Sheringham Shoal and Dudgeon Offshore Wind Farm Extension Projects

Environmental Statement

Volume 3

Appendix 6.3 - Sedimentary Processes in the Cromer Shoal Chalk Beds MCZ

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REPORT

Sedimentary Processes in the Cromer Shoal Chalk Beds MCZ

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1 Introduction and Objectives

The proposed cable corridor for the Sheringham Extension Project (SEP) and Dudgeon Extension Project (DEP) will pass through the Cromer Shoal Chalk Beds Marine Conservation Zone (MCZ). There are two potential route options for the corridor through the MCZ. The western route would cross the west side of the MCZ (adjacent and east of the cable routes for the existing wind farms) to make landfall close to Weybourne. The eastern route would cross through a more easterly part of the MCZ and make landfall close to Bacton (**Figure 1.1**)[1].

The sea bed and shallow sub-sea bed of the Cromer Shoal Chalk Beds MCZ in the vicinity of the proposed cable corridor are characterised geologically and geomorphologically in several different ways. These are:

- outcropping chalk at the sea bed with no overlying sediment;
- subcropping chalk covered by a thin lag of coarse sand and gravel;
- Pleistocene glacial sediments covered by a thin lag of coarse sand and gravel;
- chalk (or chalk with lag) overlain by Holocene sand; and
- Pleistocene glacial sediments overlain by Holocene sand.

The proposed cable corridor would be routed through these different types of sea bed and sub-sea bed. A question has been raised by Natural England about the likely mobility of the sediment that rests on the chalk, and the potential for chalk exposure or burial should the overlying sediment transport to different areas. The mobility of the overlying sediment is also important in defining a suitable route for the cables through the MCZ, ensuring an appropriate method of installation, and understanding any potential environmental impacts of construction and operation.

This report details the results of a desk-top study utilising existing geophysical and sedimentary data to understand baseline geological and geomorphological processes operating in the MCZ, and specifically along the cable corridor for the SEP and DEP. The objectives of this study are:

- Collate all existing geological and geomorphological data and develop a general understanding of the whole MCZ as context for a more detailed assessment of the SEP and DEP cable corridor (**Section 2**);
- Describe the geological and geomorphological conditions along the proposed SEP and DEP cable corridors in the MCZ (**Section 3**);
- Compare time series of bathymetric and sea bed sediment datasets along the existing Dudgeon and Sheringham Shoal offshore wind farm cable routes/corridors in the MCZ (where available) to determine historical changes in elevation and sediment composition (**Sections 4** and **0**);
- Compare the geological and geomorphological conditions along the existing cable routes/corridors in the MCZ with those along the proposed SEP and DEP cable corridor to assess similarities and differences (**Sections 4** and **0**); and
- Use the results of this comparison to predict potential sediment dynamics/transport and changes in the surface layers of the SEP and DEP cable corridor, and to assess whether additional geotechnical surveys are required in the MCZ from a consent's perspective (**Section 0**).

This report also informs other conceptual work to support the environmental impact assessment and will be appended to the Environmental Statement chapter.

[1] *In May 2020, the Weybourne landfall was chosen as the preferred location. The landfall selection was based on a technical feasibility study using the results of the geophysical survey. The feasibility study is available as a separate document.*

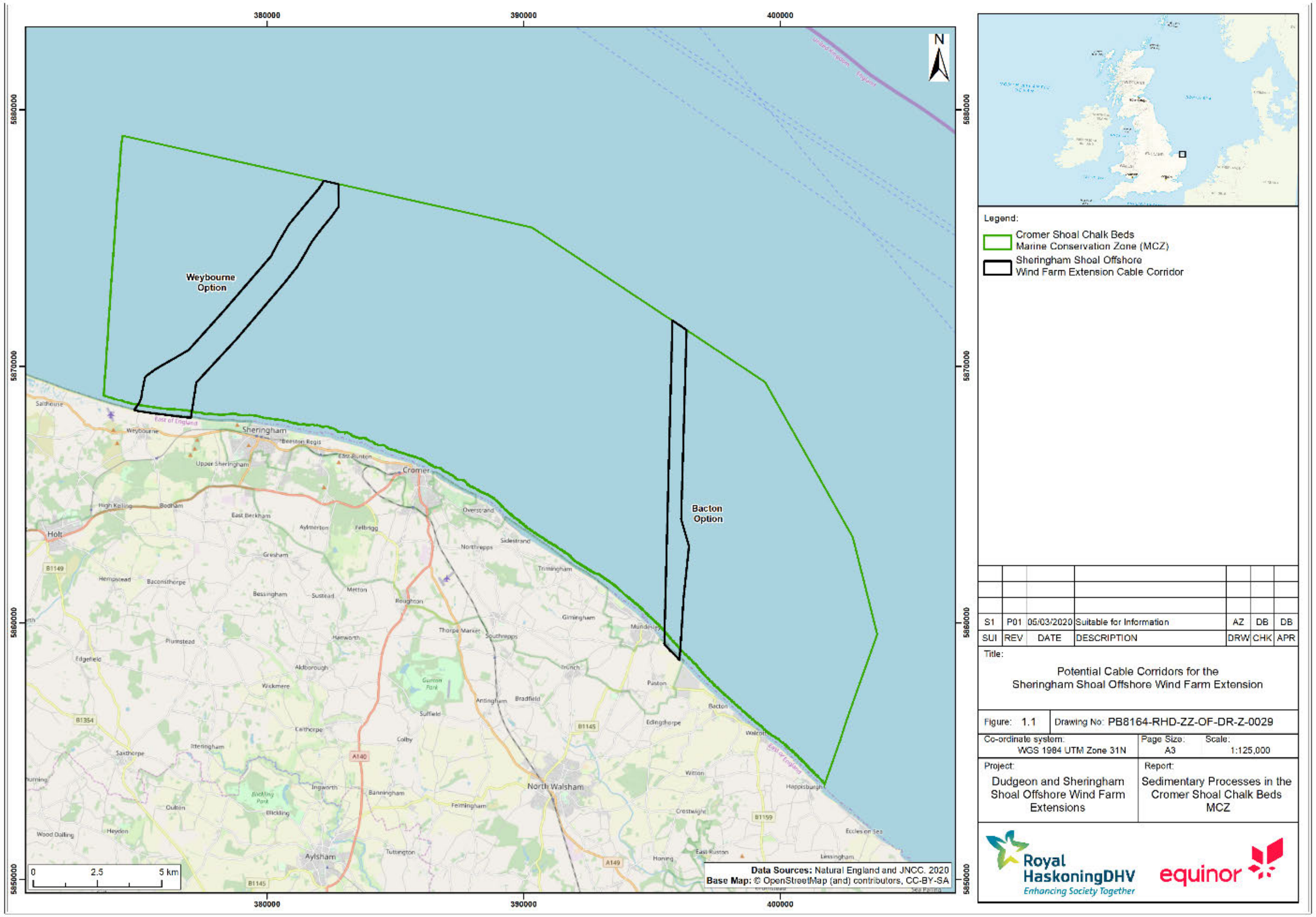

Figure 1.1. Potential cable corridors for the SEP and DEP through the MCZ

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2 Characteristics of the Cromer Shoal Chalk Beds MCZ

2.1 Designation Summary

Cromer Shoal Chalk Beds MCZ begins about 200m offshore from the north Norfolk coast with a western boundary just west of Weybourne and an eastern boundary at Happisburgh. It extends about 10km offshore and covers an area of about 320km^2. The MCZ encompasses important geological features including the best examples of subtidal chalk beds in the North Sea. The subtidal chalk feature includes both outcropping chalk (no overlying sediment) and subcropping chalk (overlain by a thin lag of coarse sand and gravel). The shallow inshore part of the MCZ out to 10m water depth features infralittoral rock which extends for almost the entire length of the site. This area of hard, stable substrate provides a suitable habitat for attached and mobile epifauna. Extending offshore from the infralittoral rock into deeper water is a band of circalittoral rock with more epifauna. The areas of infralittoral and circalittoral rock in the MCZ are comprised of subtidal chalk, as well as other rock types. It is not possible to accurately differentiate between different types of rock using geophysical data, and so areas mapped as the subtidal chalk are likely to overlap with areas mapped as circalittoral and infralittoral rock.

2.2 Bathymetry

Three geophysical surveys completed across the MCZ for Cefas between 2012 and 2014 provide a general bathymetric overview. Details of these surveys are provided in **Table 2-1**. The bathymetry slopes seaward from about -5m Lowest Astronomical Tide (LAT) close to the coast to about -20m LAT at its seaward boundary (**Figure 2.1**).

Table 2-1. Geophysical surveys across the MCZ for Cefas between 2012 and 2014

Survey	Date	Description
Titan Cruise ITT_cscb_21_2012	14th March 2012 to 1st April 2012	Mult beam bathymetry and acoustic backscatter survey of the nearshore area from approximately Sheringham to the western MCZ boundary
Cefas Cromer Shoal Chalk Beds Cruise Cefas_cend0113y	28th to 31st January 2013	Mult beam bathymetry and acoustic backscatter survey of the northeast part of the site. Inshore areas were not surveyed due to weather constraints. Survey line spacing was approximately 320m
Gardline Geosurvey Cruise ITT_cscb_3_2014	5th February 2014 to 9th March 2014	Mult beam bathymetry covering much of the western half of the MCZ (excluding the area covered in 2012) and the nearshore area to the southeast boundary

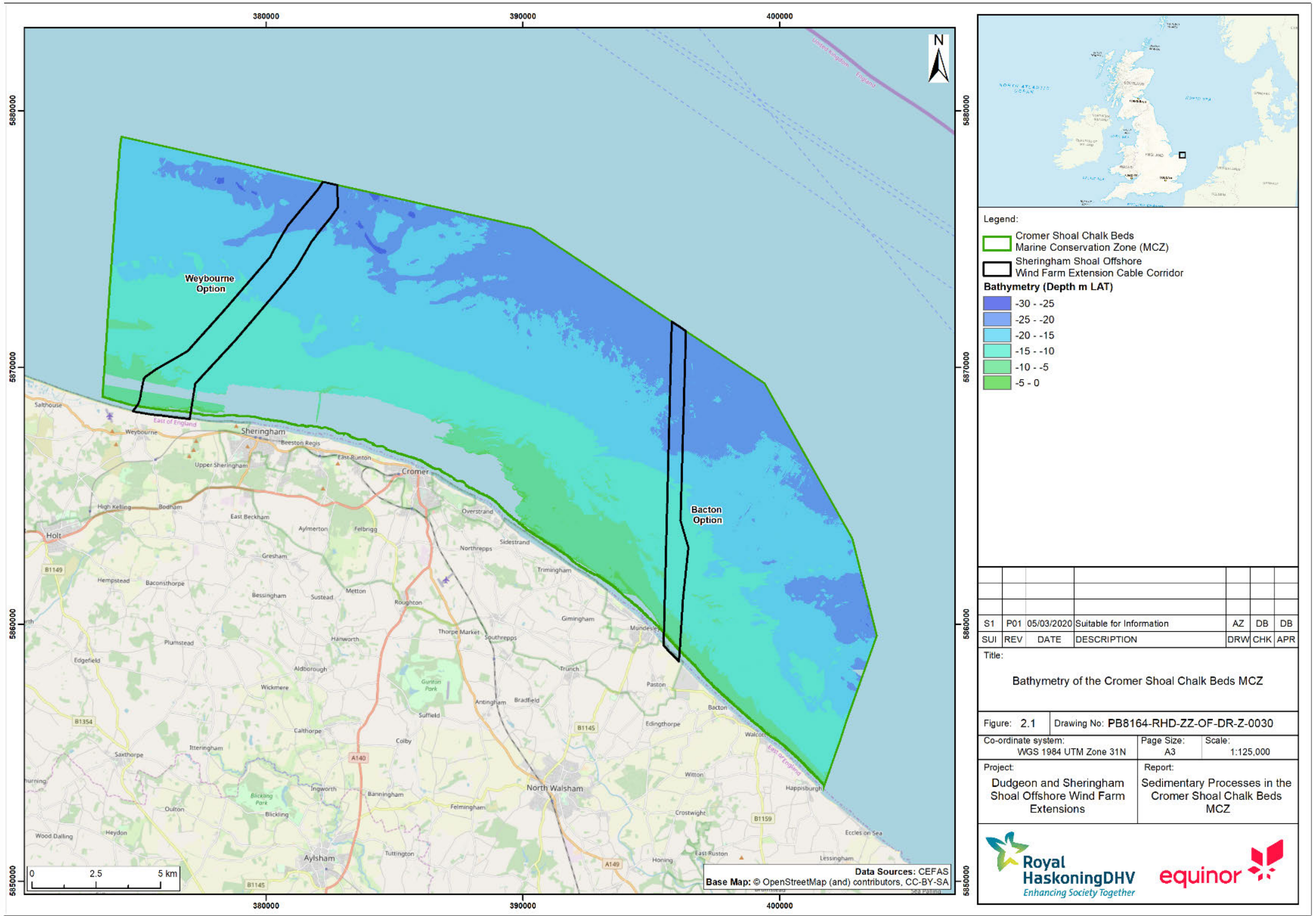

Figure 2.1. Bathymetry of the Cromer Shoal Chalk Beds MCZ between 2012 and 2014

2.3 Geology and Sea Bed Sediment

The bedrock geology across the MCZ is dominated by rocks of the Upper Cretaceous Chalk Group (Cameron *et al.*, 1992) which is around 400m thick across the site. Chalk is a very fine-grained white limestone that consists of debris from planktonic algae, with some coarser calcitic components. It is commonly over 98% calcium carbonate (excluding flints) with only small amounts of impurities, such as quartz. Flints (composed of silica) commonly occur within the chalk as irregularly shaped nodules and thin tabular sheets in layers, which follow bedding planes. In the western part of the MCZ, subtidal chalk is exposed at the sea bed close to the intertidal zone, extending further offshore in the southeast portion of the site.

According to D'Olier (2004) there is the potential for poor strength conditions at the chalk surface which has been channelled and infilled during later glacial periods. Indeed, Chroston *et al*. (1999) suggested that a surface layer of softer chalk ('putty' chalk) may be present as a result of Pleistocene weathering. This may have a variable thickness depending on the history of processes in the area. Overall, it is likely that the surface layers of chalk are weathered and relatively soft, becoming harder with depth.

Spray and Watson (2011) reported the results of 111 dives to the nearshore sea bed between Cley and Trimingham. Chalk was encountered on every dive with no dives recording only sand or sediment. The exposed chalk has a variety of characters with a continuum from low, irregular plains with scattered flints, through mounded chalk to a rugged sea bed with 1-2m-deep gullies (with partial sediment infill) and ridges, pinnacles and arches (Figure 2.2). This indicates that where the chalk outcrops at the sea bed it is complex and displays micro-variations in bathymetry (over distances of metres).

Figure 2.2. Characteristics of the chalk where it outcrops at the sea bed. Ridge (top left), plain (top right), gulley (bottom left) and arch (bottom right) (Spray and Watson, 2011)

Sediment sampling has been completed across the MCZ by Cefas (2014). Cefas (2014) deployed at 72 stations (http://data.cefas.co.uk/#/View/3826). Details of the locations of these samples are provided in **Figure 2.3** and the details of the particle size characteristics of 71 samples (excluding CSCB140) in Appendix A. The samples describe a variety of sea bed compositions. Most of the samples are composed of sand and gravel. About half the samples contain greater than 25% gravel (25-69%) and are defined as sandy gravel or gravelly sand. About 25% of the samples are greater than 90% sand with four samples predominantly mud (72-90%) with subordinate sand.

The subtidal chalk feature designation is ‘undifferentiated’ meaning it is a combination of subcropping (beneath a thin coarse lag) and outcropping (with no lag) chalk. However, the sea bed sediment data in combination with the dive results of Spray and Watson (2011) and the bathymetry data collected by Cefas suggest that most of the MCZ is composed of subcropping chalk (overlain in places by sand) with relatively small areas of outcropping chalk.

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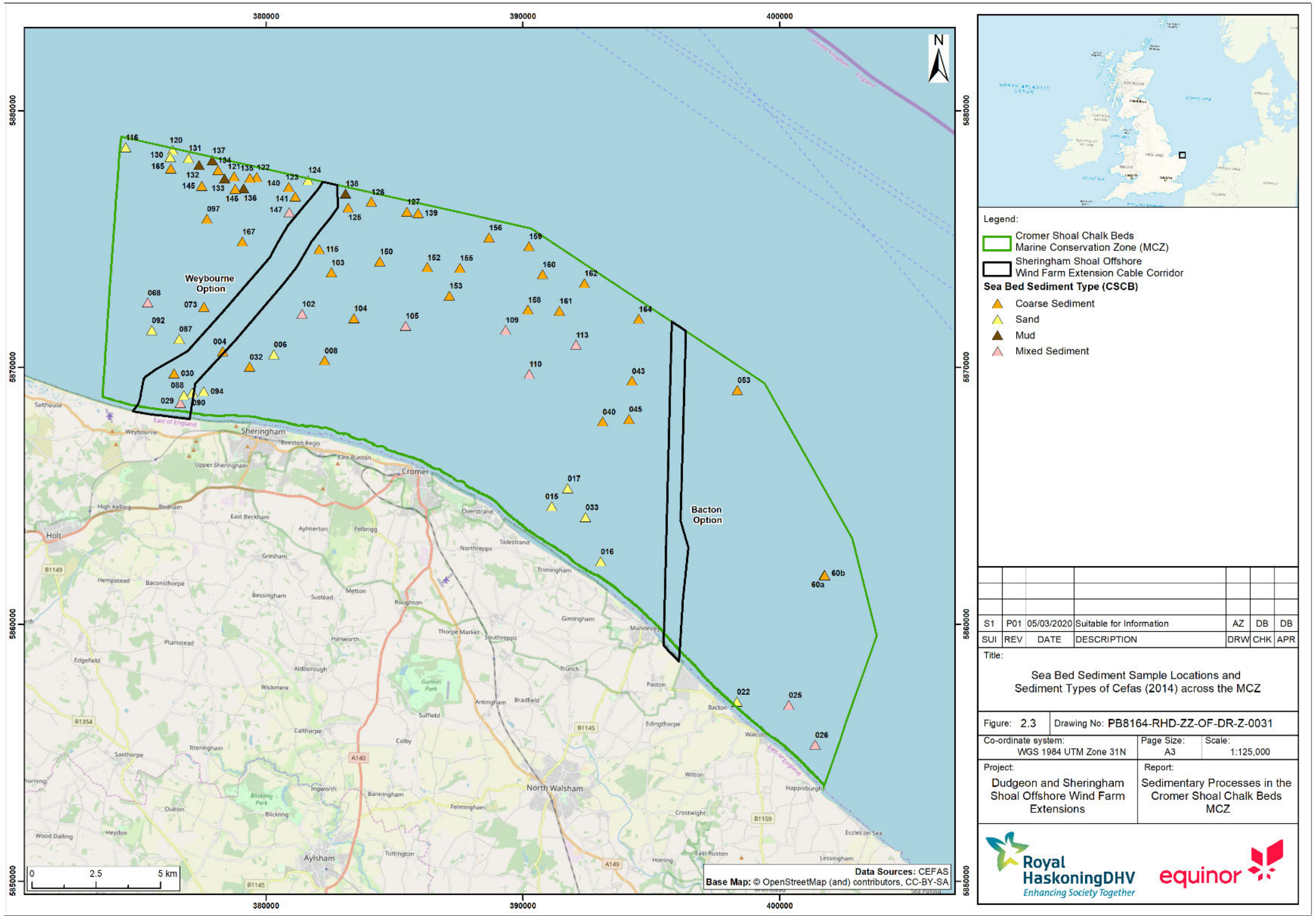

Figure 2.3. Sea bed sediment sample locations of Cefas (2014) across the MCZ

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3 2019 Geophysical Survey of the SEP and DEP Cable Corridor

Gardline (2020) completed a geophysical survey along two potential routes for the SEP and DEP in late 2019 (**Figure 1.1**). The western corridor would make landfall at Weybourne and is located east of and adjacent to the existing Dudgeon offshore wind farm cable corridor. The eastern corridor would make landfall at Bacton. The survey collected multibeam echosounder data (bathymetry), side-scan sonar (sea bed texture), and sub-bottom profiler (recent geology) along the two corridors in the MCZ.

3.1 Weybourne Cable Corridor Option

The bathymetry of the cable corridor deepens from about 0.0m LAT at the landfall end to about -24m LAT towards the boundary of the MCZ (Figure 3.1). Based on the interpretation of Gardline (2020), the MCZ within the Weybourne cable corridor option can be divided into four shore-parallel zones.

- The landward 500m of the cable corridor is outcropping chalk (Figure 3.2). This part of the corridor is likely to contain chalk at sea bed potentially sculped into the complex geo-structures photographed during the nearshore dives of Spray and Watson (2011) (Figure 2.2). This is supported by the complex irregular bathymetry recorded across this area (**Figure 3.1**). The seaward boundary of the outcropping chalk is located in water depths of about -6m LAT at the western end to -9.5m LAT at the eastern end (**Figure 3.3**). The bathymetry of the seaward boundary gradually shallows from east to west. The area of the outcropping chalk within the corridor is about 812,000m^2.
- From 500m to 4.5km offshore along the cable corridor, the sea bed is composed of alternating zones of gravelly sand/gravel and Holocene sand across a less complex bathymetry than further inshore (**Figure** 3.2). The gravelly sand/gravel is interpreted to be a lag deposit created by erosion of Pleistocene units (likely to have been mainly Bolders Bank Formation) that used to overlie the chalk. It is likely to be less than 1m thick with subcropping eroded chalk (although difficult to define the true thickness based on the geophysical data) and not mobile under existing tidal conditions. The Holocene sand is up to 3m thick and rests mainly on chalk and lag (apart from a deep infilled channel cut through the chalk to -17m LAT filled with Weybourne Channel deposits, Chroston *et al*., 1999) (**Figure 3.4** and **Figure 3.5**). Most of the sand surface is sculpted into megaripples (**Figure 3.6** and Figure 3.7), 5-10m wavelength with crests oriented north-south or north-northeast to south-southwest, indicating mobility under existing tidal conditions. Movement of the sand at its edges could bury or expose areas of lag overlying subcropping chalk). If the Holocene sand is mobile, gross migration is likely to be along an approximately east-west axis (given the crest orientations of the bedforms). The smoother bathymetry in this zone indicates that exposed chalk is absent and where it subcrops it is more regular in elevation.
- From 4.5km to about 9km from the coast along the cable corridor is a gravelly sand or gravel sea bed, which is interpreted to form a thin layer (lag) overlying eroded chalk and Botney Cut Formation in the north (Figure 3.4, **Figure 3.7** and **Figure 3.8**). This wide zone is a continuation of the gravelly sand/gravel sea bed further landward which passes beneath the Holocene sands. The overlying mobile Holocene sands do not occur in this zone. The gradually sloping bathymetry suggests that the subcropping chalk surface in this zone is an eroded surface and is relatively flat and regular. Figure 3.8 shows that determining the thickness of the lag that overlies subcropping chalk based on sub-bottom profiler data is difficult because of the ‘noise’ at the sea bed.
- In the seaward 2km of the cable corridor inside the MCZ is a field of megaripples (5-10m wavelength with crests oriented north-south) which extend further to the north as the bathymetry rises into Sheringham Shoal sand bank. Here, the chalk is locally covered with up to 2m of sand (and occasionally up to 6m).

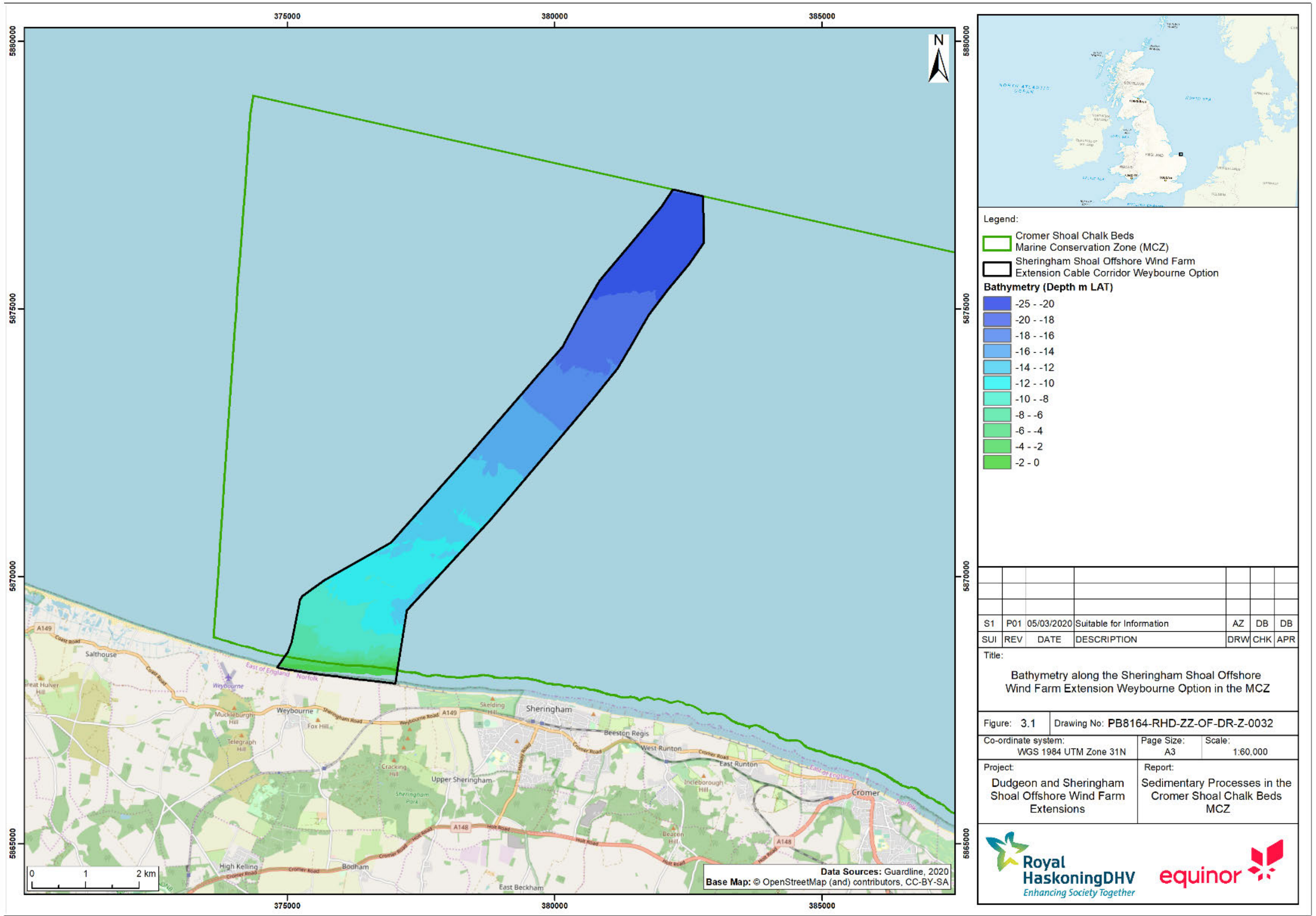

Figure 3.1. Bathymetry along the SEP and DEP Weybourne option in the MCZ (Gardline, 2020)

