Sheringham Shoal and Dudgeon Offshore Wind Farm Extension Projects

Environmental Statement

Volume 3

Appendix 6.4 - Sheringham Shoal Nearshore Cable Route - BGS Shallow Geological Assessment

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Sheringham Shoal Nearshore Cable Route - BGS Shallow Geological Assessment

Marine Geoscience Programme

Commissioned Report CR/21/039

BRITISH GEOLOGICAL SURVEY

MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/21/039

Sheringham Shoal Nearshore Cable Route - BGS Shallow Geological Assessment

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Foreword

Following conversations between Equinor and the British Geological Survey (BGS) in late 2020, BGS submitted (18 Dec. 2020) a Scope of Work to undertake a geological assessment of the shallow sub-surface for the Sheringham Shoal nearshore export cable route. The Scope of Work was promptly approved by Equinor with the contract signed in early Jan 2021. The project has comprised two phases of work, the first of which was undertaken in Jan/early Feb 2021, and the second phase in April 2021. An interim report was submitted at the end of Phase 1, together with draft geospatial deliverables (i.e. Kingdom and GIS interpreted products).

The primary objectives for Phase 1 were to map the 'Top Chalk' and 'Top Peat', as both are key factors relevant to cable installation. This work builds on the initial geophysical interpretation along the Sheringham nearshore cable route by Gardline (2019), but also integrates relevant information from other previous initiatives in the region, including the Dudgeon cable corridor (GEO, 2013), and the Dudgeon and Sheringham Shoal offshore windfarm (OWF) extension areas (BGS, 2020).

Phase 2 has involved further mapping of subsurface units and seabed characteristics, with the overarching goal of characterising potential geological constraints on cable installation. Hence the primary activity of this 2nd phase has been the development of a 'traffic light' like approach in scoring potential constraints imposed by different geological factors (e.g. shallow chalk and mobile sediments). This final report summarizes the work of both Phases 1 and 2.

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    a. Primary products (**unchanged from Phase 1 Report*)
        i. Top potential Peat (gridded at 10m and 50m horizontal resolution)
        ii. Top Chalk (gridded at 10m and 50m horizontal resolution)
        iii. Tentative Talk Chalk (Top Chalk (gridded at 10m)
    b. Secondary products *(*prepared for Phase 2 constraints mapping)*
        i. Base Marine Sediments (unconsolidated) (partial)
        ii. Base Botney Cut (BC) 3 channel (potential Peat unit)
        iii. Base BC channel
        iv. Internal BSBK horizon (tentative)

1.2 GIS PRODUCTS (RASTER PRODUCTS UNLESS STATED OTHERWISE) (FIGS)

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    a. Top Potential Peat
    b. Top Chalk
    c. Top Tentative Chalk
    d. Base Marine Sediments (unconsolidated) (partial)
    e. Base Botney Cut (BC) 3 channel (potential Peat unit)
    f. Base BC channel
    g. Internal BSBK horizon (tentative)
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2 Brief Geological Setting

The proposed Sheringham Shoal nearshore export cable route extends from Weybourne (Norfolk) towards the southern corner of the planned Sheringham Shoal windfarm extension area (Fig. 1). The cable route is within a shallow region of the southern North Sea (up to ~40m in surrounding area), and crosses the recently established Cromer Shoal Chalk Beds Marine Conservation Zone (MCZ).

A range geological processes (tectonism, glaciation and sea-level change, active sedimentation) have impacted the region (e.g. Cameron et al., 1992; Tappin et al., 2011; Sturt et al., 2013; Damen et al., 2018), and are recorded in the regional seabed morphology and shallow sub-seabed geology (Fig. 1). Previous broadscale mapping by the BGS anticipates a general geological assemblage including: Chalk bedrock at or near (within 10s of metres) seabed along the full extent of cable route; disparate glacial deposits and glacial channels infilled with Quaternary and sand-rich Holocene marine sediment; Holocene sediment banks and active sediment bedforms (BGS, 1985,1986, 1991; Cameron et al., 1992; Tappin et al., 2011). More recent assessment within the adjacent Dudgeon cable corridor (GEO, 2013), and the Sheringham and Dudgeon Offshore Windfarm (OWF) extension areas (BGS, 2020) confirms this overarching framework.

2.1 BEDROCK GEOLOGY

Previous BGS mapping (BGS, 1985, 1986; Cameron et al., 1992) indicates Cretaceous Chalk to be the only bedrock unit to be present along the full length of cable route corridor, below a variable thickness of Quaternary and Holocene sediments. Mortimore (2014) indicates that different Chalk stratigraphic units may be encountered along extent of cable route (Fig. 2), and sampling of chalk within the Dudgeon OWF suggest potential variability in Chalk characteristics as a result of variable weathering, (ranging from putty/rubble, to high-density Chalk) (Mellet et al., 2013). The shallow chalk platform also forms the basis for the recently established Cromer Shoal Chalk Beds MCZ, with the Chalk itself serving as a key benthic habitat within the region.

- http://randd.defra.gov.uk/Document.aspx?Document=12825_Cromer_Shoal_Chalk_Beds_rMCZ_SummarySiteReport_v5.pdf
- https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/492323/mcz-cromer-shoal-chalk-beds-factsheet.pdf

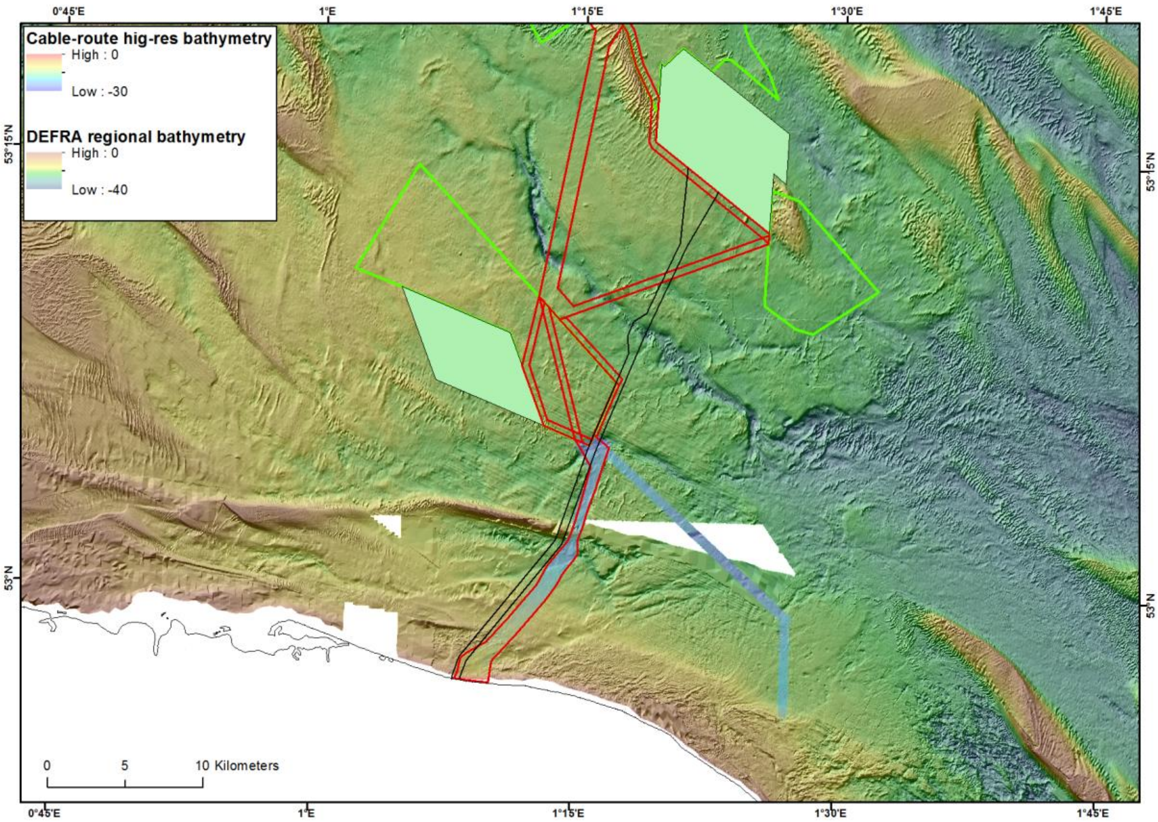

Figure 1. Sheringham export cable project area (red corridor with MBES bathymetry) from Weybourne to Sheringham extension area. Original Sheringham and Dudgeon OWFs in opaque green; extension areas in bright green polygons. Dudgeon cable corridor shown in black. Regional bathymetry (negative depth) provided by Defra.

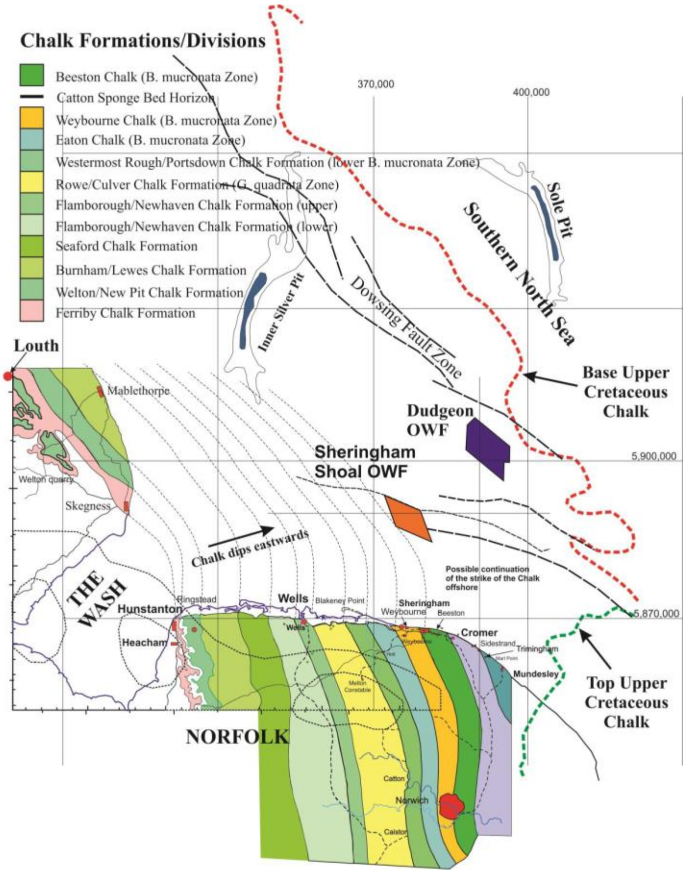

Figure 2. Projected offshore Chalk stratigraphy by Mortimore (2014).

2.2 QUATERNARY SEDIMENT COVER

According to initial BGS mapping in the region, several Quaternary units are anticipated to be present on top of the Chalk platform (oldest-youngest): Swarte Bank Formation (SBK); Bolders Bank Formation (BSBK), and Botney Cut Formation (BC) (BGS, 1991; Cameron et al., 1992). This general model was applied (though inconsistently) within the initial geophysical reporting for both the Dudgeon (GEO, 2013) and Sheringham Shoal (Gardline, 2019) nearshore export cable routes. Separately, recent detailed mapping undertaken by BGS (on behalf of Equinor) using extensive hi-resolution seismic data within the Dudgeon and Sheringham OWF extension areas has refined the regional Quaternary Framework, and Fig. 3 presents the updated stratigraphic model (BGS, 2020).

This model shows that the glacial SBK deposits infill deeply-incised glacial channels ('tunnel valleys') and broad depressions, the BSBK forms a broadly distributed unit of ~consistent thickness subglacial till, and the BC formation infills relatively shallower channels. Both the SBK and BC formations exhibit high soil-property variability with multiple infill sub-units (from hard glacial tills, to sand-rich deposits, to soft organic-rich soils). The BSBK formation frequently includes multiple seismostratigraphic members, though commonly comprises firm-stiff glacial till. To be clear, the thickness of Quaternary units within the Sheringham nearshore cable route is generally thinner and more discontinuous than portrayed in Fig. 3. For further details on the sediment and geotechnical properties of the Quaternary formations refer to BGS (2020).

Fig. 4 presents the initial geophysical mapping ('isopach contours') prepared by GEO (2013) and Gardline (2019) within the Dudgeon and Sheringham cable corridors respectively, together with further context (previous BGS mapping) on Quaternary deposits. The 'diamicton' shown in Fig. 4 shows the southern extent of BSBK mapped by BGS (e.g. BGS, 1991), together with legacy BGS sediment cores that contain glacial till (i.e. diamict). More recent analysis by Dove et al. (2017) identified glacial moraines in the region, suggesting that BSBK deposits likely extend slightly farther south than originally mapped (i.e. extending within the Sheringham cable corridor).

This is relevant here as there is a discrepancy in the initial geophysical mapping of Quaternary deposits between the Dudgeon (GEO, 2013) and Sheringham (Gardline, 2019) corridors. Within the northern ~3rd of the cable routes, BSBK is mapped (blue contours) in the Dudgeon corridor, whereas BC (red contours) is mapped in the Sheringham corridor Fig. 4. Our analysis suggests that these deposits are likely BSBK (i.e. BC incorrectly classified). These results are described in greater detail in section 3.2.

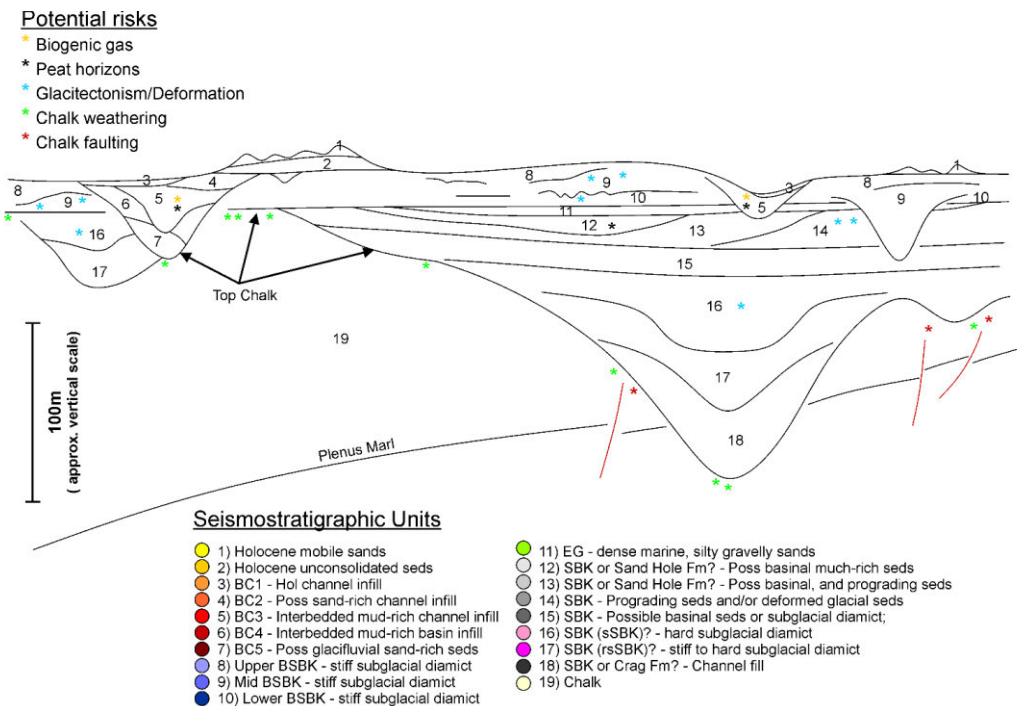

Figure 3. Revised BGS seismostratigraphic model for the Dudgeon and Sheringham Shoal extension areas (BGS, 2020). Unit abbreviations: Botney Cut (BC), Bolders Bank (BSBK), Swarte Bank (SBK).

2.3 HOLOCENE-MODERN MARINE SEDIMENTATION

Following the glacial cycles that led to the deposition of the SBK, BSBK, and BC formations, sea levels rose and marine conditions returned to this shallow sector of the North Sea within the Holocene (e.g. Tappin et al., 2011; Sturt et al., 2013, Damen et al., 2018). A range of shallow continental shelf processes interacted to modify and create sedimentary features now preserved at seabed, operating over multiple time scales (e.g. tidal, storm, seasonal, millennial). The large sand banks of the region ('Norfolk Banks') were initially formed during the early/mid Holocene (~8-5 kya) when hydrodynamic conditions were more energetic, but are maintained in their current morphology/position by the modern hydrodynamic regime. The 'Sheringham Shoal' sand bank crosses the cable corridor in an WNW-ESE orientation.

Initial mapping of the seabed sediments and seabed features by Gardline (2019) is shown in Figs. 5 and 6. Though the sediment bank itself is not classified, Gardline (2019) identify further current-induced bedforms (i.e. sand waves and megaripples) that lie atop the seabed, indicating potential sediment mobility. Seabed sediment maps show much of the seabed is dominated by coarse sediments (sandy Gravel), though finer sands dominate at the sand bank and where current-induced bedforms are dominant. Exposed Chalk bedrock is present in the far south, adjacent to the coast (Fig. 5). As a note, the seabed features were mapped under different criteria within the Dudgeon corridor, where the primary features mapped are 'mounds' associated with rugose terrain.

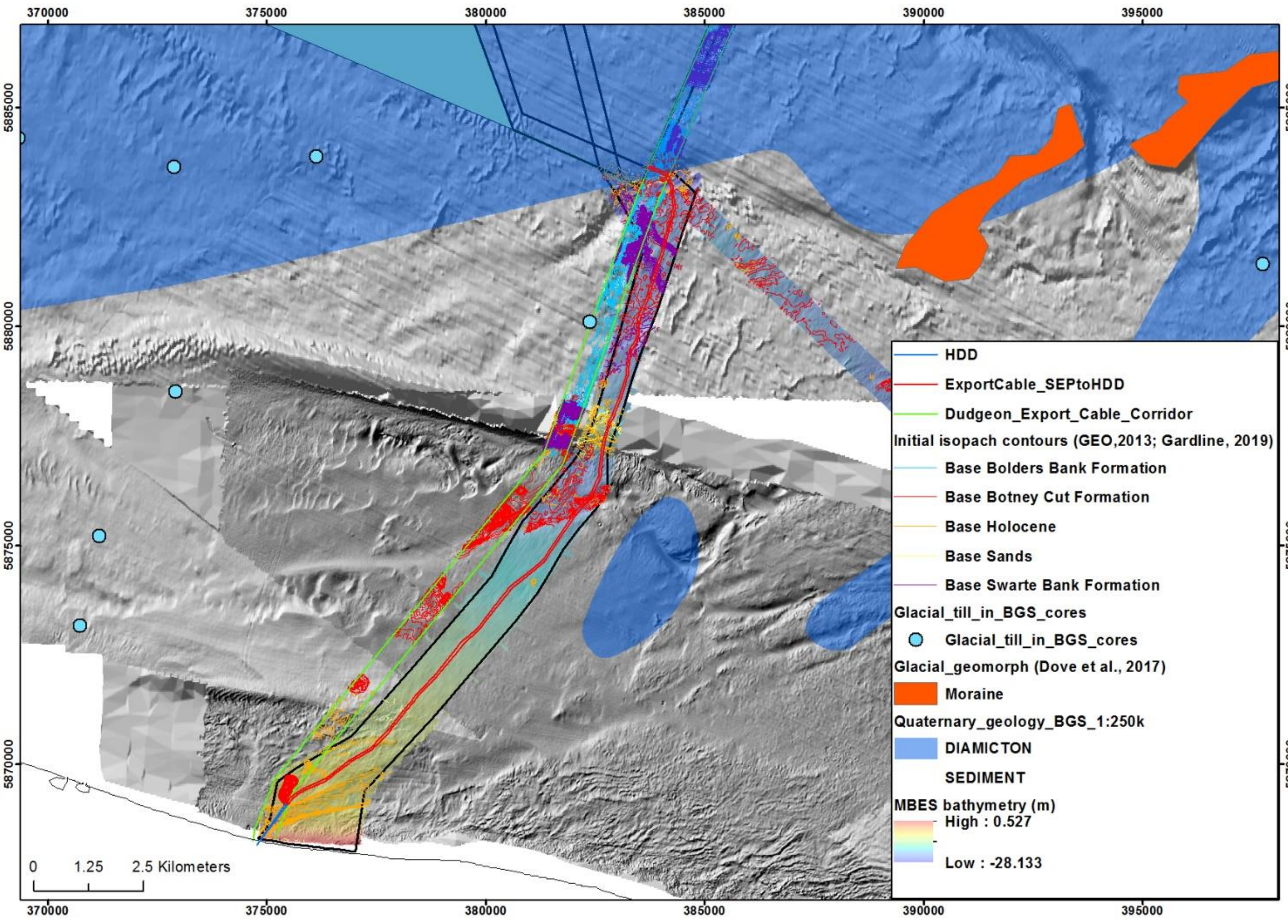

Figure 4. Initial geophysical mapping (prior to this project) within Sheringham and Dudgeon cable corridors, together with legacy BGS mapping relevant to extent of shallow glacial till (i.e. Bolders Bank Formation – BSBK). MBES bathymetry shown with negative depth.

