Geo-challenges for ground model development in previously glaciated and periglaciated terrains

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ABSTRACT: To achieve a net-zero clean energy future, developing offshore windfarm sites is fundamental to the UK's success in the renewable forms of energy. Integral to this is understanding the shallow subsurface geology which forms the foundation zone to these windfarm developments; particularly the impacts of past glaciations on the sedimentary and structural architecture of the deposits left behind following deglaciation. The range of depositional environments and distribution of deposits including diamictons, organic soils, rhythmically laminated soils, sands and gravels, result in extreme lateral and vertical heterogeneity. This variability, coupled with glaciotectonism, can make wind-turbine installation, kilometres apart, extremely challenging. Therefore, a multidisciplinary approach integrating geotechnical, geological, and geophysical data has enabled geological models to reimagine these ancient landscapes, identifying how they changed spatially and temporally, predict soil-type and behaviour, and furthers the understanding of implications for the foundation design of offshore infrastructure. Here we use knowledge of past glaciations to highlight several instances of extreme vertical and/or horizontal anisotropy, using onshore sites as analogues for observations from the North Sea, illustrating the necessity of fully characterising ancient landscapes to enable the development of ground models which overcome geo-challenges faced by offshore developments.

1 Introduction

Glaciated landsystems are highly dynamic, producing a highly variable range of environmental deposits including fluvial channels, floodplains and outwash plains (sandur deposits), and ice marginal terrains (e.g. push and thrust-block moraines, ice-marginal fans, De Geer moraines, etc.). Much of the UK and its continental shelf has been glaciated, (Lee et al., 2011) and the highly varied landsystems and processes that operated can have significant implications on engineering works, with the potential for increasing overall risk to installation projects through unexpected heterogeneity and complexity. Clarke et al. (2008) describe one such complexity where they found clay-rich diamictons in Northumberland, U.K., with undrained shear strengths of 5 to 500 kPa, across depths of 0 to 40 m. Unconfined compressive strengths of intact samples taken from various till units in north Norfolk and Holderness have a range from 96 kPa (Hessle Till, Hornsea) to 224 kPa (Cromer Till, Happisburgh) (Bell, 2002), while the study by Clarke et al. (2008) show an undrained shear strength range of c. 400 kPa from clay-matrix dominated diamictons at a site in northeast England. This variability in soil strength against depth can be attributed to the processes that tills have undergone during and after deposition, including loading and unloading by ice, shearing, reworking, desiccation and weathering. Periglacial (areas near to or adjacent to ice sheets, subject to permafrost and freeze-thaw cycles) weathering may also significantly affect rockhead, leading to unexpected thicknesses of much weaker bedrock than expected. Onshore examples of periglacial weathering of chalk show weathering depths of up to 30 m thick (Mortimore, 2014).

Consequently, when siting Wind Turbine Generators (WTGs) on previously glaciated and periglaciated terrains there are a number of geo-challenges that may require addressing during ground model development (Macdonald et al., 2023). Here we highlight several key challenges originating from previously glaciated and periglaciated terrains and faced by offshore infrastructure development.

2 Periglacial weathering of rockhead

Periglacial weathering occurs due to repeated freeze-thaw cycles, resulting in the degradation of soils and bedrock, such as chalk and mudstone, both of which are known to be highly frost-susceptible due to their fine grain size. Periglacial processes include the in-situ modification of pre-existing geology prior to glaciation, during and immediately after deglaciation leading to weathering, fracturing and erosion of soils/bedrock. Evidence of past periglacial environments are encountered across much of upland and lowland Britain and out across the present-day continental shelf, extending beyond the known maximum limits of the Quaternary ice sheets extent, pertaining to permafrost action and subsequent paraglacial landscape modification (non-glacial processes caused by deglaciation, i.e., increased sediment output and land system change) (Murton and Ballantyne, 2017). Mortimore and James (2015) highlight the necessity of onshore analogues for offshore bedrock, particularly regarding chalk weathering caused by Quaternary periglacial activity. This weathering has the potential to cause increased risk to offshore windfarm installations if not properly investigated. Here we explore examples of periglacially altered chalk deposits offshore and onshore of the UK.