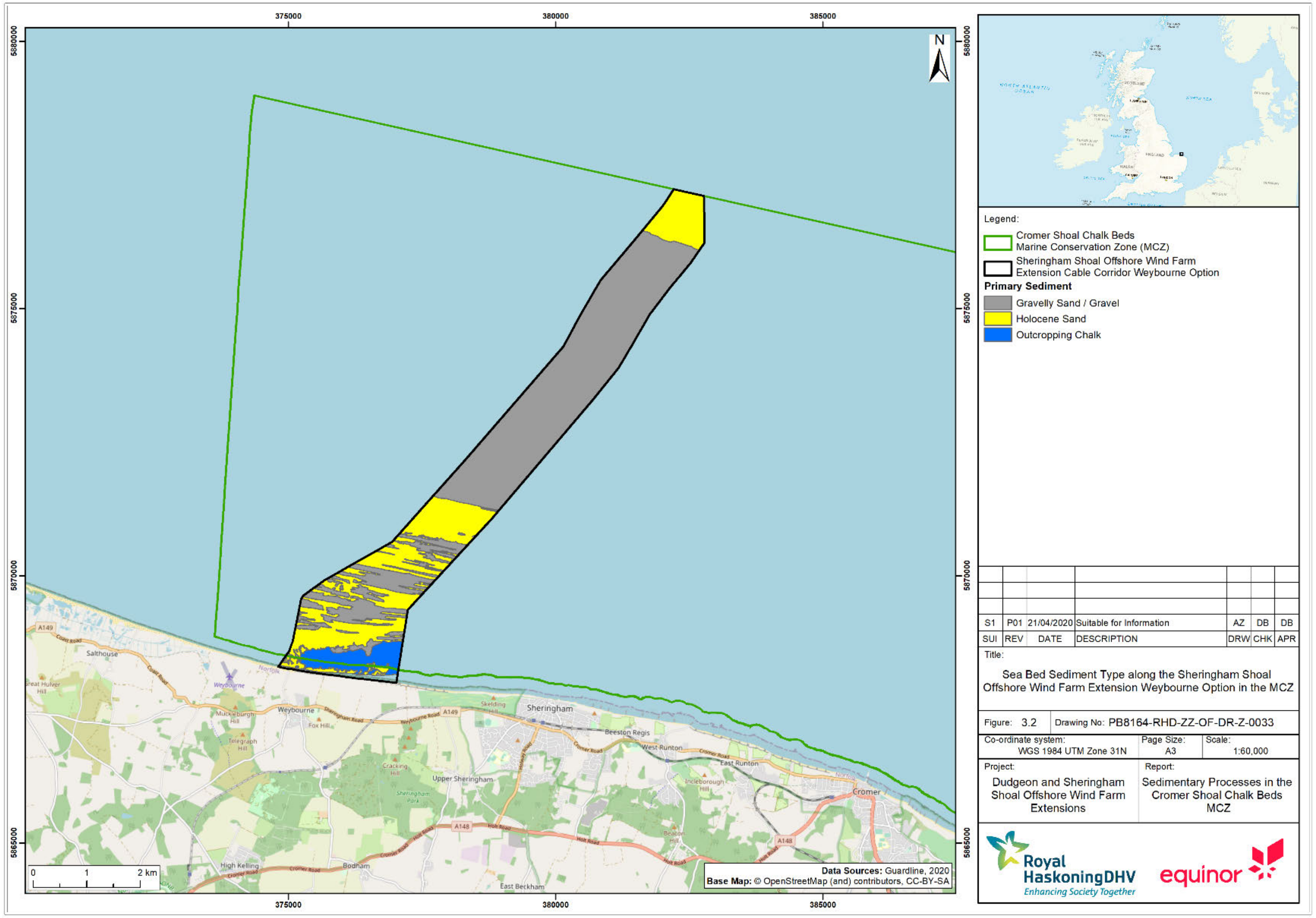

Figure 3.2. Sea bed sediment type along the SEP and DEP Weybourne option in the MCZ (Gardline, 2020)

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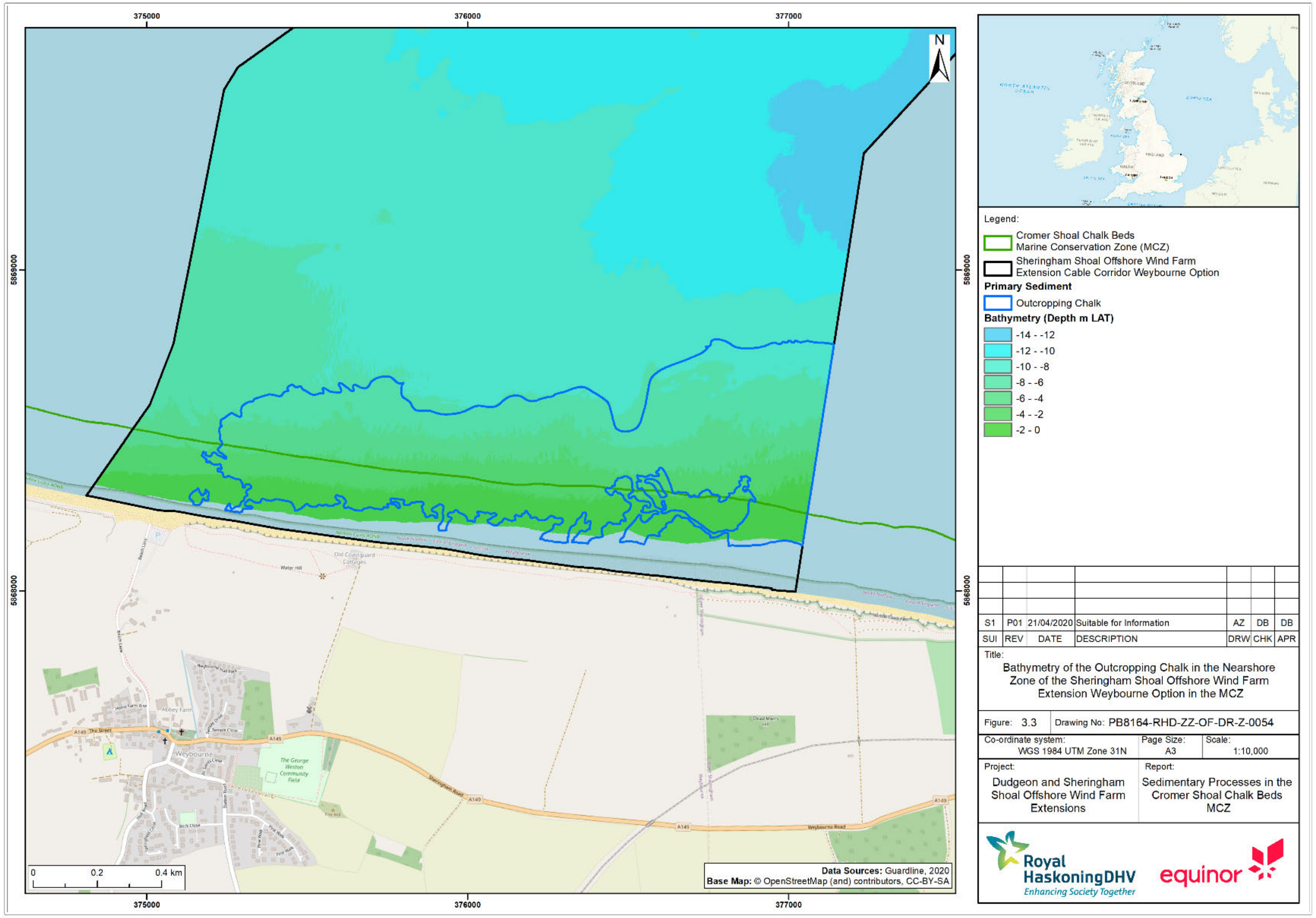

Figure 3.3. Bathymetry of the outcropping chalk in the nearshore zone of the SEP and DEP Weybourne option in the MCZ

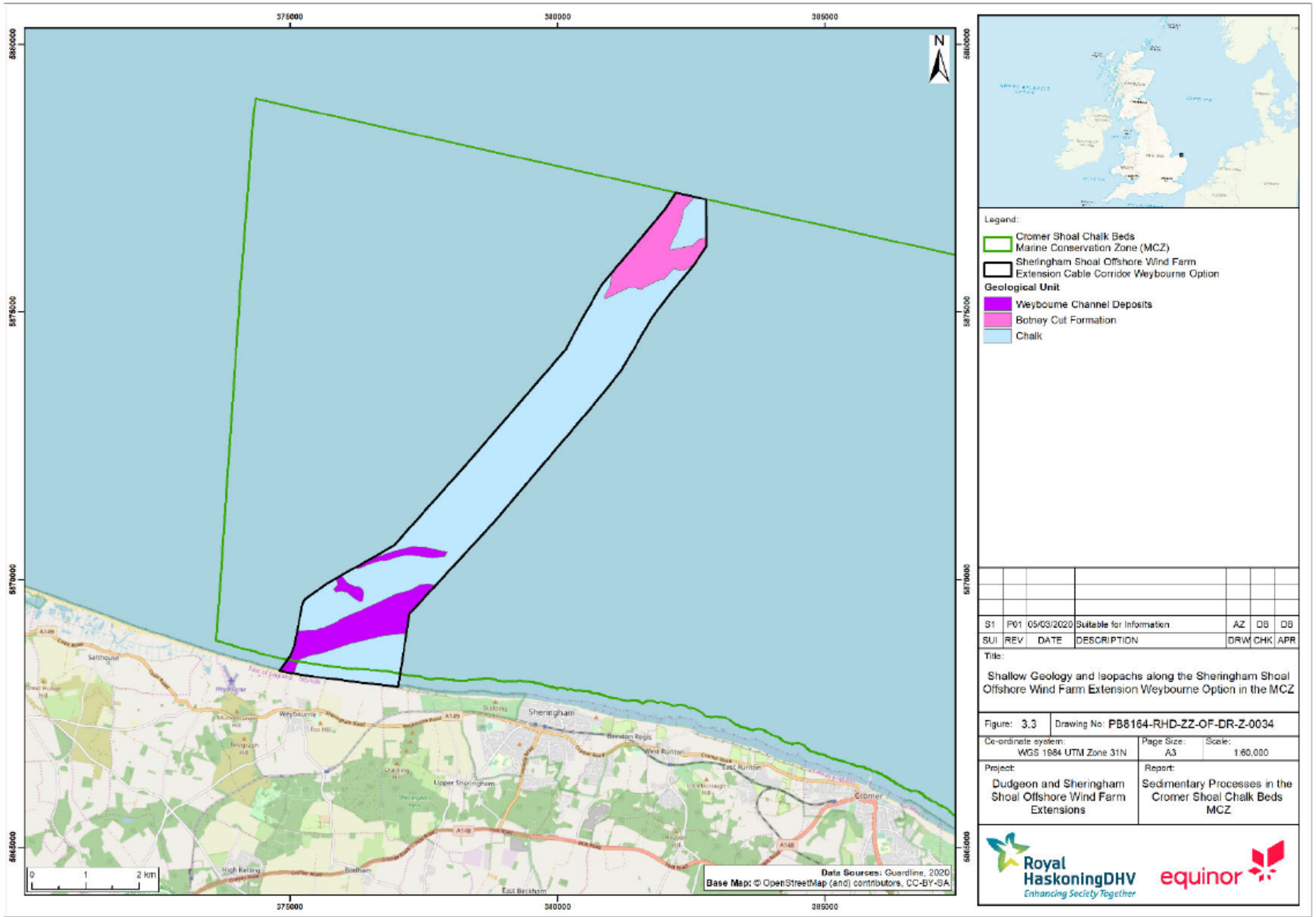

Figure 3.4. Shallow geology and isopachs along the SEP and DEP Weybourne option in the MCZ (Gardline, 2020)

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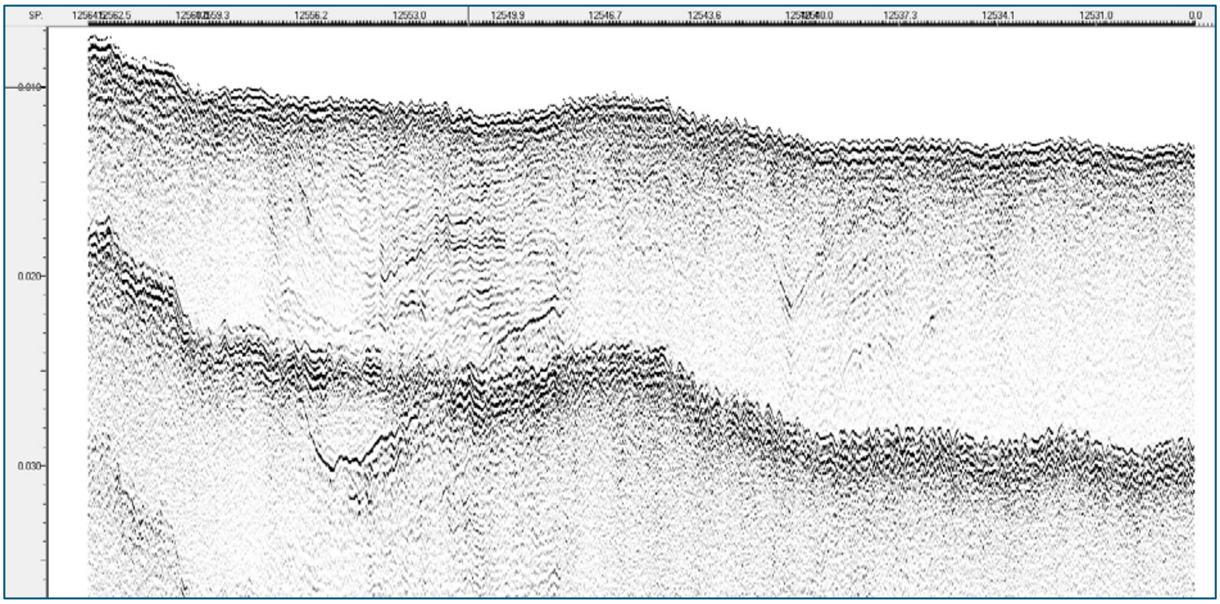

Figure 3.5. Sub-bottom profile showing the Weybourne Channel deposits along the SEP and DEP Weybourne option in the MCZ

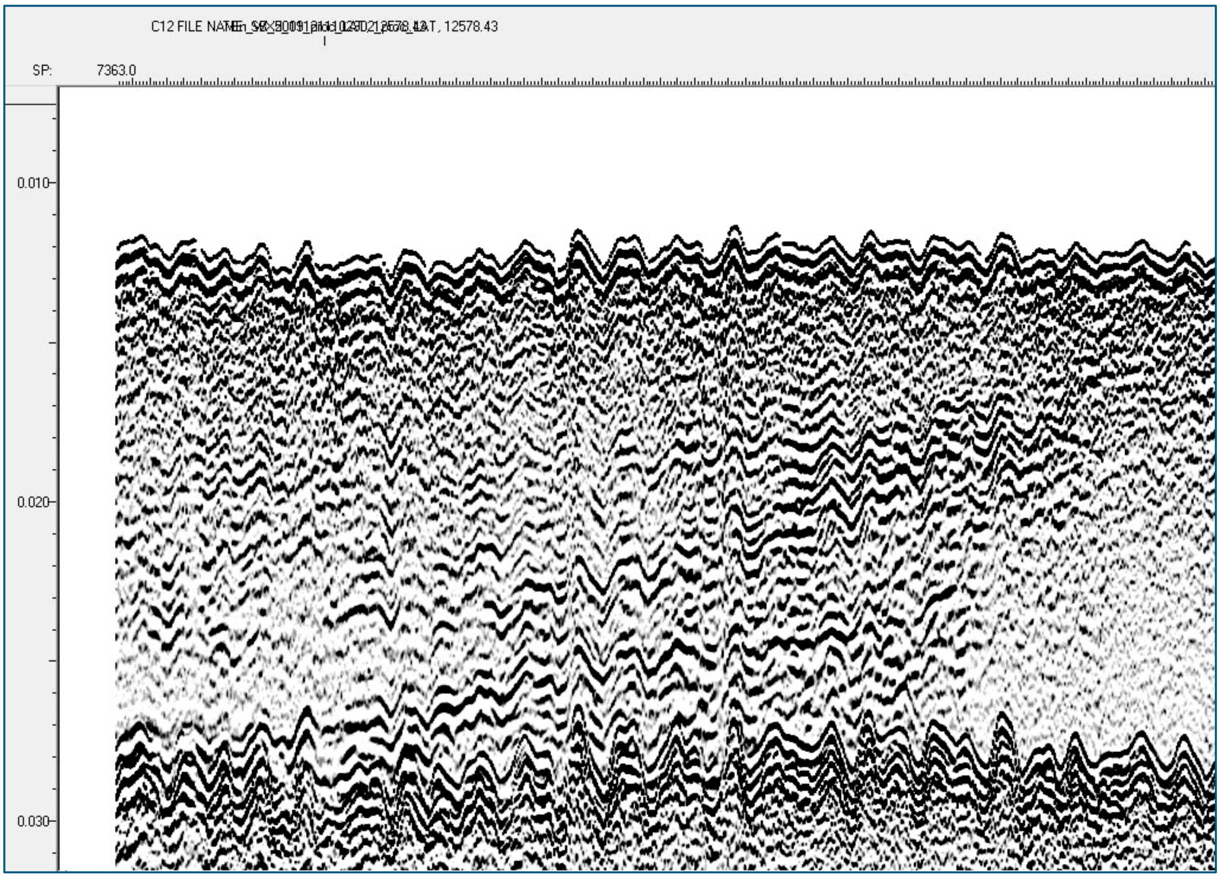

Figure 3.6. Sub-bottom profile showing megaripples along the SEP and DEP Weybourne option in the MCZ

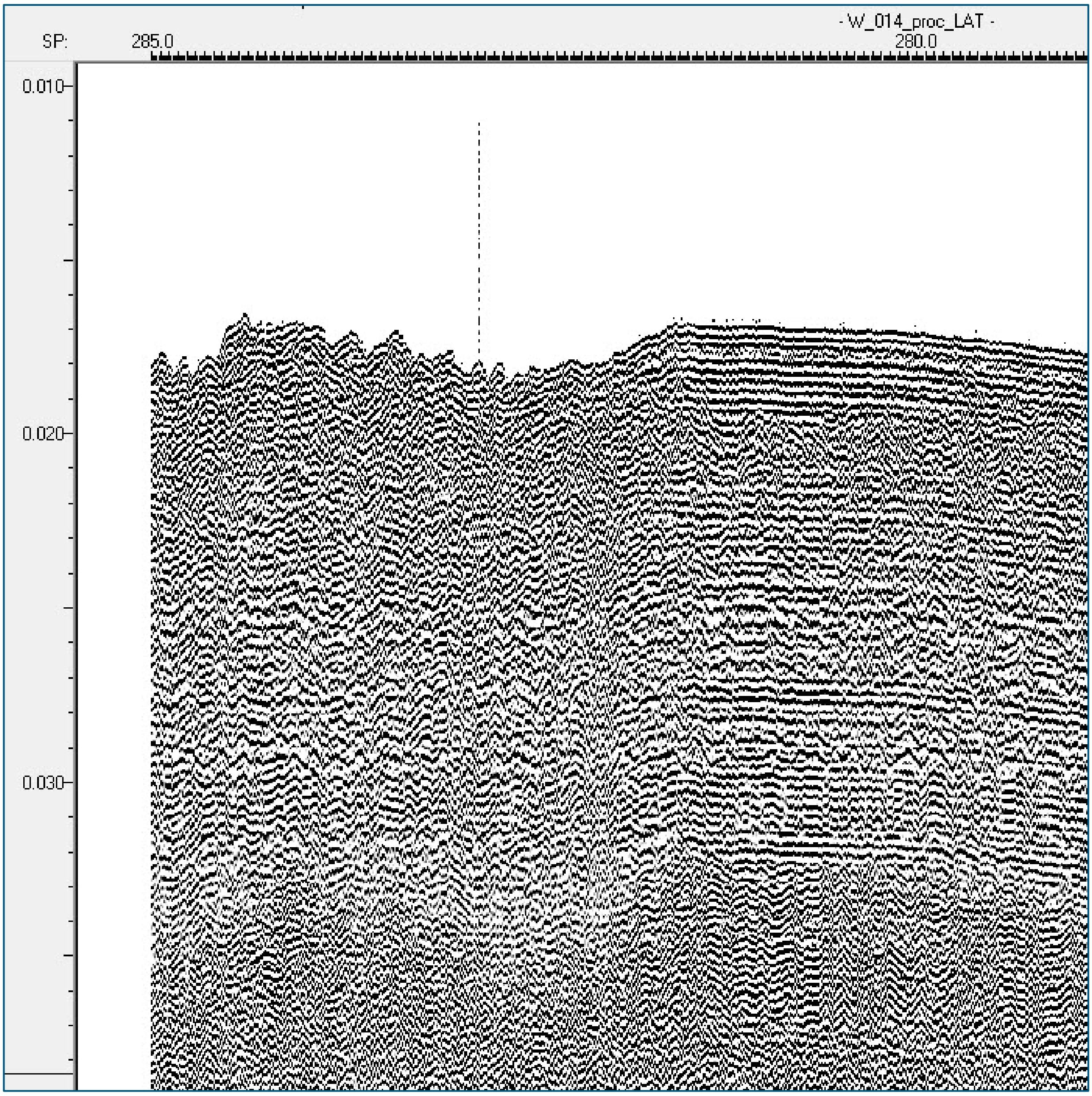

Figure 3.7. Sub-bottom profile showing the junction between megaripples and chalk close to the sea bed along the SEP and DEP Weybourne option in the MCZ

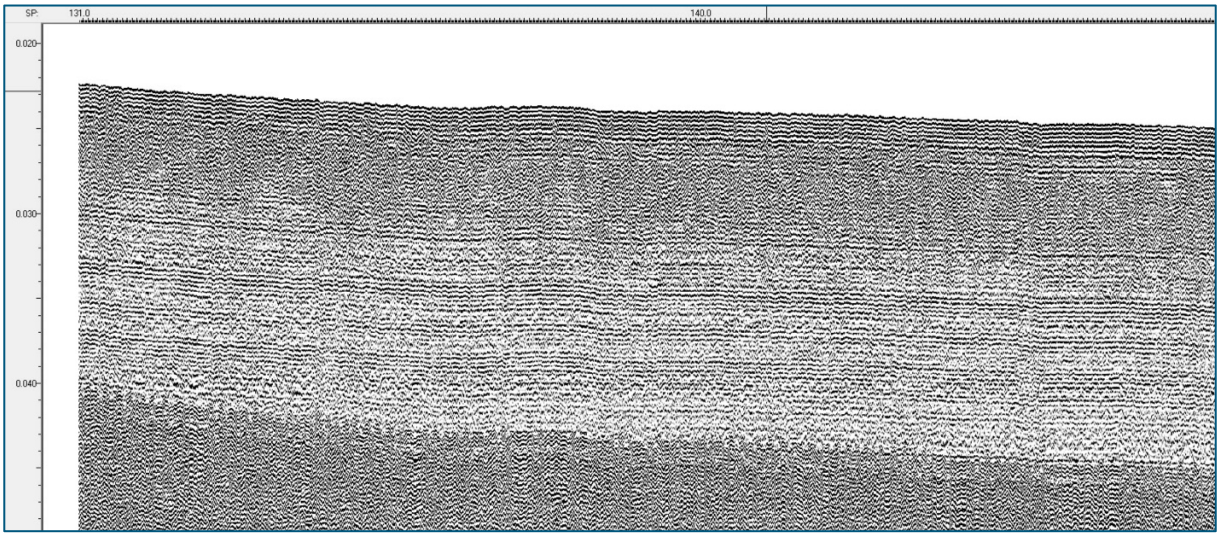

Figure 3.8. Sub-bottom profile showing the chalk close to the sea bed (with an overlying lag not visible on the profile) along the SEP and DEP Weybourne option in the MCZ

3.2 Bacton Cable Corridor Option

The bathymetry of the cable corridor deepens from about 0.0m LAT at the landfall end to about -23m LAT at the boundary of the MCZ. Based on the interpretation of Gardline (2020), the MCZ within the Bacton export cable corridor can be divided into two zones (**Figure 3.9**).

- The nearshore 500m of sea bed is composed of Holocene sand which is up to 8m thick at the coast thinning to zero offshore (**Figure 3.10**, **Figure 3.11** and **Figure 3.12**).
- Beyond the nearshore sand zone offshore to the MCZ boundary is a sea bed composed of alternating bands of sandy gravel and gravelly sand (lag deposit) with some outcropping chalk (about 236,000m^2). In this zone the sand-gravel forms a sediment veneer over the chalk and over Botney Cut Formation where present (**Figure 3.11**). It is likely to be less than 1m thick with subcropping eroded chalk (although difficult to define the true thickness based on the geophysical data) and not mobile under existing tidal conditions. Figure 3.13 and **Figure 3.14** illustrate the difficulty of determining the thickness of the lag based on sub-bottom profiler data because of the ‘ringing’ effect at the sea bed. This type of difficulty with defining the thickness of the lag based on sub-bottom profiler data is universal across all areas where chalk subcrops beneath a veneer of coarse sediment (see also along the Weybourne option).

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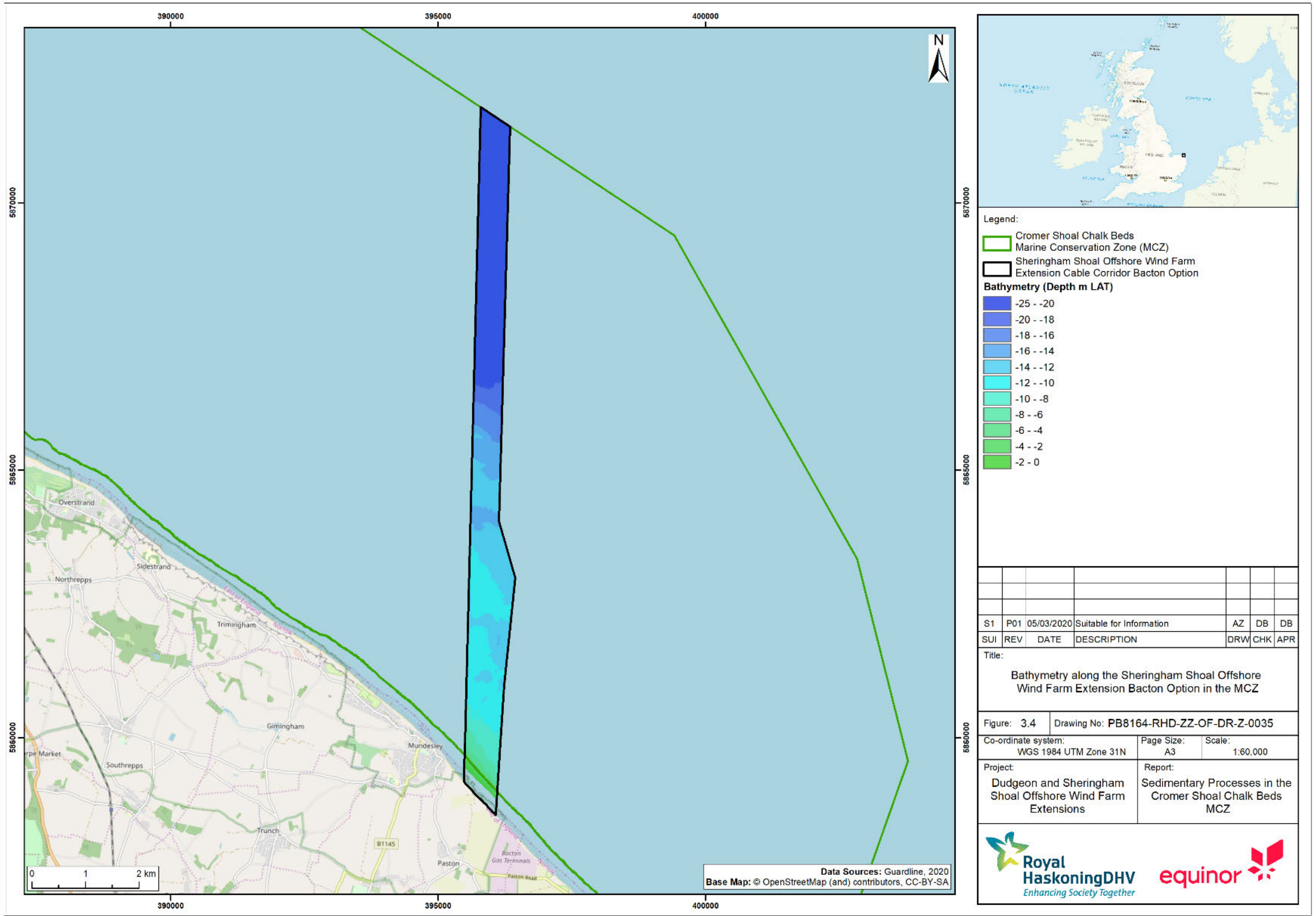

Figure 3.9. Bathymetry along the SEP and DEP Bacton option in the MCZ (Gardline, 2020)