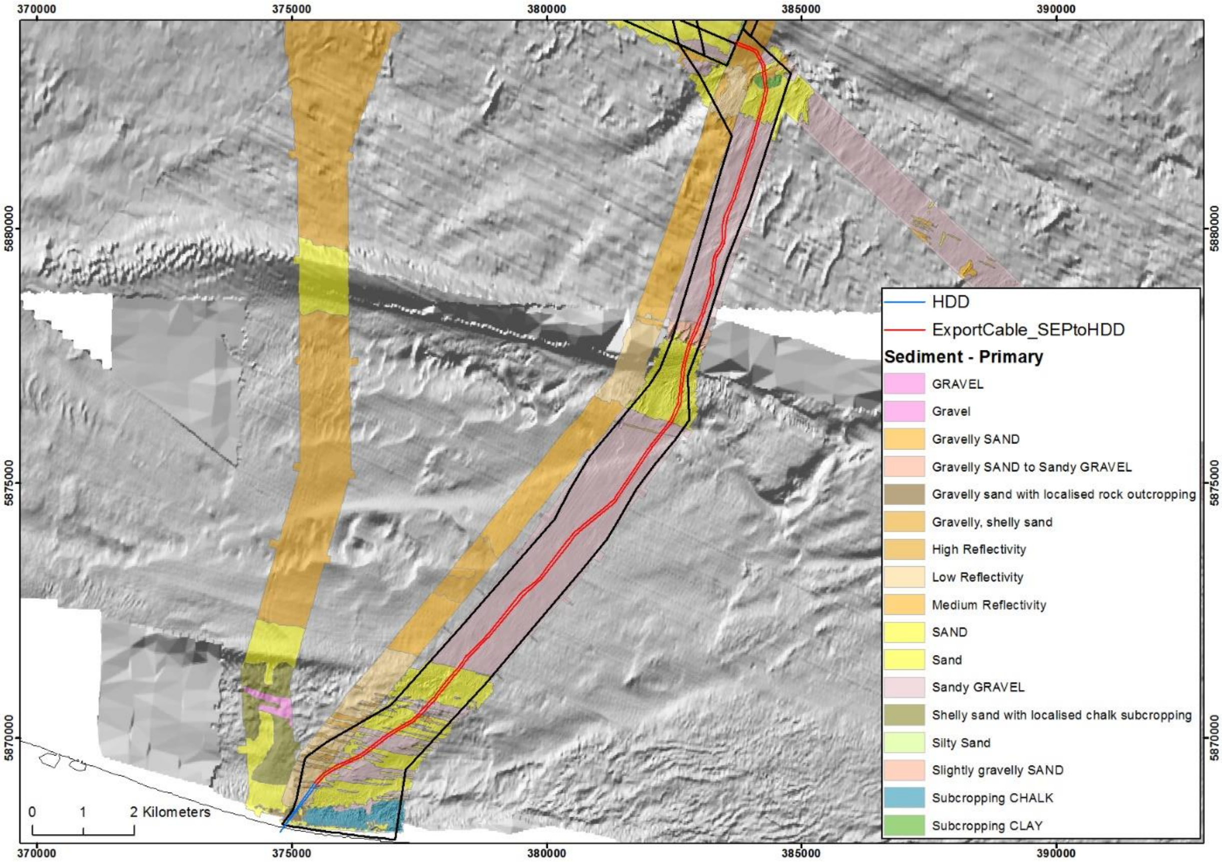

Figure 5. Seabed sediment distribution as mapped by Gardline (2019).

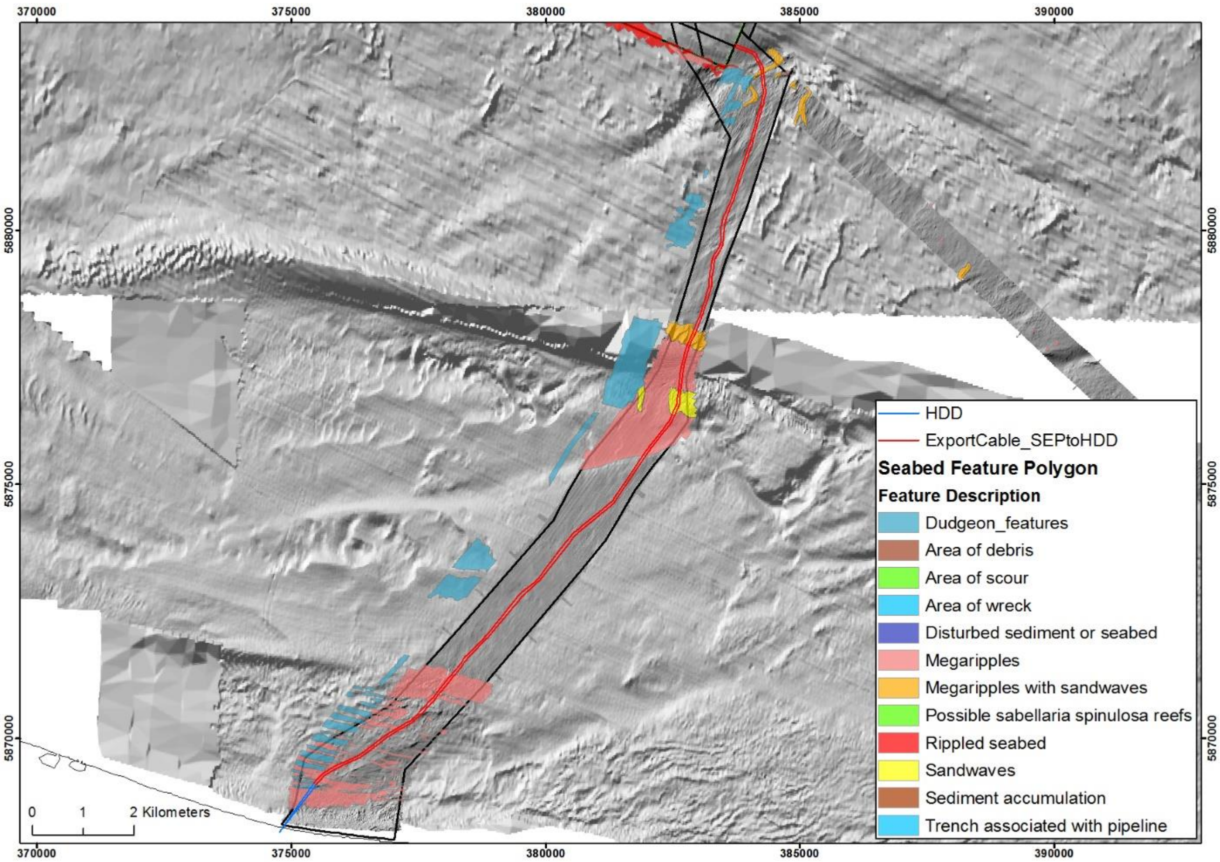

Figure 6. Seabed features as mapped by Gardline (2019).

3 Results

To assess the subsurface geology, we have analysed and interpreted pinger and boomer seismic data acquired within the Sheringham cable corridor using SMT Kingdom software (Figs. 8-11) (Gardline, 2019). Further contextual data, including high-resolution multibeam echosounder (MBES) bathymetry, have been incorporated into a GIS environment. Also included are sediment core results (via vibrocore) from the adjacent Dudgeon cable corridor, as well as available BGS data (nearby seismic lines and sediment cores) and mapping (Fig. 7). At the time of reporting, dedicated geotechnical sampling within the Sheringham nearshore cable corridor has not been undertaken. We have however used information from the adjacent Dudgeon cable corridor to inform our interpretations (e.g. previous vibrocore results) (Figs. 5-7). This information includes previous interpretation reporting (GEO, 2013), as well as GIS products (provided by Equinor) associated with this interpretation (e.g. Vibrocore location, seabed mapping, and sub-surface isopach contours). We have not analysed, nor had access to the original geophysical or geotechnical data from the adjacent Dudgeon corridor.

On the basis of our interpretations of the seabed and shallow seismic data within the Sheringham Shoal nearshore cable corridor, we propose sampling sites within Section 5 to help confirm the geological character as mapped, and/or address uncertainties in the interpretation.

3.1 SEABED GEOMORPHOLOGY

Water depths along the cable export route range from 0.5m to 28.5m depth (Fig. 7). The seabed generally deepens away from the coast, though there is local-scale variation, including the large Sheringham Shoal sand bank. While describing the seabed is not the primary focus of this phase of work, the morphology of the seabed can provide useful information/inference on the nature of the sub-seabed geology. Further MBES data were acquired for the Cromer Shoal MCZ as well as by the UKHO's Civil Hydrography Programme (CHP), and overlap much of the cable route. These datasets, acquired at different times, will be further assessed in the Geological Constraints section to characterise sediment mobility. Broad-scale seabed features within the area include: exposed Chalk platform extending from coast, several palaeochannels (and channel networks) initially formed via glacial process, km-scale Holocene sand banks, and large sediment waves (Figs. 1,6,7).

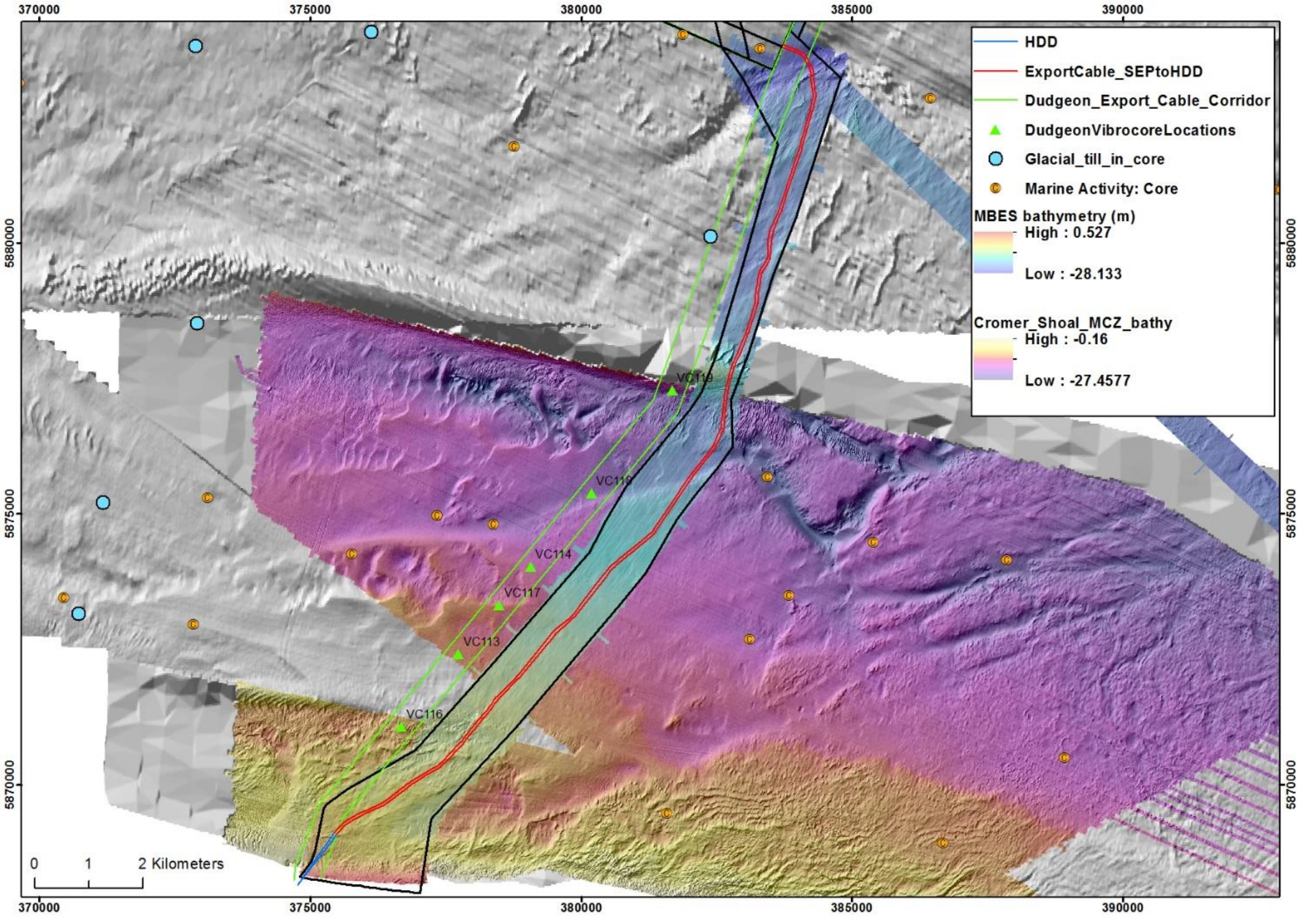

Figure 7. MBES bathymetry within Sheringham export cable corridor, together with previously acquired bathymetry data from Cromer Shoal MCZ, and sample data from the BGS database and Dudgeon cable corridor. Planned HDD (nearshore) and coble route shown in blue and red lines respectively.

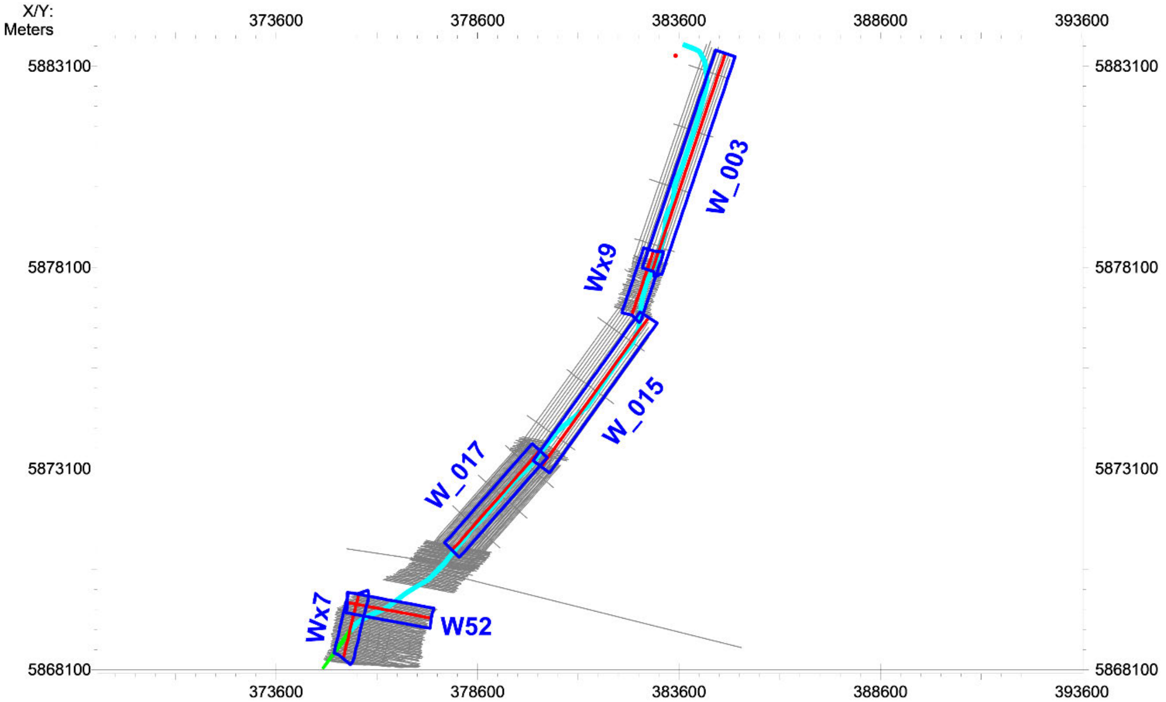

Figure 8. Geophysical lines (pinger and boomer) within the Sheringham export cable corridor.. Example profiles along planned cable route (light blue line) shown in Figs. 9-11.

3.2 SUB-SURFACE GEOLOGY

As expressed within the Scope of Work, the Top Chalk surface and the presence of potential Peat were identified as primary mapping goals for the project, and were undertaken in Phase 1.

For the purposes of developing relevant Geological Constraints layers in Phase 2 of the project, it was determined that further subdivision of the Quaternary units would be useful, and the following horizons were mapped (secondary products): 1) Base Marine Sediments (unconsolidated); 2) Base Botney Cut (BC) 3 Channel; 3) Base BC Channel; 4) Internal BSBK horizon (tentative).

All mapped horizons are described below, and example interpreted profiles along the planned cable route are given in Figs. 9-11.

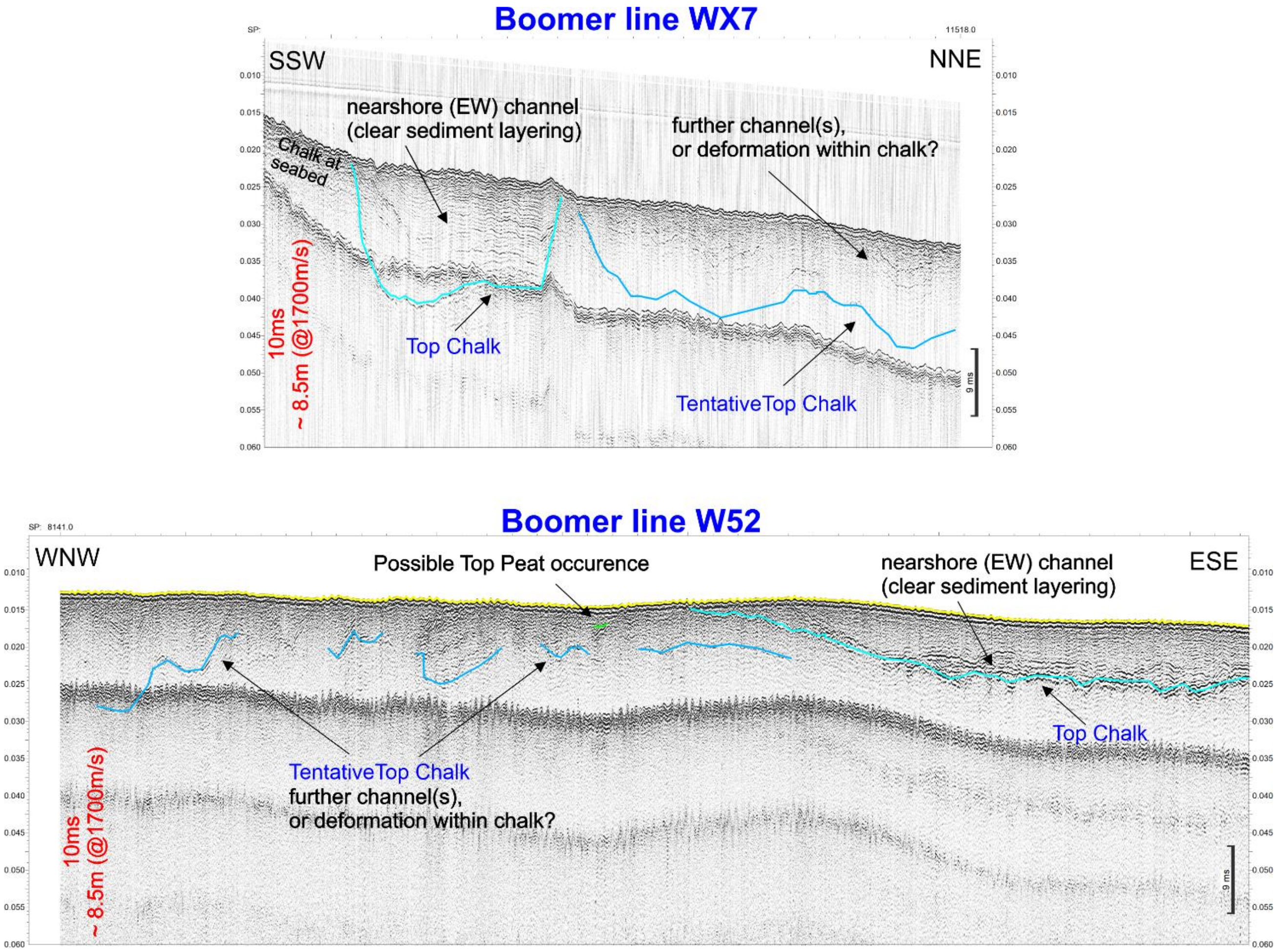

Figure 9. Interpretation of Boomer lines WX7 and W52 coincident with planned HDD and cable route. Profile locations shown in Fig. 8.

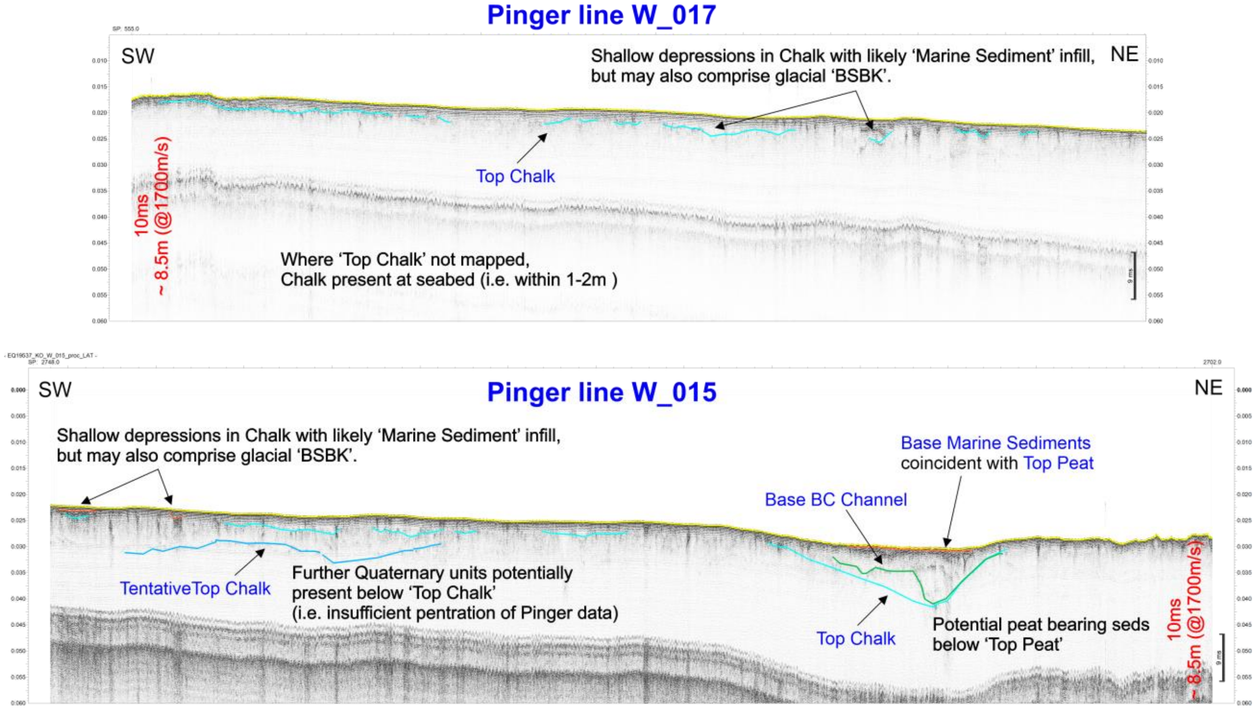

Figure 10. Interpretation of Pinger lines W_017 and W_015 coincident with planned cable route. Profile locations shown in Fig. 8.