It is important to determine the depth of periglacial weathering within the chalk, as the thickness of disturbance will have a direct influence on foundation design. In addition, where chalk is present at or near seabed (≤2 mbsf), the vertical extent of periglacial weathering can dictate what cable trenching equipment is selected and the depth of burial that can be achieved. In chalk, the depth of periglacial weathering may be suggested by the thickness of rafted blocks, which can be indicative of internal heterogeneities or zones of frost susceptibility within the chalk. During cold climates, permafrost action freezes porewater within frost susceptible layers within the rock. It causes the chalk to failure along specific discontinuities but often keeps soil structures intact, allowing entire blocks of soil to be ‘plucked’ and moved by ice. One example from the coastal cliffs of north Norfolk shows so-called chalk rafts up to 7 m in thickness, suggesting a permafrost depth of at least 7 m (Burke et al., 2009, Martin et al., 2017). The degree to which the weathering zone in chalk is preserved today is dependent upon how much of the overburden and periglacially altered bedrock was subsequently removed due to later erosion. For instance, plateaus, as seen in cliffs along the Sussex coastline, typically have thinner Quaternary cover and reduced thicknesses of weathered material as this is susceptible to being removed and transported downslope. These cliffs show a thickness of up to 20 m of degraded chalk. Within dry chalk valleys, degraded chalks can be seen to reach thicknesses greater than 30 m, most likely due to a reduced rate of weathering when compared to the chalk cliffs (Mortimore 2014).

Freeze-thaw and frost shattering can lead to fragmentation of the chalk due to the development of closely spaced vertical/subvertical and horizontal /sub-horizontal fractures. Depending on the extent and intensity of this periglacial degradation, the chalk can range from weakly jointed through to completely brecciated. Degradation of chalk can be highly variable even within a single unit, dependent upon the density (porosity and permeability) of beds. Site investigations at Sheringham Shoal OWF encountered very low-density putty-like chalk. This “putty” texture is largely attributed to decalcification during periglacial alteration leaving behind a clay/silt-rich residue. The presence of low permeability layers within the chalk can result in locally elevated moisture contents at or near saturation. Consequently, freezing and expansion of the trapped porewater during permafrost development and breakdown the rock, results in a high proportion of silty fines forming a CIRIA grade D fabric (Mortimore, 2021). High-permeability, high-porosity chalk can also enhance periglacial weathering due to high porewater content allowing the development of higher and sustained porewater pressures which increase the impact of freeze-thaw action (Mortimore 2012). Figure 1 shows examples of this type of weathering, from core obtained from the Sheringham Shoal OWF (Fugro, 2006, SEtech (Geotechnical Engineers) Limited, 2007) and from onshore *in situ* outcrops. Figure 1a and 1b show examples of U.K. based periglacially weathered (frost-heave / -shattered) *in situ* chalk resulting in brecciated gravel-sized chalk clasts surrounded by a less competent clay to silt-like matrix, as well as heavy fracturing. Figure 1c shows an example of low density “putty” Turonian aged chalk encountered at borehole VC8 between 3.00 – 6.40 m depth below seabed during site surveys of the Sheringham Shoal OWF (Fugro, 2006). Figure 1d and 1e show, respectively, a generalised undrained shear strength profile through the chalk encountered within the Sheringham Shoal OWF and cable route, and a CPT profile 2.8 m away from borehole VC8. The generalised undrained shear strength profile shows the considerably lower strength of the chalk within the upper few metres of the unit, which can be likely attributed to weathering and periglacial activity (Figure 1d).

3 Soil anisotropy

Previously glaciated terrains commonly are characterised by complex heterogeneous sediment, structural and landscape assemblages, as well as having been subject to a range of post-depositional processes, including freeze/thaw cycles, glaciotectonic deformation (which can also occur syn-depositionally), subaerial desiccation, and soil solifluction (Prins and Andresen, 2021, Bennett and Glasser, 2011, Clarke 2018).