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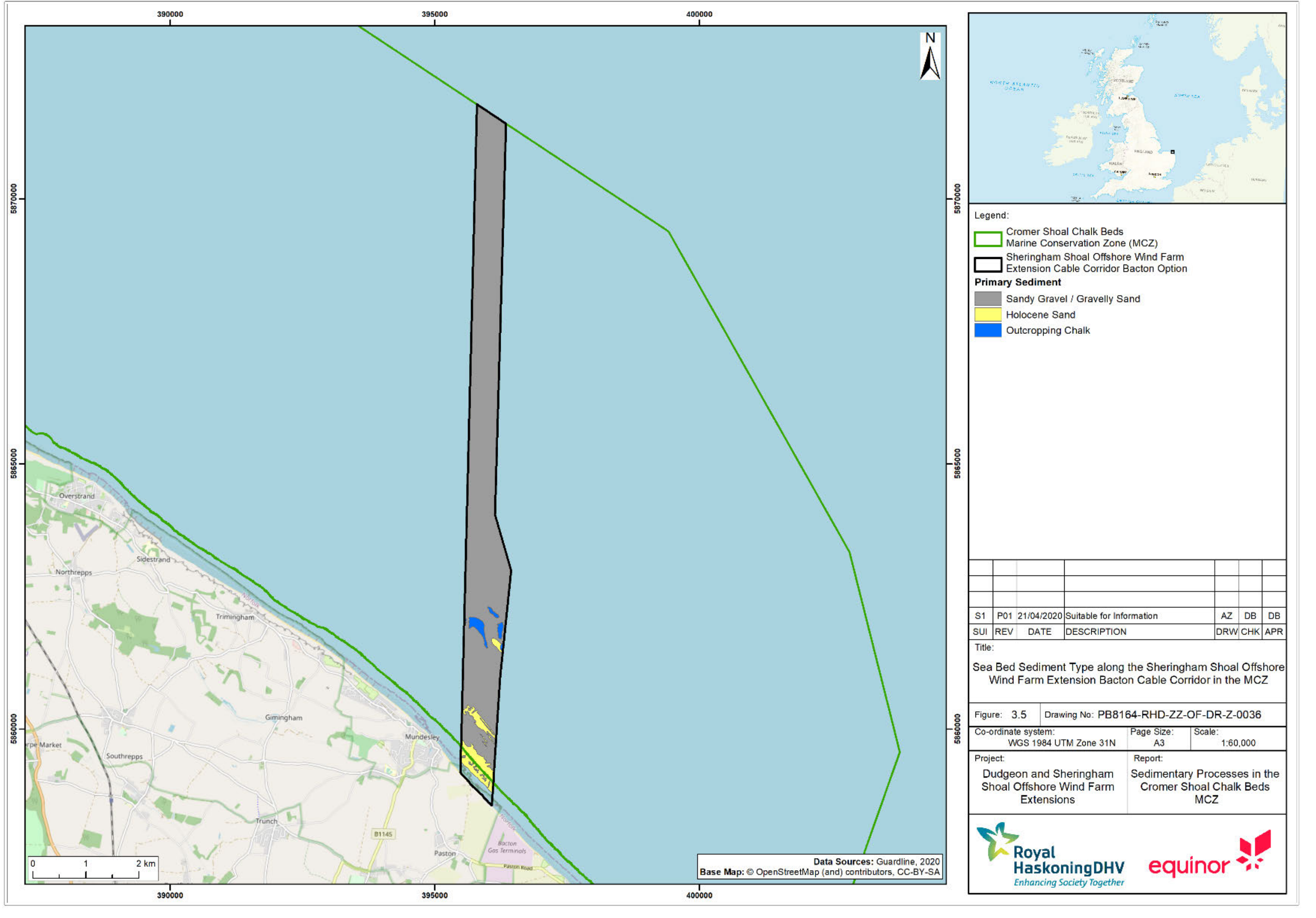

Figure 3.10. Sea bed sediment type along the SEP and DEP Bacton option in the MCZ (Gardline, 2020)

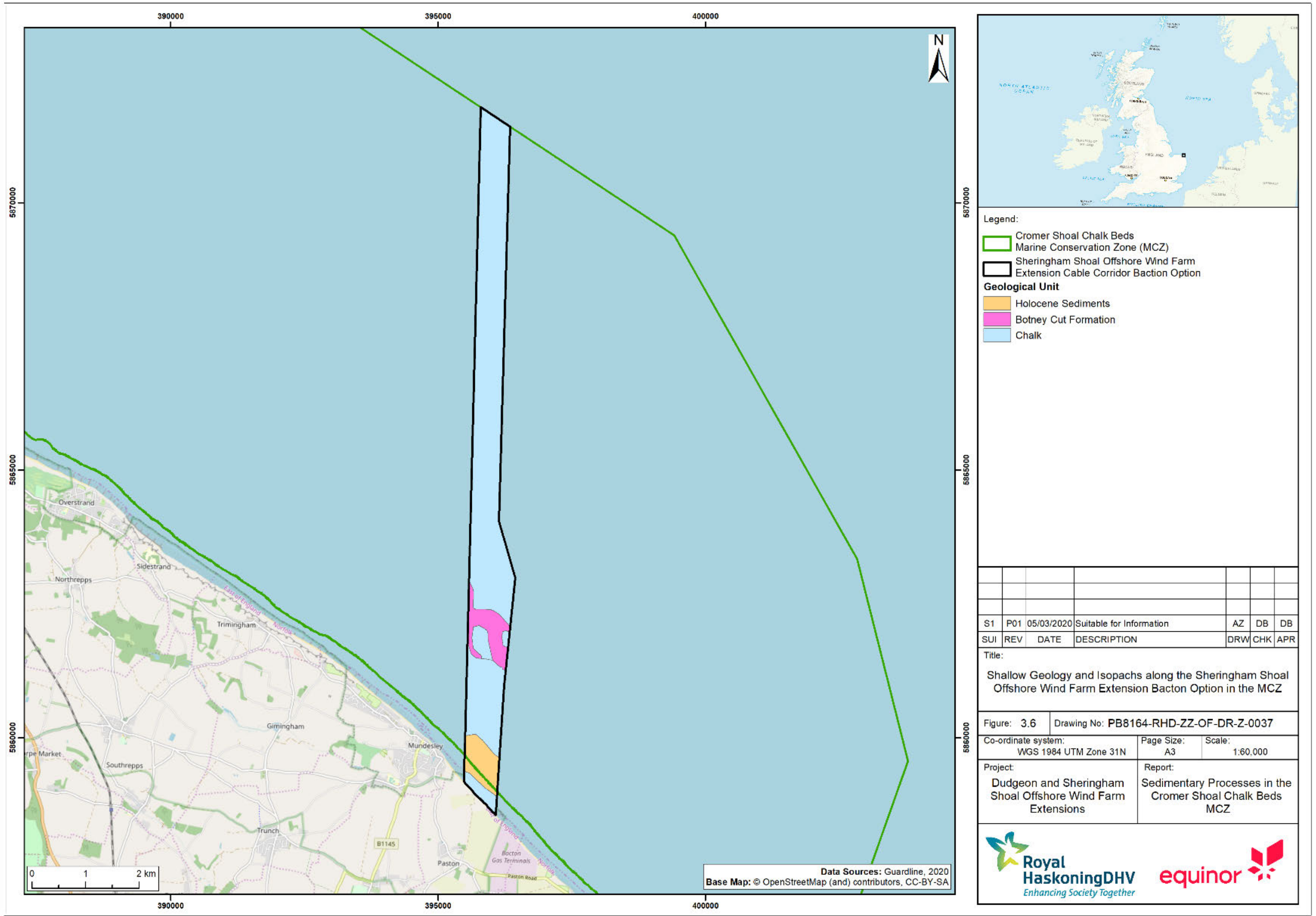

Figure 3.11. Shallow geology and isopachs along the SEP and DEP Bacton option in the MCZ (Gardline, 2020)

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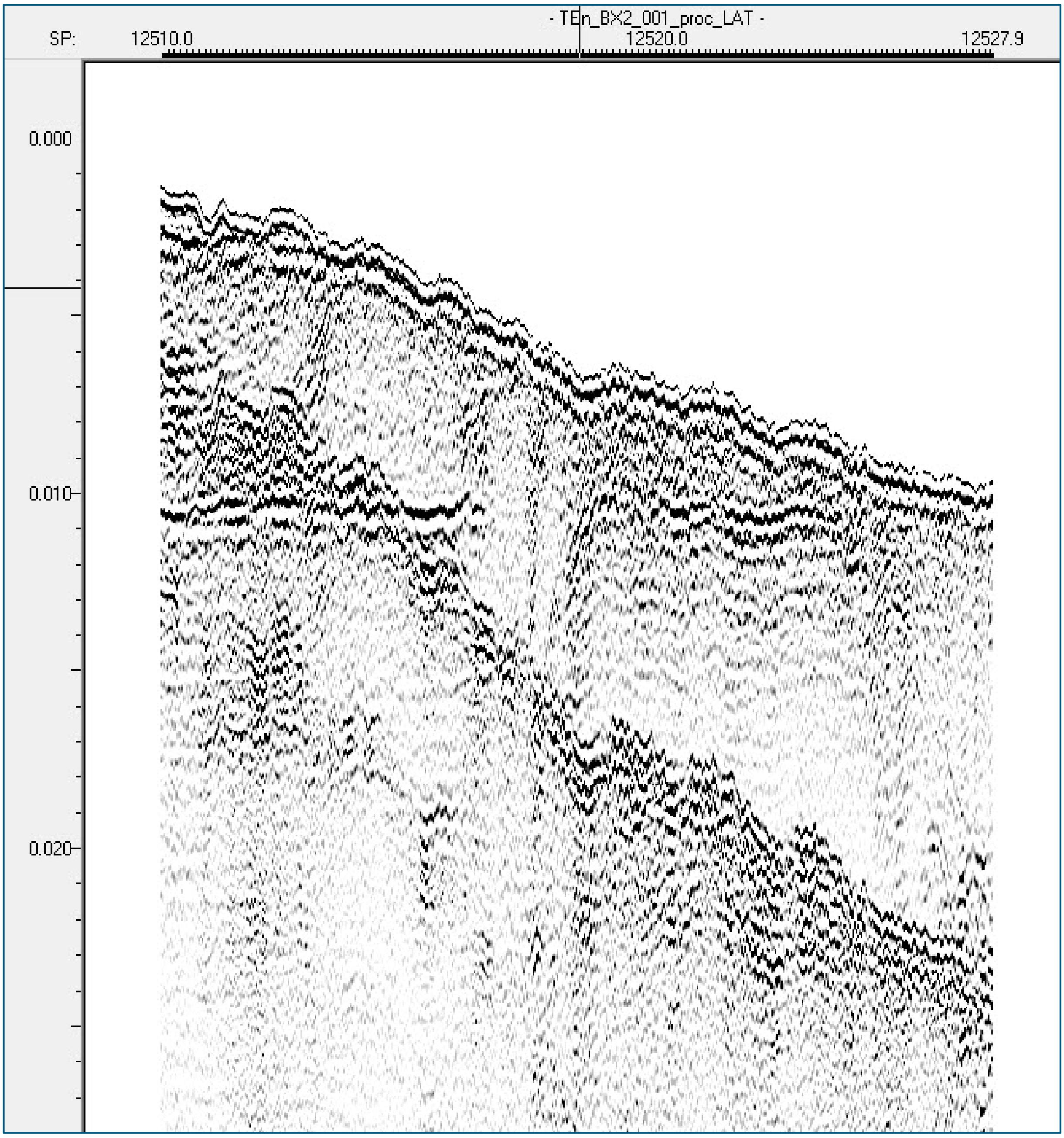

Figure 3.12. Sub-bottom profile showing the Holocene sand along the SEP and DEP Bacton option in the MCZ

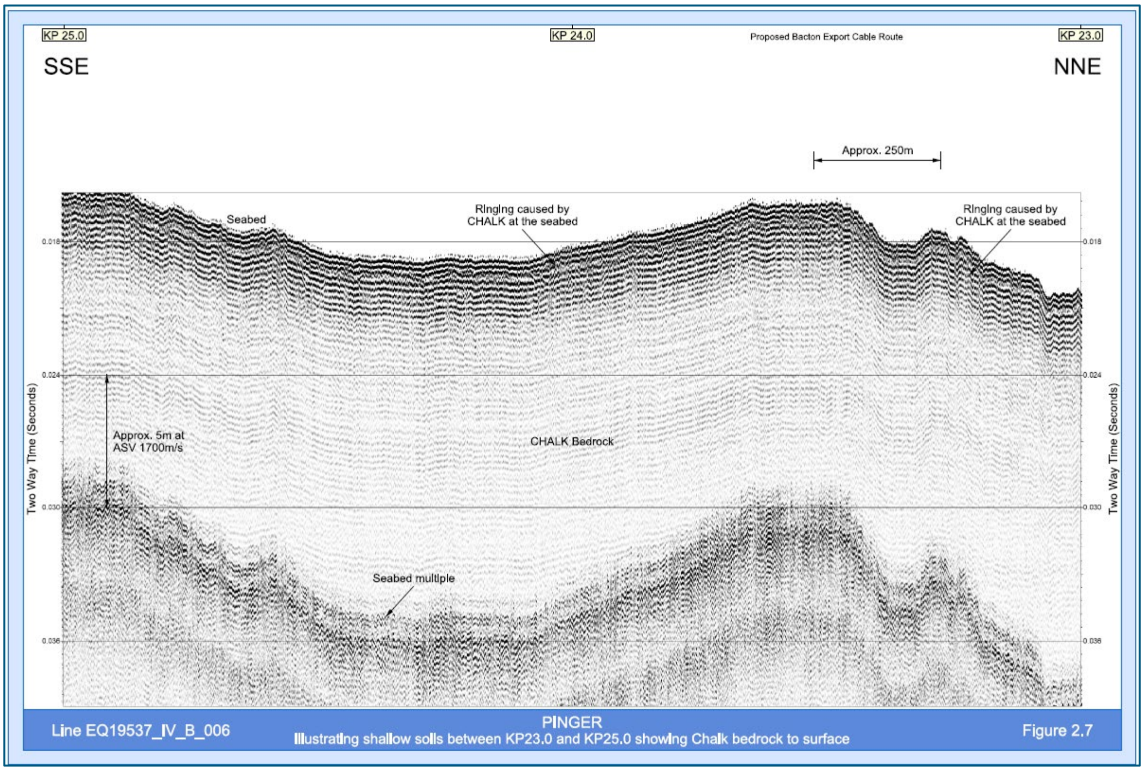

Figure 3.13. Sub-bottom profiler record about 5km offshore along the SEP and DEP Bacton option illustrating the 'ringing' effect at the sea bed and the difficulty of defining the thickness of the overlying lag (Gardline, 2020)

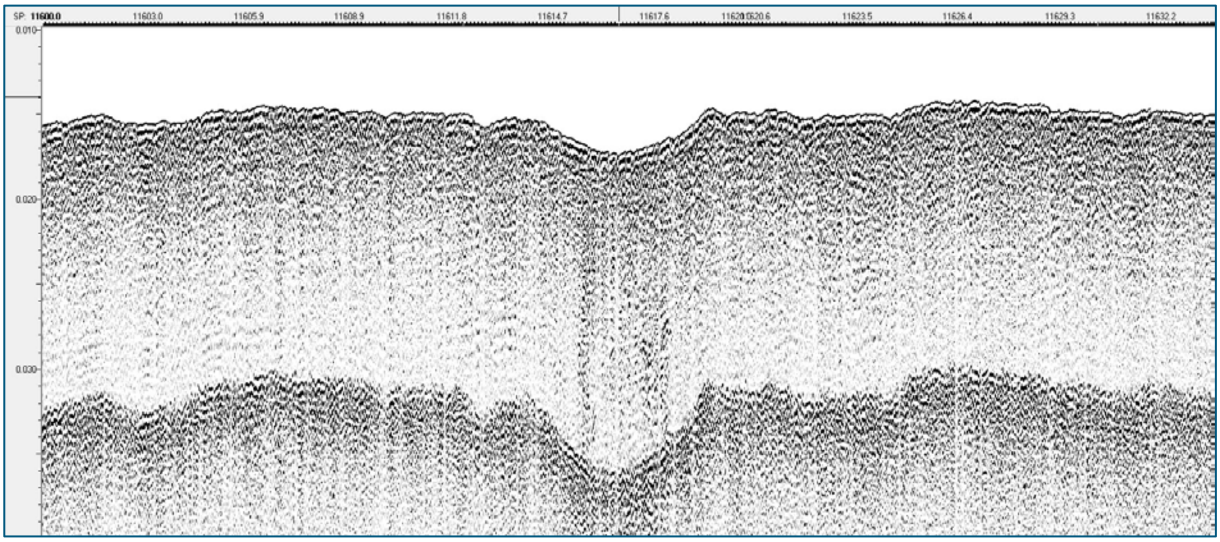

Figure 3.14. Sub-bottom profile showing the chalk close to the sea bed (with an overlying lag not visible on the profile) along the SEP and DEP Bacton option in the MCZ

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4 Historic Dudgeon Offshore Wind Farm Surveys

Three geophysical surveys, four benthic (sediment sampling) surveys and a single vibrocore survey were completed along the existing Dudgeon offshore wind farm export cable corridor in the MCZ (**Table 4-1**). The geophysical survey extents and sediment sample and vibrocore locations are shown in **Figure 4.1**.

Table 4-1. Geophysical and benthic surveys completed along the Dudgeon offshore wind farm cable corridor in the MCZ

Contractor	Survey Type	Start Date	End Date
Gardline	Geophysical	6th October 2008	10th October 2008
Titan	Benthic	December 2008	January 2009
Fugro	Geophysical	30th April 2013	7th October 2013
GEO	V brocorer	10th May 2013	6th June 2013
Fugro	Benthic	23rd August 2014	10th September 2014
Cefas	Benthic	2014	2014
MMT	Geophysical	16th August 2018	28th August 2018
MMT	Benthic	16th August 2018	28th August 2018

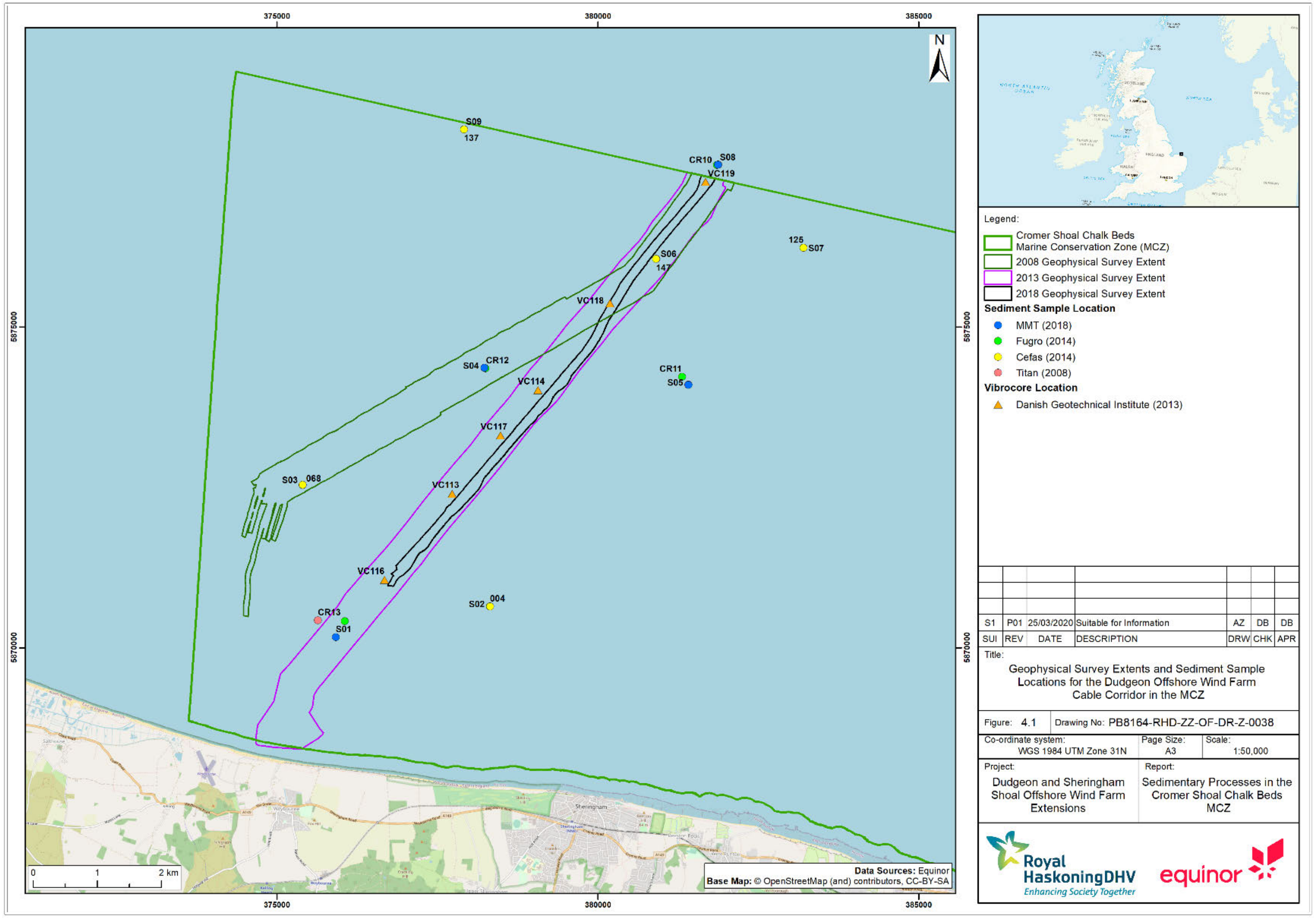

Figure 4.1. Geophysical survey extents and sea bed sediment sample and vibrocore locations for the Dudgeon offshore wind farm cable corridor in the MCZ

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4.1 Geophysical Surveys

For the purposes of this investigation, the geophysical surveys from 2013 (Fugro, 2014) and 2018 (MMT, 2018a, b) are used as a basis for comparison as they overlap along the entire length of the cable corridor. The 2008 geophysical survey (Gardline, 2008) is not analysed because it diverges from the 2013 and 2018 surveys with overlap only at the northern extent of the MCZ (**Figure 4.1**). However, a general description of the 2008 results is provided in **Appendix B**.

4.1.1 Fugro 2013

Fugro (2014) reported the results of a pre-construction geophysical survey completed along the existing Dudgeon offshore wind farm export cable corridor between 30th April 2013 and 7th October 2013. Multibeam echosounder (bathymetry), side-scan sonar (sea bed texture) and sub-bottom profilers (shallow geology) were deployed. This cable corridor is east of the originally proposed route mapped by Gardline (2008) apart from the northern 3km where there is overlap (**Figure 4.1**).

The water depths are about -4m LAT in the shallow nearshore to about -23m LAT at the MCZ boundary at the base of the southern flank of Sheringham Shoal. Along the corridor in the MCZ, the shallow geology is dominated by chalk (with a veneer of coarse sand or gravelly sand), overlain in places by Botney Cut Formation and/or Holocene sand (**Figure 4.2**).

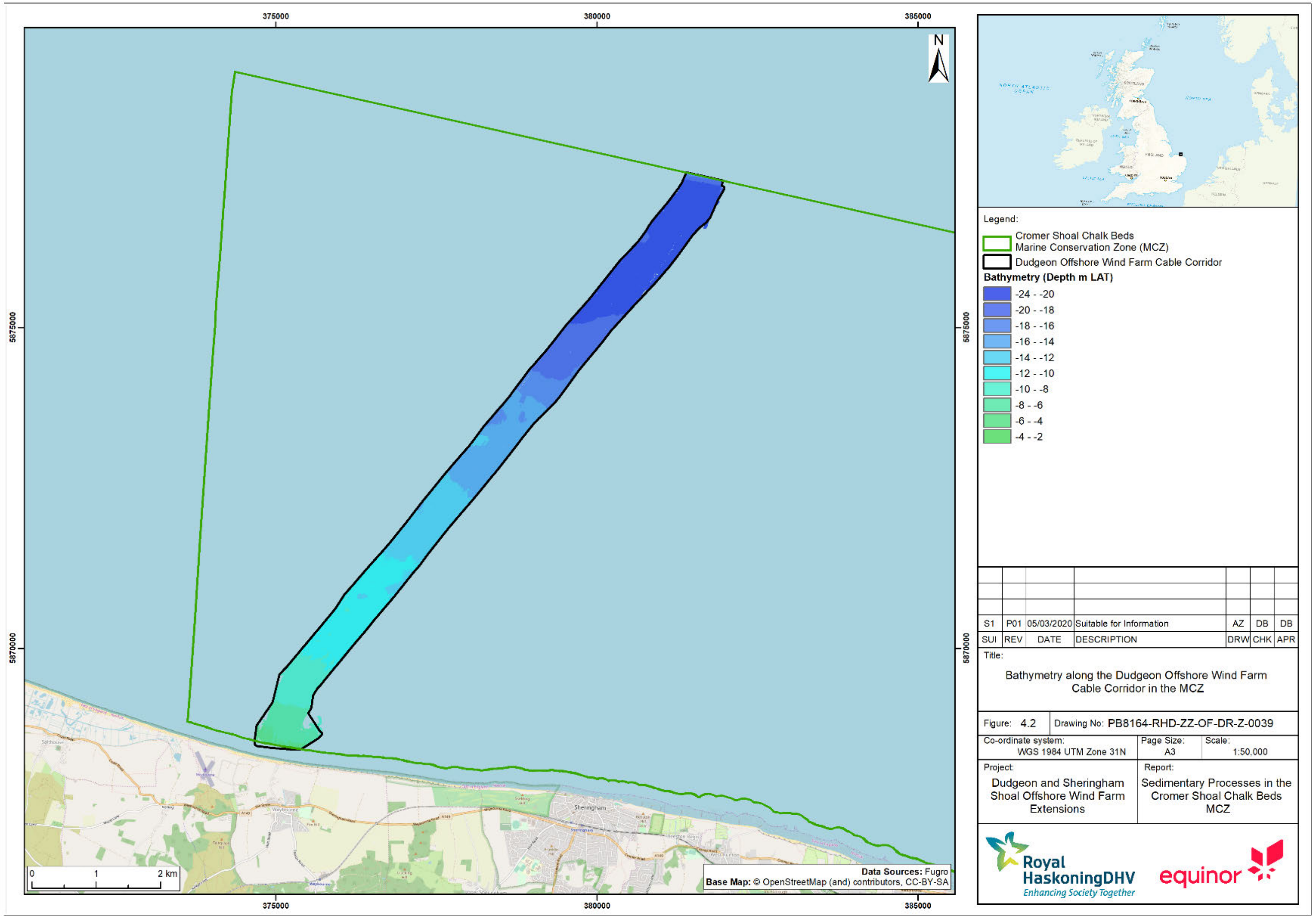

Figure 4.2. Bathymetry along the Dudgeon offshore wind farm cable corridor in the MCZ (Fugro, 2014)

Based on the interpretation of Fugro (2014), the MCZ within the Dudgeon offshore wind farm export cable corridor can be divided into four zones.

- From the coast to about 1km offshore along the corridor is Holocene sand less than 1.5m thick resting on chalk.
- From 1km to 3.2km, the sea bed is alternating Holocene sand and low (less than 0.5m high) gravelly sand 'mounds' overlying chalk (**Figure 4.3**). Fugro (2014) interpreted the mounded nature of the gravelly sand sea bed as meaning the sea bed sediment in these areas is thin, and the underlying subcropping chalk is close to the sea bed where it forms the mounds. They indicated that the sub-bottom profiler data shows that the chalk is present at (or just below) the sea bed in this area. They suggested that there was no direct evidence of outcropping chalk visible on the sea bed acoustic data and as such this sea bed type was not classified in their sea bed characterisation. This interpretation suggests that chalk is eroded to a relatively smooth surface and is generally covered by a thin layer of coarse sediment (lag) along this part of the MCZ, and that the complex erosional geo-structures of exposed chalk (such as ridges, pinnacles and arches as photographed by divers, **Figure 2.2**, and present in the nearshore along the SEP and DEP Weybourne option) are not present here. The southern part of this chalk subcrop is cut by 5m of Botney Cut Formation (1.2-1.8km) or probably a westerly continuation of the Weybourne Channel Deposits identified in the nearshore part of the SEP and DEP cable corridor. Although the low mounded nature of the sea bed was not interpreted along the SEP and DEP cable corridor, the general alternation of gravelly sand/gravel and Holocene sand is present across the inshore 3.5km.
- From 3.2km to 4.2km along the corridor, is further Holocene sand (up to 1.5m thick) sculpted into megaripples with crests oriented north-south or northeast-southwest, resting on chalk. The megaripples indicate mobility of the sand under existing tidal conditions, with gross migration along an approximately east-west and northwest-southeast axes (given the crest orientations of the bedforms).
- From 4.2km to 10.8km, the sea bed is more planar gravelly sand overlying alternating Botney Cut Formation (4-4.5m thick) and chalk (**Figure 4.4**). The gravelly sand sea bed sediments along this section of the existing Dudgeon cable corridor are like those along the SEP and DEP cable corridor and have the same origin (lag deposits from erosion of Pleistocene sediments). They are not mobile under existing tidal conditions. Botney Cut Formation was not identified along the SEP and DEP cable corridor.