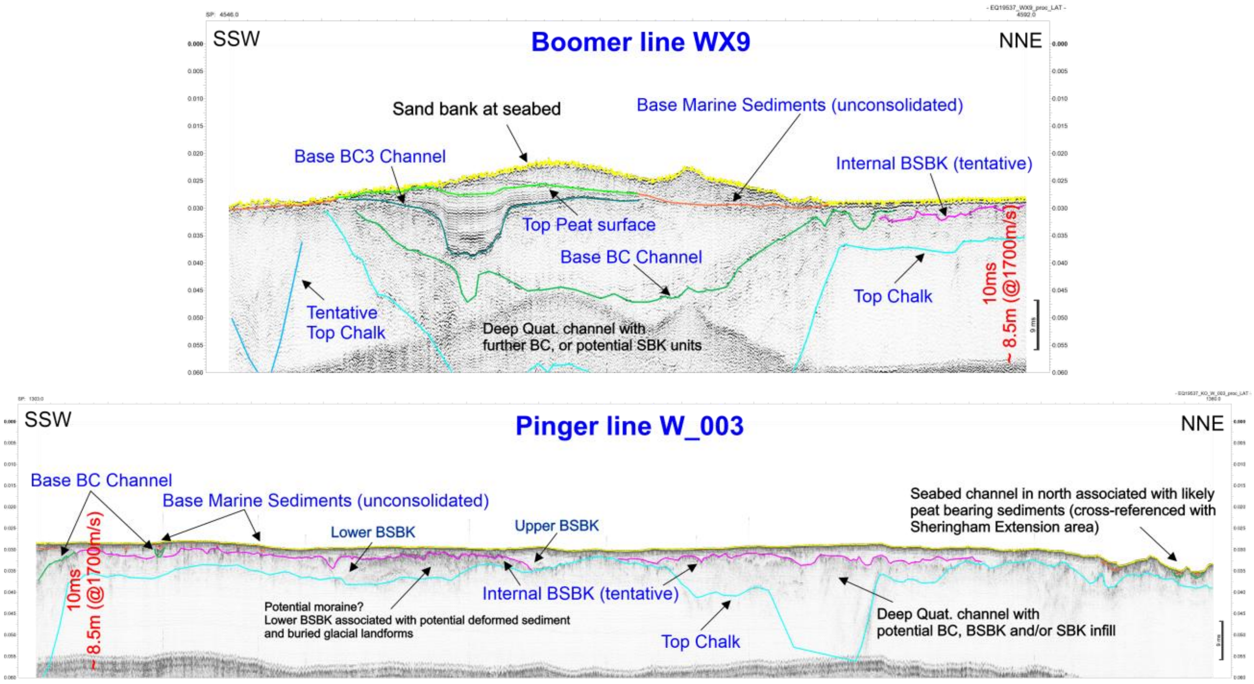

Figure 11. Interpretation of Boomer line WX9 and Pinger line W_003 coincident with planned cable route. Profile locations in Fig. 8.

3.2.1 Primary Products

3.2.1.1 Top Chalk

As a key constraint to inform cable emplacement, the Top Chalk horizon has been mapped along **all* pinger and boomer lines using SMT Kingdom software (Fig. 8). To be clear, the interpreted Top Chalk horizon represents the top surface of the Chalk bedrock. The Top Chalk horizon has been mapped in all places where a boundary between overlying sediment and the Chalk can be directly observed (or clearly inferred/extrapolated from nearby cross-lines). Because the seabed reflector within the seismic data can mask ('ringing') the top 1-2m (below seabed) within the pinger and boomer data, where Top Chalk is not mapped, Chalk is expected to be within approximately 1-2m of the seabed.

While there are no ground-truth sites within the Sheringham cable corridor, nearby BGS cores and previous BGS mapping (e.g. BGS, 1985, 1986, 1991) as well as the Dudgeon cable corridor vibrocores confirm the presence of shallow Chalk within the area (Fig. 7). Similarly, the MBES bathymetry data are used to cross-reference the seismic data where Chalk bedrock morphology (e.g. rugged morphology, with bedding planes observed in places) is apparent at seabed (Fig. 7).

The Top Chalk horizon was mapped within SMT Kingdom seismic interpretation software using manual horizon picking, targeting the first trough below the peak on both the Pinger and Boomer data. Vertical accuracy of the horizon picking is estimated to be accurate within ±1m, incorporating both data resolution and interpretation uncertainty. While not specified within the initial geophysical report (Gardline, 2019), we estimate vertical resolution of the Pinger and Boomer data to be approximately 20-50cm, and 30cm-1m respectively.

** Several nearshore boomer lines (*TEn_WX8, *TEn_WX7, *TEn_WX3) have spurious depth datums, and while used for visual interpretation, these lines have been excluded from isopach calculations.*

The Top Chalk horizon can be observed on both the pinger and boomer data but where deeper channels are incised into the Chalk, the Boomer data give better penetration. The Top Chalk horizon is commonly of moderate to high relief (as an erosional unconformity), with sediment strata (of variable character above) and typically homogenous, low-energy seismic facies below. In places there is some structure observed within the shallow Chalk. In these cases we've mapped a potentially deeper 'Tentative Top Chalk' (Section 3.2.1.2) and proposed further sampling (Section 5). This structure could represent deeper Quaternary deposits, or strata (or deformation structures) within the very shallow Chalk. In the deep channel below the Sheringham Shoal sand bank (Fig. 11 – Boomer line WX9), the Top Chalk can only be observed in the Boomer lines, and extrapolated across pinger lines. We note however that this occurs at depths greater than 20m below seabed, and is therefore not directly relevant to cable emplacement. The initial geophysical report states an average penetration of 25m for the Boomer data, though note this is variable according to substrate. We observe the maximum penetration of the Boomer data is approximately 45m over deep channel deposits (1800m/sec bulk velocity), though drops to nearer 5-10m where Chalk is present at seabed. Similarly we observed Pinger data penetration up to approximately 18m over channels, but is not expected to penetrate into the Chalk.

The Top Chalk horizon is of variable morphology along the corridor. Where very shallow, it is in places interrupted by small sediment-infilled hollows; In several locales it is incised by deep glacially-cut valleys; And in the northern ~3rd of the corridor it exhibits an irregular surface overlain by probable glacial deposits (i.e BSBK). A depth map of the 'Top Chalk' in two-way travel time (from sea-surface) is presented in Fig. 12, and an isopach map of the sediment thickness overlying the Chalk is presented in Fig. 13 (i.e. depth below seabed in metres (1800m/s sediment bulk velocity applied)). As a note, we also had to map the seabed reflector, using an automated picking routine, across all lines to produce isopach (unit thickness) maps.

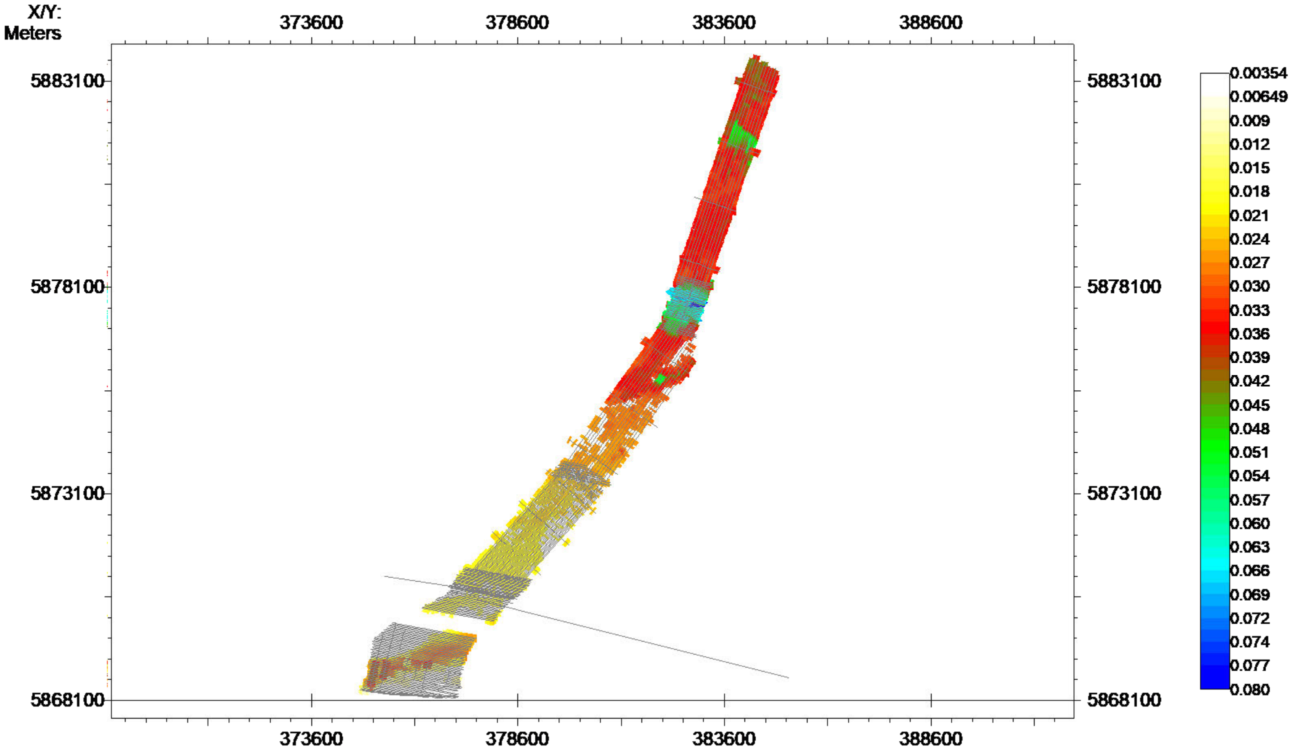

Figure 12. Top Chalk horizon: Depth from sea surface in two-way travel time (seconds), as mapped within SMT Kingdom.

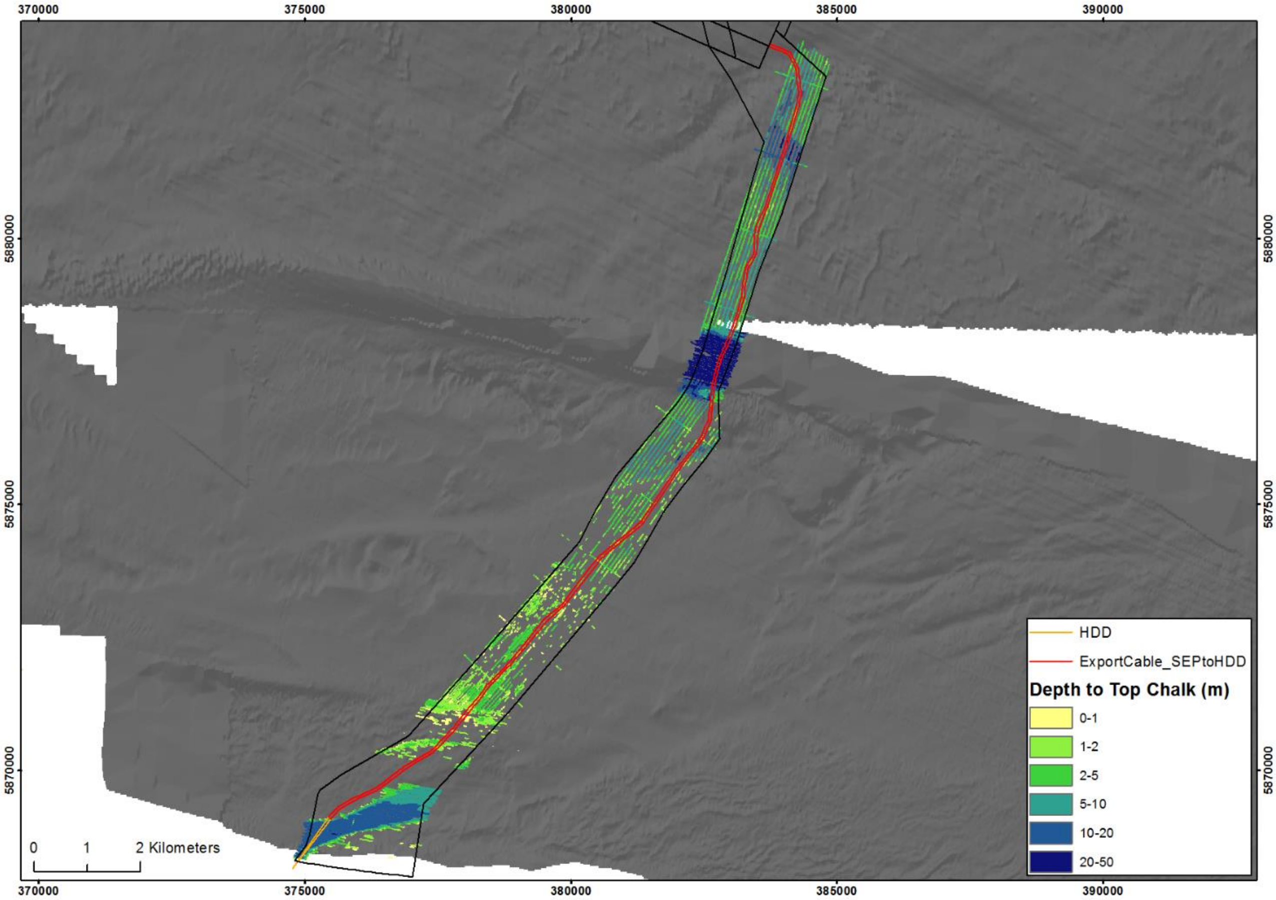

Figure 13. Top Chalk horizon Depth from seabed (e.g. unit thickness) in metres. 1800 metres/sec bulk velocity assumed. Note that where 'Top Chalk' not mapped, chalk anticipated within 1-2m of seabed (i.e. obscured by seabed reflector).

3.2.1.2 TENTATIVE TOP CHALK

In several locales (predominately observed within boomer data), an intermittent reflector(s) may be seen at stratigraphically deeper depths than the more confidently mapped 'Top Chalk'. We have mapped these incidences, and termed this horizon the 'Tentative Top Chalk' (Fig. 14). Next to the nearshore channel close to the coast, this feature may represent the base either a further sediment-filled channel(s) (i.e. Top Chalk -in which seismic facies suggest a stiffer/harder infill than the layered infill of the prominent E-W channel), or alternatively may represent deformation structures (e.g. folds and faults) within the chalk relating to glaciation (e.g. Mellet et al., 2020). It is recommended this site is targeted for future geotechnical sampling to constrain soil characteristics (Fig. 37).

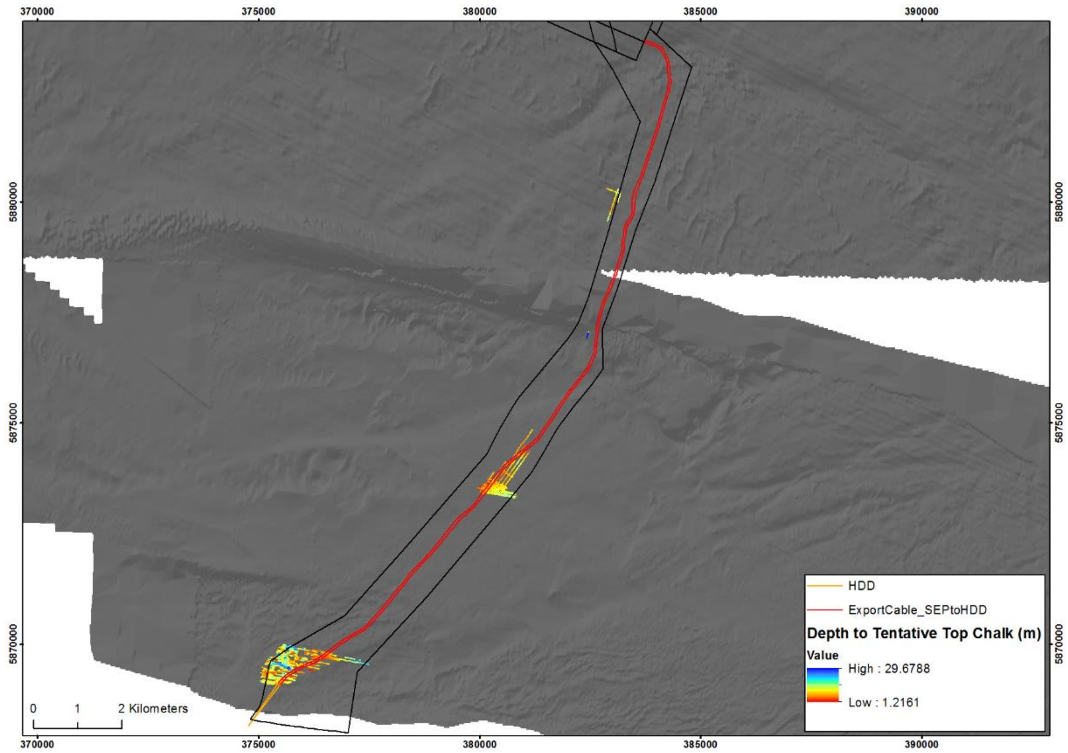

Figure 14. Interpreted 'Tentative Top Chalk' horizon – Depth from seabed (e.g. unit thickness).

3.2.1.3 TOP PEAT

Further to the Top Chalk, the potential presence of Peat within the shallow soils overlying the Chalk was identified as a key factor impacting cable emplacement. And similar to the Top Chalk, the Top Peat has been mapped wherever it has been identified along all pinger and boomer lines. To be clear, there is currently not sufficient information to positively identify peat beds, but rather we have identified sedimentary units that exhibit seismic characteristics (conformably layered reflectors within depressions and channels) indicative of potential organic-rich, peat bearing sediment. Further supporting this interpretation, the presence of peat (within channels and depressions) has been previously recorded in the region (e.g. Tappin et al., 2011; Mellett et al., 2013; Roberts et al., 2018; BGS, 2020)

'Top Peat' refers to the uppermost surface of seismostragraphic units interpreted to be potentially peat bearing, i.e. seismostratigraphic unit Botney Cut (BC) 3 described below. BC3 nomenclature is adopted from Dove et al. (2020).. We have mapped the top surface, as opposed to the conventional base of the unit, as this surface is more applicable to cable emplacement considerations. Peat deposits are primarily associated with the larger channels (potentially excluding the nearshore channel), but may also be present in several smaller depressions/hollows observed. Depth to Top Peat from the sea surface (in two-way travel time) is presented in Fig. 15, with depth from seabed (in metres - 1700m/s sediment bulk velocity applied) presented in Fig. 16.

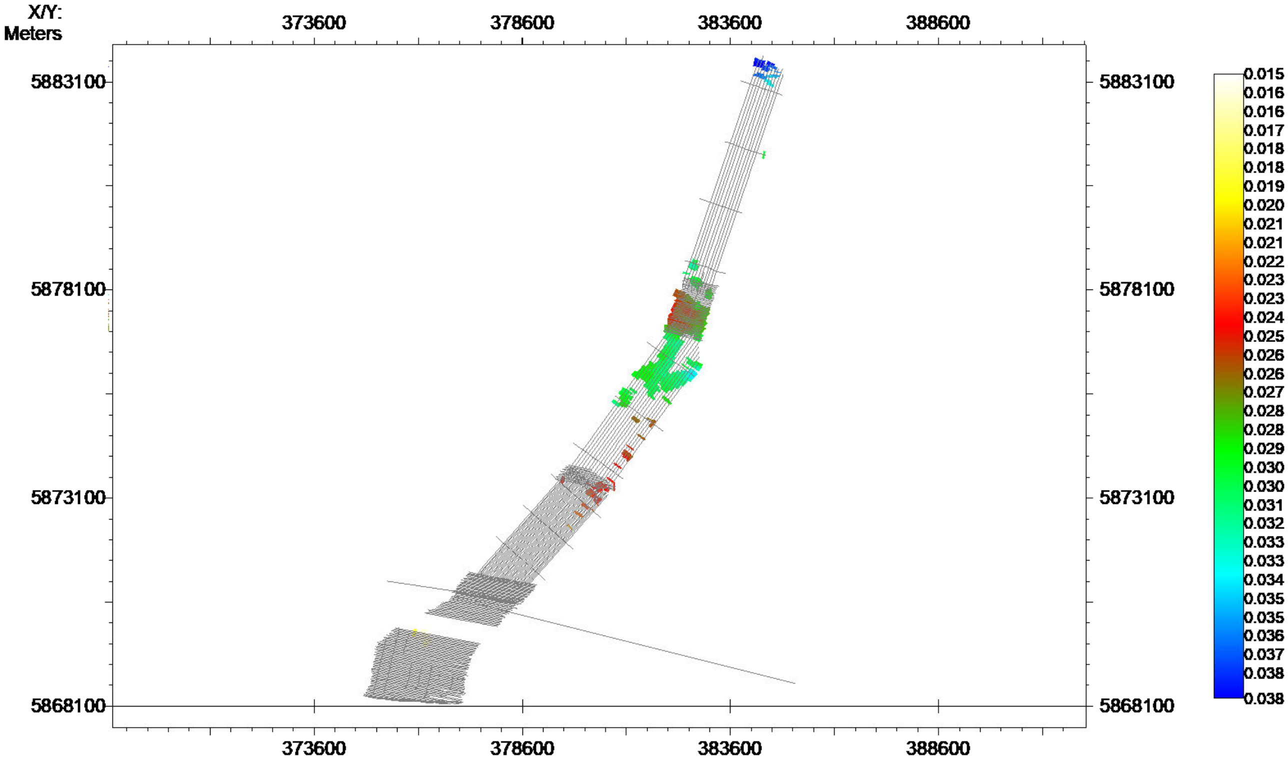

Figure 15. Top Peat horizon: Depth from sea surface in two-way travel time (seconds), as mapped within SMT Kingdom.