Cotterill et al. (2017a, b), Emery et al. (2019a, 2020) and Phillips et al. (2018, 2022), describe in detail the evolution of the Dogger Bank area of the southern North Sea during the Quaternary, particularly during the last glacial stage. The Dogger Bank experienced at least two major glacial episodes throughout the Quaternary – during the Elsterian

(MIS 12) and Weichselian (MIS2). These glacial periods resulted in preserved soils deposited within a range of environments (subglacial, ice-marginal, proglacial), which have been subject to varying degrees of periglacial and postglacial modification. The actively retreating margin of the Late Weichselian ice sheet is recorded by the development of a series of large thrust-block moraines and ice-marginal fans, as well as prograding outwash plains incised by meltwater channels. Geological borehole samples and geotechnical data throughout the Dogger Bank sites provide information on the nature and physical properties of the soils (Cotterill et al, 2017b, Emery et al, 2019a, b, 2020), revealing that the glacial deposits underlying Dogger Bank are highly variable and include laminated rhythmites, diamictons with varying size of coarse clastic material (gravel to (rarely) cobble in size), clays of varying stiffness, as well as units

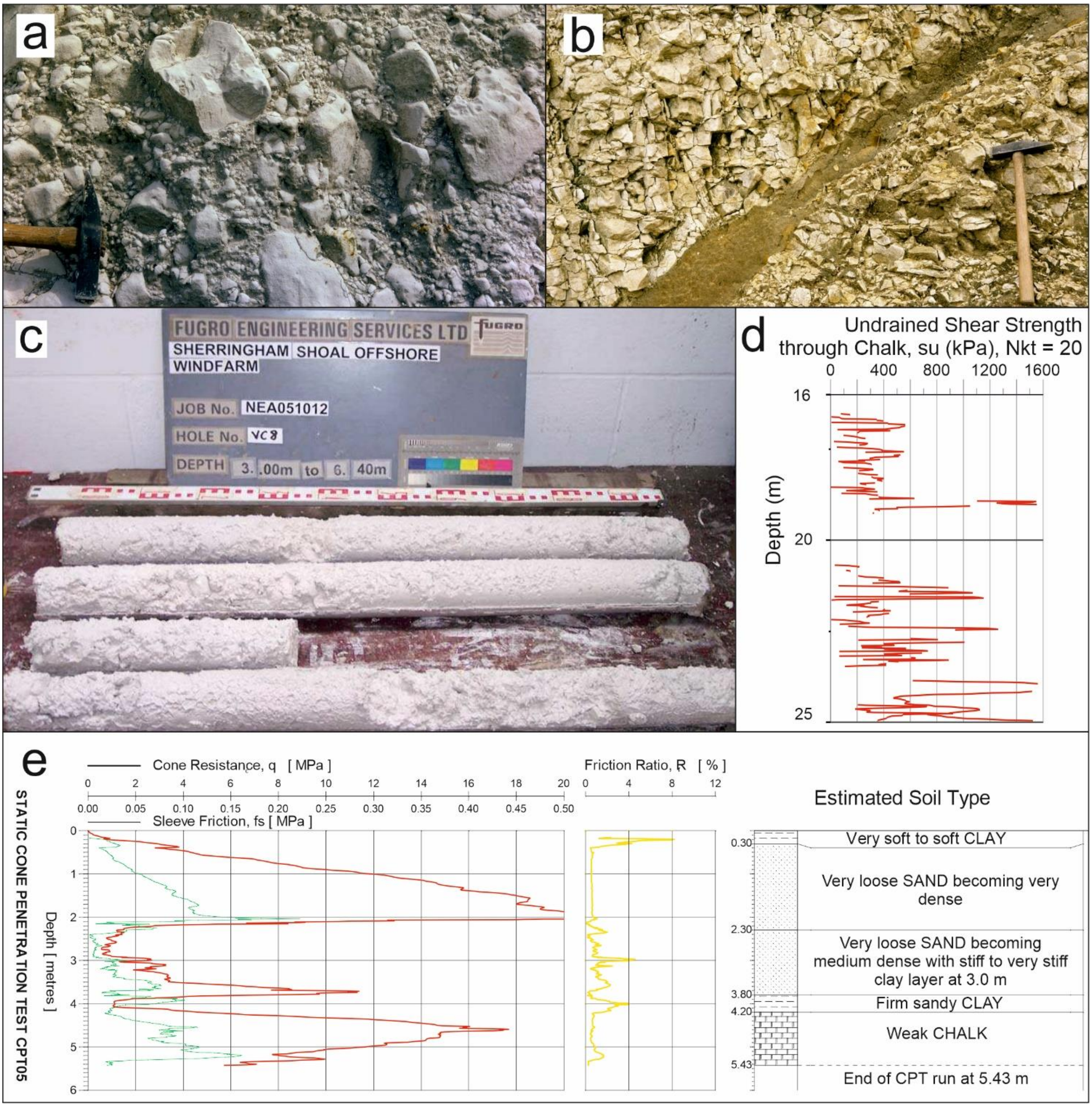

Figure 1. a. Frost-shattered chalk at Little Cliffsend, Pegwell Bay, near Ramsgate, England. Chalk clasts (boulder and gravel sized) within a severely weathered chalk matrix. Most likely mechanically broken up by frost-heave. The process may have been accentuated due to the presence of faulting within the outcrop. Photo © BGS / UKRI. b. Frost-shattered chalk with a narrow, sand and silt infilled crack located at West Norfolk Super Lime Co. Pit, Hillington, England. Crack is a solution pipe running irregularly through the chalk outcrop. The chalk has undergone significant periglacial weathering. Photo © BGS / UKRI. c. Vibrocore from 3.00 to 6.40 m below seafloor. Core comprises 3.40 m of low density crumbly and putty-like chalk (From Fugro, 2006). Distance between VC5 and CPT05 is ~2.8 m. d. Results of CPT testing for the upper ~8 m of chalk encountered in Sheringham Shoal showing undrained shear strength (su, kPa) (SEtech (Geotechnical Engineers) Limited, 2007).