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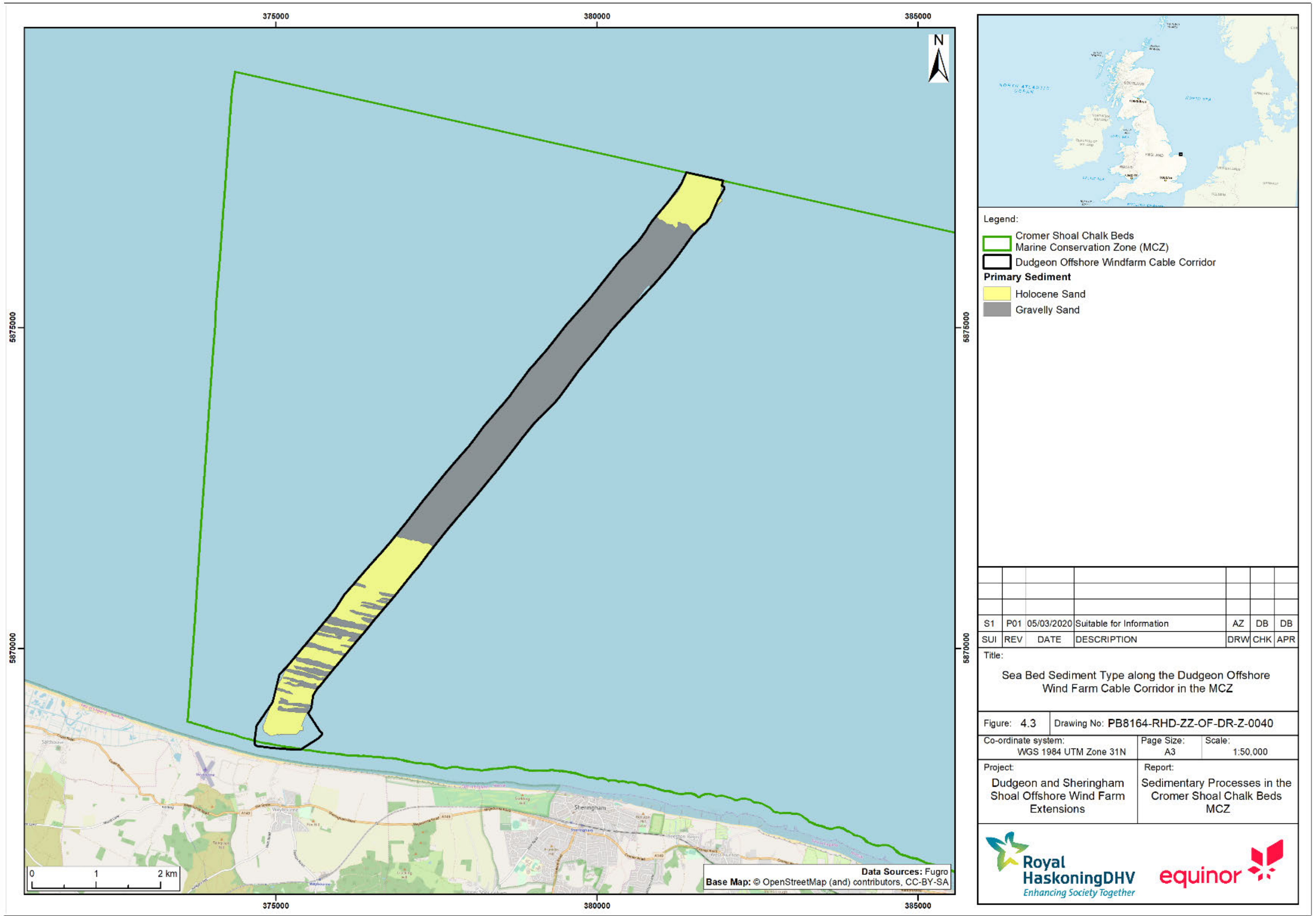

Figure 4.3. Sea bed sediment type along the Dudgeon offshore wind farm cable corridor in the MCZ (Fugro, 2014)

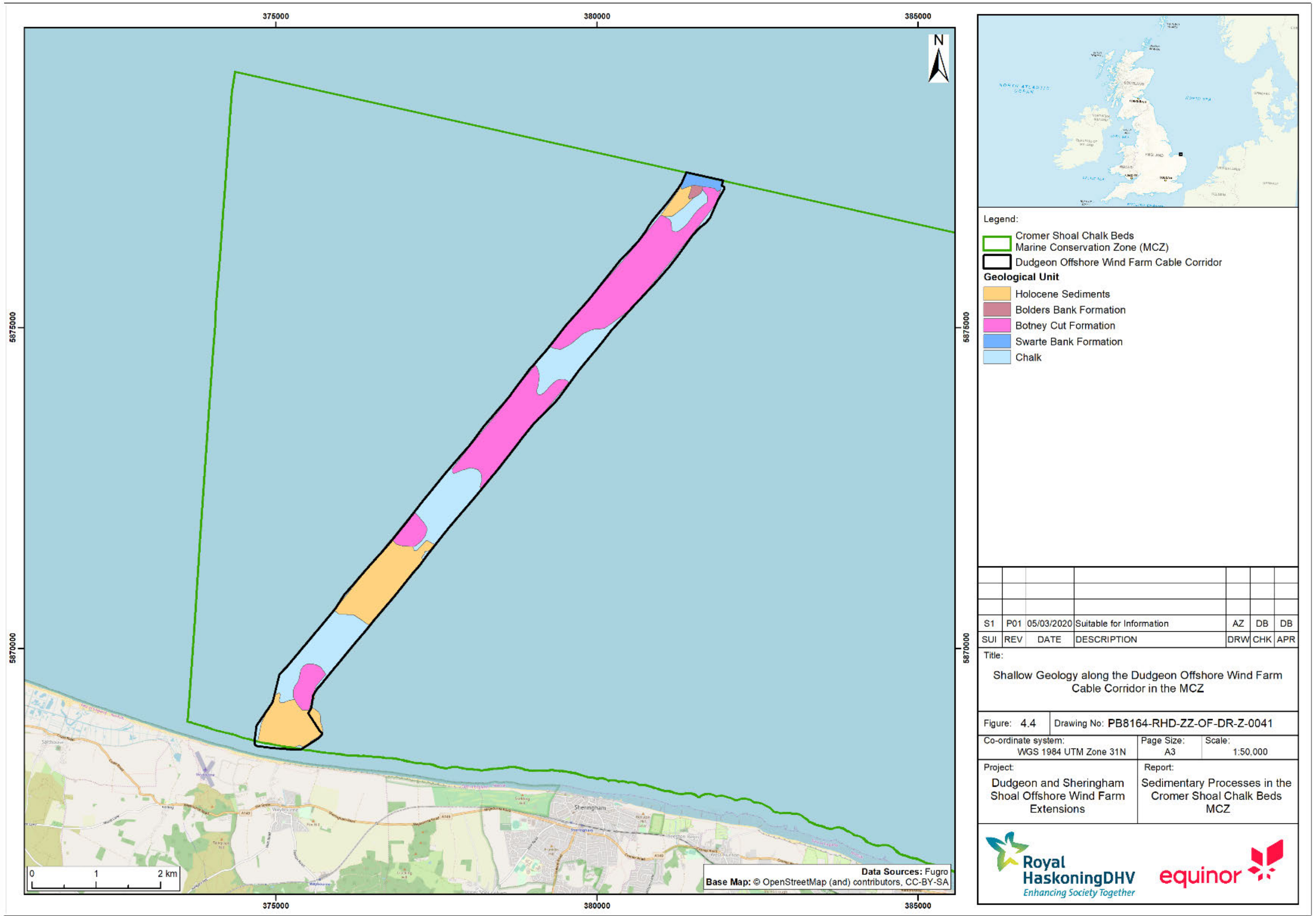

Figure 4.4. Shallow geology along the Dudgeon offshore wind farm cable corridor in the MCZ (Fugro, 2014)

Adjacent to the boundary of the MCZ is a field of megaripples which extend further to the north as the bathymetry rises into Sheringham Shoal sand bank.

4.1.2 Danish Geotechnical Institute 2013 (Vibrocores)

GEO (Danish Geotechnical Institute) completed a vibrocore survey along the Dudgeon offshore wind farm cable corridor in the MCZ in May and June 2013. Details of the geology recovered in the vibrocores is provided in GEO (2014) and their locations are shown on **Figure 4.1**. The chalk was penetrated by VC116, where it was overlain by 0.3m of gravelly, fine to medium sand. Two of the of the vibrocores (VC113 and VC114) penetrated Bolders Bank Formation close to the sea bed comprising slightly sandy, gravelly (calcareous) clay. VC117 and VC119 recovered slightly sandy, silty (calcareous) clay close to the sea bed, which is likely to be the Botney Cut Formation (it was not defined as Bolders Bank Formation by GEO, 2014). VC118 recovered 2.4m of Holocene sand without reaching the underlying geological unit.

4.1.3 MMT 2018 and Comparison with 2013

Between 16th and 28th August 2018, MMT (2018a, b) completed a high-resolution bathymetry (multibeam echosounder) and side-scan sonar survey of the export cables to a shallowest depth of 10m. The survey covered a narrow strip of sea bed within the wider corridor mapped in 2013 by Fugro (2014).

Comparison of the 2018 bathymetry with the 2013 bathymetry where they overlap was assessed in GIS. Along most of the overlapping cable route, bathymetric change has been less than 0.25m. This is effectively a non-mobile bed given that the vertical accuracy of the multibeam echosounder is +/-0.2m. This supports the interpretation of the gravelly sand sea bed as a thin static lag deposit resting on chalk. Elevation change greater than 0.25m occurred in two locations where mobile bedforms are present. These are the Holocene sand areas 3.2km to 4.2km offshore along the corridor and at the boundary of the MCZ (**Figure** 4.5).

The 2013 to 2018 Dudgeon comparison doesn't show the continued existence of trenches in 2018 compared to 2013 like the Sheringham Shoal comparison does between 2008 (pre-trench) and 2013 (post-trench) (**Section 5.1.3**). This is likely due to the different trenching processes employed along each corridor. The trenches for the Sheringham Shoal export cables were cut by jetting, which essentially removes all the sediment from a relatively wide trench and jets it some distance away. Hence, once the trench is created, it is maintained, as long as there is no significant sediment transport across it. The trenches for the Dudgeon export cables trench are much smaller (30cm) and were ploughed; a process which fills the trench back-in with sediment after the cut.

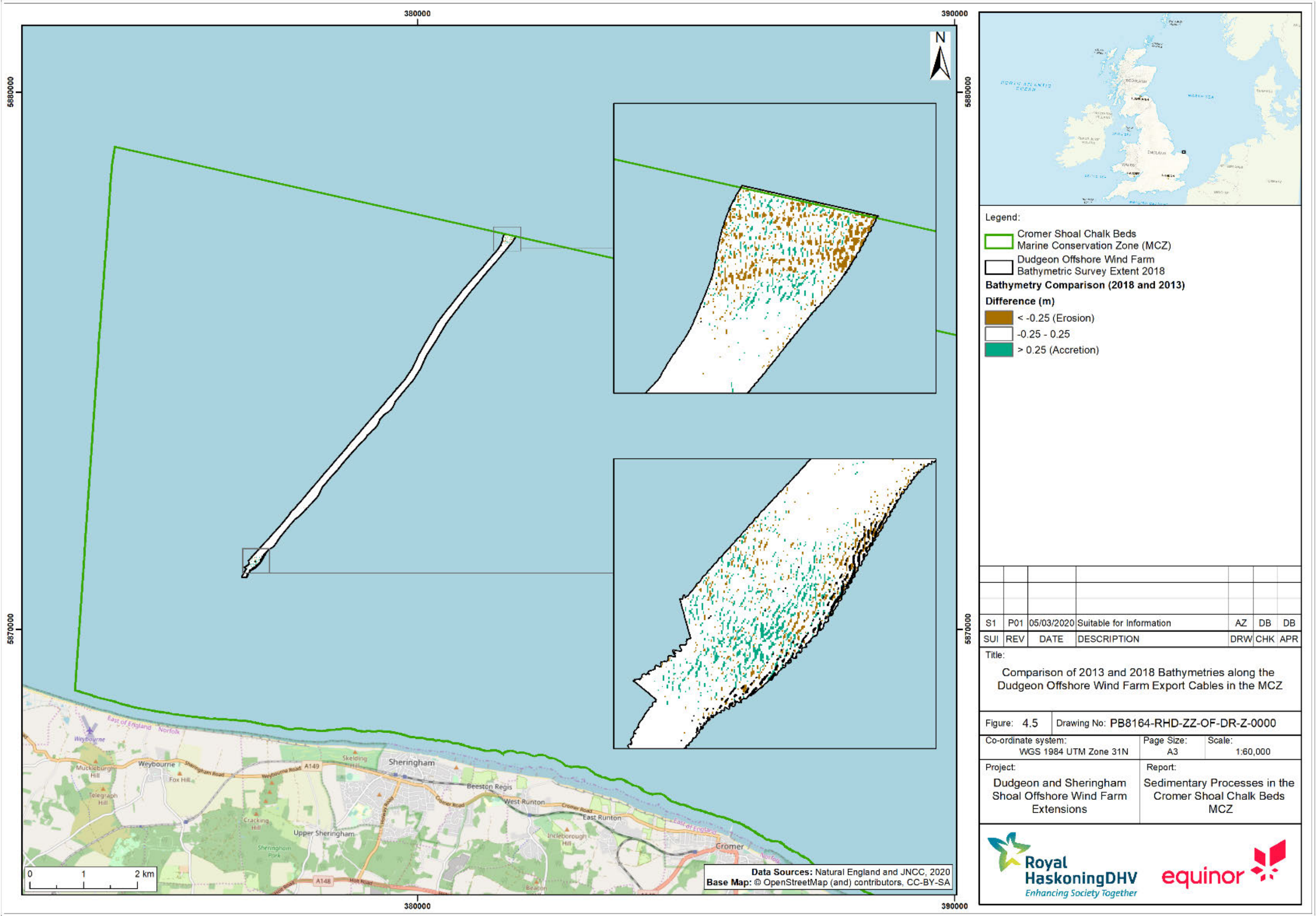

Figure 4.5. Comparison of 2013 and 2018 bathymetries along Dudgeon offshore wind farm export cables in the MCZ where elevation change greater than 0.25m has occurred. Holocene sand at the MCZ boundary (top) and Holocene sand area 3.2-4.2km offshore (bottom)

4.2 Benthic Surveys

Nine duplicate sediment samples close to the Dudgeon corridor are assessed here to understand how sea bed composition has changed over time. It should be noted that although the sea bed sediment samples from different years are located close to each other, they will not be from the same positions exactly, and given the potential changes in composition over short distances, only a general appreciation of change can be established. Sea bed sediment samples from 2008/2009 (Titan, 2009), 2014 (Cefas, 2014; Fugro, 2015) and 2018 (MMT, 2019) are compared here (**Table 4-2**).

Table 4-2. Time series of sea bed sediment samples collected for Dudgeon offshore wind farm cable corridor

2008 ID (Titan)	2014 ID (Fugro)	2014 ID (Cefas)	2018 ID (MMT)
CR10	CR10		S08
CR11	CR11		S05
CR12	CR12		S04
CR13	CR13		S01
		CSCB004	S02
		CSCB068	S03
		CSCB125	S07
		CSCB137	S09
		CSCB147	S06

4.2.1 Titan 2008/2009

In December 2008 and January 2009, Titan (2009) completed a benthic survey of Dudgeon offshore wind farm scoped using the side-scan sonar data of Gardline (2008). Four grab samples were recovered in the MCZ (CR11 to CR13) and on the adjacent Sheringham Shoal (CR10). The sample from Sheringham Shoal is 100% sand with a median particle size of 0.27mm (medium sand) (**Table 4-3** and **Figure 4.6**). Samples along the corridor in the MCZ are similar in composition containing 38-48% gravel and 52-62% sand. Median particle sizes range from 0.44mm (medium sand) to 1.5mm (very coarse sand).

Table 4-3. Particle size characteristics of sea bed samples collected in 2008/2009 (Titan, 2009) close to the Dudgeon cable corridor

Location	% gravel	% sand	% mud	%coarse sand or greater	Median (mm)	Median Class
CR10	0	100	0	0.1	0.27	Medium sand
CR11	47.7	52.3	0	57.1	1.5	Very coarse sand
CR12	38.1	61.9	0	45.9	0.44	Medium sand
CR13	46.2	53.8	0	58.3	1.3	Very coarse sand

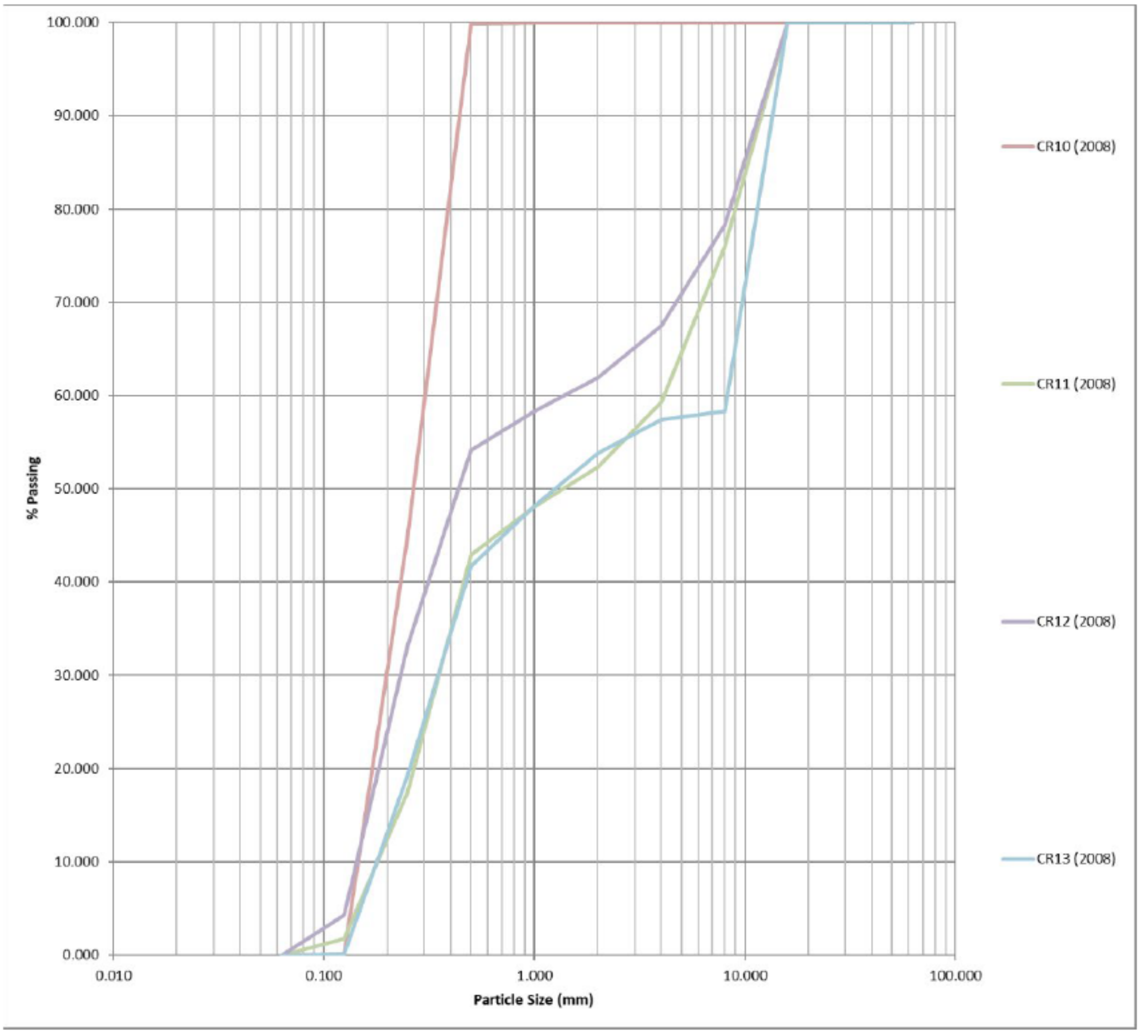

Figure 4.6. Cumulative particle size distribution of sea bed sediment samples collected in 2008/2009 (Titan, 2009) along the Dudgeon cable corridor

4.2.2 Fugro 2014

The grab sampling in the pre-construction survey (23rd August 2014 and 10th September 2014, Fugro, 2015) was undertaken at four sites along the export cable corridor in the MCZ (CR11-CR13) and on the adjacent Sheringham Shoal (CR10), which were established during the 2008 survey (Titan, 2009). The sample from Sheringham Shoal is 100% sand with a median particle size of 0.25mm (medium sand) (**Table 4-4**). The composition is like the sample taken at the same location in 2008 (**Figure 4.7**). Samples along the corridor in the MCZ vary in composition but contain 26-52% gravel and 49-63% sand. Median particle sizes range from 0.36mm (medium sand) to 2.59mm (very fine gravel). These overall compositions are comparable within an envelope to those collected in 2008 (**Figure 4.7**).

Table 4-4. Particle size characteristics of sea bed samples collected in 2014 (Fugro, 2014) along the Dudgeon cable corridor

Location	% gravel	% sand	% mud	% coarse sand or greater	Median (mm)	Median class
CR10	0	100	0	0.2	0.25	Medium sand
CR11	25.7	63.3	11.0	39.2	0.36	Medium sand
CR12	39.0	49.9	11.1	48.9	0.48	Medium sand
CR13	51.5	48.5	0	57.7	2.59	Very fine gravel

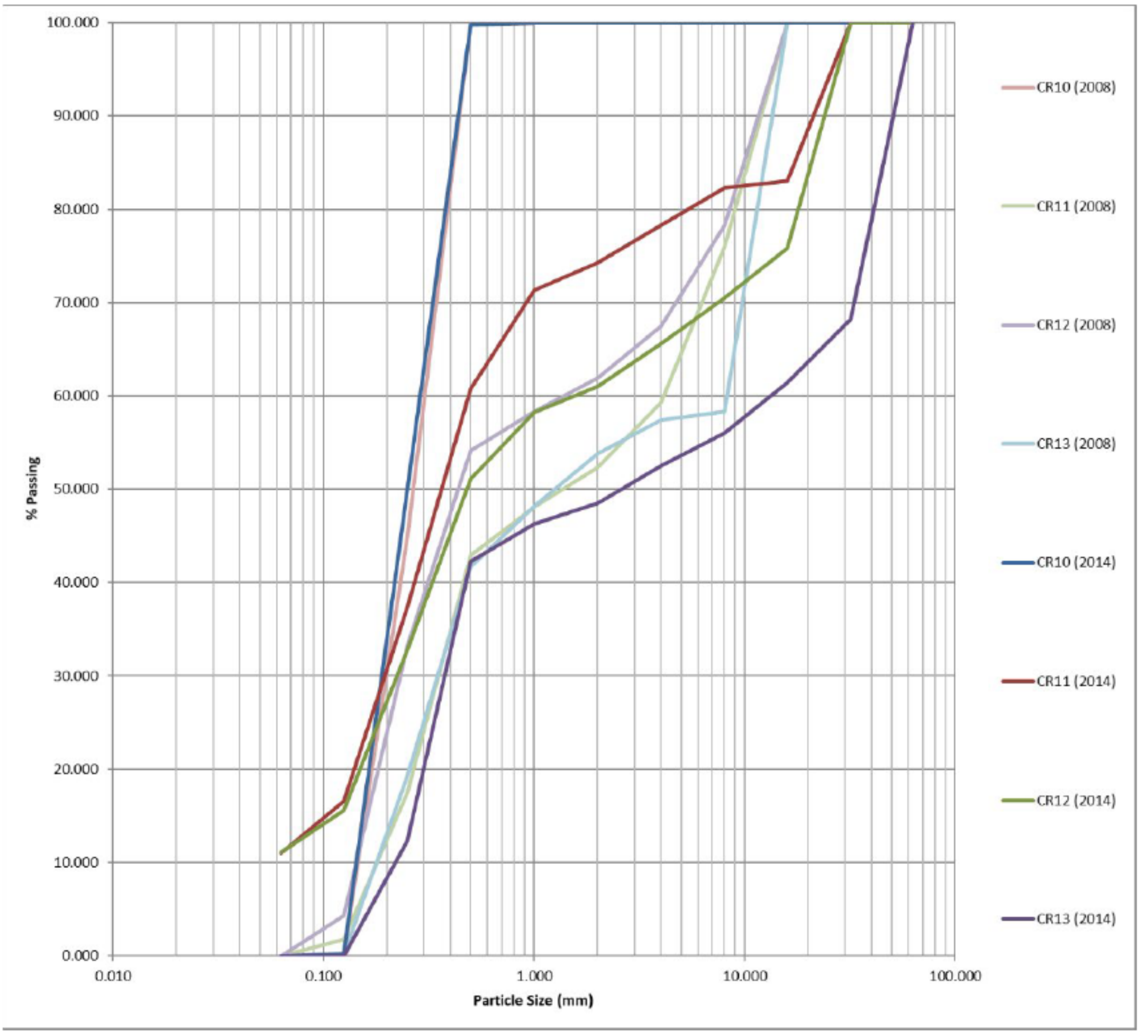

Figure 4.7. Cumulative particle size distribution of sea bed sediment samples collected in 2008/2009 (Titan, 2009) and 2014 (Fugro, 2014) along the Dudgeon cable corridor

4.2.3 Cefas 2014

The cable route was sparsely sampled in 2014. Therefore, an additional five sea bed samples (Cefas, 2014) were added (CSCB004, 068, 125, 137 and 147) to the original Fugro (2014) pre-construction sediment data. The samples vary in composition containing 0-52% gravel, 28-73% sand and 0-72% mud. Median particle sizes range from less than 0.063mm (mud) to 2.5mm (very fine gravel) (**Table 4-5** and **Figure 4.8**).

Table 4-5. Particle size characteristics of sea bed samples collected in 2014 (Cefas, 2014) along the Dudgeon cable corridor

Location	% gravel	% sand	% mud	% coarse sand or greater	Median (mm)	Median class
CSCB004	51.56	48.44	0	54.70	2.5	Very fine gravel
CSCB068	21.60	64.55	13.85	41.35	0.37	Medium sand
CSCB125	25.45	73.26	1.29	54.74	0.57	Coarse sand
CSCB137	0	28.43	71.57	0.16	<0.063	Mud
CSCB147	13.62	66.03	20.35	30.42	0.29	Medium sand

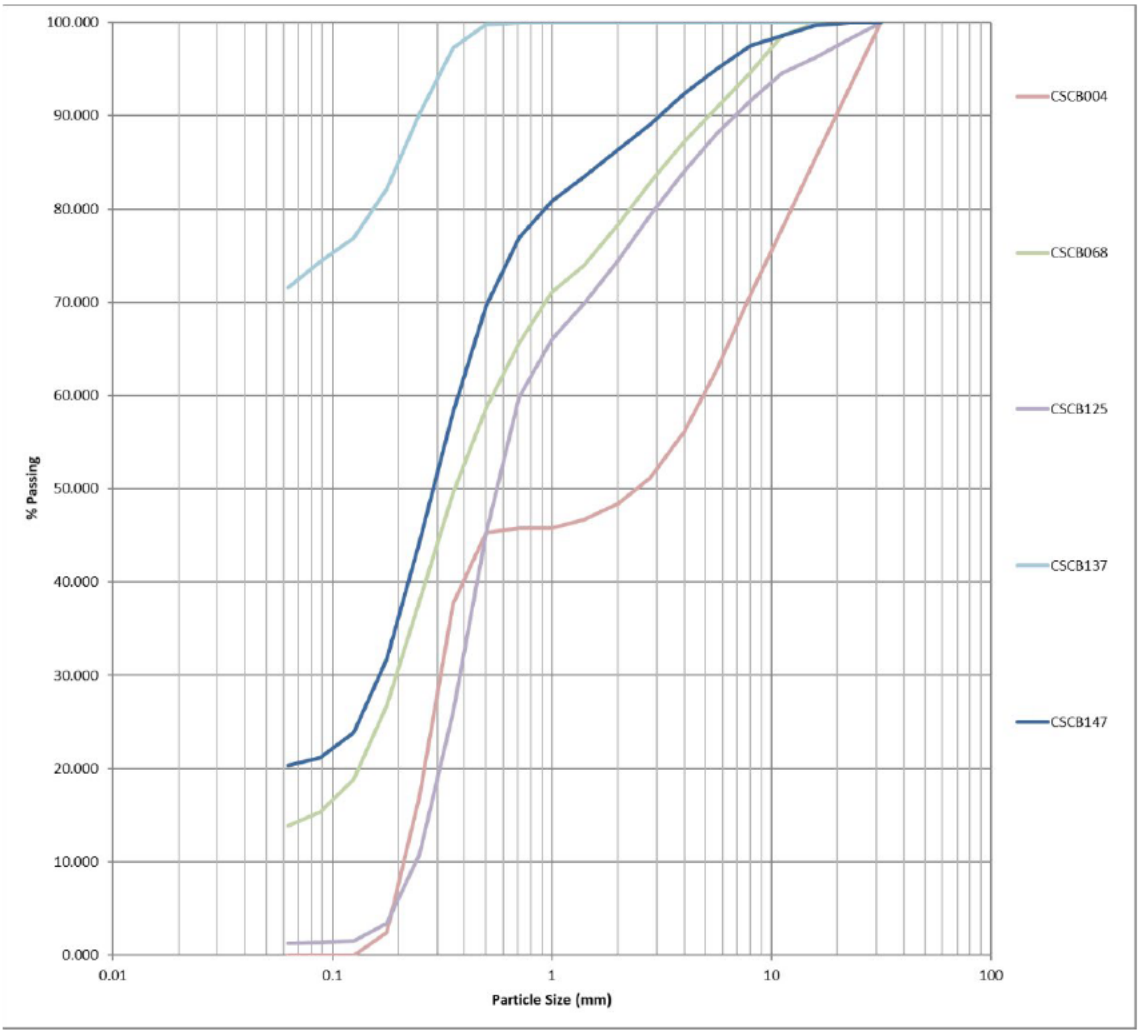

Figure 4.8. Cumulative particle size distribution of sea bed sediment samples collected in 2014 (Cefas, 2014) along the Dudgeon cable corridor

4.2.4 MMT 2018

Between 24th August and 4th September 2018, MMT (2019) completed a post-construction sea bed sediment sampling and drop-down video survey along the Dudgeon export cables in the MCZ. Nine sites (S01 to S09) were sampled, four of which were at similar locations to the Titan (2009) and Fugro (2014) sites from the original pre-construction surveys and five sites were revisited Cefas (2014) sites (**Figure 4.9** and **Figure** 4.10). Grab sample S08 was located on Sheringham Shoal.