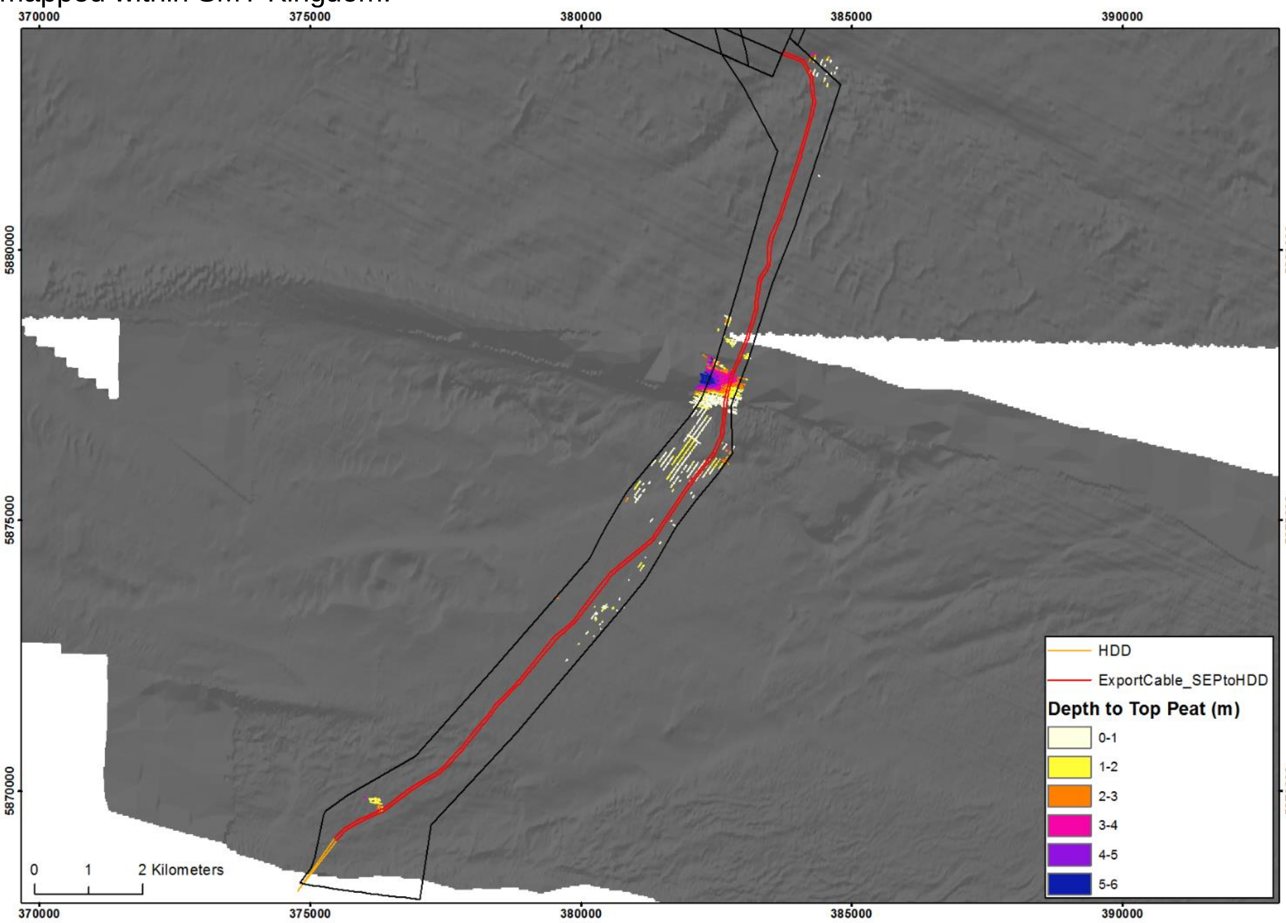

Figure 16. Top Peat horizon Depth from seabed (e.g. unit thickness) in metres. 1700 metres/sec bulk velocity assumed.

3.2.2 Quaternary units – Secondary Products

Sediment assemblages overlying the Chalk vary along the corridor, and through seismostratigraphic analysis are interpreted to include (Oldest to youngest): (possible) Swarte Bank (SBK) Fm. (deep channel infill in two northern channels); Bolders Bank (BSBK) Fm (subglacial till - shallow cover of irregular chalk surface north of sand bank); Botney Cut Fm (shallow infill of small and deeper channels; multiple units incl. potential peat-bearing layers); Holocene to modern unconsolidated marine sediments (sands and gravelly sands). Vibrocores within the Dudgeon corridor include units of both subglacial till (VCs 113, 114,119), organic material (VCs 117, 118, 119), as well as marine sediments (Fig. 7).

Though SBK may be present within two deep channels along the cable route (Fig. 11), it was observed that this sediment package never reached within approximately 5m of seabed and was therefore not of immediate relevance for this cable project, and thus SBK is not mapped.

The below seismostratigraphic units have been mapped with the primary purpose of informing the Geological Constraints analysis presented in Section 4. Example seismostratigraphic results are presented in Figs.9-11.

3.2.2.1 Base Marine Sediments (unconsolidated) – partial mapping

Though Fig. (4) ('Base Holocene') indicates that this unit was previously mapped (Gardline, 2019), the final seismic interpretation products have not been available, and hence the sediment unit has been re-mapped by BGS. We have opted for the term 'Base Marine Sediments (unconsolidated)' rather than 'Base Holocene' as we interpret this unit may comprise Holocene through modern marine sediments comprising sand with mixed proportions of gravel, shell, and rarer mud. This unit captures the base of the large sediment bank (Sheringham Shoal), several sediment waves, and a number of small depressions and channels in the Quaternary or Chalk (Fig. 17).

The unit has not been mapped in detail within the southern portion of the cable route, as for the purposes of the Constraints mapping we've assumed that all sediment between the shallow Chalk and seabed is Marine Sediment (unconsolidated). This includes the large nearshore channel, which we tentatively interpret comprises Holocene marine sediments (especially in shallower depths), rather than Botney Cut infill.

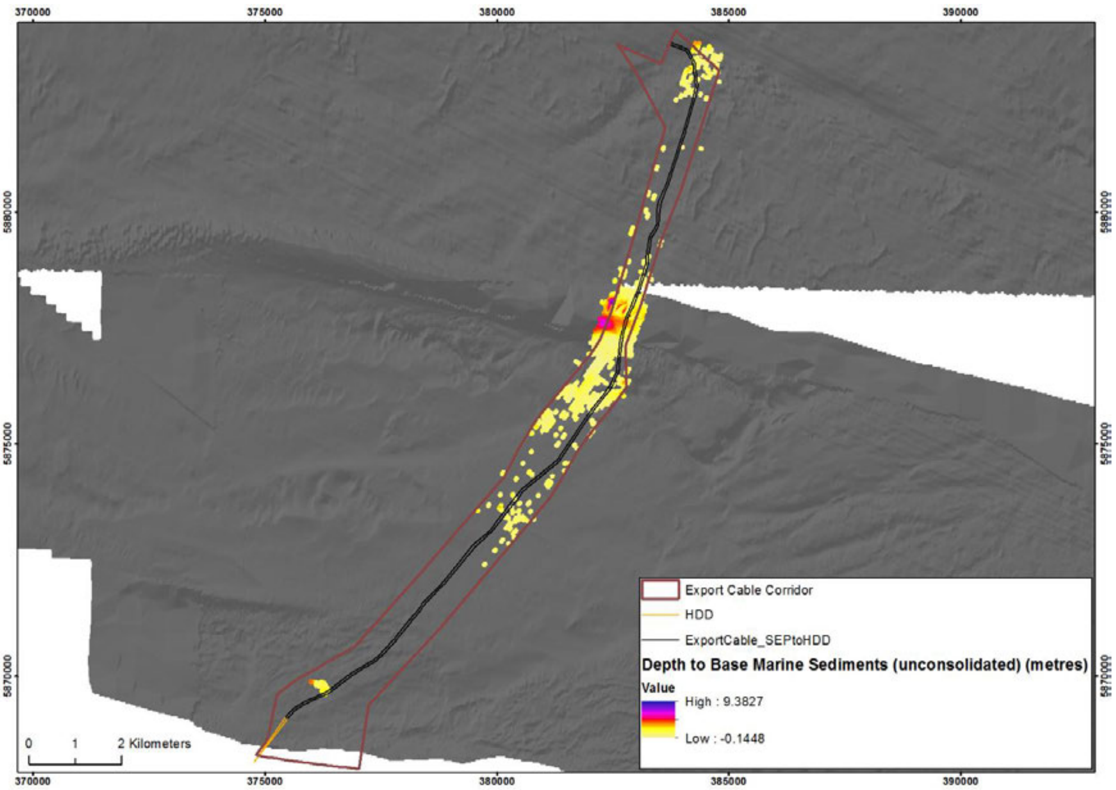

Figure 17. Depth to Base Marine Sediments (unsol.) (metres below seabed). 1700 metres/sec bulk velocity assumed.

3.2.2.2 Base Botney Cut (BC) 3 Channel

The ‘Top Peat’ horizon represents the upper surface of a Botney Cut (BC) sub-unit, mapped in Phase 2 as Base BC 3. This nomenclature is adopted from BGS (2020) which subdivided the Botney Cut into multiple seismostratigraphic units. BC3 is characterised by conformable, laminated reflectors that elsewhere in the region are associated with potential peat bearing sediment (organic-rich muds and sands).

Base BC3 is primarily observed in the central part of the cable route, within one large channel and several smaller tributary channels and depressions (Fig. 18)

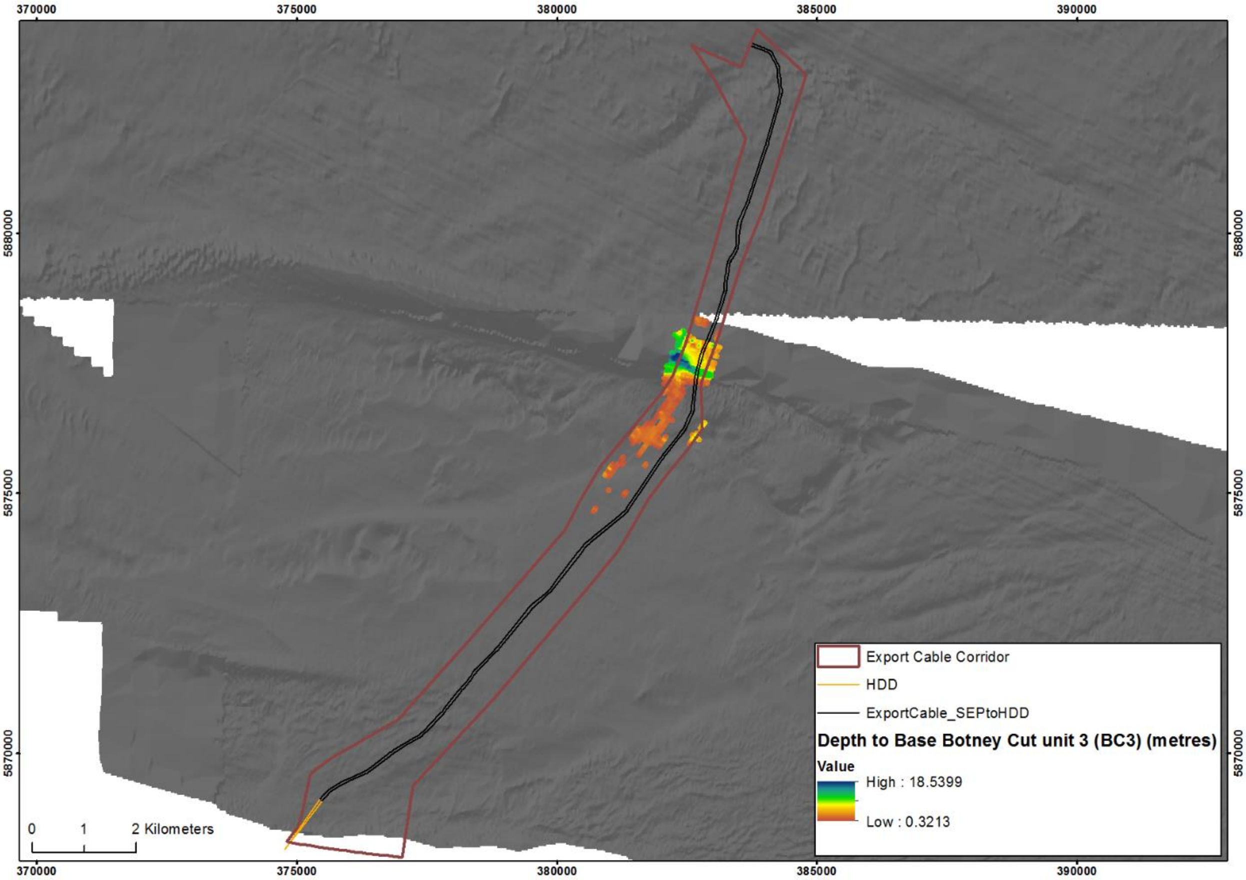

Figure 18. Depth to Base BC3 (metres below seabed). 1700 metres/sec bulk velocity assumed.

3.2.2.3 Base BC Channel

The base of the Botney Cut (BC) (where visible) has been mapped using all pinger and boomer lines. BC channels are observed incised into deeper Quaternary units as well as shallow Chalk. To be clear, there is no current sample evidence identifying BC sediments, but this interpretation is consistent with other regional assessments based on stratigraphic position, morphology, and multiple infill units (e.g. BGS, 2020).

Shallower BC sub-units commonly have sand-dominated sediment similar to Holocene sediment packages, though may have higher proportions of silt, mud, and organics. Deeper sub-units may comprise dense glacifluvial sands, and potentially over-consolidated glacial till.

Within the very deep multi-fill channel in the central part of the cable route (Fig. 19), the deep ‘Base BC Channel’ may in fact be deeper (instead of possible SBK), but we have no sample evidence to cross-reference. Further to this, the limited boomer data quality at those depths precludes the ability to discriminate based on seismic facies. In either case, these depths are outside the area of interest for cable trenching.

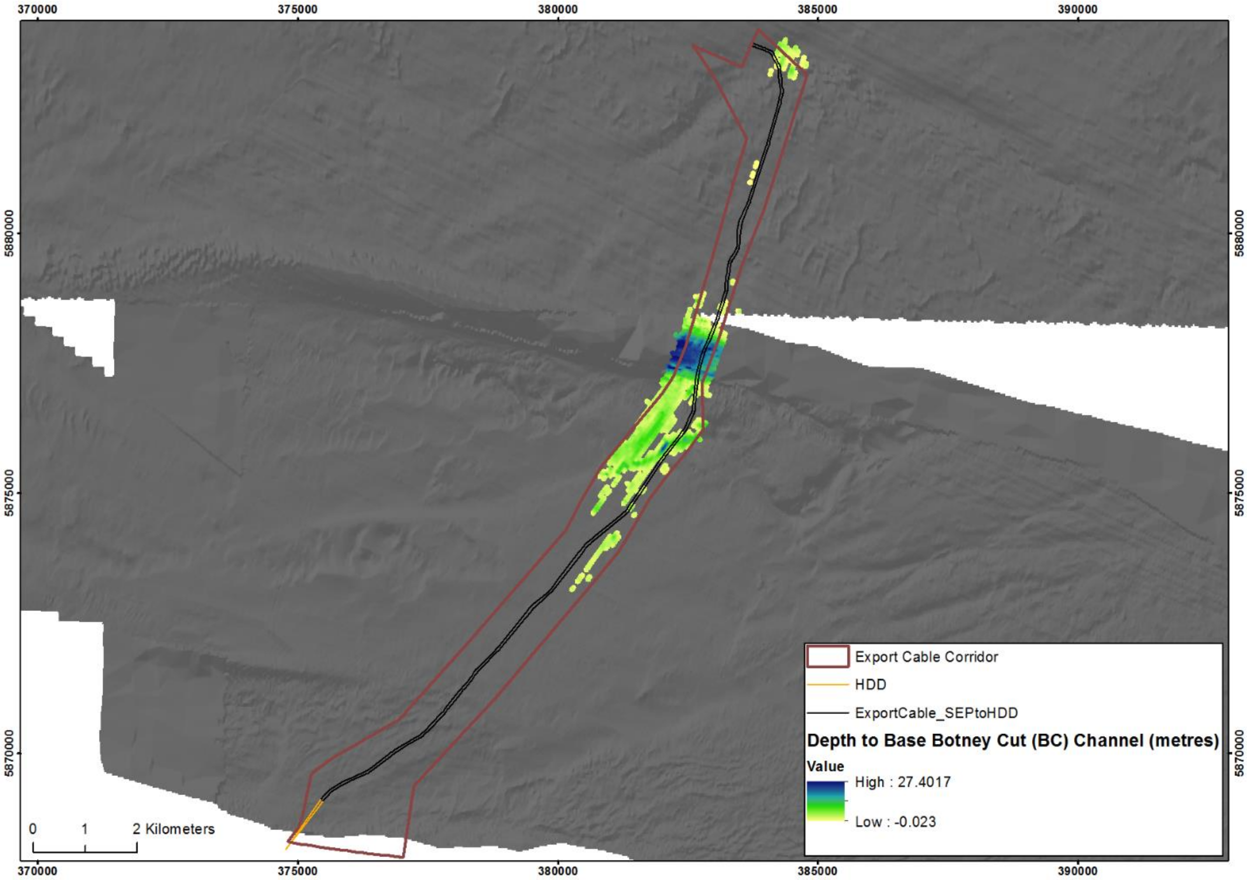

Figure 19. Depth to Base Botney Cut Channel (metres below seabed). 1750 metres/sec bulk velocity assumed.

3.2.2.4 INTERNAL BSBK HORIZON.

North of the sediment bank, a variable relief seismic horizon is observed separating two seismostratigraphic units above the Chalk. From previous mapping (Dove et al., 2017), BGS samples (Fig. 7), and seismic facies, we interpret this horizon to be an internal boundary between two members of the Bolders Bank Formation (BSBK) (Fig. 20). The upper member is relatively acoustically homogenous and ~transparent. The lower member has higher acoustic energy and more observed structure indicative of potential deformed sediment. We tentatively interpret that this lower member may include buried glacial landforms like moraines (Fig.11). In either case, if BSBK, both members are expected to comprise over-consolidated glacial till to coarse ice-marginal deposits.

While the Internal BSBK horizon is not observed south of the sediment bank, where the Top Chalk is at or near seabed, it is possible the BSBK deposits are present in shallow depressions in the Chalk (Fig. 10). Sampling locations have been proposed to test this hypothesis (Fig. 37).

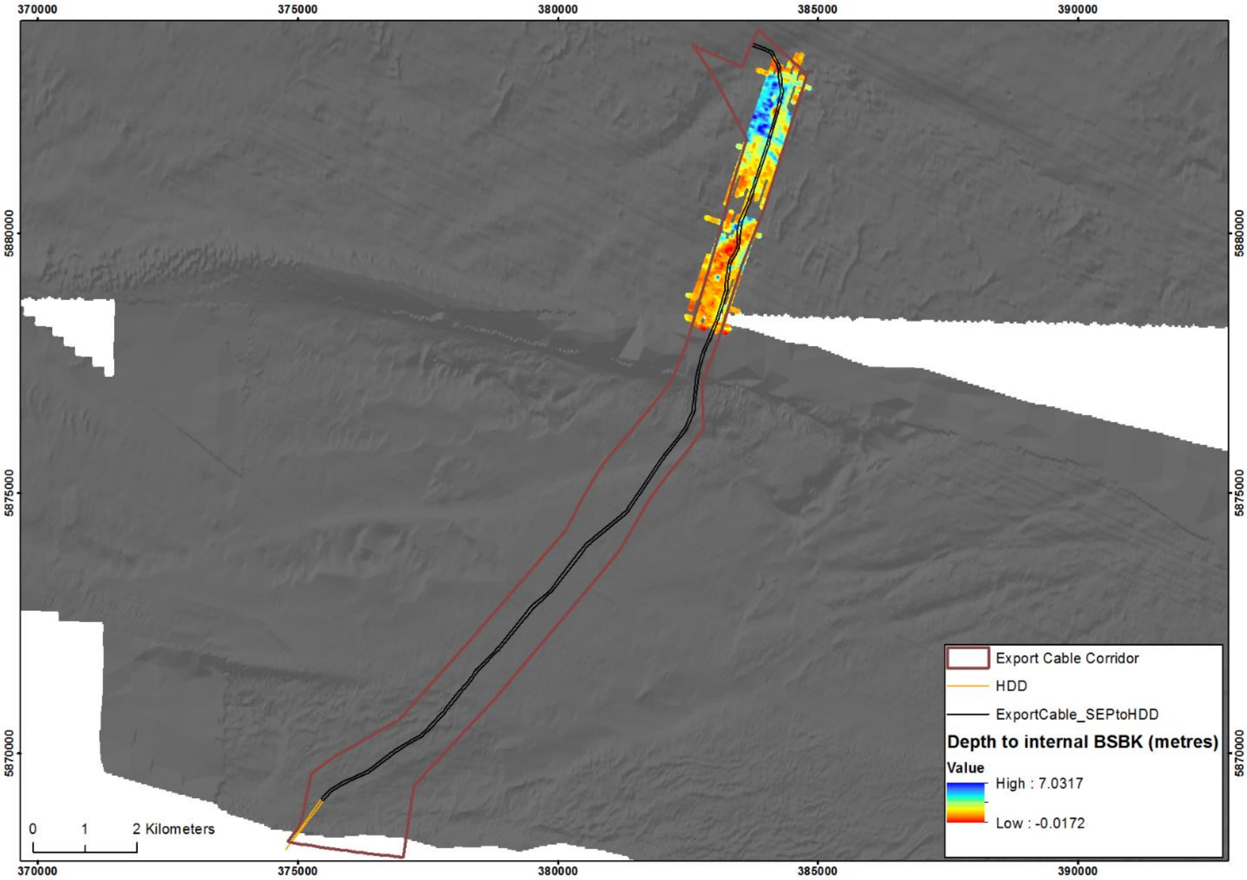

Figure 20. Depth to Internal BSBK horizon (metres below seabed). 1800 metres/sec bulk velocity assumed.

4 Geological Constraints on cable emplacement

4.1 RATIONALE AND OBJECTIVES

The objective of this analysis is to use the interpreted seabed and sub-surface products as predictive metrics (or 'factors') towards characterising potential constraints on cable emplacement. BGS interpreted products from this project are used as input 'factors', as well as previous Gardline products (i.e. Sediment Composition and Seabed Features maps). To be clear, these interpreted products are based on interpretations of the geophysical source data (pinger and boomer seismic, MBES bathymetry), as well as products from the adjacent Dudgeon cable corridor (GEO, 2013) and legacy BGS data (e.g. https://mapapps2.bgs.ac.uk/geoindex_offshore/home.html).

The BGS have substantial experience in undertaking similar assessments for offshore infrastructure. In 2013-2014, the BGS were commissioned by The Crown Estate to employ a similar scoring mechanism, with the end-product being a series of 'traffic light' maps illustrating the suitability of different areas of the entire UK Continental Shelf (UKCS) for various types of offshore infrastructure (e.g. driven monopile vs gravity base structure) (Westhead et al., 2014). The adopted approach involved the creation of a series of GIS 'factor maps', each encompassing a different geological factor that can negatively impact upon the installation and performance of various offshore structures.

