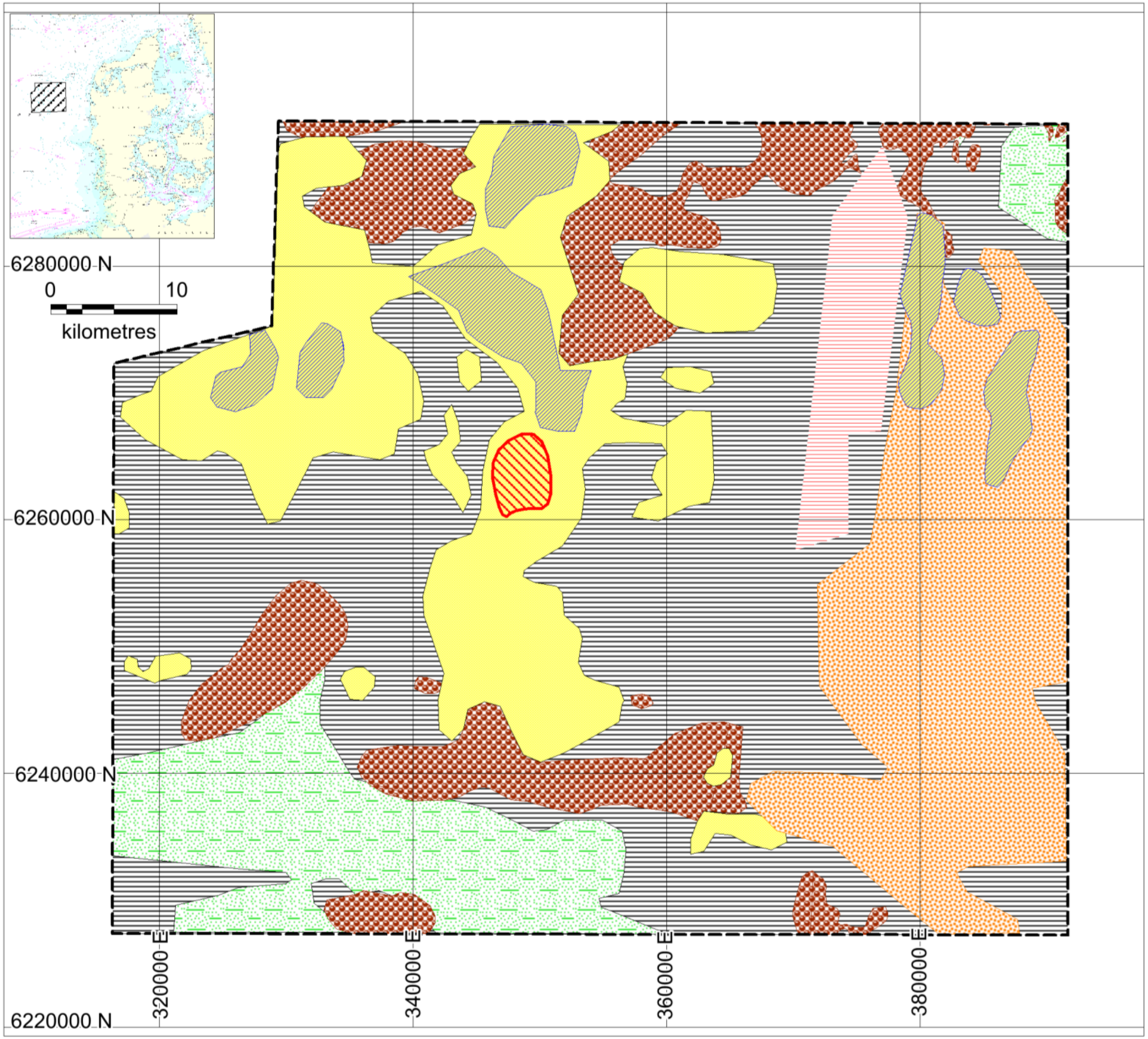
Danish Energy Agency

GEUS

Version: NNP 08-03-2022

Appendix A6:

Weichsel meltwater deposits



Sand resources for energy island
- Danish North Sea

Screening study

Legend

- Screening area
- Planned energy island
- Thick Holocene marine sand unit (Potential sand resource)
- Meltwater deposits (sand/silt/clay units) (Potential sand resource)
- Thin Holocene marine sand cover
- Holocene marine silty sand
- Till/moraine
- Undifferentiated late glacial clay/silt/sand
- Area with insufficient data