Table 4-6. Particle size characteristics of sea bed samples collected in 2018 along the Dudgeon cable corridor (MMT, 2019)

Location	Original ID	% gravel	% sand	% mud	% coarse sand or greater	Median (mm)	Median class
S01	CR13	2	97	1	6	0.28	Medium sand
S02	CSCB004	43	51	6	45	0.30	Medium sand
S03	CSCB068	44	48	8	56	1.3	Very coarse sand
S04	CR12	67	27	6	75	7.7	Fine gravel
S05	CR11	53	46	1	61	2.8	Very fine gravel

Location	Original ID	% gravel	% sand	% mud	% coarse sand or greater	Median (mm)	Median class
S06	CSCB147	41	52	7	55	0.90	Coarse sand
S07	CSCB125	37	62	1	47	0.56	Coarse sand
S08	CR10	0	99	1	0	0.24	Fine sand
S09	CSCB137	0	92	8	0	0.23	Fine sand

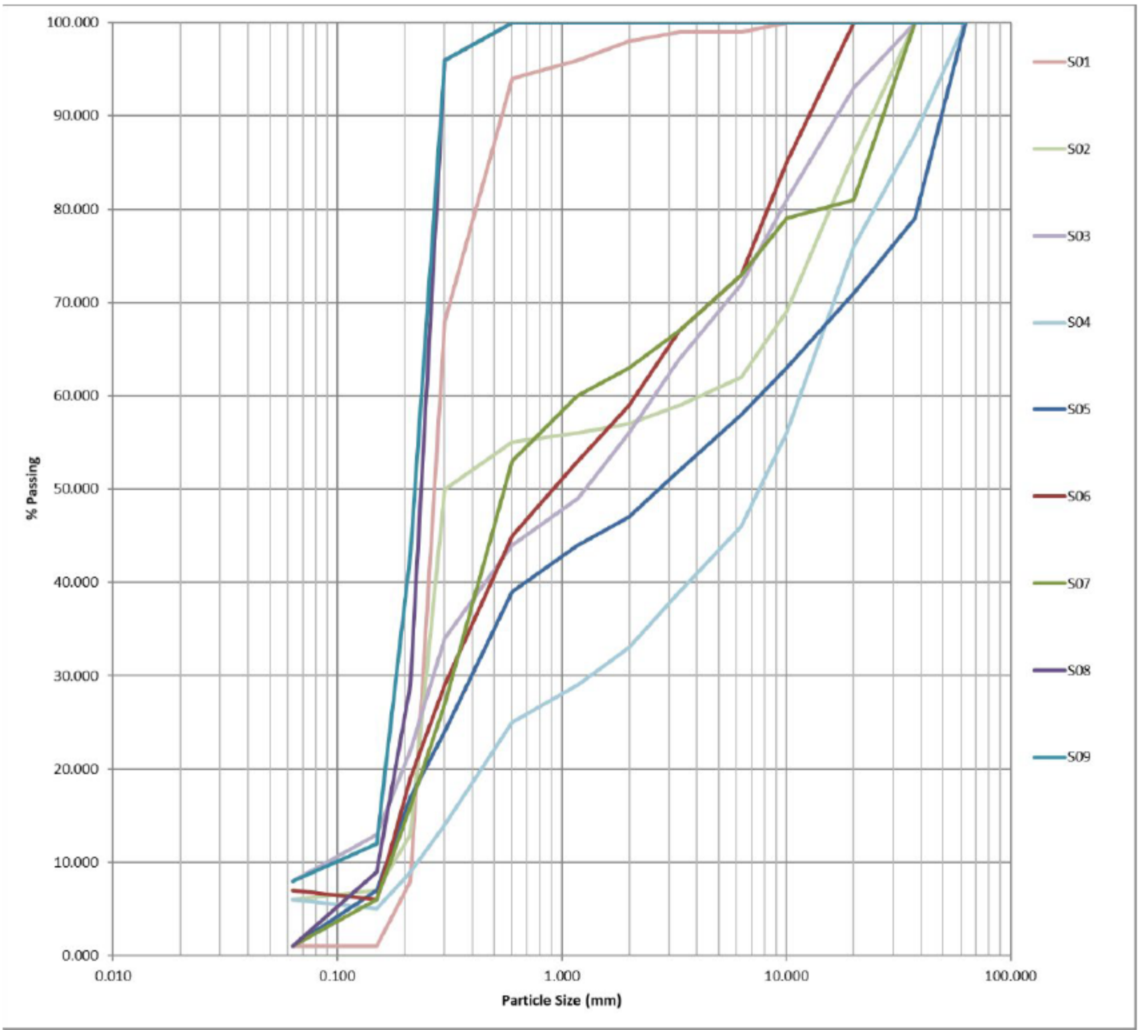

Figure 4.9. Cumulative particle size distribution of sea bed sediment samples collected in 2018 (MMT, 2019) along the Dudgeon cable corridor

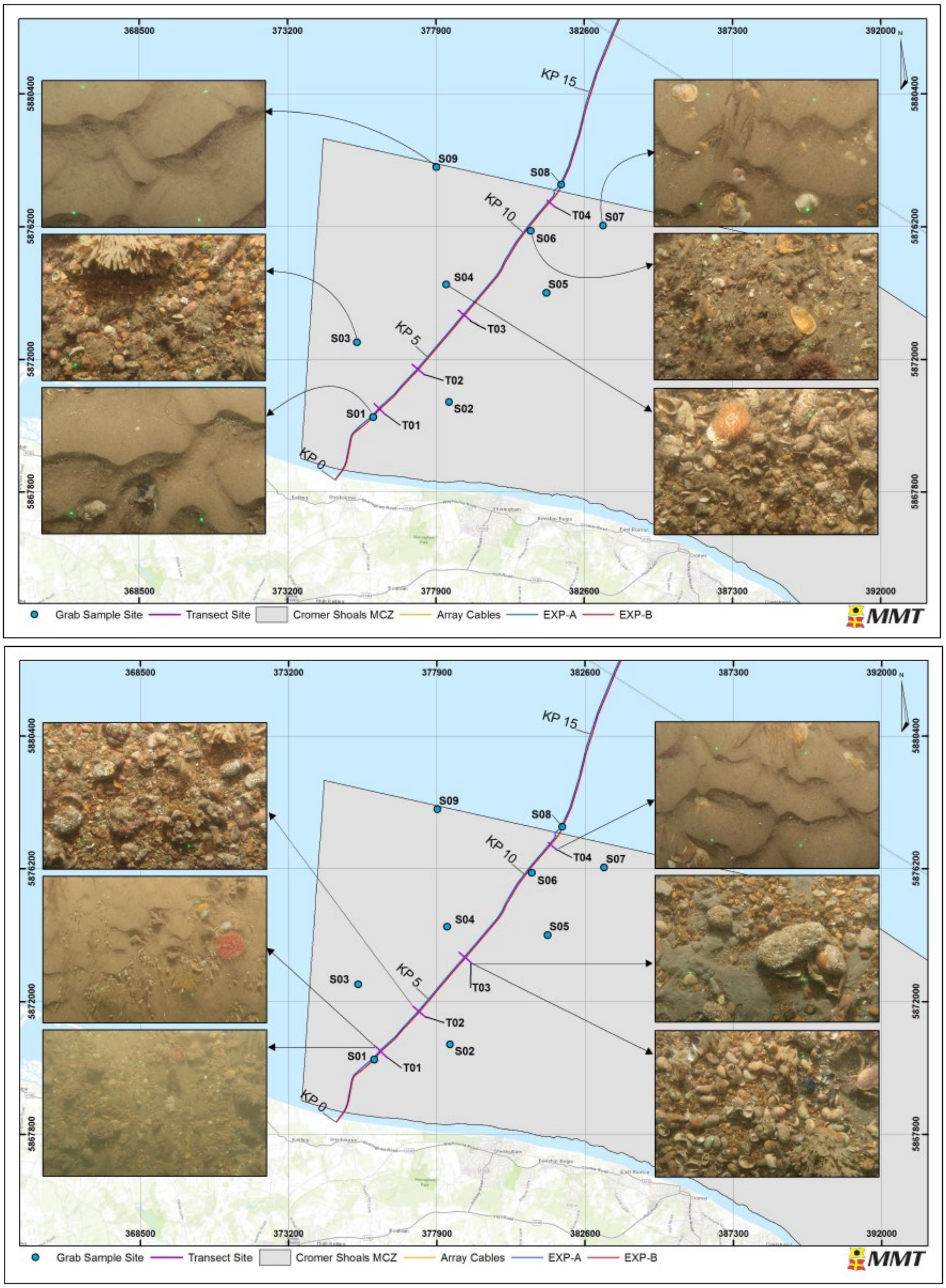

Figure 4.10. Drop-down video locations and stills from each location (MMT, 2019)

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4.2.5 Comparison of Particle Size Data

Table 4-7 provides a comparison of the medium particle sizes of samples taken at similar locations. All the duplicate sample locations in the MCZ show variability in median particle size, apart from the samples from Sheringham Shoal sand bank (just outside the MCZ, locations CR10/S08), which are consistently medium sand. Differences in median particle sizes range from 0.44mm to 7.7mm (CR12/S04) and from less than 0.063mm to 0.23mm (CSCB137/S09). Other comparisons are closer, such as 0.57mm and 0.56mm at CSCB125/S07. However, overall, most of the median particle sizes, regardless of when or where they were captured are medium to coarse sand or coarser and the samples contain relatively large proportions of gravel (25-70%). These distributions suggest that they are not mobile under the existing current regime. The differences in particle size at each location are due to capture at slightly different positions on the sea bed in each year.

Table 4-7. Comparison of median particle sizes of sea bed samples collected in 2008, 2014 and 2018 along the Dudgeon cable corridor

Location		Median particle size (mm)		
		2008	2014	2018
CR10	S08	0.27	0.25	0.24
CR11	S05	1.5	0.36	2.8
CR12	S04	0.44	0.48	7.7
CR13	S01	1.3	2.59	0.28
CSCB004	S02		2.5	0.30
CSCB068	S03		0.37	1.3
CSCB125	S07		0.57	0.56
CSCB137	S09		<0.063	0.23
CSCB147	S06		0.29	0.9

5 Historic Sheringham Shoal Offshore Wind Farm Surveys

Nine geophysical surveys, three benthic (sea bed sediment sampling) surveys and a single vibrocore survey are assessed here to understand geomorphological conditions along the existing Sheringham Shoal offshore wind farm export cable corridor (**Table 5-1**). The geophysical survey extents and sediment sample and vibrocore locations are shown in **Figure 5.1**.

Table 5-1. Geophysical, sediment sampling and vibrocore surveys completed along and adjacent to the Sheringham Shoal offshore wind farm cable corridor

Contractor	Survey Type	Start Date	End Date
Titan	Geophysical	4th July 2005	8th July 2008
Fugro	V brocorer	17th August 2005	18th August 2005
IECS	Sea bed sediment	2005	2005
EMU	Geophysical	1st March 2008	5th April 2008
EMU	Sea bed sediment	4th November 2009	5th November 2009
Fugro EMU	Geophysical	1st November 2013	3rd December 2013
Fugro EMU	Geophysical	30th April 2014	4th May 2014
MES	Sea bed sediment	April 2014	May 2014
Fugro EMU	Geophysical	1st November 2014	6th January 2015
Fugro EMU	Geophysical	20th May 2015	23rd May 2015
Fugro EMU	Geophysical	7th November 2015	25th January 2016
Fugro	Geophysical	17th October 2018	23rd November 2018

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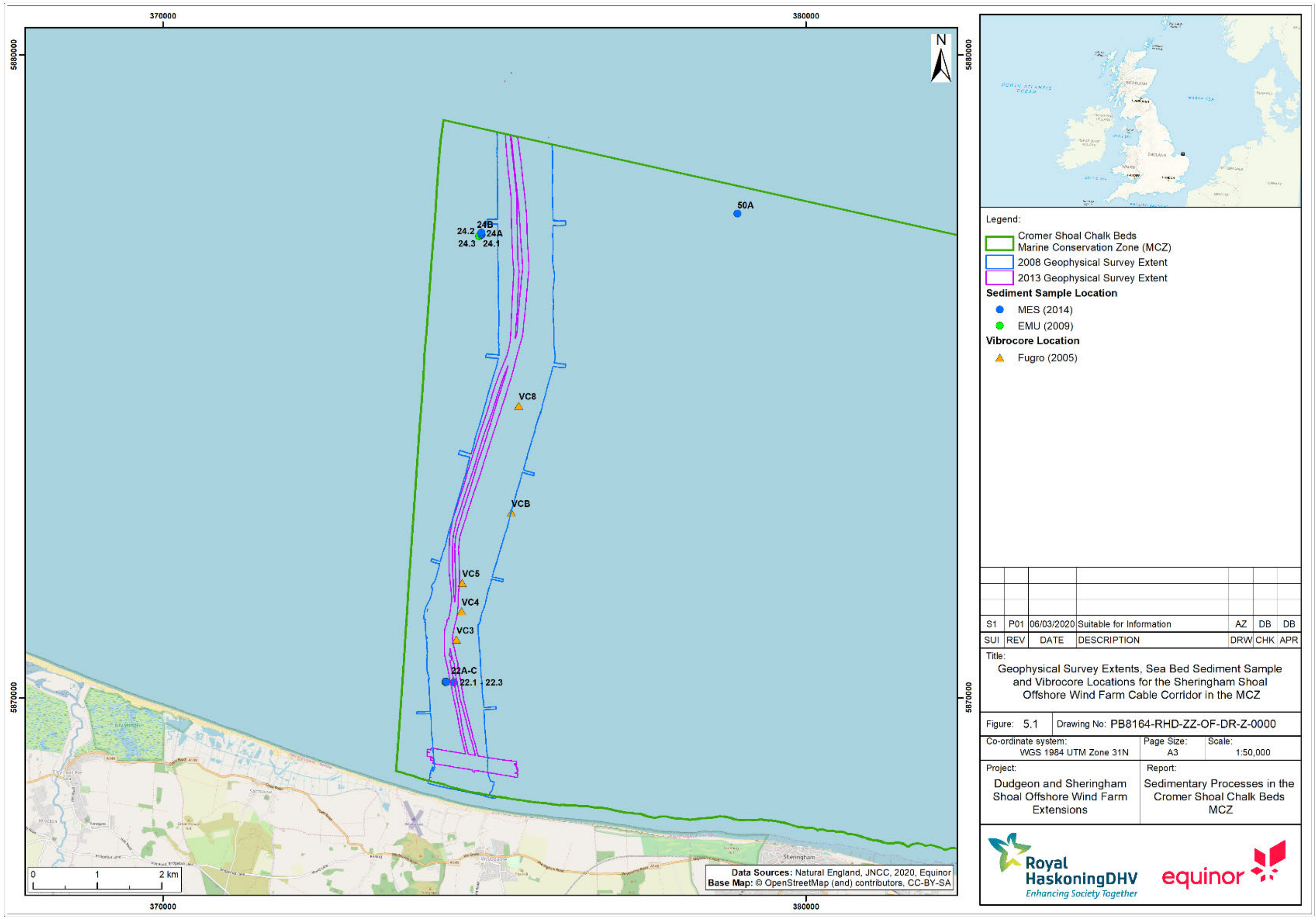

Figure 5.1. 2008 and 2013 geophysical survey extents, sea bed sediment sample (duplicate samples at 22, 24 and 50) and vibrocore locations for the Sheringham Shoal offshore wind farm cable corridor in the MCZ

5.1 Geophysical Surveys

For the purposes of description and comparison, the geophysical data from March-April 2008 (EMU, 2008), winter 2013 (Fugro EMU, 2014), winter 2015/2016 (Fugro EMU, 2016a), and winter 2018 (Fugro, 2019a) are used. The geophysical data from summer 2014, winter 2014, and summer 2015 geophysical data sets were not accessed as they were considered superfluous to the required analysis. However, a general description of the July 2005 results is provided in Appendix C. The comparisons of bathymetry along the cable corridor were completed by Fugro EMU (2014), Fugro EMU, (2016b) and Fugro (2019b) and so a new analysis of the data was not conducted here.

5.1.1 EMU 2008

The survey between 1st March 2008 and 5th April 2008 was a full pre-construction geophysical survey to collect bathymetry (multibeam echosounder), shallow geology (sub-bottom profiling) and sea bed features (side-scan sonar) data, to determine the best possible route for the export cables (EMU, 2008). The water depths are about -4m LAT in the shallow nearshore to about -21m LAT at the MCZ boundary. The sea bed of the cable corridor in the MCZ can be divided into three sections; an inshore area south of Pollard Bank, Pollard Bank, and Pollard Bank to the MCZ boundary.

- The inshore area exhibits four sea bed sediment types with irregular boundaries (**Figure 5.2** and **Figure** 5.3). Closest to shore is an area of sandy gravel and gravelly sand with chalk outcrops, which becomes a mix of gravelly sand/chalk outcrop and Holocene sand further offshore to the southern flank of Pollard Bank (about 3km offshore). The gravelly sand layer is interpreted to be thin because outcrops of chalk do occur as low-lying east-west oriented ridges. It is likely that these sediments are not mobile under the existing tidal regime and form a lag on top of chalk subcrop. An east-west oriented zone of gravel bisects the chalk outcrop about 2-2.5km offshore. The Holocene sand is mainly featureless but in places its surface is sculpted into megaripples with crests oriented north-south. EMU (2008) indicated that the sand is up to 5m thick and underlain by chalk. The presence of bedforms indicates that these sands are mobile under the existing tidal regime.
- Pollard Bank consists of sand with megaripples and sand waves. The approach to the southern flank is sculpted into southwest-northeast aligned megaripples and sand waves which are up to 1.6m high. The maximum thickness of Holocene sand in the bank is about 6m and it is underlain by either Bolders Bank Formation or chalk (EMU, 2008). The bank is asymmetric with the northern flank having a gentler slope than the southern flank implying migration south. The northern flank contains megaripples with crests oriented southwest-northeast. Pollard Bank disappears to the east and is not present along the Dudgeon cable corridor or the SEP and DEP cable corridor.
- North of Pollard Bank the sea bed is composed of gravelly sand which continues north uninterrupted to the boundary of the MCZ. EMU (2008) indicated that the gravelly sand is 0-2m thick and underlain by either Bolders Bank Formation (to depths below sea bed up to 5m) or chalk where the Bolders Bank Formation is absent.

The sandy gravel and gravelly sand with chalk outcrops is a westerly (and narrower) continuation of the outcropping chalk that occurs in the inshore 500m of the SEP and DEP Weybourne corridor option (Figure 5.5). The mix of gravelly sand/chalk outcrop and Holocene sand further offshore to Pollard Bank is a westerly continuation of the alternating zones of gravelly sand/gravel (lag deposit) and Holocene sand mapped to about 5.5km offshore along the SEP and DEP cable corridor. This substrate is also a westerly continuation of the alternating Holocene sand and low (less than 0.5m high) gravelly sand ‘mounds’ overlying chalk interpreted along the inshore part of the Dudgeon cable corridor.

The Bolders Bank Formation mapped along the Sheringham Shoal and Dudgeon cable corridors in the MCZ thins to the east and is absent along the SEP and DEP cable corridor where chalk is the dominant subcrop. However, the gravelly sand sea bed forming a lag on top of older formations, which extends offshore to the MCZ boundary appears to be a continuous substrate mapped across all three cable corridors (**Figure 5.6**).

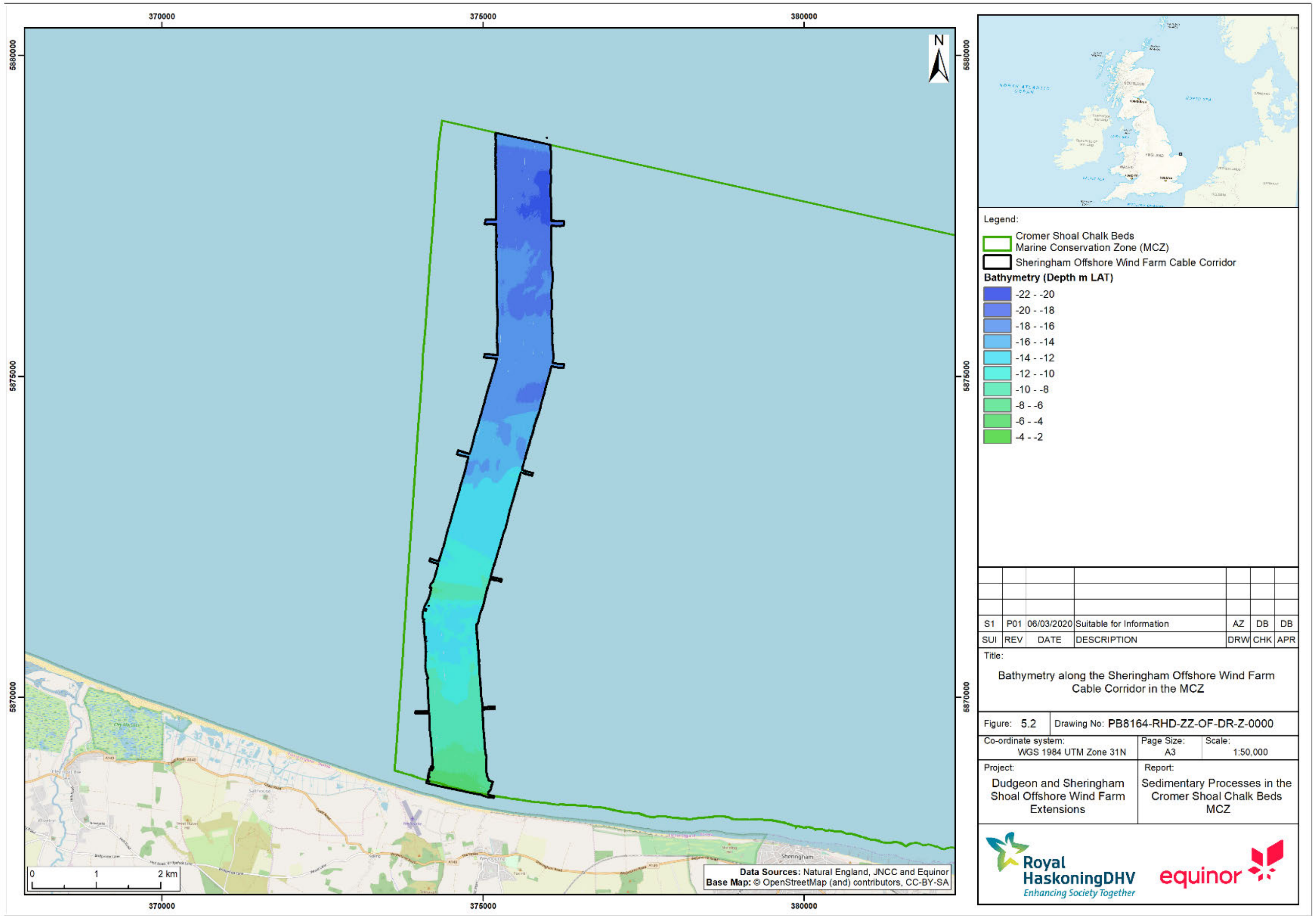

Figure 5.2. Bathymetry along the Sheringham Shoal offshore wind farm cable corridor in the MCZ (EMU, 2008)

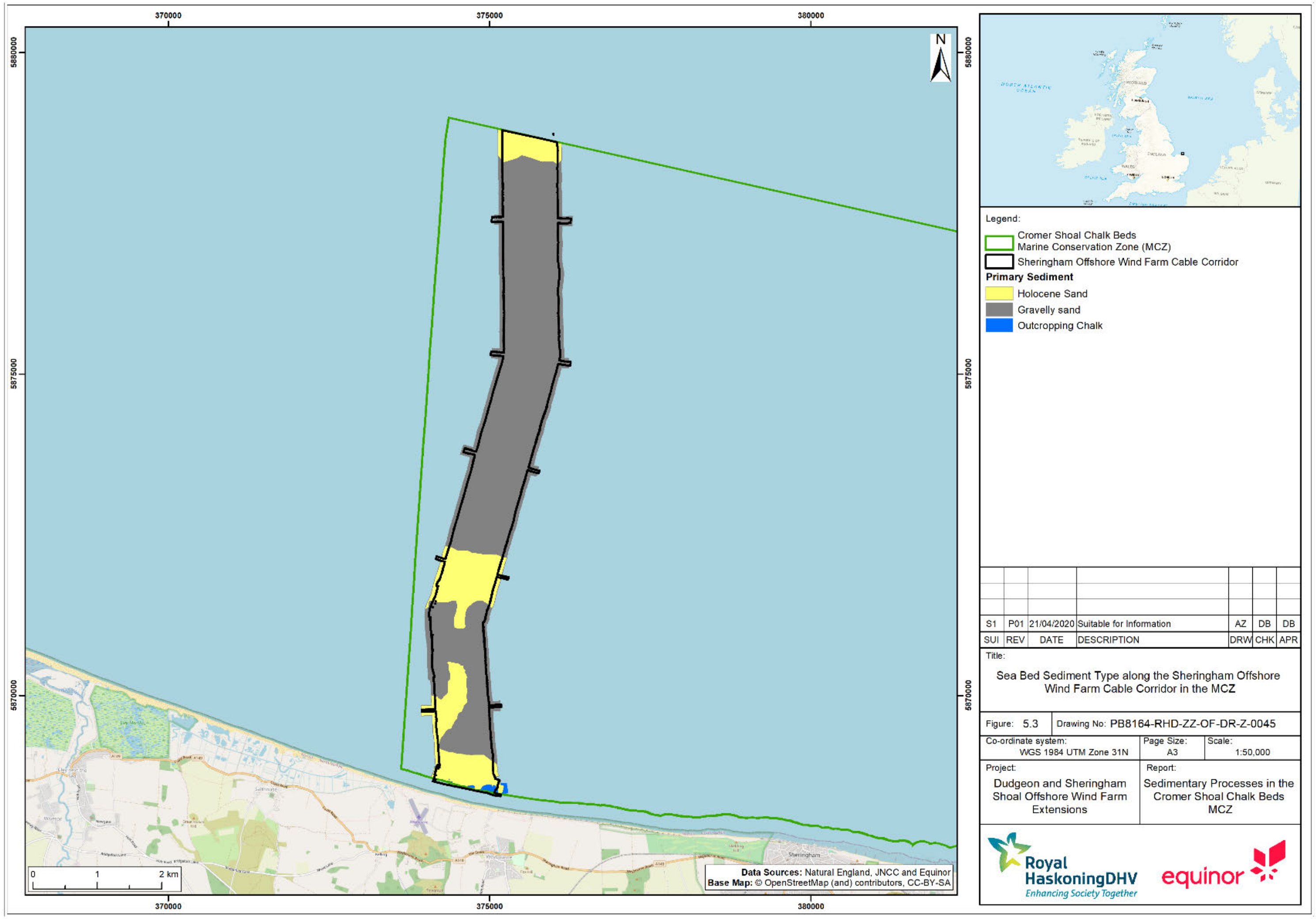

Figure 5.3. Sea bed sediment type along the Sheringham Shoal offshore wind farm cable corridor in the MCZ (EMU, 2008)