For this project, we have implemented a simple approach based on compiling the individual geological factors (listed below), applying a score to each factor based on a scale of 0-3 (less to more constraint), and producing combined constraints map based on the summing of overlapping constraints (i.e. identifying areas of multiple constraints). Within this project we have developed four new geological 'Factors' (below), and we also use two previously provided Gardline products as factors (i.e. Sediment Composition and Seabed Geomorphology).

a. New BGS-developed Factor Maps (not listing Gardline products)
    i. Observed bathymetric change (Sed mobility sub-factor) (metres)
    ii. Depth to Top Peat (metres)
    iii. Depth to Top Chalk (metres)
    iv. Geological subcrop at 2m (coded raster + labelled shapefile) (Geological unit present -unitless)
b. Scored Geological Constraints (scored on 0-3 scale) (based on above baseline factors)
    i. Sediment Composition (Gardline)
    ii. Sediment mobility
        1. Observed bathymetry change (0.3m+)
        2. Sediment Composition (Gardline)
        3. Seabed Geomorphology (Gardline)
    iii. Shallow Peat
    iv. Shallow Chalk
    v. Geological subcrop at 2m
c. Combined constraints map (GIS raster) (Phase 2)

4.2 GEOLOGICAL FACTORS AND SCORED GEOLOGICAL CONSTRAINTS

This section is ordered according to item (b) in the above list (i.e. Scored Geological Constraints). Firstly, the factors used to develop the Scored Geological Constraint maps are described within each section, follow by the presentation of the Factor and Scored Constraint maps together for comparison.

In each case, the Scored Geological Constraints are scored according to a scale of (0-3), where scores are assigned subjectively according our knowledge of the relative risk imposed by each factor. A justification for this scoring is given within each respective section.

Scoring scale

- 0 (black) – no risk
- 1 (green) – low risk
- 2 (amber – moderate risk
- 3 (red) – significant risk

This traffic-light scoring approach is intended to provide a simple and clear way to communicate potential constraints spatially, according to the interpreted character of the seabed and shallow sub-surface. Because however this is a subjective scoring approach, which is based on interpretations of data with further inherent limitations and uncertainties, the constraint scores should not be treated as absolute and definitive (i.e. an assigned value of '0' does not mean that it's impossible for a risk/constraint to be present, but that based on the available data, no risk/constraint is identified at the spatial scale of the data).

Preparation and scoring of the geological factors has been undertaken in a GIS environment, where mathematical operations were made using raster datasets of each factor. Typically we have cropped the factor and/or contains maps to the Sheringham Shoal nearshore cable route polygon, but for the avoidance of doubt, our findings relate only to areas within the planned cable route. Further to this, there was no seismic data acquisition covering the far northern terminus of the cable route (e.g. Fig. 13), hence all factor and constraints mapping within this 'no data' region should be considered invalid.

4.2.1 Sediment Composition (Gardline) (Scored Geological Constraint)

Seabed and shallow subsurface (0-1 mbsb) sediment composition is a key factor in planning cable trenching works. Whilst recent (Quaternary) sediment cover is of benefit to cable burial works, as it provides a substrate in which the cable can be buried and protected, the sediment grainsize presents some considerations. Dense accumulations of coarse-grained sediments, ranging from gravel (6.3-63 mm) and cobble (63-200 mm) lags through to larger boulders (>200 mm), can create negative impacts such as plough deviation and unexpectedly high tow force requirements (grain sizes based on BS5930:2015 (BSI, 2015)). As a result, coarser lag deposits have been scored the highest out of the seabed sediments mapped across the corridor.

Sediment composition was mapped previously (Gardline, 2019), and has not been modified by BGS. The Gardline sediment map (Fig. 5, 21) is here employed as a 'Factor' map and has been assigned constraint scores as follows:

Constraint Scoring

- Sand (0)
- Gravelly Sand, and Sandy Gravel (1)
- Gravel (2)
- Subcropping Clay (1)
- Subcropping Chalk (3)

It should be noted that, although accumulations of fine-grained sediments do not typically pose a constraint on cable trenching works, their presence should be identified at an early stage of project planning, as trenching works may facilitate the creation of locally significant suspended particulate matter (SPM) plumes. These plumes may have environmental implications, such as reduced water quality and blanketing of surrounding benthic ecosystems/habitats. However, for the purpose of this project, which focuses on geological constraints to cable trenching works, fine-grained sediments have been given the 'low' risk score of 1 where present (Fig. 22).

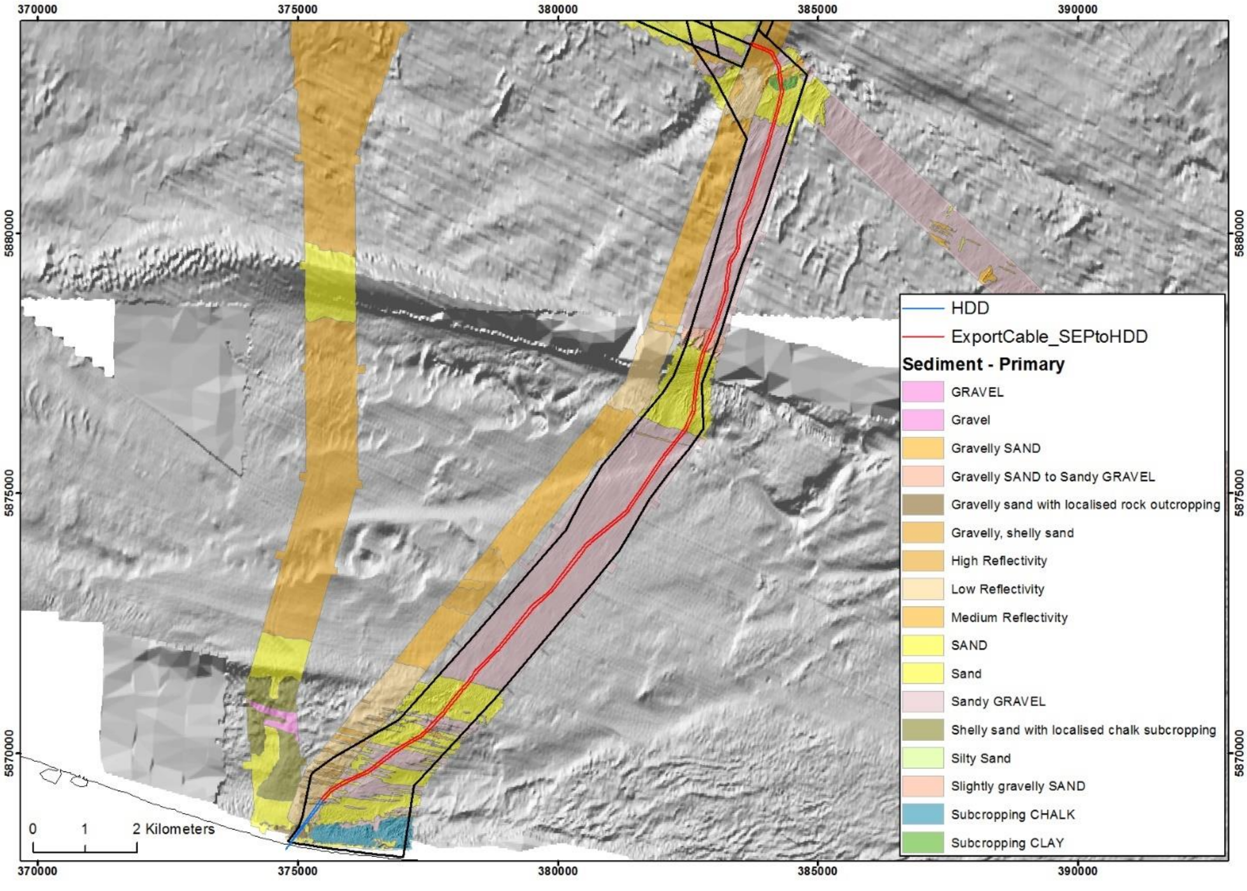

Figure 21. Gardline (2019) sediment composition map. Used as Geological Factor.

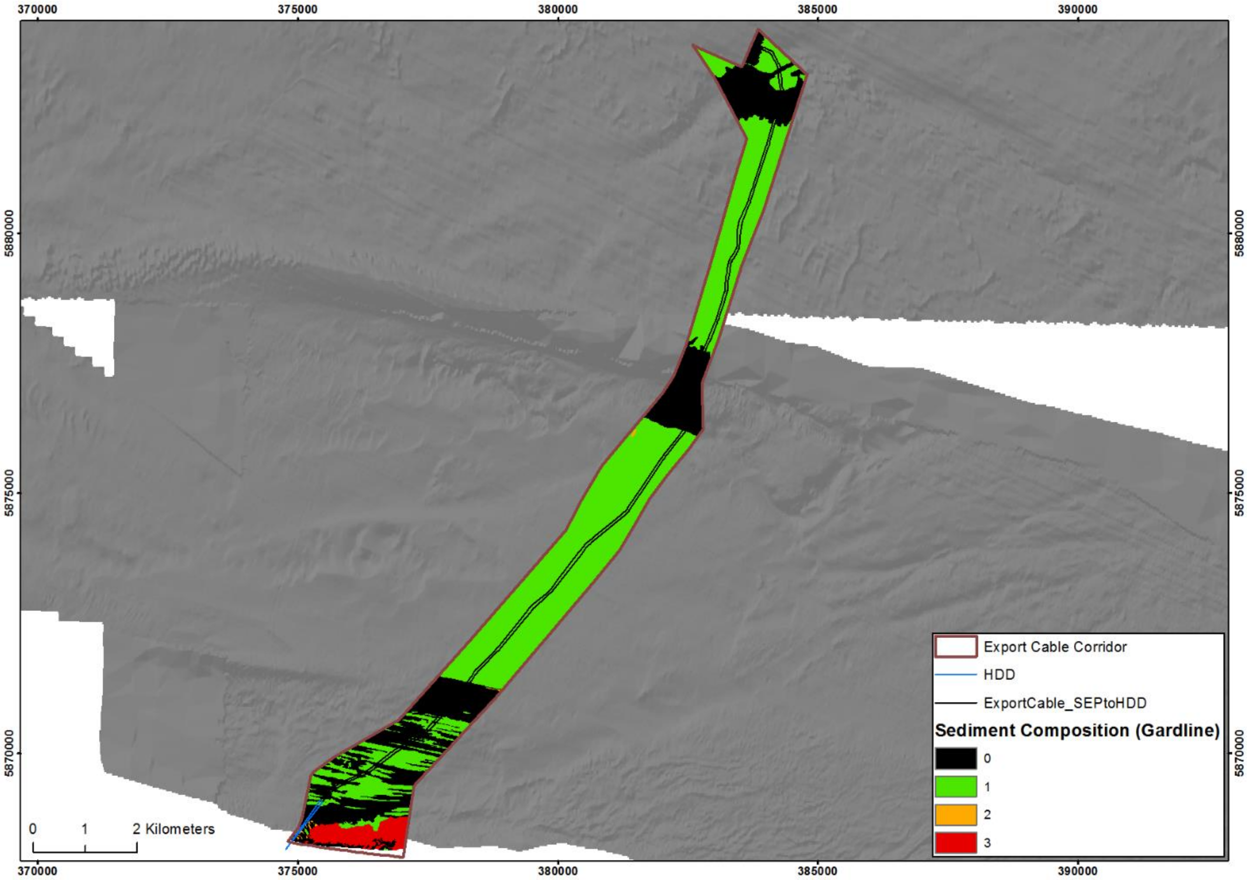

Figure 22. Scored Geological Constraint of Sediment Composition, based on Gardline's seabed sediment mapping (Fig. 21).

4.2.2 Sediment Mobility (Scored Geological Constraint)

The susceptibility of seabed and shallow sub-surface sediment to current-induced mobility (e.g. bedform migration) is a key consideration for cable emplacement. This Scored Geological Constraint is itself based on three separate sub-factors: 1) Observed Bathymetric Change, 2) Sediment Composition, and 3) Seabed Geomorphology.

These three sub-factors are described below, and each given their own constraint score. The assigning of each sub-factors took into consideration it's significance relative to the other subfactors. To calculate the final 'Sediment Mobility' constraint score (Fig. 29), we merged all sub-factors together, adopting the highest constraint score in all locations.

4.2.2.1 Observed Bathymetric Change

This factor represents observed bathymetric change along the cable route (>0.3m). To develop this factor map we have used two other high-resolution MBES bathymetry datasets that overlap the cable-route bathymetry. This gives the opportunity to undertake time-series analysis, assessing potential bathymetric (vertical) change between the three different surveys. Both the MCZ and CHP data are publicly available Fig (23).

Survey dates:

- o Cromer Shoal MCZ (Survey: 2012-2014) - [redacted]
- o Cable route MBES (Survey Sep-Dec 2019)
- o CHP (HI1673) (Survey Mar-Aug, 2020) - [redacted]

A GIS-based approach was taken to calculate bathymetric change between the three surveys

- Data were sub-sampled to 2m horizontal resolution and smoothed (to reduce erroneous change predictions from noise in data);
- The difference between the three datasets was calculated, taking the highest change in any one location;
- Absolute value calculated (to avoid minor vertical datum offsets between datasets)
- Show all change greater than 0.3m (to avoid spurious results from noise in data).

Firstly, it's important to note that one area in the southern part of the cable route has no overlap with either the MCZ or CHP data, so no observations of bathymetric change can be made here (Fig. 23). In a general sense, areas of bathymetric change are consistent with the bedform mapping by Gardline (Fig. 6), though further detail is provided. In the far south, it is clear there is bedform migration over the Chalk platform that was not previously mapped. Also, going north, along the shallow chalk province (with 'Sandy Gravel' in sediment map (Fig. 5)), there are indications of minor bathymetric change. The highest amplitude change is consistent with the prominent sand waves both on the Sheringham Shoal bank, and the sediment waves in the far north of the cable route.

The value of this factor is not to forecast precise morphological change (i.e. variable time lag between surveys), but rather to highlight areas susceptible to sediment mobility based on empirical observations of past change.

Constraint Scores

- Bathymetric change < 0.3m, or null (0)
- Bathymetric change > 0.3m (3)

We have assigned the high constraint score of '3' to all areas of bathymetric change (>0.3m) because this factor reflects observed sediment mobility (as opposed to potential for mobility, e.g. 'sand' at seabed).

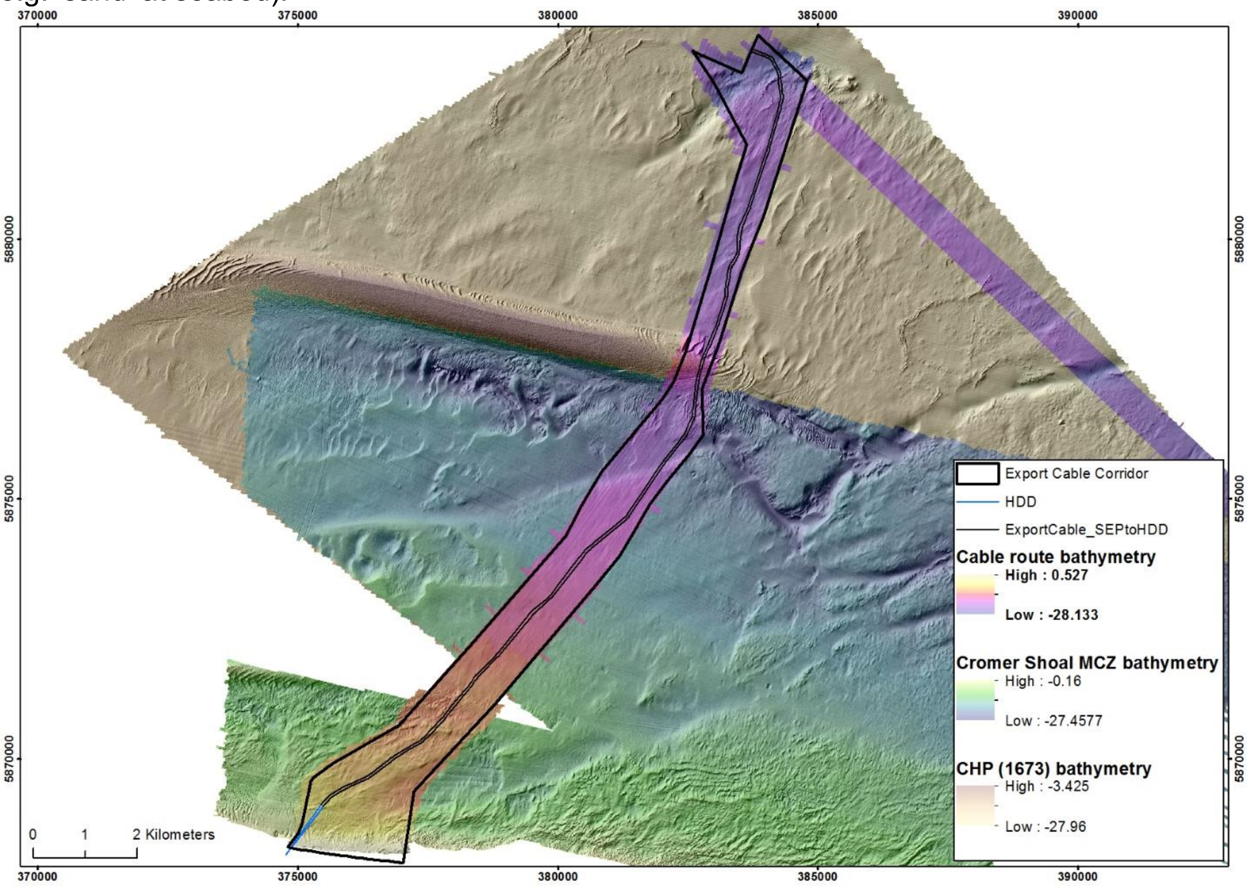

Figure 23. Three MBES bathymetry datasets used to calculate Observed Bathymetric Change.

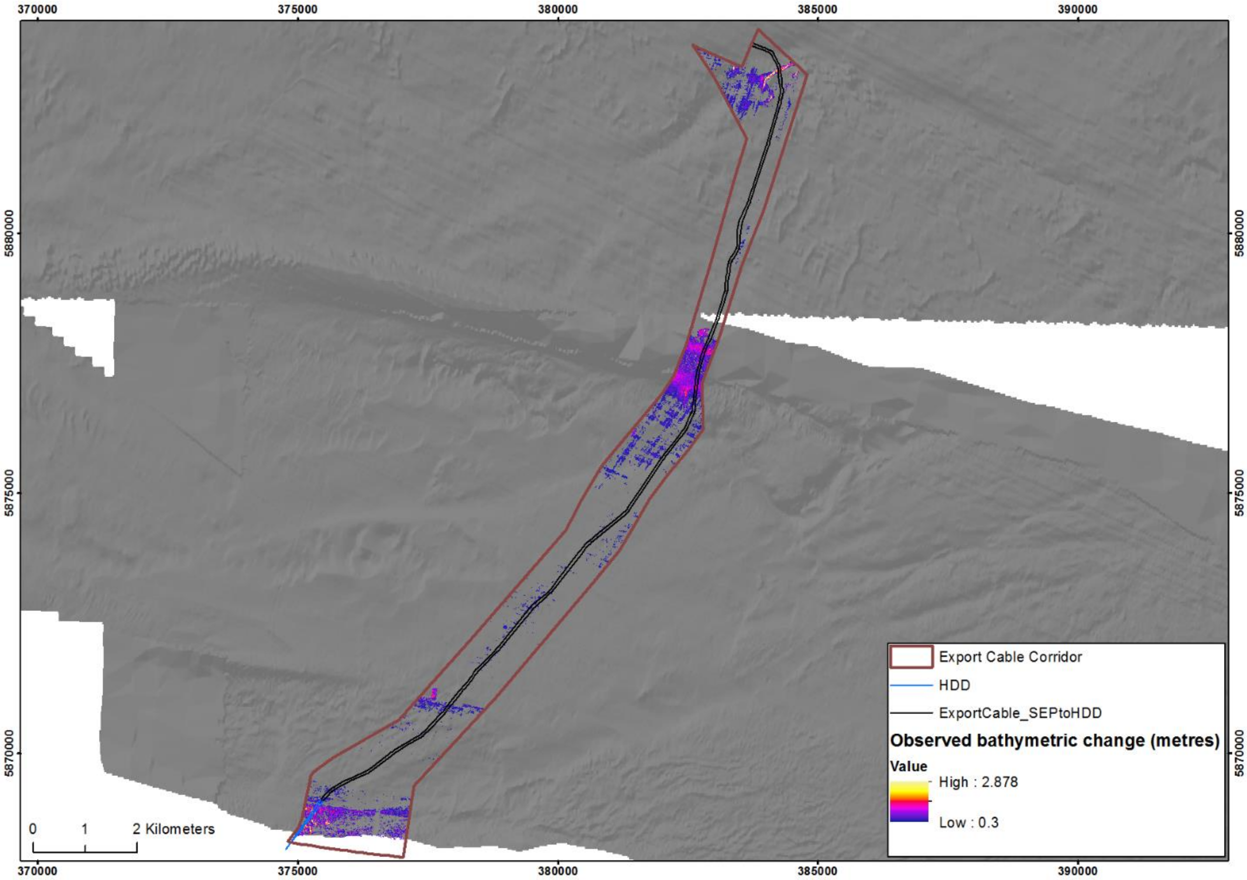

Figure 24. Observed bathymetric change (0.3m). Geological sub-factor developed by BGS based on multiple overlapping surveys (Fig. 23).