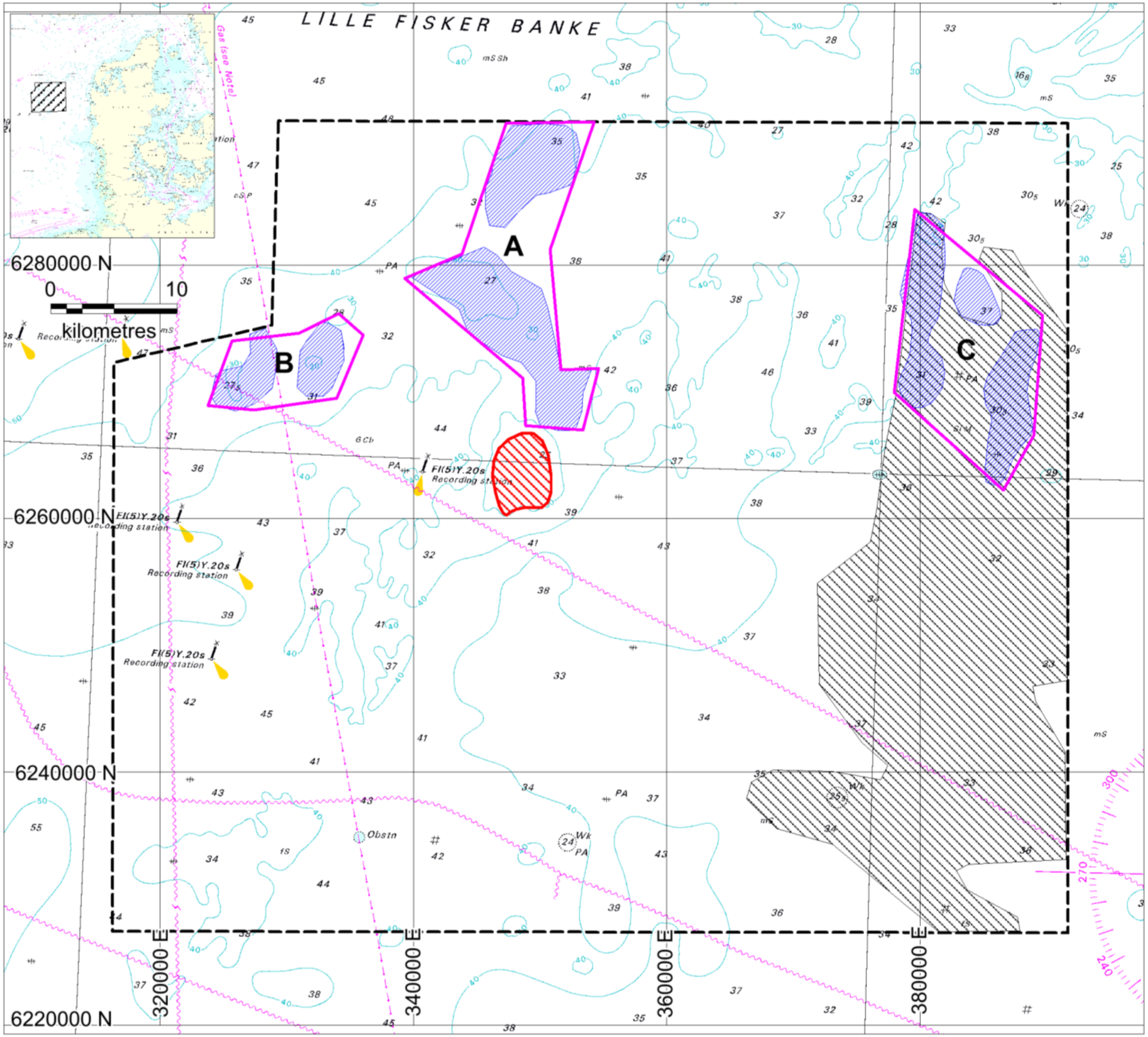
Projection: ETRS89 zone 32N

Client: Danish Energy Agency

GEUS

Version: NNP 09-03-2022

Appendix A7:
Surficial sediment units -
Resource and non-resource



Sand resources for energy island - Danish North Sea

Screening study

Legend

- Screening area
- Planned energy island
- Thick Holocene marine sand unit (top layer)
- Meltwater deposits (sand/silt/clay units)
- Prioritized sand resource survey area

Projection: ETRS89 zone 32N

Client: Danish Energy Agency

GEUS

Version: NNP 08-03-2022

Appendix A8:

Prioritized sand resource survey areas