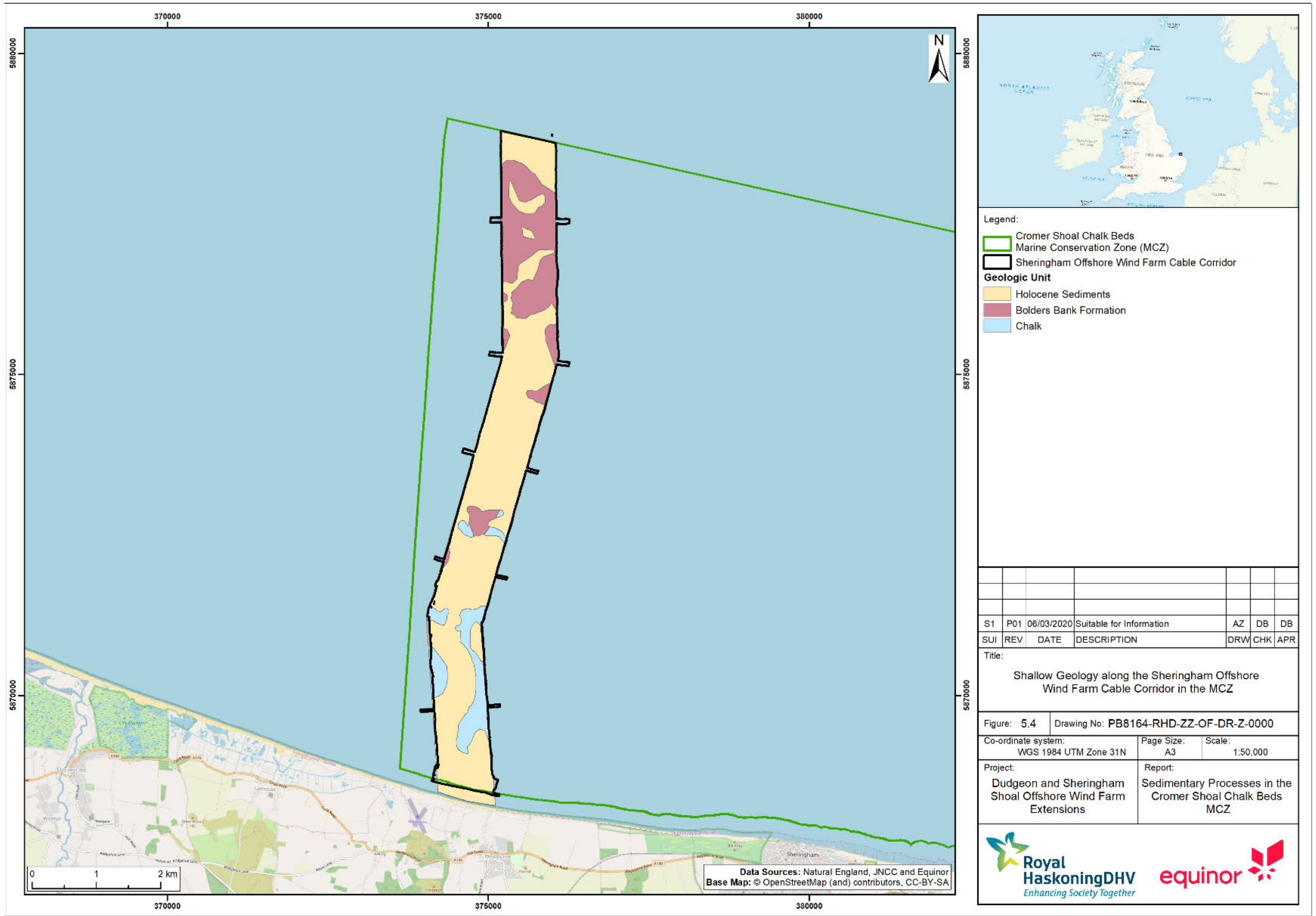

Figure 5.4. Shallow geology along the Sheringham Shoal offshore wind farm cable corridor in the MCZ (EMU, 2008)

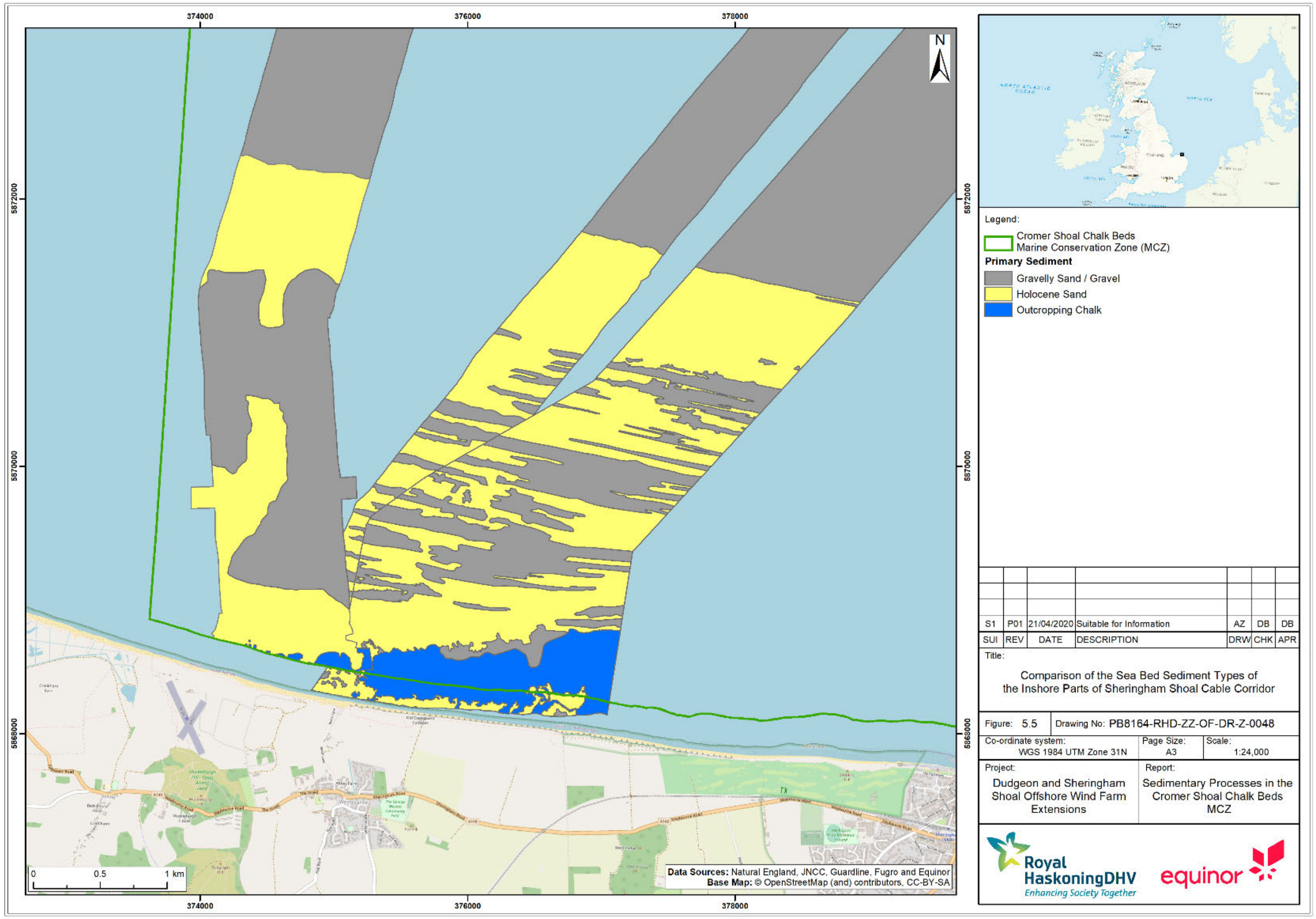

Figure 5.5. Comparison of the sea bed sediment types of the inshore parts of the Sheringham Shoal cable corridor (left), Dudgeon cable corridor (centre) and SEP and DEP Weybourne cable corridor option (right)

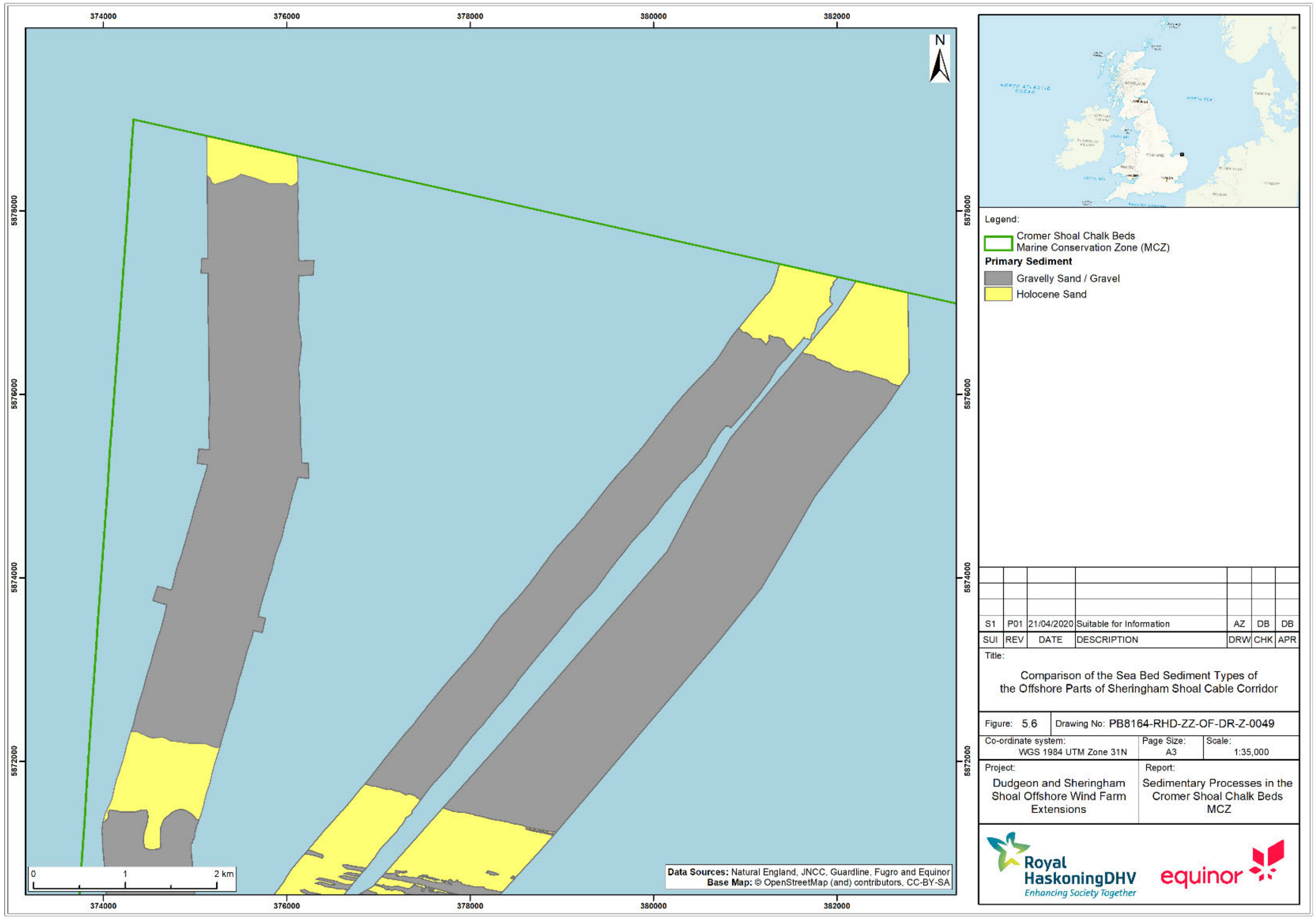

Figure 5.6. Comparison of the sea bed sediment types of the offshore parts of the Sheringham Shoal cable corridor (left), Dudgeon cable corridor (centre) and SEP and DEP Weybourne cable corridor (right)

5.1.2 Fugro 2005 (Vibrocores)

Fugro completed a vibrocore survey along the Sheringham Shoal offshore wind farm cable corridor in the MCZ on 17th and 18th August 2005 (Fugro, 2006). The vibrocores are used here to ground-truth the geophysical data and can provide an indication of the thickness of the coarse-grained lag resting on the underlying geological units. The chalk was penetrated by VC's 3, 4, 5, 8 and B in the MCZ. Details of the geology recovered in the vibrocores is provided in Royal Haskoning (2005) and Fugro (2006) and the locations of those that recovered chalk are shown on **Figure 5.1**. The geological units recovered in the vibrocores from south to north are:

- In VC3, the chalk is overlain by 1.5m of sediment comprising 1.0m of sandy clay (Weybourne Channel sediment) and 0.5m of Holocene fine to medium sand.
- In VC4, the chalk is overlain by 1.0m of sediment comprising 0.3m of sandy fine to coarse gravel (lag) overlain by 0.7m of Holocene silty fine to medium sand and sand.
- In VC5, the chalk is overlain by 4.25m of sediment comprising 1.25m of gravelly sand (lag) overlain by 3.0m of sand and silty sand (Pollard sand bank).
- VC6 did not penetrate the chalk but bottomed in Bolders Bank Formation (till) at 1.35m depth. The till is overlain by 0.4m of sandy silt (possibly eroded till) and 0.95m of gravelly sand (lag).
- In VCB, a complex stratigraphy was recovered above chalk comprising 0.65m of gravelly sand (lag) overlain by 3.1m of sediment comprising a mix of peat, mud and sand which are likely to be remnants of Holocene deposits on top of the lag.
- VC7 did not reach chalk and comprises 3.45m of gravelly sand overlain by 2.40m of peat, mud and sand.
- In VC8, the chalk is overlain by 0.7m of Bolders Bank Formation and 0.55m of Holocene coarse sand.
- VCC recovered 2.5m of Bolders Bank Formation overlain by Holocene sediments comprised of 1.6m of clayey sand, sandy mud and fine to coarse sand.
- In VC9, Bolders Bank Formation was recovered at 1.7m overlain by Holocene peat, mud and sand.
- In VC10 and VC11, Bolders Bank Formation was recovered at the sea bed.

In summary, four vibrocores (VC4, VC5, VC6, and VCB) penetrated chalk overlain by a sandy gravel/gravelly sand lag. In these vibrocores the recovered lag was between 0.3m and 1.25m thick (**Figure 5.7**).

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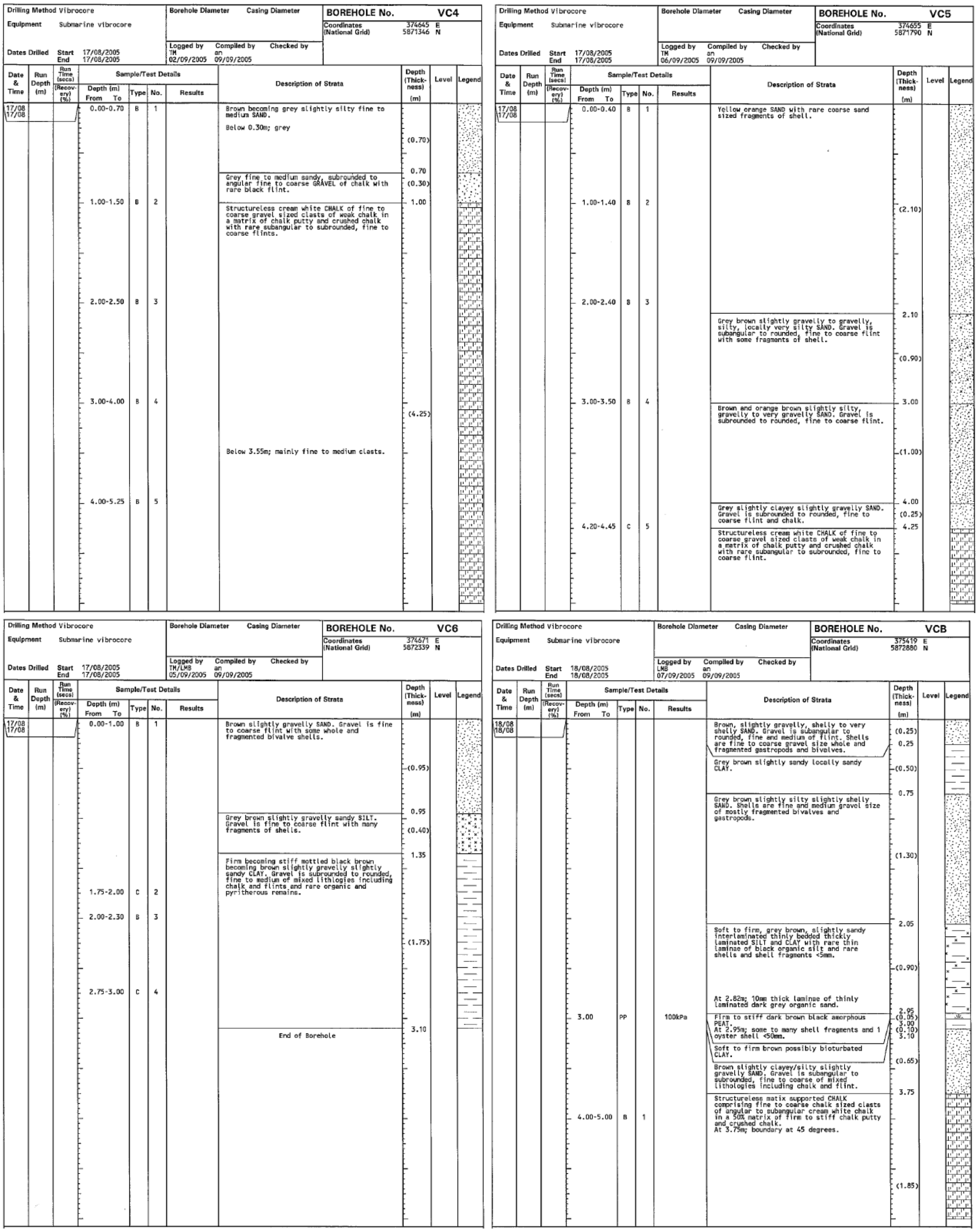

Figure 5.7. Logs of vibrocore that recovered chalk overlain by lag along the Sheringham Shoal cable corridor in the MCZ. VC4 (top left), VC5 (top right), VC6 (bottom left), VCB (bottom right) (Fugro, 2006)

5.1.3 Fugro EMU Winter 2013 and Comparison with 2008

The 2013 winter geophysical survey (1st November 2013 to 3rd December 2013, Fugro EMU, 2014) was completed to understand any changes that have taken place along the export cables since the pre-construction survey in 2008. The survey was undertaken along the routes of the export cables and not across the full extent of the cable corridor mapped in 2008.

The main difference in sea bed elevation along the cables is the discontinuous presence of the trenches in which they sit (Figure 5.8) (Fugro EMU, 2014). Preservation of the trenches indicates that in these areas, sediment transport is limited and incapable of filling them in. The parts of the trenches that have not filled with sediment were deepest in the north, where they were up to 1.2m deeper than the surrounding sea bed and up to 20m wide in places. This is the sea bed occupied by a lag of gravelly sand resting on chalk. The western export cable was visible as a trench 4m to 15m wide and up to 1.2m deep (**Figure 5.9**), and the eastern export cable was visible as a trench 2m to 20m wide and up to 1.1m deep. Other parts of the trench are filled with sediment indicating transport is active. For example, the trenches were not visible over Pollard Bank or across the inshore 2km of the cable routes to the landfall where mobile sand is present. Apart from the trenches, most of the bathymetric differences recorded between 2008 and 2013 along the export cable routes were less than 0.25m indicating a non-mobile sea bed (Fugro EMU, 2014). The vertical accuracy of the multibeam echosounder is +/-0.2m.

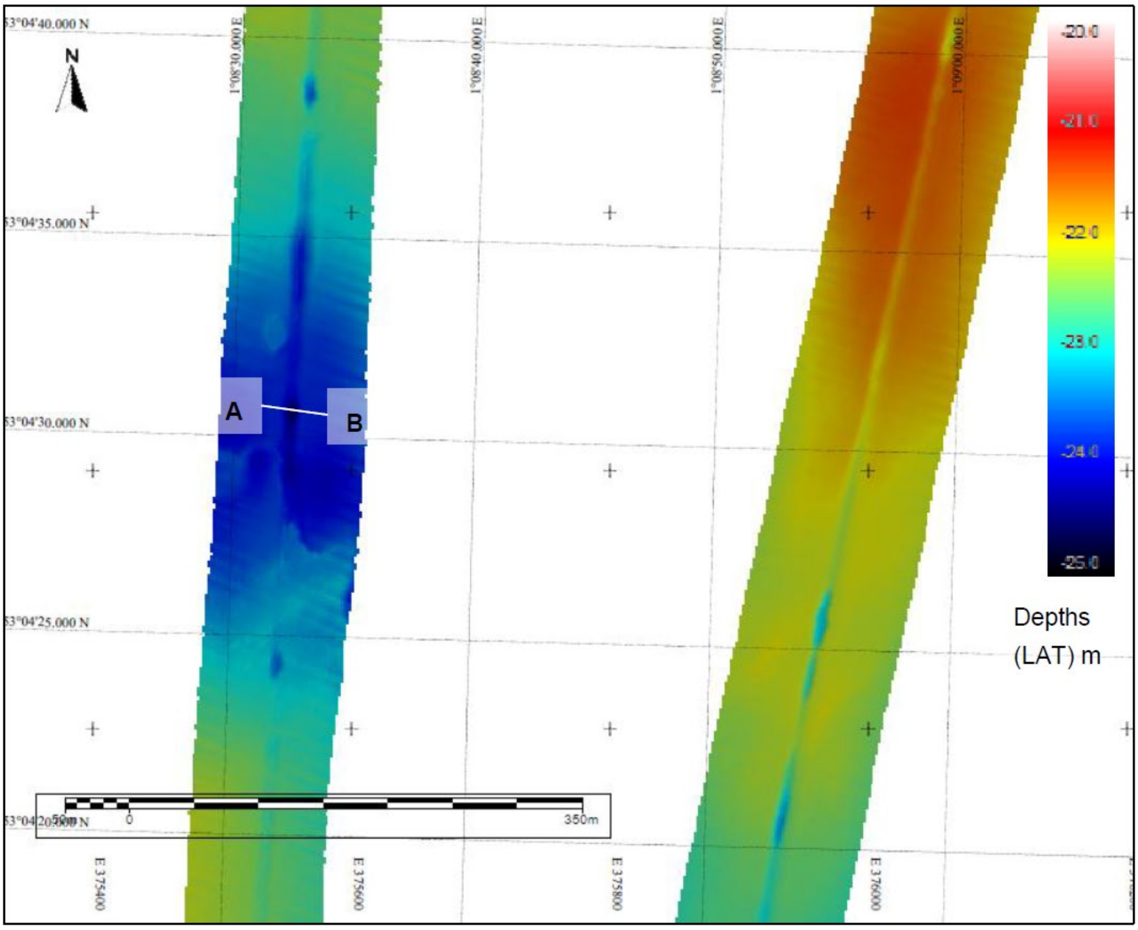

Figure 5.8. Example of the export cable trenches visible on the 2013 bathymetry along the Sheringham Shoal cable routes. Section A-B is shown on Figure 5.9 (Fugro EMU, 2014)

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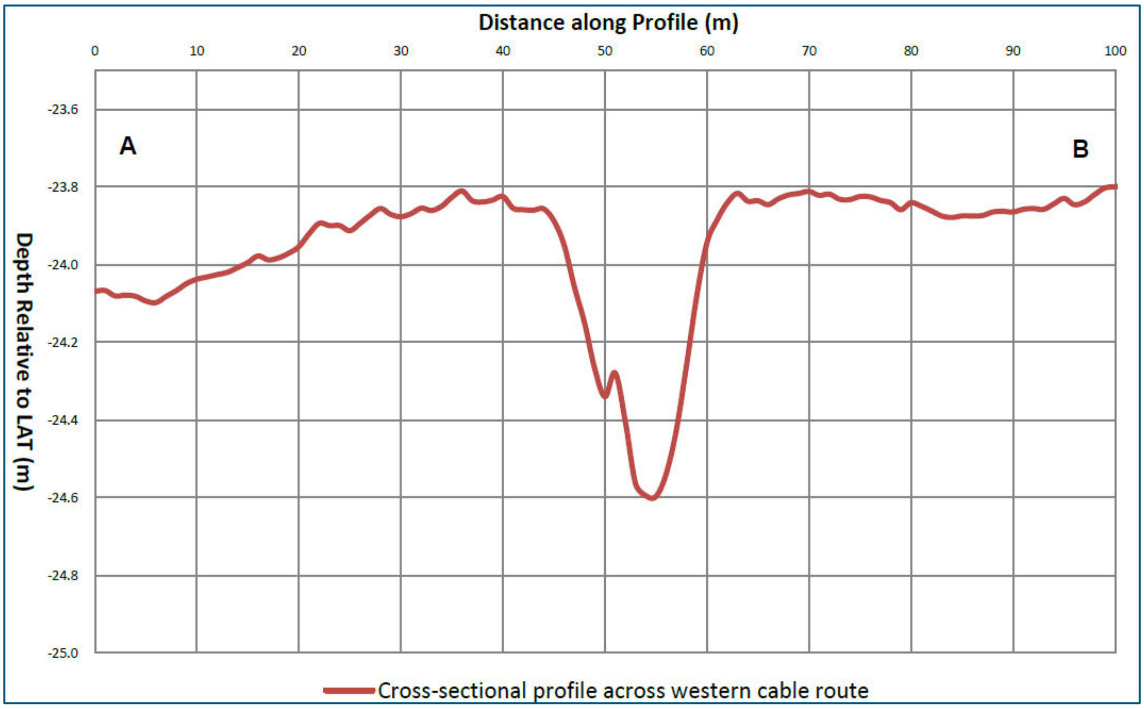

Figure 5.9. Cross-section of the Sheringham Shoal western cable trench. Location is shown on Figure 5.8 (Fugro EMU, 2014)

5.1.4 Fugro EMU Winter 2015/2016 and Comparison with 2008

The survey from 7th November 2015 to 25th January 2016 was carried out in the MCZ across the full width of the cable corridor mapped in 2008 plus an additional 200m wide buffer either side (Fugro EMU, 2016a). Fugro EMU (2016b) compared the 2015/2016 and 2008 geophysical data. As in 2013, the trenches associated with the export cables were visible along both the western and eastern cable routes. The scale of the change was like the 2008-2013 comparison indicating continued non-mobility of sea bed sediments. The trenches were not visible across Pollard Bank. Here, the migration of sand waves is manifest as alternating areas of erosion (up to 1.3m) and accretion (up to 1.7m) (Figure 5.10). Also, at the inshore end of the cable corridor, approximately 1.5-2.0km offshore, small depth changes of -0.9m to +0.6m occurred in the mobile Holocene sand areas. Apart from the trenches and the mobile Pollard Bank and inshore sand areas, bathymetric differences between 2008 and 2015/2016 along the cable corridor were less than 0.25m (**Figure 5.10**).

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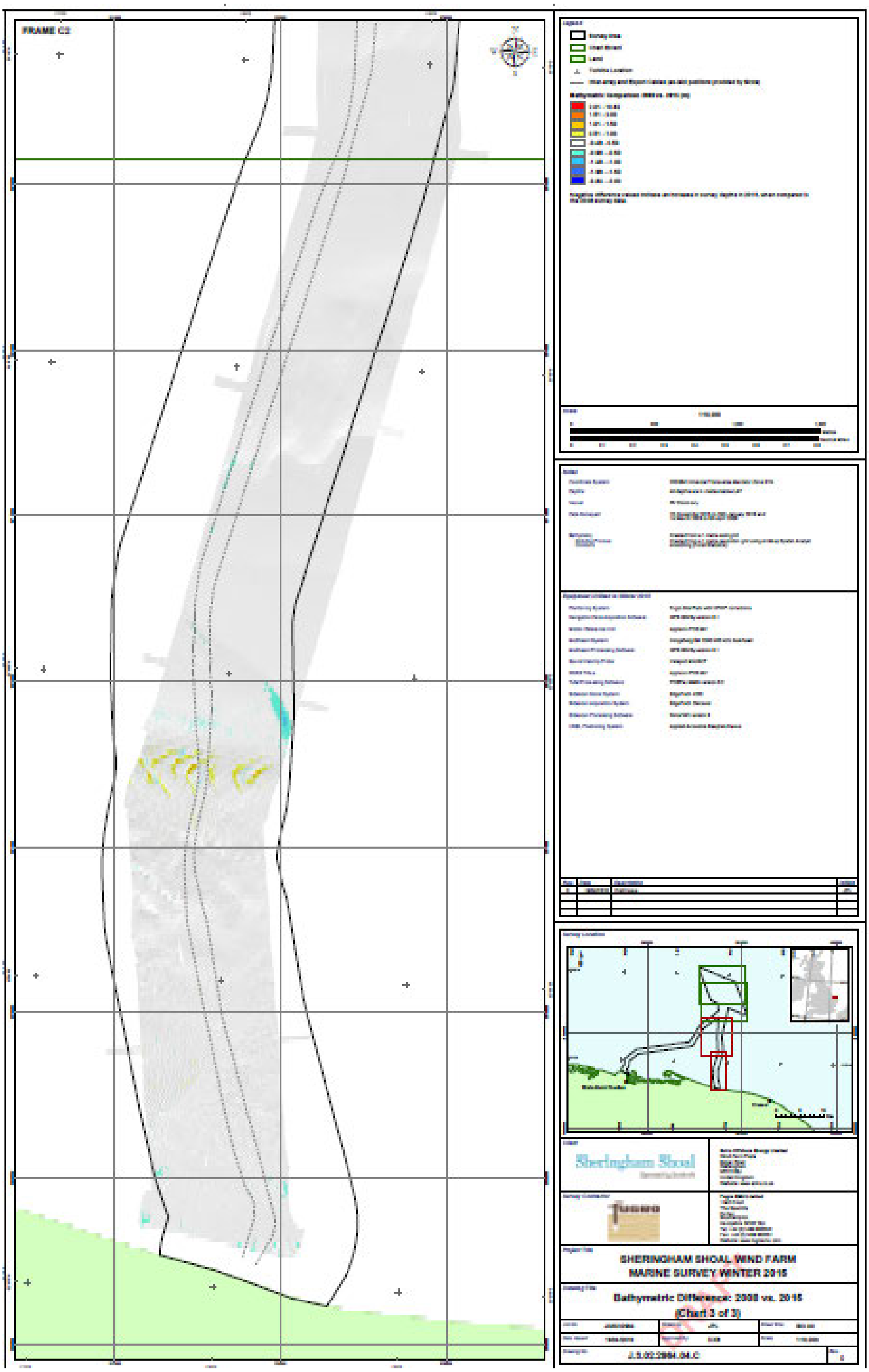

Figure 5.10. Change in sea bed elevation between 2008 and 2015/2016 along Sheringham Shoal offshore wind farm export cable corridor in the MCZ (Fugro EMU, 2016b)

5.1.5 Fugro 2018 and Comparison with 2008

The latest geophysical survey along the Sheringham Shoal cable corridor was completed by Fugro (2019a) between 17th October 2018 and 23rd November 2018. Trenches associated with the export cables were still visible along both cable routes apart from across Pollard Bank. The trenches were deepest in the north, where they were up to 0.7m deeper than the surrounding sea bed and up to 30m wide in places.