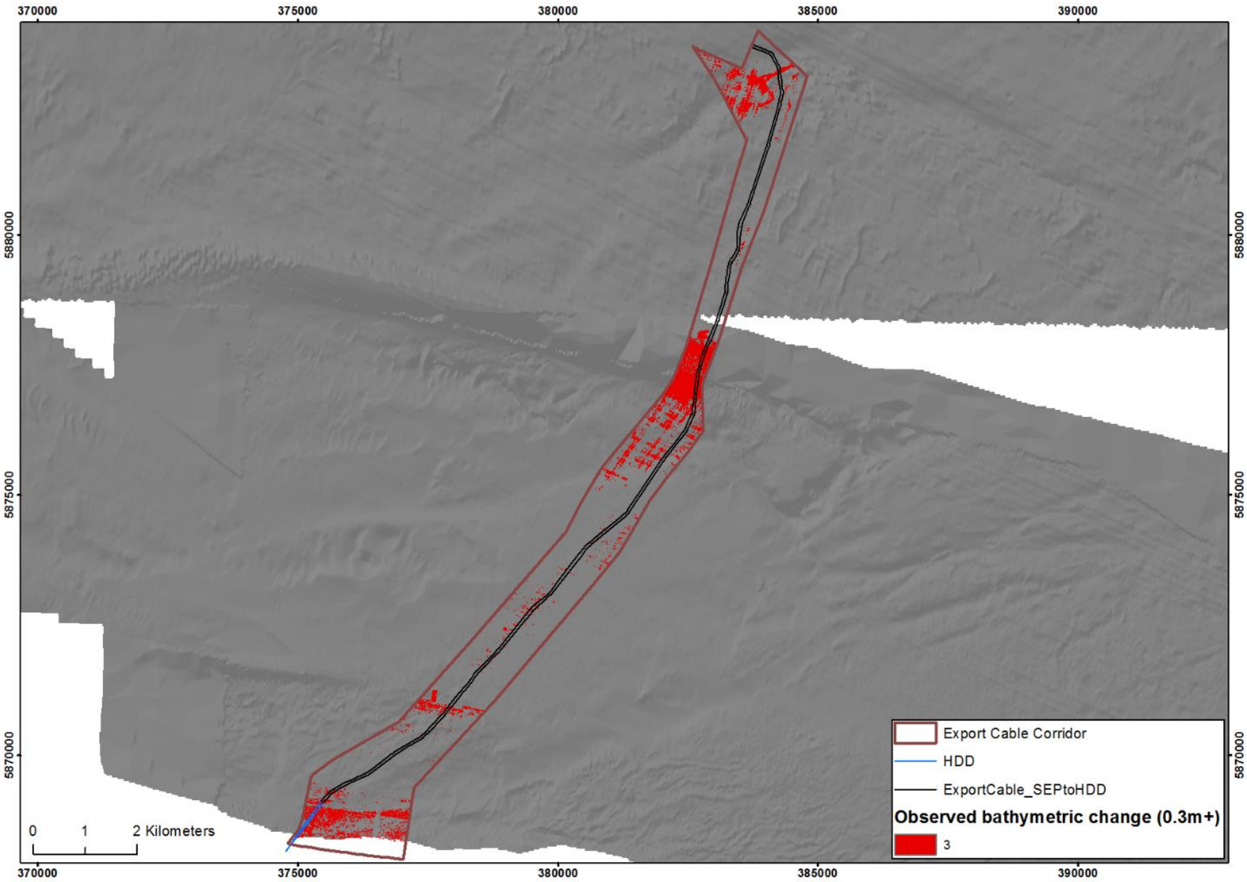

Figure 25. Scored Geological Constraint of sub-factor Observed Bathymetric Change.

4.2.2.2 Sediment Composition (Gardline)

Separate to its use as an independent Scored Geological Factor (Fig. 22), we also use Gardline's mapping of Sediment Composition as a sub-factor for Sediment Mobility (Fig. 26). Sediment classes are scored differently in this case, to reflect the susceptibility of each sediment class to being mobilized, leading to morphological change of the seabed.

Constraint Scores

- Sand (2)
- Gravelly Sand (2)
- Sandy Gravel, and Gravel (1)
- Subcropping Clay (1)
- Subcropping Chalk (0)

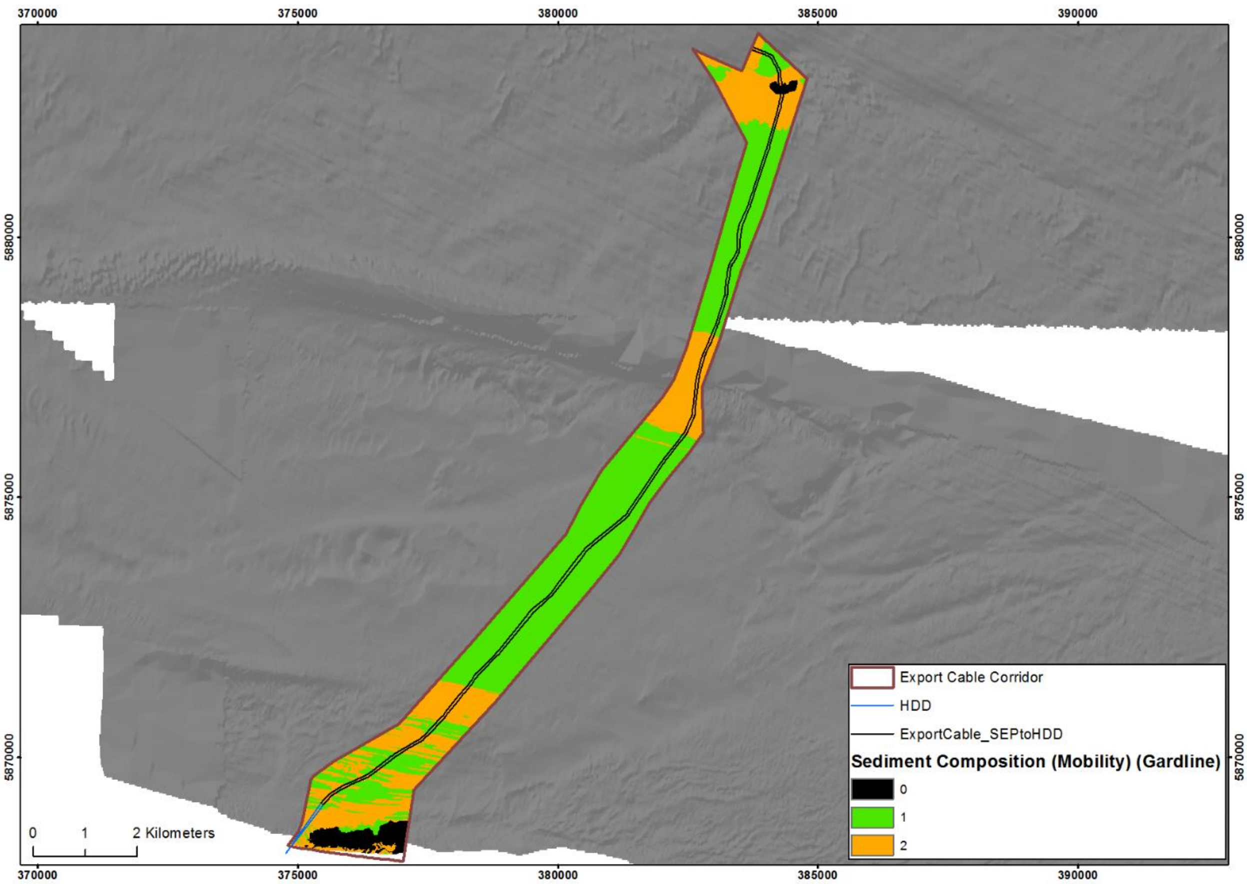

Figure 26. Scored Geological Constraint of sub-factor Sediment Composition (with respect to Sediment Mobility). Sediment Composition sub-factor presented in Fig. 21.

4.2.2.3 Seabed Geomorphology ('Seabed Features' - Gardline)

Similar to Sediment Composition, we have also made use of Gardline's 'Seabed Features' product as a Seabed Geomorphology sub-factor (Fig. 27). Current-induced bedforms are indicative sediment mobility, though the degree of this activity can not be determined through morphology alone. Despite this, visual inspection of the seabed geomorphology along the cable route reveals a suite of high-relief bedforms (i.e. not smoothed out and moribund), that reflect active mobility. Scoring reflects both the likelihood and probable degree of mobility (Fig. 28).

Constraint Scoring:

- Mounds (1)
- Ripples and Large Ripples (2)
- Megaripples (2)
- Dunes, and Sand Waves (3)

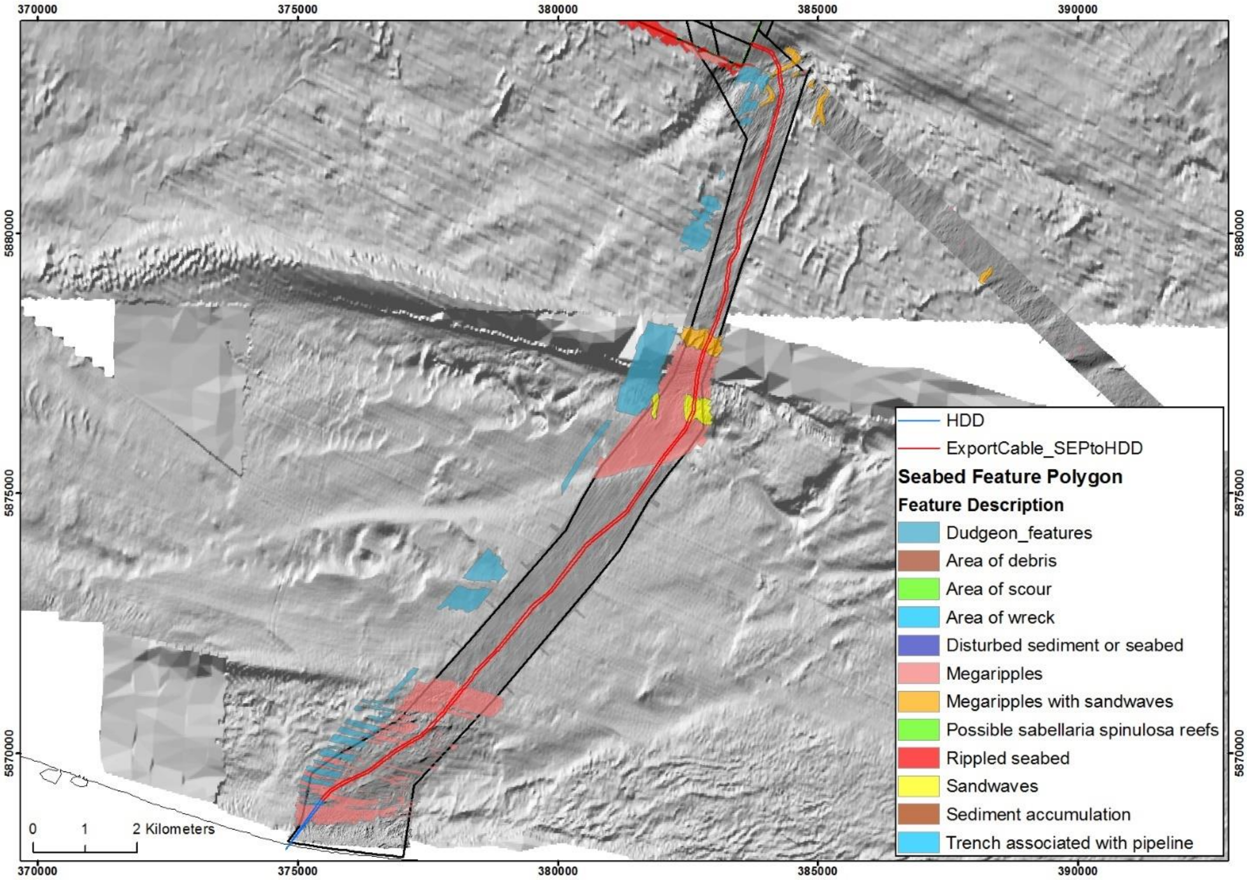

Figure 27. Seabed Geomorphology sub-factor provided by Gardline's 'Seabed Feature' mapping.

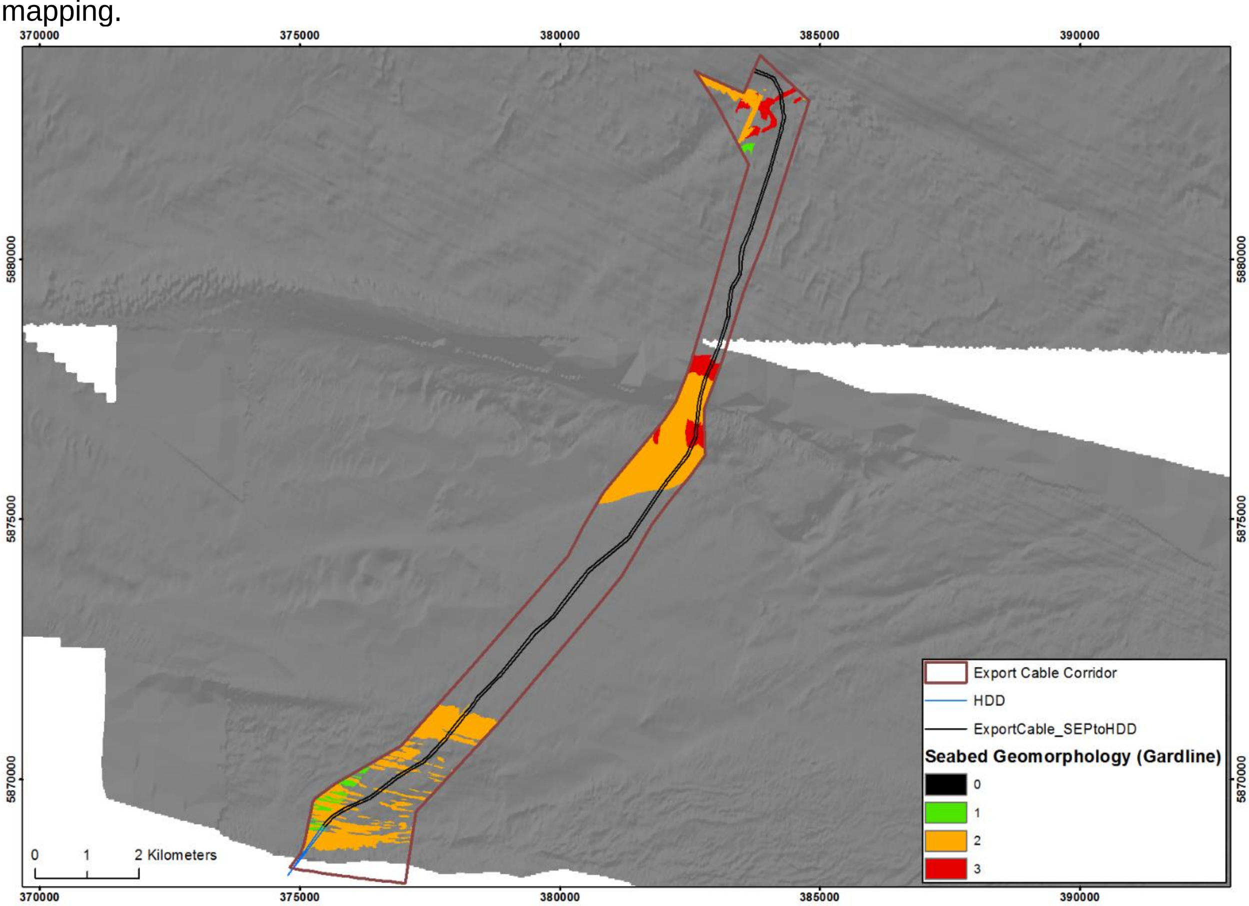

Figure 28. Scored Geological Constraint of sub-factor Seabed Geomorphology (with respect to Sediment Mobility). Seabed Geomorphology sub-factor presented in Fig. 27.

4.2.2.4 Final 'Sediment Mobility' Geological Constraint Map

To calculate the final 'Sediment Mobility' constraint score (Fig. 29), we merged all sub-factors together, adopting the highest constraint score in all locations.

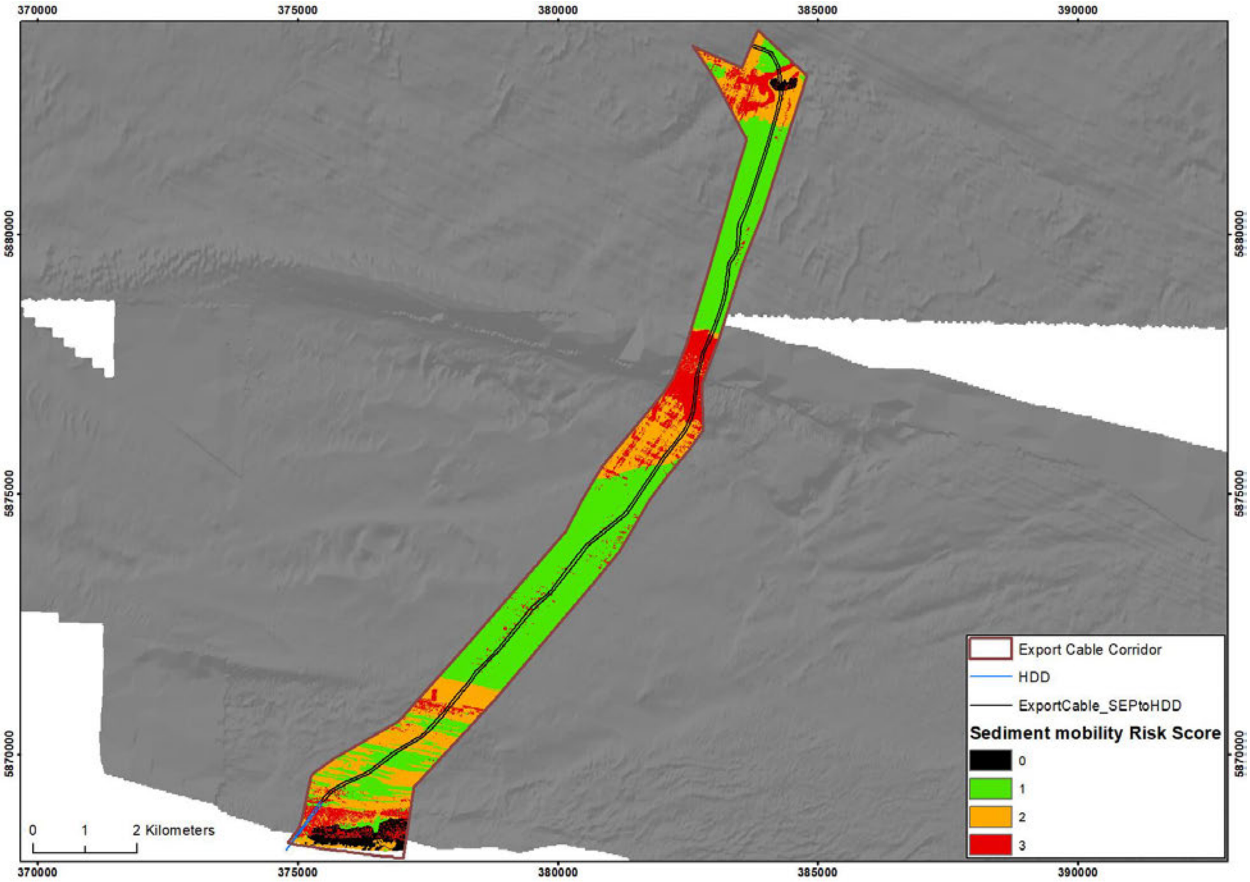

Figure 29. Scored Geological Constraint of Sediment Mobility. Final scoring based on scoring of 3 sub-factors: Observed Bathymetric Change (Fig. 25), Sediment Composition (Fig. 26), and Seabed Geomorphology (Fig. 28)

4.2.3 Shallow Chalk (Scored Geological Constraint)

This Shallow Chalk constraint uses the factor Depth to Top Chalk (Fig. 30). This is modified slightly from the Top Chalk isopach map presented in Fig. (13), in that all areas of the planned cable-route have been assigned a value for depth to Top Chalk (m). Fig. (13) presents where Top Chalk was mapped from the geophysical lines, but as noted earlier in the report, the Top Chalk surface could not be observed or mapped where the seabed reflector obscured the data within the top 1-2 metres below seabed. For the purposes of constraints mapping, we have applied an estimated value of 1m depth for all locations where the Top Chalk was too shallow to map.

For preparing the factor map presented in Fig. 30, this involved infilling all non-mapped areas with a nominal value of 1m. Note that the far north of the area (where no geophysical data was collected) is erroneously assigned a value of 1m, where we know this to be incorrect. However as there are no geophysical data available at present to correct these values, this area must be considered unconstrained at present.

Bedrock at or near (<2 mbsb) seabed can cause significant constraints on subsea cable trenching works, with some lithologies (for instance, Lewisian Gneiss) prohibiting trenching work altogether. In the present study, bedrock has been identified as being Cretaceous Chalk which, depending upon the rock mass classification and degree of weathering experienced by the upper surface, may be suitable for trenching. However, it still constitutes the most significant potential geological constraint across the proposed cable corridor, due to the lack of information pertaining to the physical nature of the chalk along this route. Should the chalk contain a high flint concentration, this can have a negative influence upon subsea trencher performance, for instance reduced chain life and increased wear patterns (Pyrah et al., 2018), all of which negatively impact the overall project programme and cost.

Constraint Scoring

Shallow Chalk has been scored according to three depth ranges for Depth to Top Chalk:

- <2 metres (3)
- 2-5 metres (1)
- >5 metres (0)

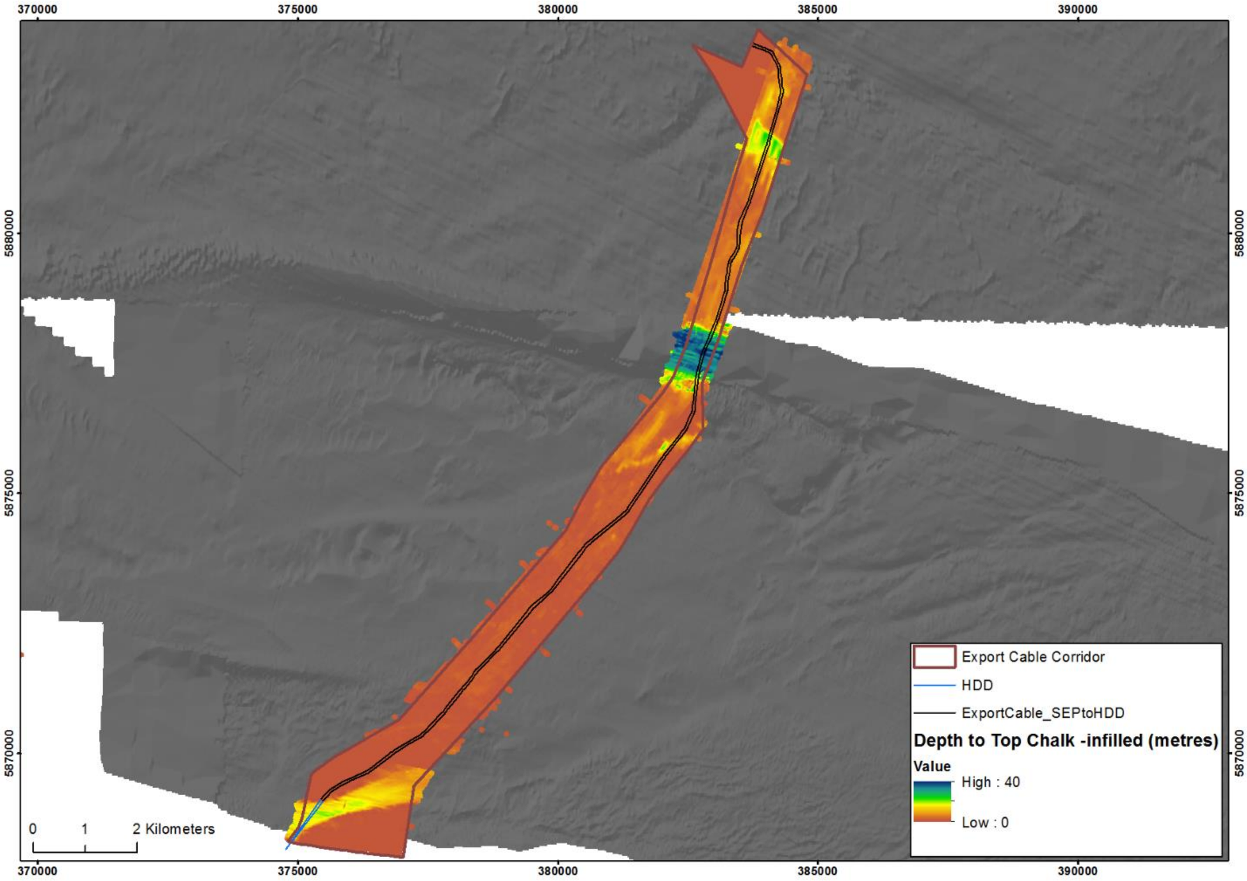

Figure 30. Depth to Top Chalk isopach map used as Geologial Factor for Shallow Chalk constraint scoring.