Fugro (2019b) compared the results of the 2008 pre-installation survey and the winter 2018 survey. Over most of the cable corridor changes in sea bed elevation were less than 0.25m (**Figure 5.11**). Sea bed change occurred across Pollard Bank, with elevation changes of -1.3m (erosion) to +2.0m (accretion) and at the inshore end of the cable route, approximately 0.25-1.25km offshore, where elevation changes of -1.4m to +1.3m occurred.

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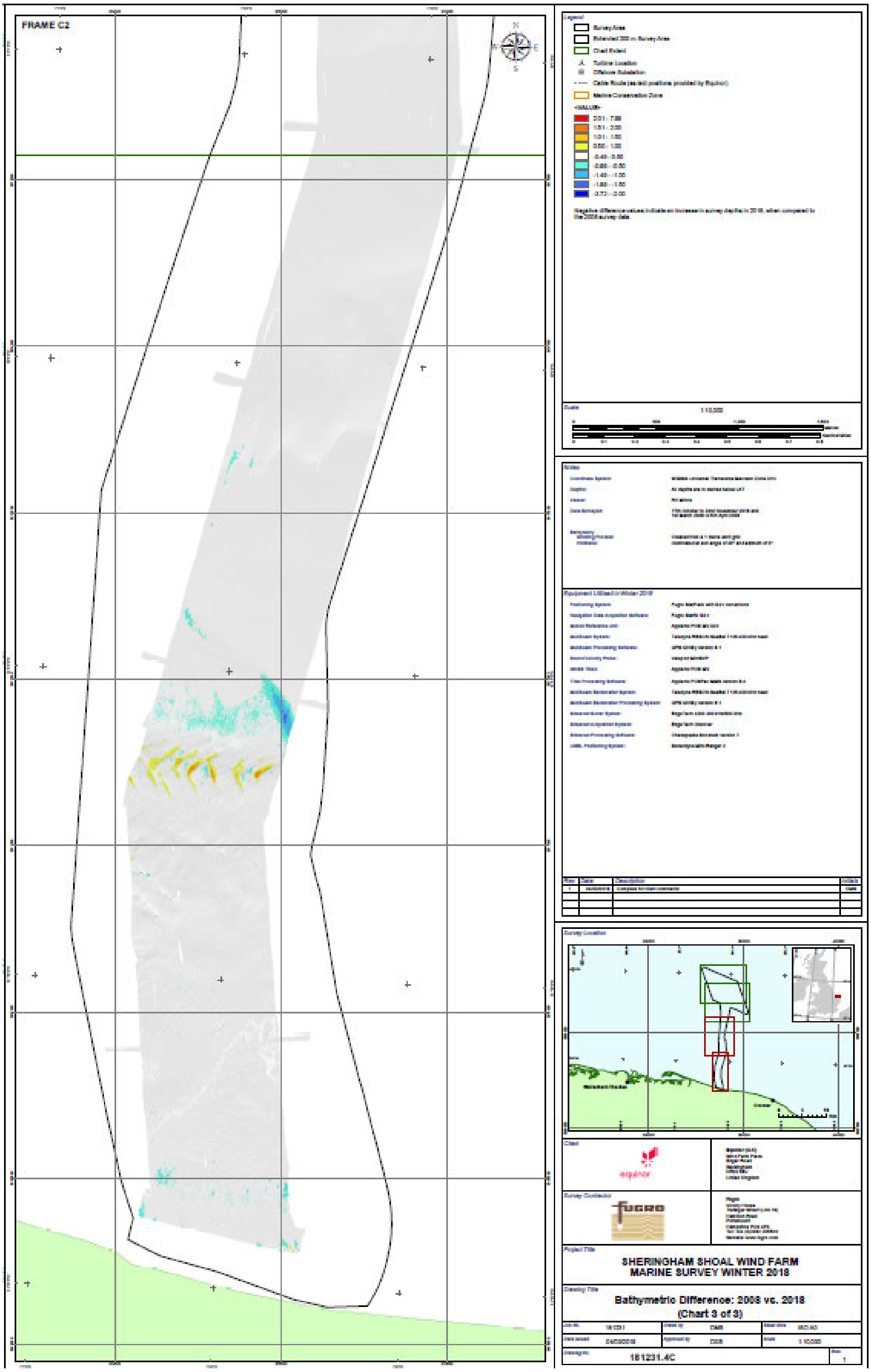

Figure 5.11. Difference in sea bed elevation between 2018 and 2008 along Sheringham Shoal offshore wind farm export cable corridor in the MCZ (Fugro, 2019b)

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5.2 Benthic Surveys

Data from three sea bed sediment sampling campaigns within and close to the Sheringham Shoal cable corridor are assessed here to understand sea bed composition and how it has changed over time. It should be noted that although the sea bed sediment samples from different years are located close to each other, they will not be from the same positions exactly, and given the potential for changes in composition over short distances, only a general appreciation of change can be established. Sea bed sediment samples from 2005 (IECS, 2005), 2009 (EMU, 2010) and 2014 (MES, 2014) are assessed here (**Table 5-2**). Only sampling at stations 22, 24, and 50 is duplicated over time, allowing comparisons to be made.

Table 5-2. Time series of sea bed sediment samples collected for Sheringham Shoal offshore wind farm cable corridor in the MCZ

2005 ID (IECS)	2009 ID (EMU)	2014 ID (MES)
3		
22	22	22
23		
24	24	24
25		
29		
49		
50		50
51		
52		

5.2.1 IECS 2005

IECS (2005) completed a benthic survey of Sheringham Shoal offshore wind farm and collected ten grab samples across the MCZ near the cable corridor (**Figure 5.1**). Particle size analysis was completed on nine of the samples, but only summary data was reported (**Table 5-3**).

Table 5-3. Particle size characteristics of sea bed sediment samples collected by IECS (2005) for Sheringham Shoal offshore wind farm cable corridor in the MCZ

Station	% Gravel	% Sand	% Mud	Median (mm)	Median class
3	32.76	60.98	6.26	0.28	Medium sand
22	0	100	0	0.31	Medium sand
23	54.53	42.3	3.17	3.2	Very fine gravel
24	30.53	69.47	0	0.35	Medium sand
25	41.39	57.44	1.16	0.79	Coarse sand
29	27.85	65.06	7.09	0.4	Medium sand
50	11.38	88.62	0	0.34	Medium sand
51	46.34	47.49	6.16	1.2	Very coarse sand
52	3.4	96.6	0	0.44	Medium sand

The sediment characteristics across this part of the MCZ in 2005 were mainly medium sand with some coarse/very coarse sand and very fine gravel. The finest sediment was at stations 3, 22, 24 and 50, where median particle sizes ranged from 0.28mm to 0.35mm (medium sand) with the coarsest sediment at station

23 where the median particle size was 3.2mm (very fine gravel). Gravel content ranged from 0% at station 22 to 55% at station 23. A maximum content of 100% sand was recorded at site 22 with a minimum content of 42% at station 23. Mud content was less than 8% at all sites.

5.2.2 EMU 2009

EMU (2010) completed a benthic survey on 4th and 5th November 2009, with a single day of survey on 21st December 2009. During this survey, two of the IECS (2005) sample sites (22 and 24) in the MCZ were selected for additional data collection. Three samples were taken at each station and analysed for particle size. The samples at station 22 were similar (Table 5-4 and Figure 5.12) containing 99% sand with median particle sizes of 0.22-0.25mm (fine to medium sand). The samples at station 24 vary more in composition, containing 19-40% gravel and 60-81% sand, with median particle sizes ranging from 0.22mm (fine sand) to 0.54mm (coarse sand).

Table 5-4. Particle size characteristics of sea bed samples collected in 2009 (EMU, 2010) along the Sheringham Shoal cable corridor

Location	% gravel	% sand	% mud	Coarse sand or greater	Median (mm)	Median class
22.1	0.24	99.73	0.03	1.57	0.23	Fine sand
22.2	0.02	99.95	0.03	0.68	0.22	Fine sand
22.3	0.77	99.19	0.04	3.24	0.25	Medium sand
24.1	39.53	60.44	0.03	44.45	0.30	Medium sand
24.2	19.09	80.83	0.08	29.34	0.22	Fine sand
24.3	39.71	60.23	0.06	50.33	0.54	Coarse sand

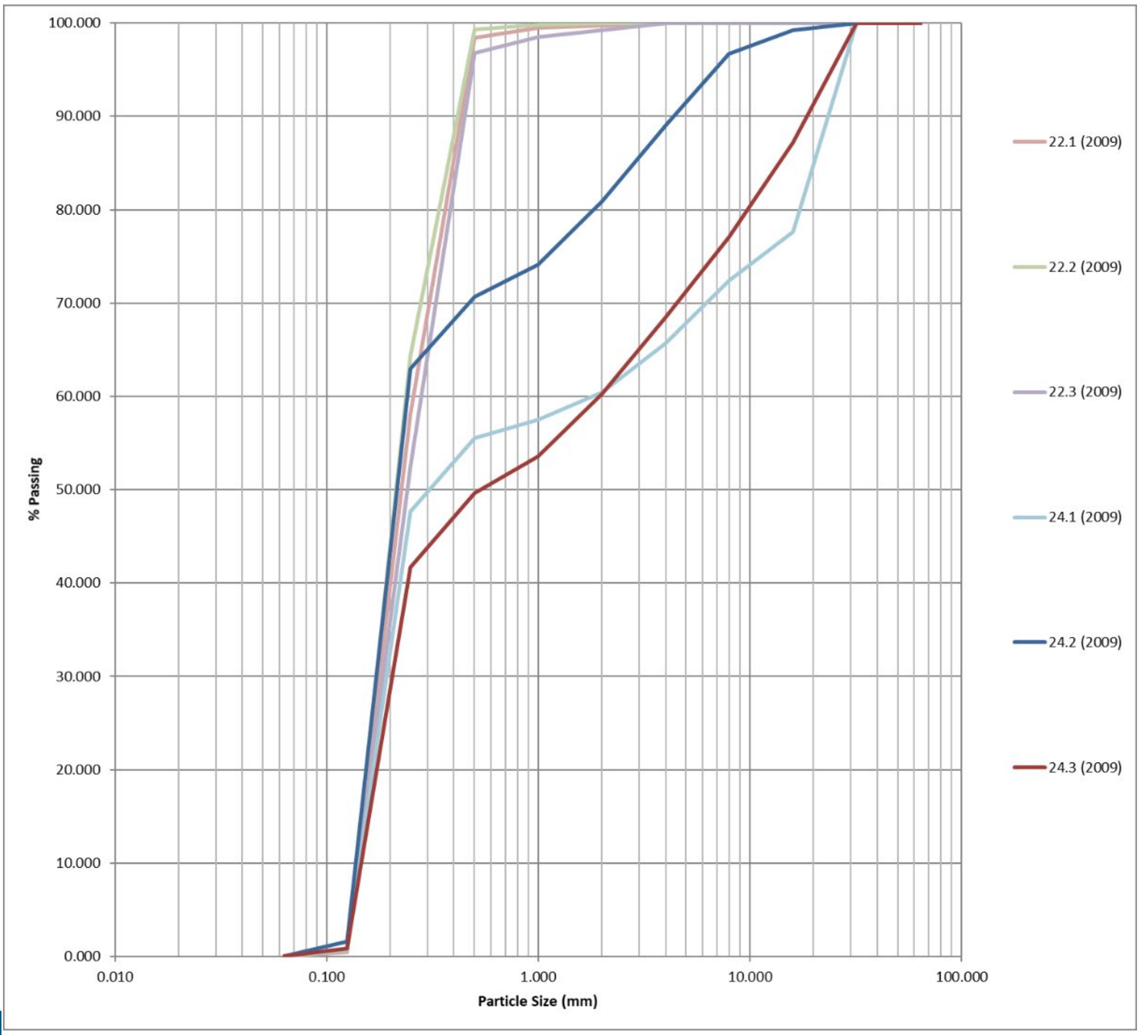

Figure 5.12. Cumulative particle size distribution of sea bed sediment samples collected in 2009 (EMU, 2010) along the Sheringham Shoal cable corridor

In addition to the two grab site locations, two video transects (inshore and mid-shore) were also completed across the cable corridor in the MCZ. The inshore transect recorded non-reef silty shelly gravelly sand with pebbles and the mid-shore transect recorded slightly shelly sand.

5.2.3 Fugro 2012 and MES 2014

Following the EMU (2010) survey, a first post-construction benthic survey was undertaken by Fugro EMU between 14th and 18th December 2012. Particle size data was not accessed from this survey. A second post-construction benthic survey was undertaken by MES (2014) in April 2014. Three samples were analysed for particle size at station 22, one at station 24, and one at station 50 (**Table 5-5** and **Figure 5.13**). The three samples at station 22 were similar containing 96-99% sand with median particle sizes of 0.25-0.29mm (medium sand). The sample at station 24 comprised 17% gravel and 82% sand, with a median particle size of 0.22mm (fine sand). The sample at station 50 comprised 99% sand with a median particle size of 0.32mm (medium sand).

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Table 5-5 Particle size characteristics of sea bed samples collected in 2014 (MES, 2014) along the Sheringham Shoal cable corridor

Location	% gravel	% sand	% mud	Coarse sand or greater	Median (mm)	Median class
22A	3.01	95.98	1.01	5.44	0.28	Medium sand
22B	1.94	96.75	1.31	3.99	0.25	Medium sand
22C	0.19	98.63	1.18	1.24	0.29	Medium sand
24A	17.27	81.73	1.00	22.04	0.22	Fine sand
50A	0.90	98.53	0.57	3.92	0.32	Medium sand

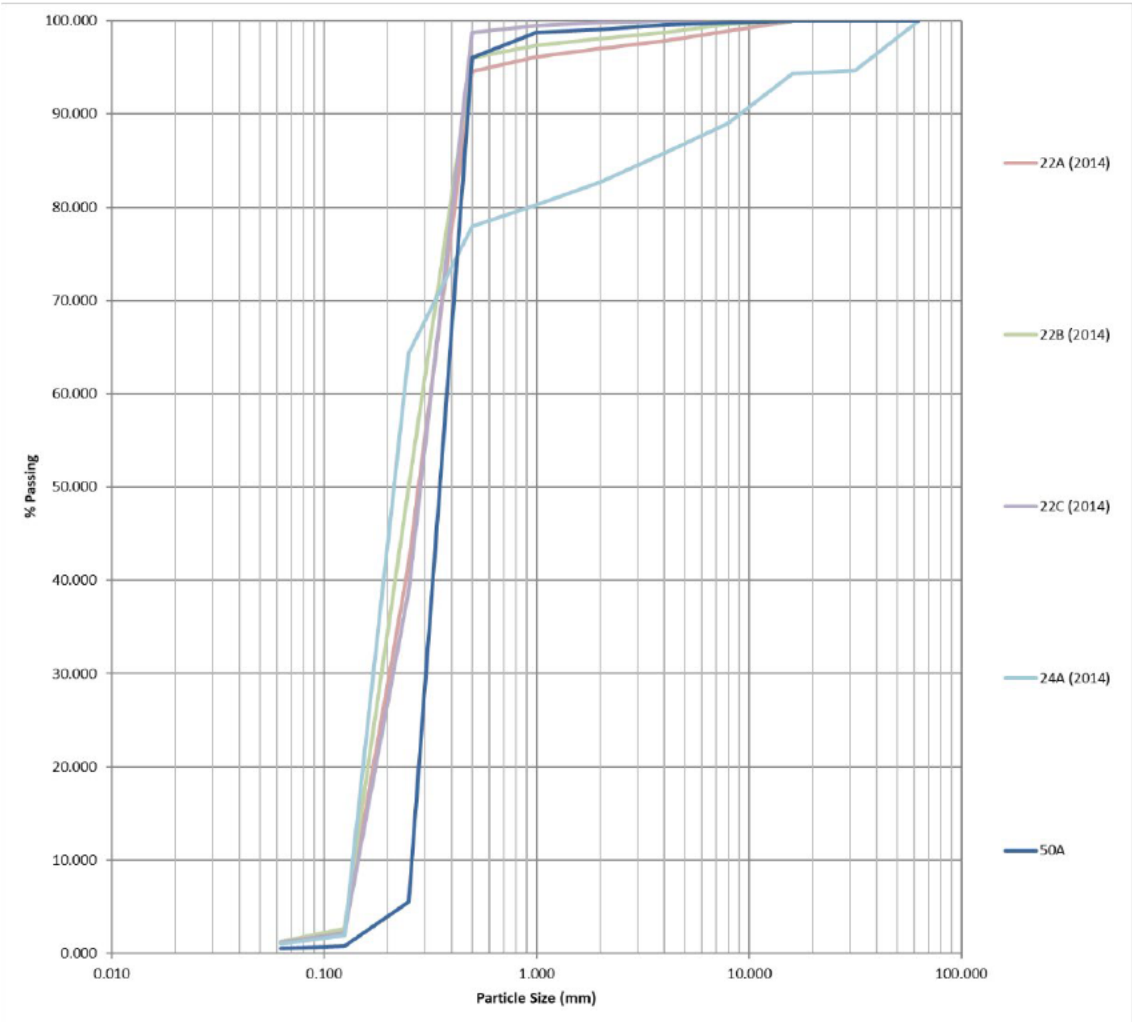

Figure 5.13. Cumulative particle size distribution of sea bed sediment samples collected in 2014 (MES, 2014) along the Sheringham Shoal cable corridor

5.2.4 Comparison of Particle Size Data

The 2009 pre-construction survey particle size data and 2014 post-construction particle size data at stations 22 and 24 is compared here (**Figure 5.14**). The comparison shows that there is little difference between the samples collected at stations 22 and 24.

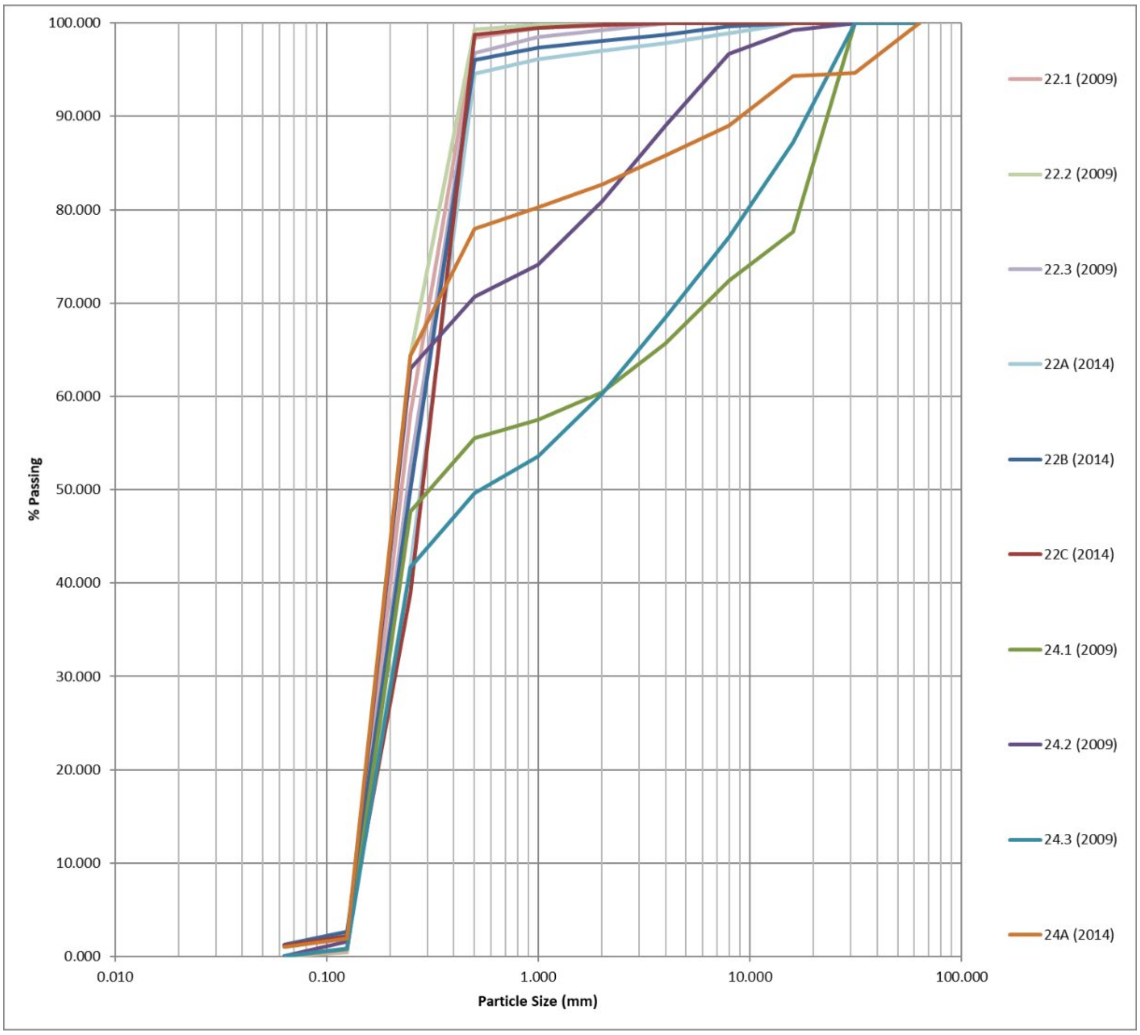

Figure 5.14. Comparison of cumulative particle size distributions of sea bed sediment samples 22 and 24 collected in 2009 and 2014 along the Sheringham Shoal cable corridor

6 Sediment Dynamics along the SEP and DEP Cable Corridor

Sections 3 to **5** describe the geomorphological and geological conditions along the SEP and DEP cable corridor Weybourne option and how they compare with the conditions established previously along the Dudgeon offshore wind farm and Sheringham Shoal offshore wind farm cable corridors to the west.

6.1 Stratigraphy

The stratigraphy of the three western cable corridors (Sheringham Shoal, Dudgeon and SEP and DEP Weybourne option) is similar comprising chalk overlain in places by Pleistocene sediments and/or Holocene sediments. The geographical distribution of these units is similar between corridors comprising:

- An inshore area of outcropping chalk which narrows from about 600m at the eastern boundary of the SEP and DEP Weybourne option to less than 50m at the western boundary of the Sheringham Shoal cable corridor. This zone is likely to contain chalk outcrops at the sea bed formed into complex erosional structures such as gullies ridges, pinnacles and arches;
- A nearshore area beyond the outcropping chalk to about 4km offshore composed of subcropping chalk and a variety of Pleistocene sediments infilling channels in the chalk, overlain by alternating zones of gravelly sand/sandy gravel (an erosional lag deposit up to about 1.5m thick) and Holocene sand (up to 3m thick with bedforms). The seaward unit of Holocene sand along the Sheringham Shoal cable corridor is the thicker Pollard Bank which is not present along the SEP and DEP Weybourne option;
- An offshore area from about 4km offshore to the southern flank of Sheringham Shoal sand bank composed of subcropping chalk and a variety of Pleistocene sediments infilling channels in the chalk, overlain by gravelly sand/sandy gravel (a continuation of the erosional lag deposit further inshore up to about 1.5m thick). Along the SEP and DEP Weybourne option, Pleistocene sediment occurs only at the northern end, with most of this zone underlain by chalk. Holocene sand is generally absent across this offshore zone; and
- The southern flank of Sheringham Shoal sand bank comprising thicker Holocene sand with bedforms.

The cable corridor of the SEP and DEP Bacton option contains only a relatively small, patchier and more offshore area of outcropping chalk. Most of the corridor is dominated by chalk (with some Botney Cut Formation) overlain by alternating bands of sandy gravel and gravelly sand (an erosional lag deposit up to about 1.5m thick). In contrast to the SEP and DEP Weybourne option, the nearshore 500m of sea bed is composed of Holocene sand which is up to 8m thick at the coast.

6.2 Sediment Transport

There is a range of sediment transport potentials across the stratigraphic units mapped along the SEP and DEP cable corridor. The chalk and the Pleistocene geological units that fill channels in the chalk (e.g. Botney Cut Formation and Weybourne Channel Deposits) are static (and can only be eroded), whereas the surface of the Holocene sand is mobile under existing tidal conditions, and so can erode, transport and deposit depending on the physical processes. The mobility of the Holocene sand is supported by the existence of megaripples across its surface in places (mainly along the Weybourne option). This indicates that there is a possibility that movement of this sediment may result in exposure or burial of the underlying geological units. Given the thickness of the Holocene sands, it would only be possible for movement of the feather edges (where the sediment is thin and could all move), to generate new sea bed substrate. In areas where the sand is thicker, the movement of the surface layer would only result in exposure of further sand deeper in the sediment column.

Between the chalk or Pleistocene geological units and the sea bed or overlying Holocene sand is a layer of gravelly sand/sandy gravel. This coarse-grained layer is interpreted as a lag deposit created by erosion of

Pleistocene units that were originally present on the sea bed (e.g. Bolders Bank Formation). There are four main reasons why the transport potential of this sediment layer is zero or very low:

- The sediment recorded in eight sea bed samples along the Dudgeon and Sheringham Shoal offshore wind farm cable corridors contains large proportions (22-75%) of coarse sand, very coarse sand and gravel that are not mobile under the existing tidal regime (**Table 6-1**). This particle size composition is distinct from the particle size characteristics of the Holocene sand which is almost 100% sand (three samples).

Table 6-1. Coarse sediment characteristics of samples recovered along the Dudgeon and Sheringham Shoal offshore wind farm cable corridors

Location	% gravel	% sand	%coarse sand or greater	Geological unit
CR11/S05	26-53	46-63	39-61	Sand/gravel lag
CR12/S04	38-67	27-62	46-75	
CR13/S01	46-52	49-54	58	
CSCB004/S02	43-52	48-51	45-55	
CSCB068/S03	22-44	48-65	41-56	
CSCB125/S07	25-37	62-73	47-55	
CSCB147/S06	14-41	52-66	30-55	
24	17-39	60-82	22-50	
22	0-3	96-100	1-5	Holocene sand
CR10/S08	0	99-100	0	
50	1	99	4	

- The sediment recorded in a single vibrocore along the Dudgeon offshore wind farm cable corridor and four vibrocores along the Sheringham Shoal offshore wind farm cable corridor is also coarse grained and varies in thickness from 0.3m to 1.25m resting directly on top of chalk (**Table 6-2**). The lithological descriptions of the lag in the vibrocore logs indicate that much of the gravel is composed of chalk and/or flint, which would have been derived from erosion of the underlying geological units.