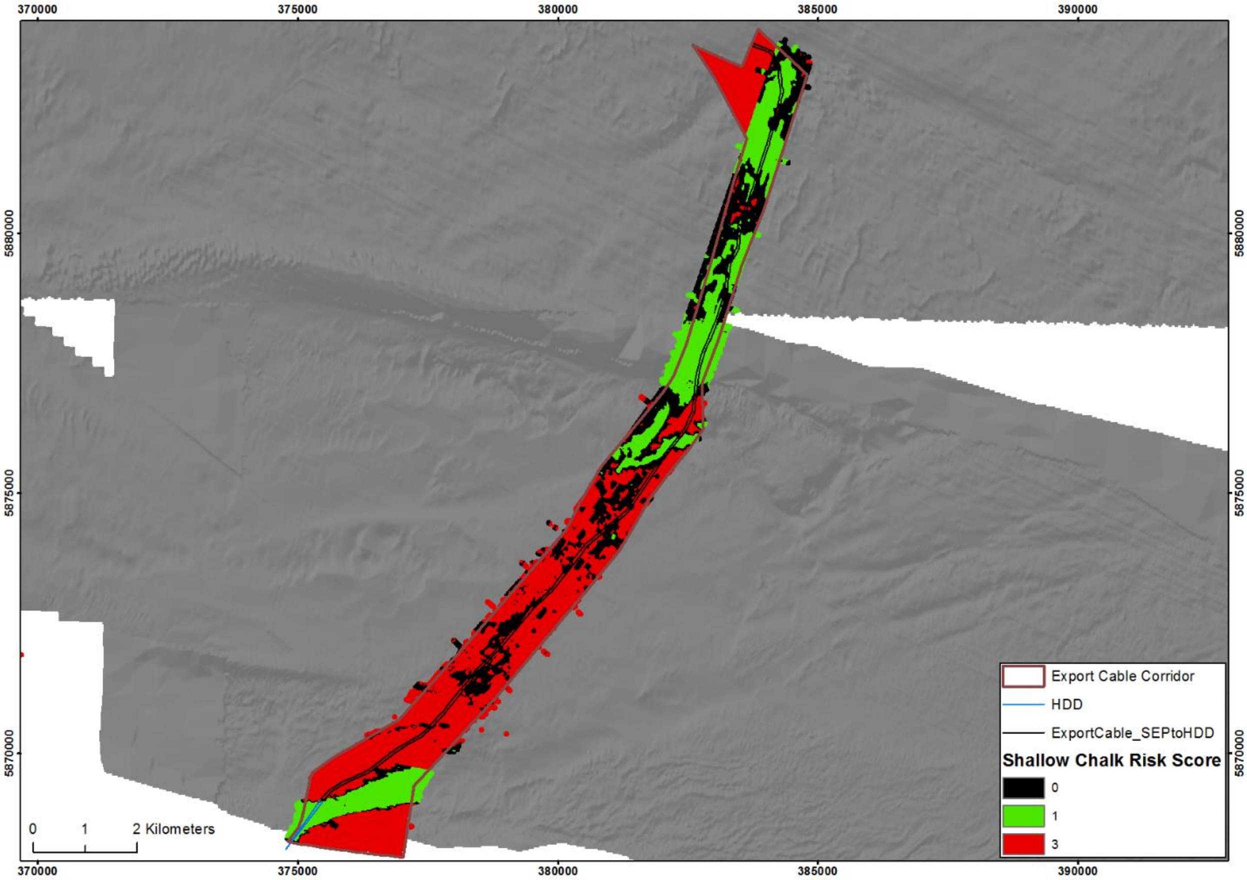

Figure 31. Scored Geological Constraint for Shallow Chalk. Scoring based on depth to top Chalk (0-2m = 3; 2-5m =1; >5m = 0).

4.2.4 Shallow Peat (Scored Geological Constraint)

Similar to Shallow Chalk, the scored Shallow Peat constraint (Fig. 33) is derived from the isopach map of Depth to Top Peat, however in this case the isopach map is used directly (unmodified) as input (Figs. 16, 32) to the constraints scoring.

Competent fibrous soils, such as peat, may have the potential to effectively reinforce the surrounding sand (Jewell & Wroth, 1987), and as a result the DNV (2016) suggest that fibrous soils can present significant challenges for all burial techniques. Laboratory model experiments have shown that this reinforcement of soil through inclusions of fibrous peat in sand can result in reduced plough progress by increasing tow force and causing potential 'ride-out' of the plough, which in turn results in significant loss of trenching depth (Brown *et al*., 2015). Therefore, potential peat deposits have been mapped and scored appropriately across the entire extent of the proposed export cable corridor.

In addition, fibrous soils such as peat generally have a lower sediment thermal conductivity when compared with quartz sands for instance (1 W/mK compared with 3 W/mK) (Callender et al., 2020). Furthermore, finite element method (FEM) simulations suggest that soils with high permeability can facilitate heat transfer from the HV cable to the surrounding environment, whereas low/lower permeable soils, such as peat, may actually lead to an increase in cable temperatures (Hughes, 2016). As a result, the DNV (2016) suggest that additional investigation of the seabed material may be required to evaluate how high organic material content (e.g. peat) can impact upon heat transfer. For these reasons, mapped potential shallow peat deposits with <2 m below seafloor have been given a constraint score of 3, signifying zones of relative high risk.

Constraint Scoring

Shallow Peat is scored similarly to Shallow Chalk, and has been scored according to three depth ranges for Depth to Top Peat:

- <2 metres (3)
- 2-5 metres (1)
- >5 metres (0)

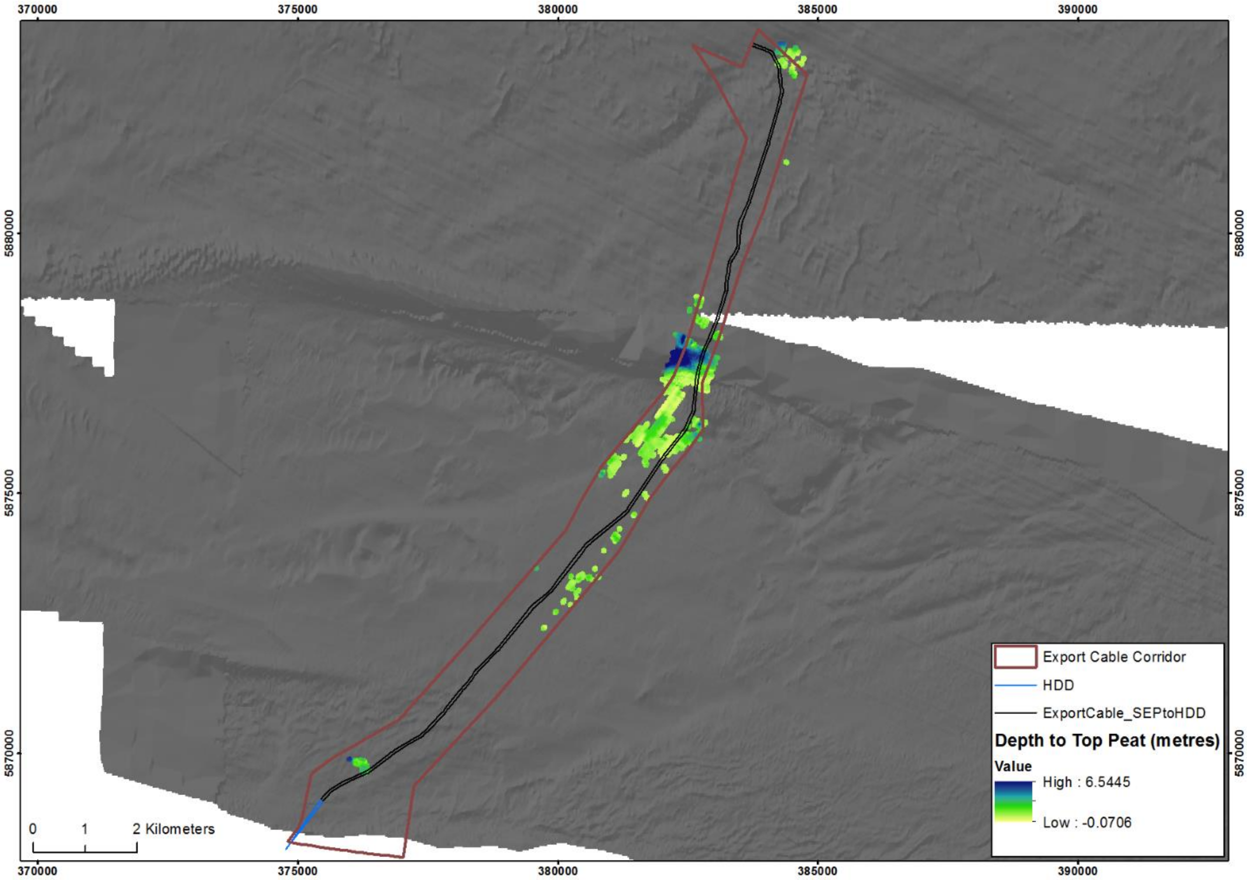

Figure 32. Depth to Top Peat isopach map used as Geological Factor for Shallow Peat constraint scoring.

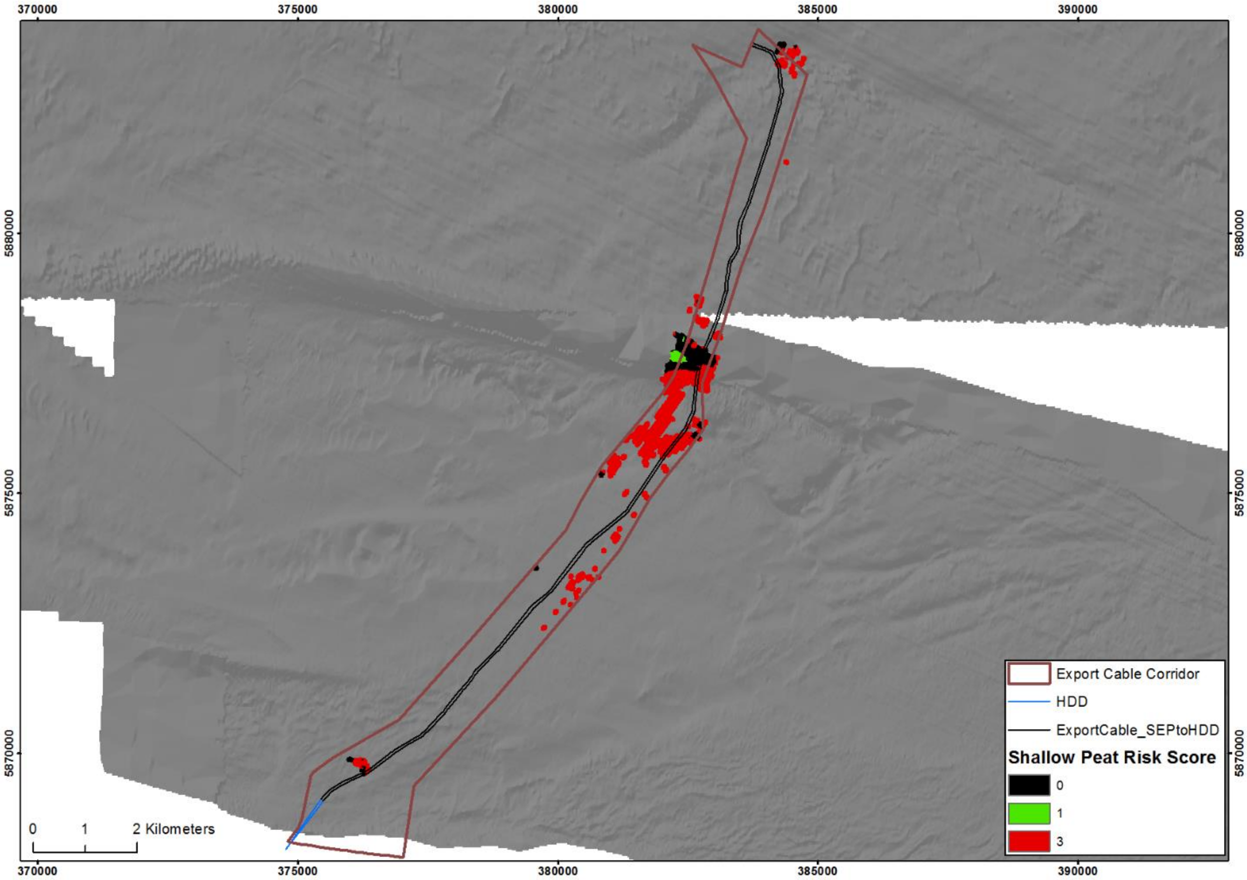

Figure 33. Scored Geological Constraint for Shallow Peat. Scoring based on depth to Top Peat (0-2m = 3; 2-5m =1; >5m = 0).

4.2.5 Geological Subcrop at 2m (Scored Geological Constraint)

This final constraint is based on what geological unit is predicted to be present at approximately 2m below seabed, and makes use of all horizons interpreted from the seismic data (Base Marine Sediments (unconsolidated), Base BC3 Channel, Base BC Channel, Internal BSBK horizon (tentative), and Top Chalk). Rather than reflect unit boundaries, this subcrop map (Fig. 34) is effectively a final geological map of the cable route area (at a depth of 2m).

To produce the map, we ran a series of routines in a GIS environment, based on the Kingdom-derived isopach map for each horizon, to identify which geological unit is present at 2m below seabed.

4.2.5.1 Geological Factor preparation

The below units make up the final geological subcrop factor map (Fig. 34):

Marine sediments (unconsolidated)
The distribution of Marine Sediments is determined by where ‘Base Marine Sediment’ was mapped on the seismic data, plus where Chalk is <2m below seabed and where no other Quaternary units are mapped (primarily in southern part of cable corridor).

BC3 Channel (potential Peat bearing)
The distribution of the BC3 Channel sediment is determined by where ‘Base BC3 Channel was mapped on the seismic data.

Base BC Channel
The distribution of the BC Channel unit (excluding BC3 channel) is determined by where ‘Base BC Channel’ was mapped on the seismic data.

Upper BSBK
The distribution of the Upper BSBK unit is determined where the Internal BSBK horizon (tentative) was mapped on the seismic data.

Lower BSBK
The distribution of the Upper BSBK unit is determined where the Internal BSBK horizon (tentative) is absent in the area north of the large sediment bank, i.e. where the Upper BSBK is absent, the Lower BSBK is present at/near seabed.

Chalk
The Shallow Chalk Geological Factor is used for the distribution of the Chalk unit. In this case Chalk is predicted at seabed in all locations where Chalk is mapped at less than 2m.

Constraint Scoring

- Marine sediments (unconsolidated) (0)
- BC3 Channel (potential Peat bearing)(2)
- Base BC Channel (1)
- Upper BSBK (2)
- Lower BSBK (2)
- Chalk (3)

Holocene-modern unconsolidated marine sediments (clay – coarse sand particle size) generally do not pose a constraint on ploughing performance. Coarse clasts (gravel to boulder size) have the potential to cause issues with increased tow force where in dense accumulations, and may cause plough deviation when large (boulder) clasts are encountered. However, as part of this study, pinger and boomer profiles were examined for any evidence of coarse (gravel-cobble) lag deposits (i.e. multiple hyperbolae along a specific, consistent horizon) and boulders at or near seabed (i.e. diffractions). It was concluded that no evidence for such deposits and clasts could be positively identified using the available datasets. Therefore, Holocene unconsolidated sediments have been assigned a low 'risk' score in this assessment (Fig. 35).

Risks and challenges posed by fibrous soils, such as **Peat**, are detailed previously. For the stated reasons, potential peat deposits have been assigned a moderate relative 'risk' score for this assessment.

Buried glaciofluvial and fluvial channels pose challenges to offshore infrastructure developments as they provide an abrupt change in ground conditions, with channel fill material often varying greatly from the surrounding substrate. However, in the case of the **Botney Cut (BC) channels**, infill is unlikely to consist of soils that will cause any significant issues to burial techniques, as infill typically consists of interbedded fine (clay – silt grade) and coarse (sand grade) sediments. Due to the depositional history of these soils (i.e. pro-glacial to post-glacial deposition), it is unlikely that shallower members of the BC formation would have experienced ice loading at any point in their history, and therefore normal consolidation can be expected. Therefore, Botney Cut channels have been given a 'low' risk score.

The Bolders Bank (BSBK) Formation represents a stiff diamicton that is rich in gravel to boulder grade clasts, primarily dominated by chalk clasts. These soils were deposited during the Devensian glaciation, and experienced ice loading leading to over-consolidation. If unanticipated, these soils have the potential to prove problematic to plough performance, partly due to the high shear strengths and due to the high risk of encountering large clasts such as cobbles and boulders. As a result, areas where the Upper BSBK and Lower BSBK were mapped have been given a moderate 'risk' score.

As previously detailed, **Chalk** at seabed can cause issues with trench cutting equipment in particular, especially if the surface Chalk has not undergone a great degree of weathering and also if the uppermost chalk unit is rich in chalk nodules and flints. Unfortunately, there is not enough data available on the condition and properties of the upper chalk across the proposed corridor route, and therefore Top Chalk has been assigned the highest level of ‘risk’ score, in an attempt to be conservative in the absence of adequate data.

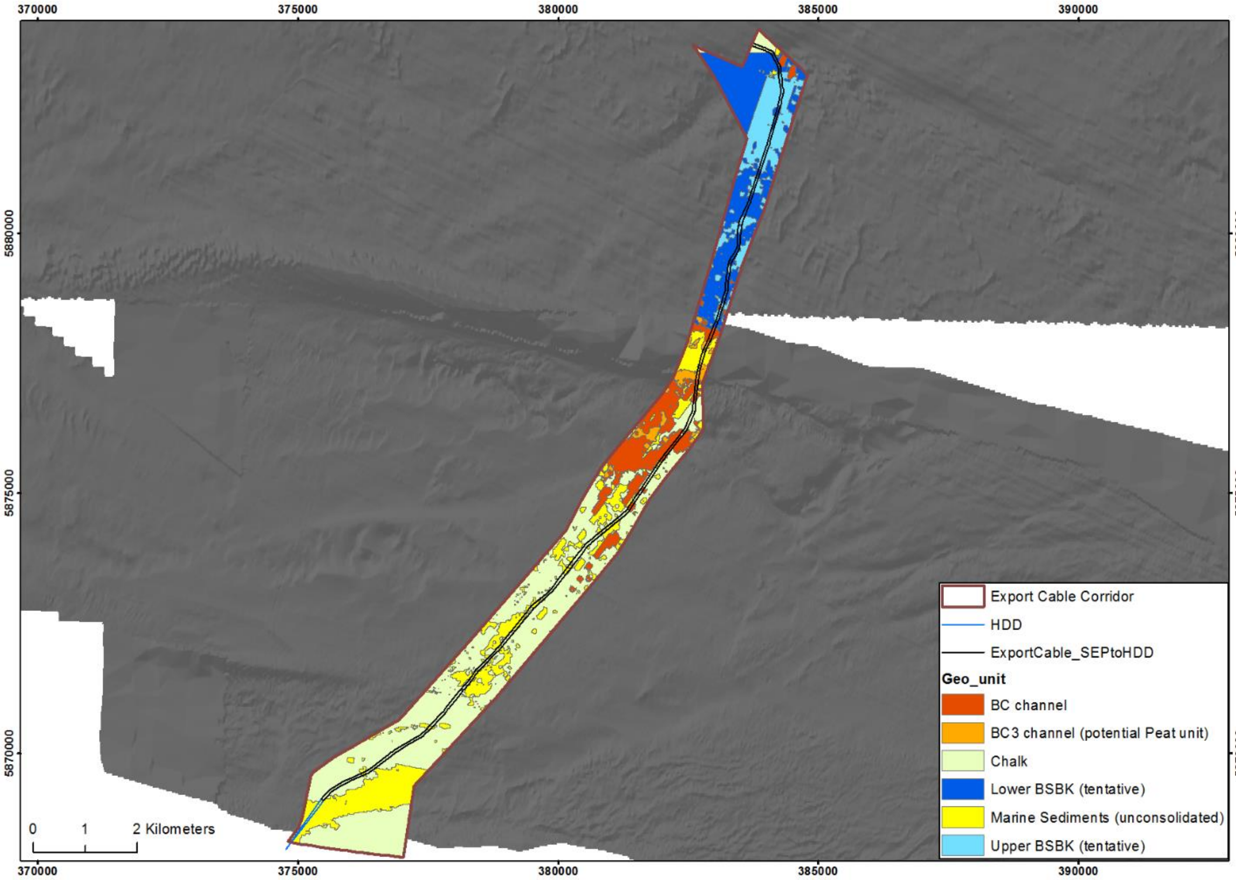

Figure 34. Geological Subcrop at 2m (Geological Factor), shows geological unit predicted at 2m below seabed.

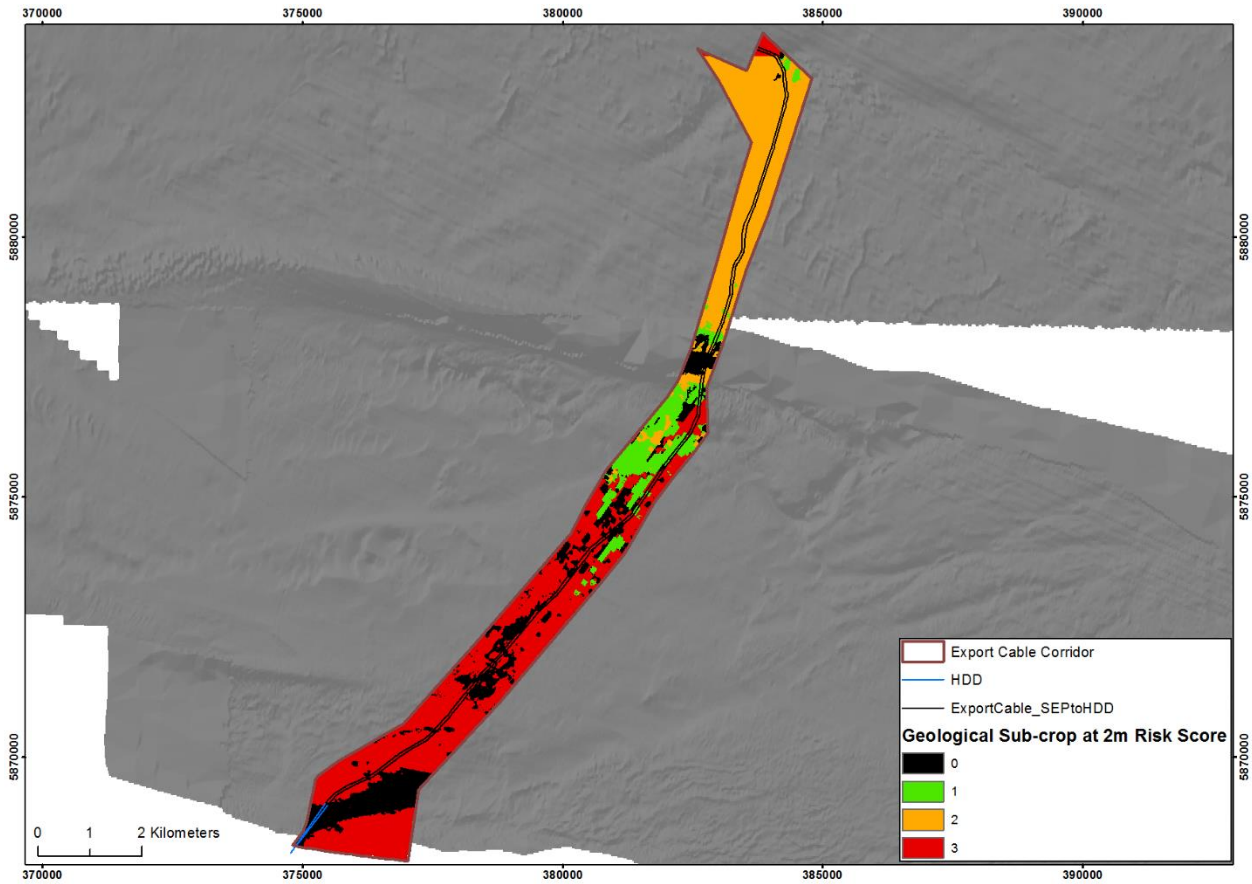

Figure 35. Scored Geological Constraint for Geological Subcrop at 2m.

COMBINED CONSTRAINTS MAP

This map is a final additive constraints map based on all Scored Geological factors, summing the constraints scores of spatially overlapping factors (Fig. 36). We have intentionally not presented this map in the 'traffic light' style, but rather suggest this map is most useful in identifying area of multiple overlapping constraints, or conversely areas of fewer overlapping constraints.

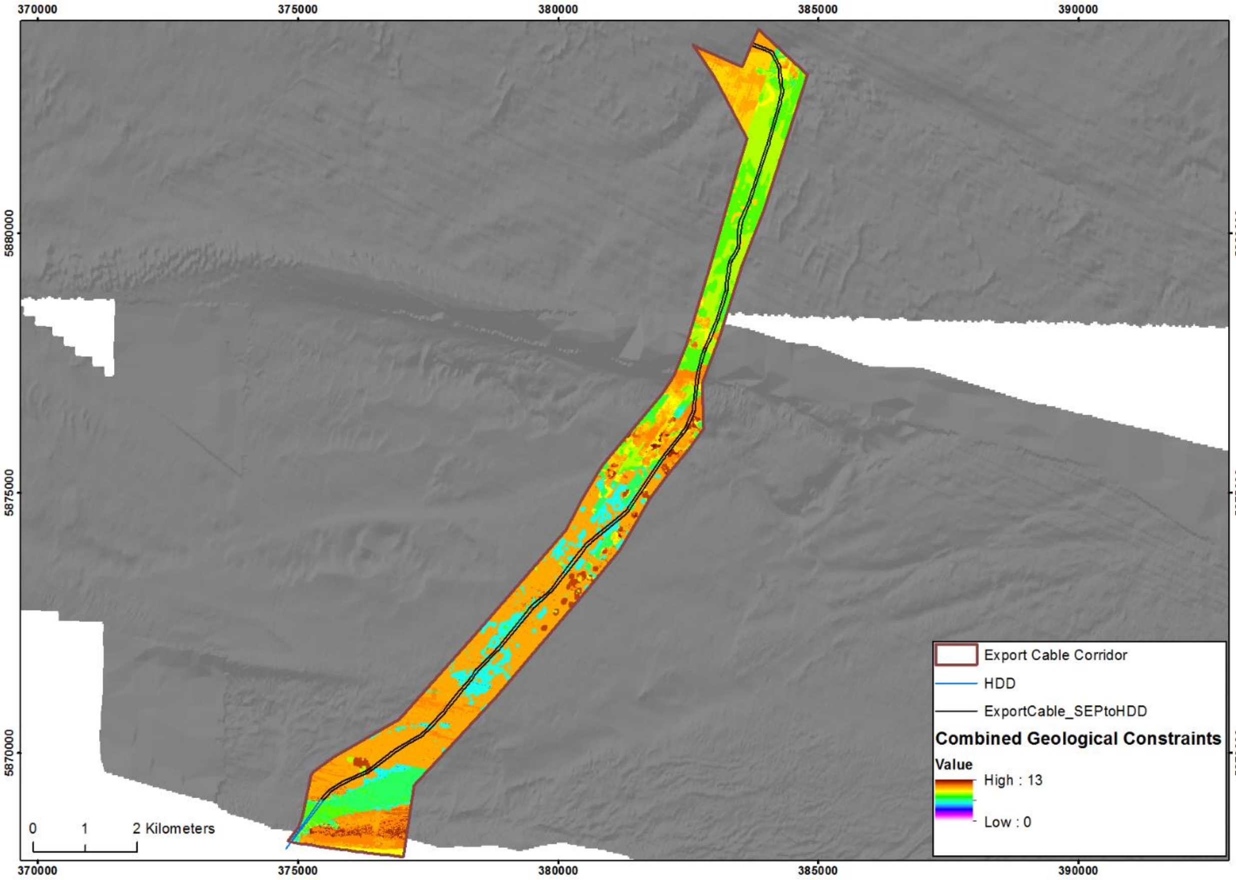

Figure 36. Combined Geological Constraints. Summation of all spatially overlapping constraints.

4.3 KEY FINDINGS – GEOLOGICAL CONSTRAINTS MAPPING

A series of geological factors relating to both seabed processes and sub-surface architecture (and predicted properties) have been compiled to assess potential constraints on cable emplacement. These factors have been subjectively scored (0-3 scale) according to their interpreted level of constraint. Finally, we combined all factors into a single constraint map, which sums all overlapping risks, highlighting areas with greater (or less) overlapping constraints.

In review of the results, we suggest that the original factor basemaps (e.g. areas of bathymetric change), the scored individual factor maps, and the final combined constraints map all provide value.

- The original factor basemaps (e.g. 'Areas of bathymetric change') are most useful for understanding the basic geological process/characteristic.
- The scored individual factor maps (e.g. 'Sediment Mobility') are most useful to understand the potential risk/constraint with respect to that particular factor;
- The combined constraints map is most useful of identifying areas of multiple (or fewer) overlapping constraints. We have intentionally not presented this combined map in a 'traffic light' style, as we believe the individual factor maps are more effective for characterising risk for specific applications.

5 Proposed Sample Locations

Following interpretation of the seabed and sub-surface, BGS have identified a number of proposed sample locations, that would help to confirm geological characteristics, and address uncertainties in the existing interpretation based on the cable-route geophysical data. Fig. (37) presents the locations of the proposed sample sits, and Table (1) provides a brief justification for each site, together with a recommended sampling technology. This assessment is not intended as a comprehensive geotechnical sampling plan and/or testing programme. These sample sites have been optimised, with feedback from Equinor, to further target shallow Chalk and be located on in-lines / cross-lines intersections where possible.

Table 1. Proposed sample locations.

Site_ID	Northing (UTM31)	Easting (UTM31)	Equip.	Justification
1	384230	5883263	CPT & VC	Sample for presence of peat in a small BC3 channel. Physical sample (VC) preferable.
2	383949	5881502	CPT & VC	Transparent unit in pinger, confirmation of whether this is upper BSBK or marine (Holocene) sediments is required. Penetration should aim to capture the channel infill stratigraphically below, as clarification on whether this channel is associated with SBK or BSBK is required. CPT is appropriate for obtaining engineering parameters relevant for trenching work, and VC required to confirm presence of BSBK.
3	383782	5880745	CPT & VC	Target shallow top Chalk between Location 2 and Location 3
4	383550	5880062	CPT & VC	Buried high-acoustic energy ridge/mound present at/near seabed. Possible moraine of BSBK. Vibrocore appropriate for the identification of composition and internal structures that may be indicative of BSBK, as well as sediments above internal BSBK.
5	383188	5878779	CPT & VC	Unit of possible upper BSBK above rugose reflector. Needs confirming that this horizon does indeed represent BSBK, as characteristic of the northern area of proposed corridor. As this unit is present across much of the northern extent of the route, CPT required to obtain engineering parameters and VC required to confirm lithological unit (e.g. BSBK).
6	382968	5878123	CPT & VC	Flank of channel north of large sediment back. Suspected BC channel; sample required for confirmation. CPT would benefit characterising the physical parameters associated with BC channel fill sediments for trenching work.
7	382690	5877185	CPT & VC	Potential peat within BC3 unit, over deeper BC member. Thin Holocene sediments above. Physical sample to confirm presence of peat required.
8	382288	5876081	CPT & VC	Potential peat within probable BC channel, and penetration of top Chalk. Physical sample required for confirmation.
9	381603	5875130	CPT & VC	Verify presence of shallow chalk. No interpretation of top Chalk (masked by ringing)
10	381016	5874311	CPT & VC	Clarification required on the nature of the thin sediment unit overlying chalk (potentially glacigenic in original, but may be Holocene sediment cover). Crucially, this sample site is characteristic of area south of BC channels. Physical sample preferable.
11	379196	5872420	CPT & VC	Verify presence of shallow chalk. No interpretation of top Chalk (masked by ringing)

12	378312	5871408	CPT & VC	Further confirmation of the nature of the sediment cover overlying the shallow chalk, and penetration of shallow Chalk. CPT would be appropriate as can tie in with above (Site 8) VC.
13	377573	5870491	CPT & VC	Material in low-relief ridges/mounds; possible gravel mounds or possible glacigenics. Physical sample useful to confirm whether these ridges are loose gravel or associated with glacial deposits.
14	376434	5869695	CPT & VC	Sample for confirmation of layered/deformed chalk or complex/deformed Quaternary unit. Interpretation of peat just west of location 14. Believed to not be relevant for cable burial as it is very local and deeper than 1m below seabed. Capturing internal structure important, so physical sample required.
15	375703	5869374	CPT & VC	Further confirmation of presence of deformed/layered chalk vs deformed Quaternary sediments.
16	375393	5869006	CPT & VC	Test nearshore channel material (northern of 3 sites across channel)
17	375278	5868842	CPT & VC	Test nearshore channel material (central of 3 sites across channel). VC allows validation of CPT response results within this channel, giving greater confidence in interpretation of northern (Site 13) and southern (Site 15) channel sites.
18	375109	5868597	CPT & VC	Test nearshore channel material (southern of 3 sites across channel)

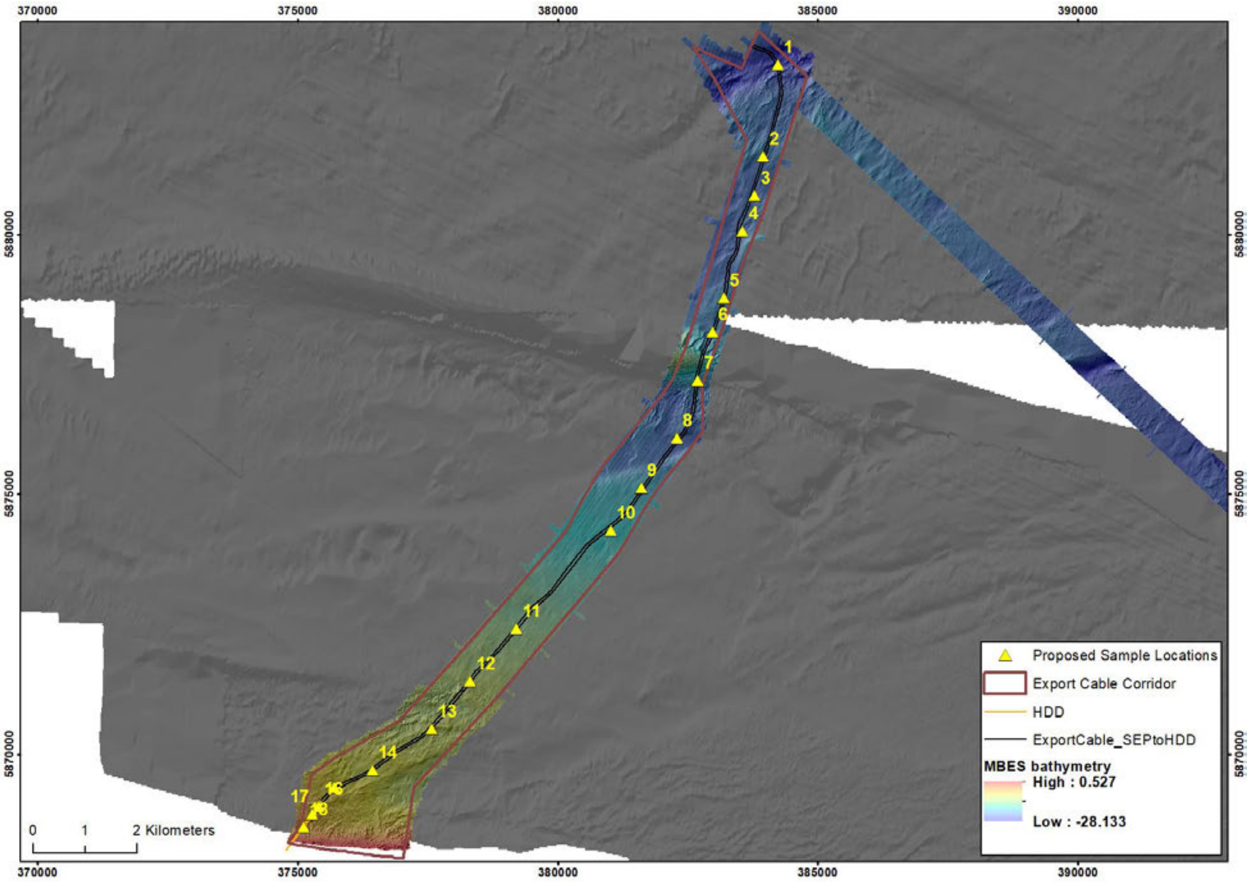

Figure 37. Proposed sample locations.

6 Integrated geological summary along the SS nearshore cable route

Near the coast, rugose seabed morphology corresponds with an outcropping chalk platform at seabed (to the east of the cable corridor the platform extends ~3-4km offshore) (Fig. 7). The Chalk platform is mantled in places by (likely) fine sands. Comparison between the cable route and MCZ bathymetry indicate these mantling sediments are mobile (e.g. intermittently exposing or burying the bedrock). This is confirmed by the 'Observative Bathymetric Change' factor (Fig. 24). North of the outcropping chalk within the cable corridor, a low-relief seabed channel crosses (orange 'Holocene' isopach contours in Fig. 4) the cable route in WSW-ENE orientation, and is in part covered by megaripples (Figs. 6,7). This seabed channel is also associated with a prominent channel observed in the seismic data, incised into the Chalk (Figs. 9,12,13). The seismic data shows layering within the channel, though not as conformably bedded as the channels farther north. This nearshore channel is also known onshore, and is thought to have formed via erosion from glacial meltwaters (Fig. 17) (Moorlock et al., 2008). The sediment infill of the channel however is not currently well constrained. The channel may incorporate sand-rich glacifluvial sediments, estuarine and coastal softer organic rich silty/sandy sediments (e.g. potential Peat), or marine sands and gravels. At present, we tentatively prefer the latter interpretation (e.g. infill by variable beds of marine sand and coarser gravel rich beds), though recommend that future geotechnical sampling targets this nearshore channel. Several sample locations have been proposed to examine the nature of the channel infill (Fig. 37).

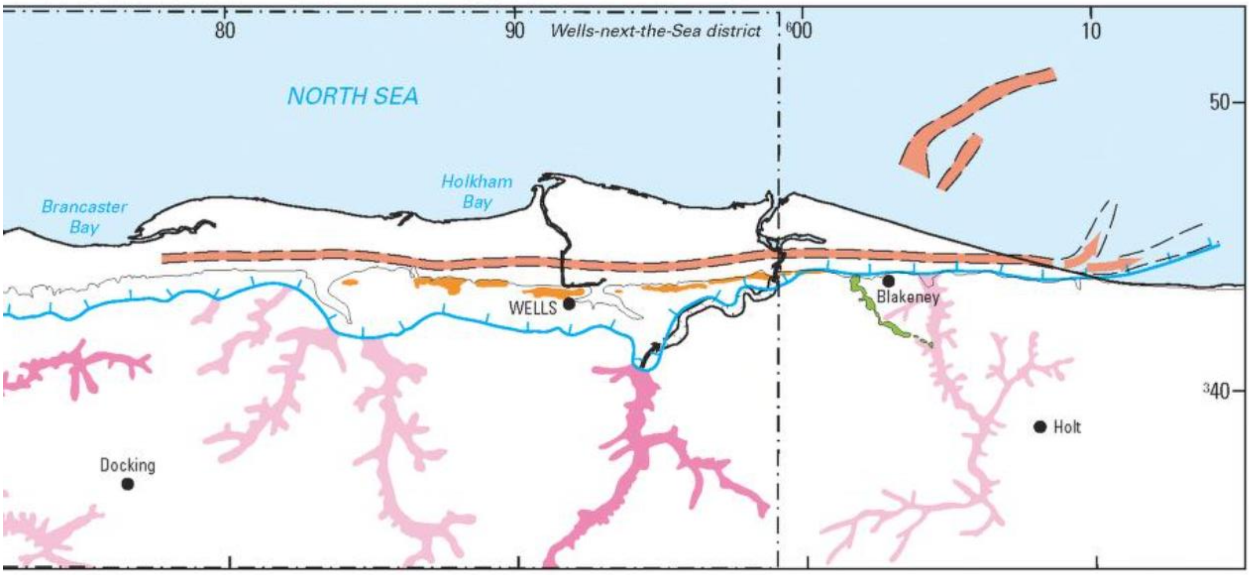

Figure 38. Onshore projection of the nearshore infilled channel (modified from Moorlock et al., 2008).

To the north of the channel, a series of moderate-relief ridges/mounds are apparent, superimposed by smaller-scale megaripples, sediment streaks, and low-relief sand waves (Fig. 6). These mounds/ridges appear to mimic the underlying Chalk morphology, though are also clearly modified by active mobile sedimentation (i.e. corresponding to area of shallow chalk). This area appears to be characterised by a thin, variably absent cover of fine sand and mobile bedforms atop coarser sediments and shallow Chalk. The fine sand and bedforms appear dynamic, and as such, accumulations of fine sediment in this area are considered active and changeable. This area also hosts complex structure within the seismic data which may reflect variability and/or deformation within the Chalk, or represent Quaternary cover over the Chalk. Sample locations have been proposed to test these competing hypothesis (Fig. 37).

North of the mounds/ridges, the cable corridor is characterised by a generally flat/featureless seabed (associated with Sandy Gravel seabed sediments). Chalk is generally expected in depths shallower than 2m (Fig.30), but sediment infill within the shallow depressions is interpreted to be unconsolidated marine sediment. There is a possibility that some of this thin sediment infill may comprise BSBK glacial sediments, and sample locations have been proposed to test this. Moving north, there is another seabed channel ('palaeovalley') approximately half way along the route (just south of Sheringham Shoal sand bank). Within the channel, and up onto the sand bank, fields of megaripples dominate the seabed together with several types of sand waves, not all of which are mapped by Gardline (Figs. 6,7).The Observed Bathymetric Change analysis indicates that the megaripples and the sediment waves are active, however, it is worth noting that migration of the sand waves may result in changes in seabed morphology by up to several metres, as opposed to 10's of centimetres for the megaripples. This seabed channel is also clearly apparent as infilled channels within the pinger and boomer data, reaching up to 50m below seabed (Figs. 10, 11). Both BC deposits (Base BC and BC3 mapped are anticipated within the larger channel (Fig. 11). The BC component here also includes the largest potential peat-bearing deposit mapped along the cable corridor (Figs. 15, 34). While the Top Peat surface is in places covered by the Sheringham Shoal sand bank, it is also regularly present at/near seabed (Figs. 16,34).

The Sheringham Shoal sand bank has a relief of up 10m above the surrounding seabed, with the bank expected to predominantly comprise loose, fine-grained sand. On the northern flank of the sand bank there are several large ~N/S oriented sand waves (up to ~4m relief), which repeat surveys analysis shows are associated with >1m change in bathymetry. North of the Sheringham shoal sand bank the seabed is characterised by low-relief, relatively broad mounds and ridges which then transitions northwards to sand wave assemblages and mega-ripple fields. The sub-surface data along this stretch is characterised by variable Top Chalk depths (~2-8m), with a notable deep channel incised into the Chalk (Fig. 11). While Gardline ascribes the shallow sediments in this zone to the BC (Fig. 4), we instead interpret that the shallow sediment infill is instead likely to be BSBK (as interpreted within Dudgeon corridor). The BSBK comprises upper and lower members, separated by a moderate relief internal reflector (Fig. 20).

In the far north of the corridor, The seabed descends into another seabed channel (Fig. 7), which is infilled with further potential Peat deposits (Figs. 11, 15, 34). While the geophysical data available do not intersect with the Sheringham OWF extension area, cross-referencing of interpretation of the high-res geophysical data within OWF area confirms general chalk depths, and the presence of potential peat beds within BC channels (BGS, 2020).

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