Table 6-2. Coarse sediment characteristics of samples recovered from vibrocores along the Sheringham Shoal offshore wind farm cable corridor

Location	Corridor	Thickness (m)	Description on Log
VC116	Dudgeon	0.3	Gravelly, fine to medium sand
VC4	Sheringham Shoal	0.3	Fine to medium sandy, sub-rounded to angular fine to coarse gravel
VC5		1.25	Slightly clayey, slightly gravelly sand overlain by slightly silty, gravelly to very gravelly sand. Gravel is sub-rounded to rounded, fine to coarse
VC6		0.95	Slightly gravelly sand. Gravel is fine to coarse
VCB		0.65	Slightly muddy, slightly gravelly sand. Gravel is sub-angular to sub-rounded, fine to coarse

- The areas of sea bed where the lag is recorded are generally featureless or has a topography dictated by the underlying geological units (recorded as 'mounds' along the Sheringham Shoal offshore wind farm cable corridor. The absence of bedforms suggests that the substrate is likely to have low dynamism. The evidence for a bathymetry dictated by an antecedent surface also suggests low mobility and limited transport capable of 'smoothing' the buried surface.

- Comparison of the pre-construction and post-construction bathymetries along Sheringham Shoal offshore wind farm cable corridor where the coarse lag is present shows that the trenches in which the export cables sit are visible on the post-construction sea bed. They are up to 1.2m deep and up to 20m wide. Where the sea bed is mobile in the Holocene sand areas or across Pollard Bank, the trenches have been filled with sediment and the sea bed bathymetries are similar pre-construction and post-construction; there is no evidence for the original trenches. These differential infilling rates suggest that the coarse lag is static and sediment transport is not capable of filling the trenches. Also, across the sea bed with a coarse lag deposit, the changes to the elevations between pre-construction and post-construction have been less than 0.25m. This is effectively a non-mobile bed given that the vertical accuracy of the multibeam echosounder is +/-0.2m.

6.3 Cable Routing

The main geological and geomorphological obstacle to routing cables through the MCZ is the presence of outcropping chalk on the sea bed sculpted into a variety of erosional features with significant topography above the general sea bed. Along the Weybourne option these features are extensive covering an area of about 812,000m^2 in the shallowest part of the corridor towards the coast (water depths less than -6m LAT along the western side to less than -9.5m LAT along the eastern side). Along the Bacton option, these features cover a smaller area (236,000m^2), are exposed in isolated patches and in deeper water.

Another difference between the Weybourne and Bacton options is the presence of wide areas of mobile Holocene sand (several metres thick with small migrating bedforms) further offshore along the Weybourne option where it is interspersed with the chalk and lag stratigraphy, whereas the Bacton option appears devoid of mobile sediment across most of its offshore area beyond a thick 500m-wide sand unit at the coast. Hence, along the Weybourne option the sea bed is alternately static (lag) and mobile (Holocene sand), whereas along the Bacton option most of the sea bed is static (lag).

7 Requirement for Geotechnical Survey

The resolution of the sub-bottom profilers used to collect shallow geological data along the three cable corridors is insufficient to determine the thickness of the thin (less than 1.5m) coarse sediment layer resting on chalk. This is because the unit is 'lost' within the noise at the sea bed as the sound pulse reflects off the sea bed. Although, outcropping chalk and the characteristics of the sea bed sediment can be mapped using multibeam echosounder and side-scan sonar, the depth to chalk beneath any thin sediment cover cannot, unless its thickness is greater than the resolving power of the equipment. This is the case across the Holocene sand areas and sand banks (Pollard Bank and Sheringham Shoal) where the sediment thickness is greater than 2-3m.

The thickness of the lag can be determined using borehole and/or vibrocorers, and this has been done along Sheringham Shoal offshore wind farm cable corridor. At four locations, vibrocores penetrated coarse-grained sediments that were between 0.3m and 1.25m thick (below the resolving power of sub-bottom profilers) resting directly on chalk.

Although vibrocore data ground-truths the sub-bottom profiler at specific locations, it is not possible to interpolate between them using the geophysical data. A degree of expert judgement is required to define the stratigraphy across wider areas of sea bed using all the evidence available. Hence, although additional geotechnical data through recovery of further vibrocores would improve the evidence base, it would only provide limited additional ground-truthing data, because the uncertainty regarding the geology along most of the cable corridor would remain where ground-truthing did not take place.

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Appendix A: 2014 Cefas MCZ Particle Size Summary

Station	% gravel	% sand	% mud	Folk Classification	Habitat
CSCB004	51.56	48.44	0	sG	Coarse Sediment
CSCB006	1.48	98.52	0	(g)S	Sand
CSCB008	24.12	75.88	0	gS	Coarse Sediment
CSCB015	0.01	99.99	0	S	Sand
CSCB016	0	100	0	S	Sand
CSCB017	1.11	98.89	0	(g)S	Sand
CSCB022	1.31	98.69	0	(g)S	Sand
CSCB025	34.01	58.12	7.87	msG	Mixed Sediment
CSCB026	38.82	53.56	7.62	msG	Mixed Sediment
CSCB029	53.44	32.98	13.58	msG	Mixed Sediment
CSCB030	51.41	46.85	1.74	sG	Coarse Sediment
CSCB032	25.96	72.82	1.22	gS	Coarse Sediment
CSCB033	0.54	99.46	0	S	Sand
CSCB040	53.96	41.49	4.56	sG	Coarse Sediment
CSCB043	46.75	50.61	2.65	sG	Coarse Sediment
CSCB045	55.76	42.09	2.14	sG	Coarse Sediment
CSCB053	38.48	61.16	0.36	sG	Coarse Sediment
CSCB060a	36.82	59.48	3.7	sG	Coarse Sediment
CSCB060b	39.66	56.17	4.17	sG	Coarse Sediment
CSCB068	21.6	64.55	13.85	gmS	Mixed Sediment
CSCB073	51.97	43.88	4.15	sG	Coarse Sediment
CSCB087	0.37	99.63	0	S	Sand
CSCB088	0.35	99.65	0	S	Sand
CSCB090	1.99	98.01	0	(g)S	Sand
CSCB092	0.1	99.9	0	S	Sand
CSCB094	0.64	99.36	0	S	Sand
CSCB097	43.38	55.07	1.56	sG	Coarse Sediment
CSCB102	24.33	41.61	34.06	gmS	Mixed Sediment
CSCB103	50.21	46.45	3.33	sG	Coarse Sediment
CSCB104	52.3	43.97	3.73	sG	Coarse Sediment
CSCB105	45.73	48.3	5.97	msG	Mixed Sediment
CSCB109	64.19	31.52	4.28	msG	Mixed Sediment
CSCB110	43.62	48.82	7.56	msG	Mixed Sediment
CSCB113	35.33	56.41	8.26	msG	Mixed Sediment
CSCB115	41.24	55.53	3.23	sG	Coarse Sediment

Station	% gravel	% sand	% mud	Folk Classification	Habitat
CSCB116	0.94	99.06	0	S	Sand
CSCB120	0	100	0	S	Sand
CSCB121	29.78	70.22	0	gS	Coarse Sediment
CSCB122	16.8	83.2	0	gS	Coarse Sediment
CSCB123	19.24	80.76	0	gS	Coarse Sediment
CSCB124	0	100	0	S	Sand
CSCB125	25.45	73.26	1.29	gS	Coarse Sediment
CSCB126	9.36	90.64	0	gS	Coarse Sediment
CSCB127	22.82	74.65	2.53	gS	Coarse Sediment
CSCB130	3.91	96.09	0	(g)S	Sand
CSCB131	0.04	99.96	0	S	Sand
CSCB132	0	18.72	81.28	sM	Mud
CSCB133	0	15.96	84.04	sM	Mud
CSCB134	17.55	82.45	0	gS	Coarse Sediment
CSCB135	22.92	77.08	0	gS	Coarse Sediment
CSCB136	0	9.96	90.04	M	Mud
CSCB137	0	28.43	71.57	sM	Mud
CSCB138	4.57	35.55	59.88	(g)sM	Mud
CSCB139	57.24	42.01	0.76	sG	Coarse Sediment
CSCB141	33.91	65.28	0.82	sG	Coarse Sediment
CSCB145	16.63	81.18	2.2	gS	Coarse Sediment
CSCB146	13.43	85.12	1.45	gS	Coarse Sediment
CSCB147	13.62	66.03	20.35	gmS	Mixed Sediment
CSCB150	29	68.44	2.56	gS	Coarse Sediment
CSCB152	69.14	28.28	2.58	sG	Coarse Sediment
CSCB153	51.25	44.94	3.82	sG	Coarse Sediment
CSCB155	37.92	59.6	2.48	sG	Coarse Sediment
CSCB156	35.81	60.76	3.44	sG	Coarse Sediment
CSCB158	44.18	52.26	3.56	sG	Coarse Sediment
CSCB159	45.95	50.95	3.09	sG	Coarse Sediment
CSCB160	22.2	70.21	7.58	gS	Coarse Sediment
CSCB161	39.04	55.79	5.18	sG	Coarse Sediment
CSCB162	40.43	54.63	4.94	sG	Coarse Sediment
CSCB164	25.6	70.33	4.08	gS	Coarse Sediment
CSCB165	31.46	68.54	0	sG	Coarse Sediment
CSCB167	24.11	68.86	7.03	gS	Coarse Sediment

Appendix B: 2008 Dudgeon Geophysical Survey

Between 6th October and 10th October 2008, Gardline (2008) completed a geophysical survey along the initially proposed Dudgeon offshore wind farm export cable corridor (**Figure 4.1**). Deployments included single and multibeam echosounder, side-scan sonar, and sub-bottom profiler. Maps of bathymetry and sea bed features and shallow geology were provided along the cable corridor in the MCZ from about 2km offshore.

Water depths along the corridor in the MCZ range from 8.1m LAT on the crest of a minor sand bank about 3km offshore to about -21m LAT at the MCZ boundary. Most of the sea bed along the corridor in the MCZ (from 2km to 12km offshore along the corridor) consists of a veneer of gravelly sand with occasional cobbles (with a small 500m-wide patch of thin megarippled Holocene sand towards the seaward end). Pleistocene sediments are absent, and weathered chalk is at or close to sea bed. A very small shallow channel (infilled to 4m below sea bed) was mapped about 5km offshore along the corridor. There are also two areas where Holocene sands are present, characterised by ripples. A minor sand bank up to 3m thick occurs to about 3.5km offshore along the corridor. From 12km to 12.5km along the corridor is thin megarippled sand forming the feather edge of the southern flank of Sheringham Shoal. At 12.5km the sand thickens significantly into Sheringham Shoal with a maximum thickness of 9m at the crest outside the boundary of the MCZ.

Appendix C: 2004/2005 Sheringham Shoal Geophysical Surveys

D'Olier 2004

To plan for the proposed Sheringham Shoal offshore wind farm, D'Olier (2004) prepared a note on the general geological conditions at the site. The focus of the review was the area bounded by the turbines but the general description south of Sheringham Shoal sand bank was thin, shelly, gravelly sand over chalk bedrock.

Envision 2005

After the high-level review of D'Olier (2004), Envision (2005) completed swath, acoustic ground discrimination system (AGDS), sub-bottom profiling, and video and grab samples in March to June 2005. Within the MCZ, the following geophysical data was collected:

- several north-south aligned AGDS and swath tracks from the sand bank to nearshore; and
- twelve east-west aligned sub-bottom profiles and a single north-south aligned profile connecting the western ends of the nearshore east-west lines.

The AGDS data in the MCZ was ground-truthed using four video drops and five grab samples at the same locations. Maps of sediment class across the MCZ were produced from combining the AGDS, grab and video sample data (Figure B.1). The swathe data was used to compile a limited bathymetry along the tracks and an offshore limit to the exposure of rock at the sea bed.

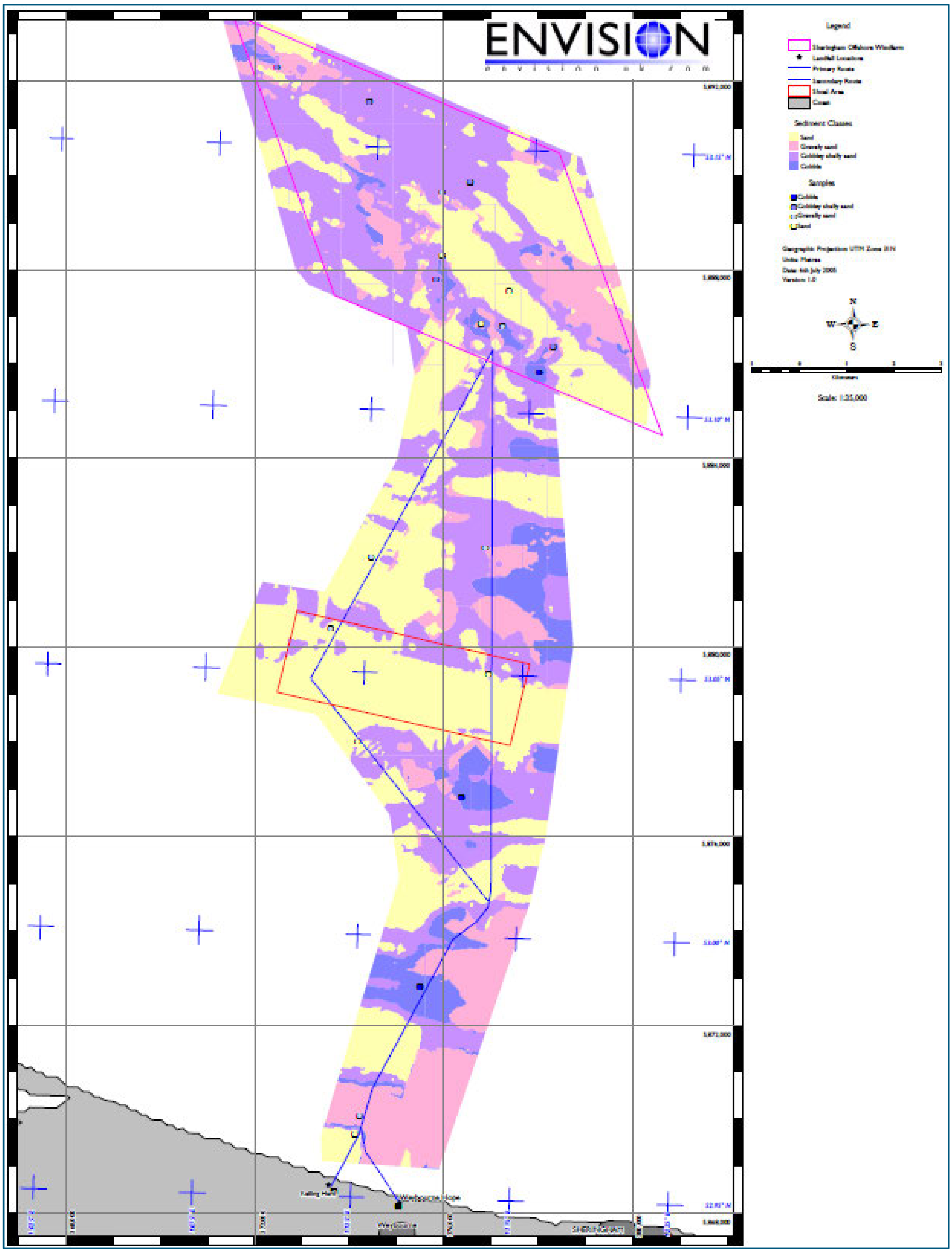

Figure B.1. Sediment class map produced from AGDS, grab and video sample data (Envision, 2005)

Envision, Titan and Royal Haskoning 2005

Between 4th and 8th July 2005, Titan (2005) completed a sub-bottom profiling survey of Sheringham Shoal. Royal Haskoning (2005) completed a combined interpretation of these data, the sub-bottom profiling data of Envision (2005), and earlier sub-bottom data collected by the British Geological Survey from 1993 to 1995. The sub-bottom geophysical data was ground-truthed using vibrocore logs provided by Fugro in 2005. These initial sub-bottom surveys provide data for an initial interpretation of the stratigraphy of the geological units along the proposed Sheringham Shoal export cable corridor in the MCZ. The recorded sequence is from oldest to youngest; Chalk Group, Swarte Bank Formation, Bolders Bank Formation, Weybourne Channel Deposits, Pollard Sand Bank and Sea Bed Sediments.

Chalk

Along the cable corridor in the MCZ, the chalk is either buried beneath younger deposits or exposed at the sea bed. The depth to the top of the chalk below sea bed is variable, with areas of sea bed exposure and areas where the chalk is buried to 25m depth beneath Pleistocene and Holocene deposits (**Figure B.2**).

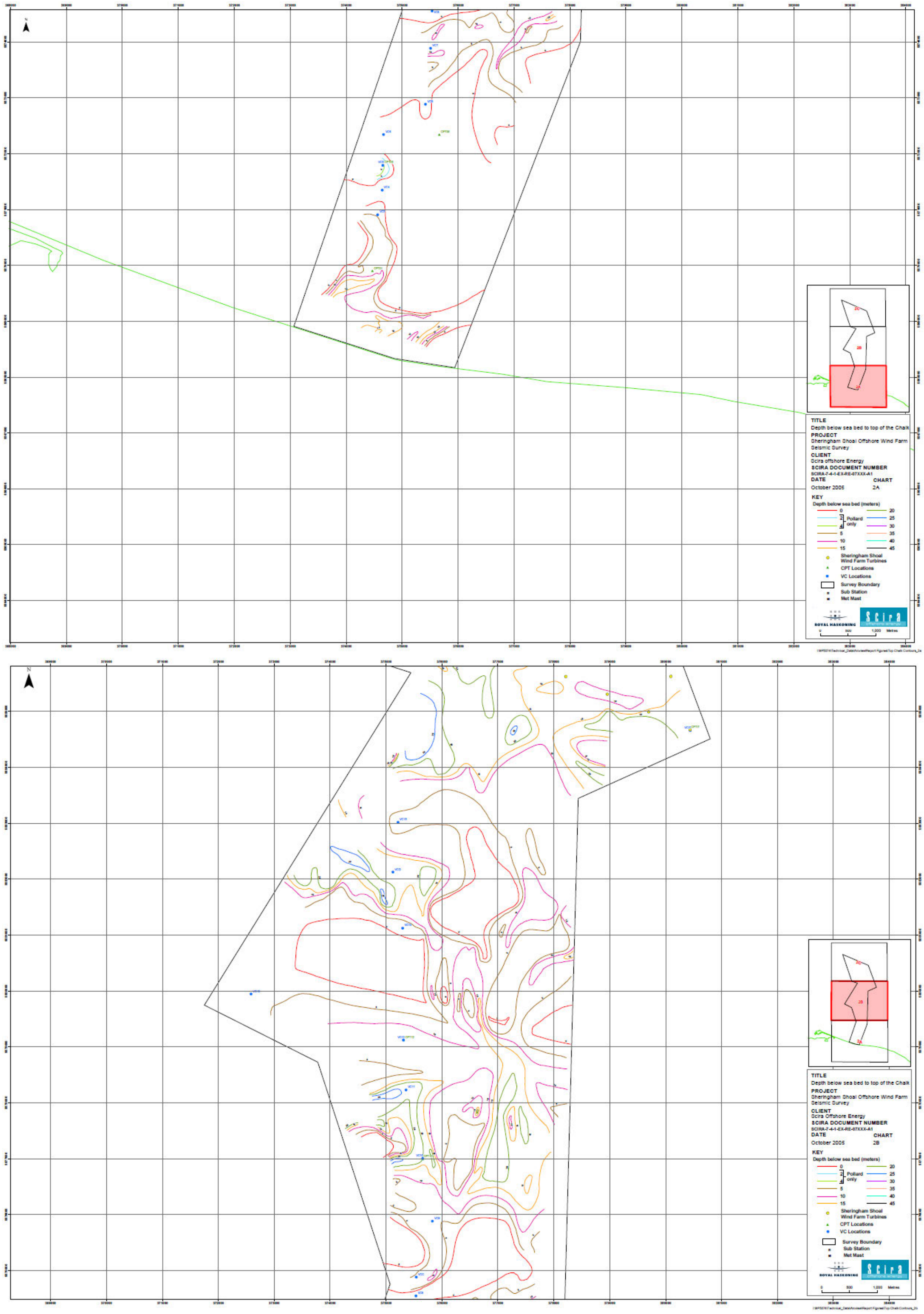

Figure B.2. Depth to the top of the chalk (Royal Haskoning, 2005)

According to D'Olier (2004) there is the potential for poor strength conditions at the chalk surface which has been channelled and infilled during later glacial periods. Indeed, Chroston et al. (1999) suggested that a surface layer of softer chalk ('putty' chalk) may be present as a result of Pleistocene weathering. This may have a variable thickness depending on the history of processes in the area. Overall, it is likely that the surface layers of chalk are weathered, becoming more competent with depth.

Swarte Bank Formation

Overlying the chalk is a series of heterogeneous sediments of Pleistocene age. These have been classified by the British Geological Survey (1991) and Cameron et al. (1992) as the Swarte Bank Formation which forms the infill of sub-glacial valley complexes which cut into the chalk. The infill can reach depths of 45m below sea bed (top chalk) along the corridor. British Geological Survey (1991) suggested that the sediments comprise a basal infill of sand, gravel and re-sedimented tills overlain by sands and muds.

Bolders Bank Formation

Within the MCZ south to the 5876000 UTM northing grid line, the older Pleistocene sediments and chalk are overlain by glacial till (Bolders Bank Formation, British Geological Survey, 1991; Cameron et al., 1992). The cable corridor crosses the southern feather edge of the Bolders Bank Formation and consequently along the cable route south of this edge there is little till (apart from isolated patches) at sea bed. The depth below sea bed to the base of the Bolders Bank Formation is shown in Figure B.3.

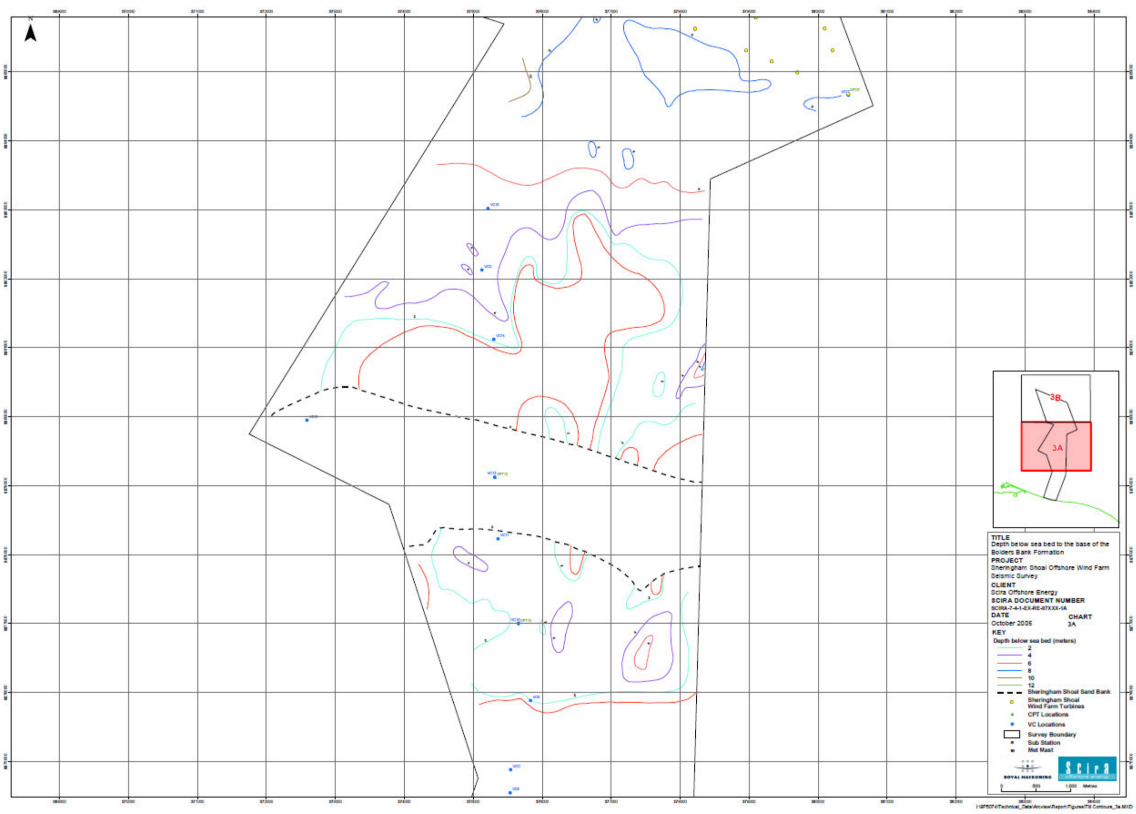

Figure B.3. Depth to the base of the Bolders Bank Formation (Royal Haskoning, 2005)

Weybourne Channel Deposits

Figure B.4 shows the location and thickness of the Weybourne Channel (Chroston et al., 1999). The data reveal two broad channels, one trending north-south and the other east-west, cut into Chalk. The channels merge around 500m from the coast. They have maximum depths below the sea bed of -17m.

Royal HaskoningDHV

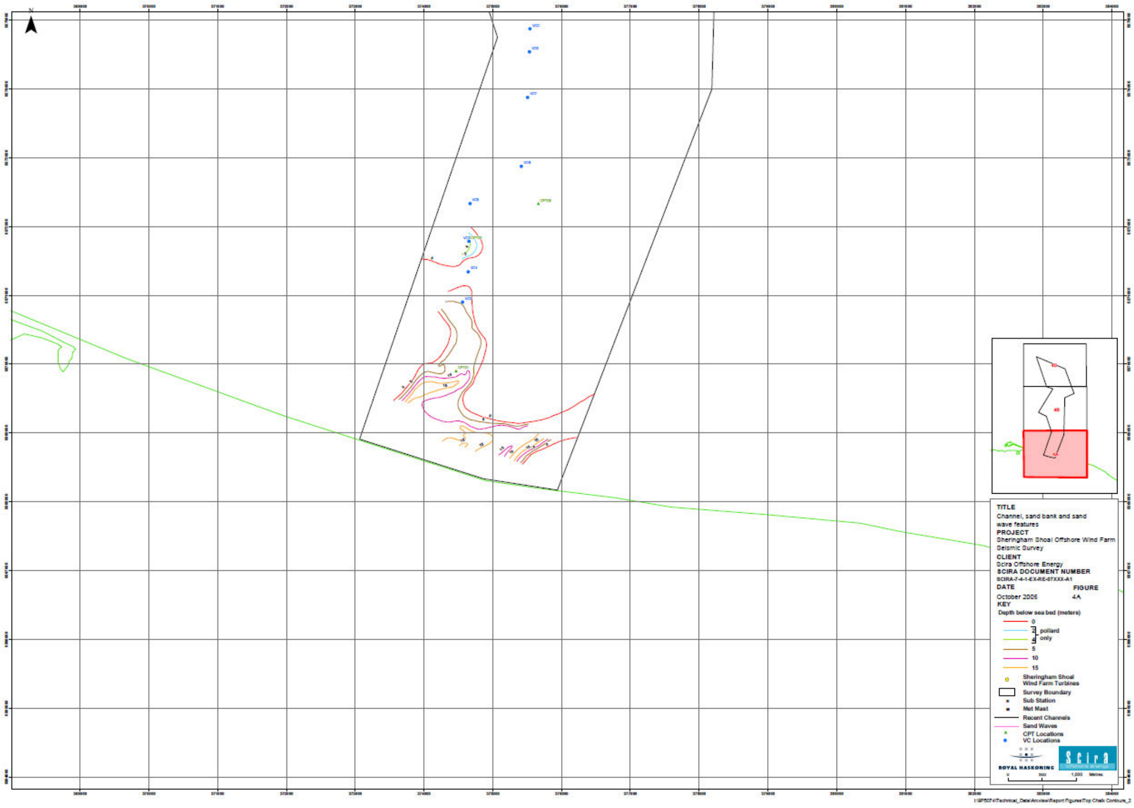

Figure B.5. Location and thickness of Weybourne Channel deposits (Royal Haskoning, 2005)

It is difficult to provide a comprehensive interpretation of sediment types in the Weybourne Channel based on one shallow vibrocore. However, the seismic facies can be divided into basal facies of strong reflectors infilling the deeper parts of the fill overlain by lower amplitude parallel reflectors or transparent facies infilling the bulk (Chroston et al., 1999). These units are interpreted as older sand and gravel overlain by laminated silts and sands (the latter found in VC3).

Pollard Sand Bank

Pollard sand bank could be encountered along the western side of the cable corridor. Where it is recorded on the sub-bottom profiles it is up to 4.5m thick and rests directly on chalk. VC5 recovered 4.25m of bank sediment (on chalk) with the following stratigraphy; 0-2.1m sand, 2.1-3.0m gravelly silty sand, 3.0-4.0m gravelly sand, 4.0-4.25m sand.

Sea Bed Sediments

Across most of the cable corridor a veneer of sand and gravel is likely to coat the sea bed. Evans et al. (1998) showed sea bed sediments comprised of either gravelly sand or sandy gravel (less than 0.5m thick) with some sand. The sea bed sediments are likely to have derived as a lag from erosion of the till. Envision (2005) supported Evans et al. (1998) and showed that along the cable corridor, the sea bed sediments were gravelly sand, with some sandy gravel and sand.