comprising interbedded sand, silt, and clay deposits. There can be some difficulty in predicting soil conditions due to inherent anisotropy within these sequences. These varying soil types are found to be not just restricted to a change in depositional environment, but may also be intrinsically linked to the nature of certain landforms and the physical processes occurring within these environments. For example, glaciotectonised thrust-block moraines comprise a variety of soil types which were incorporated into these complex landforms from pre-existing materials during ice sheet advance. Glaciotectonism at the margin and beneath the ice sheet can produce highly deformed soils (glacitectonites) containing lenses and entrained blocks and rafts of highly heterogeneous material, (including weathered rock and relatively undeformed sequences of clast-rich unlithified to semi-lithified soils). In addition to these varied soil types, glaciotectonism can also incorporate soils which may have experienced varying degrees of periglacial weathering. This results in a structurally complex sequence characterised by an inherent variation in soil strength, with or without a change in soil type. Figure 2 shows examples of soil heterogeneity within the glaciotectonised sequence from the Dogger Bank. The figure shows two different examples of interpreted seismic data through moraine complexes (coloured purple), with simplified soil behaviour type (SBT) curves generated from cone penetration test (CPT) data. CPT_A shows that at this site the moraine comprises an alternating sequence of clay rich material and coarser sand rich material, which approximately corresponds to amplitude changes in the seismic data. The CPT_A is located ~25m away from the seismic data, so exact correlation is not expected. CPT_B is ~10 m away from the seismic line and shows that the glaciotectonised sequence comprises thicker, coarser sand rich soil units interbedded with thinner clay dominant layers. The seismic response within the moraine complex at CPT_B is low amplitude to transparent, and is very chaotic in appearance, with no continuous horizons or amplitude changes which may suggest dominant soil type changes within the moraine complex at this location.

Aerial exposure and subsequent desiccation can lead to an increase in stiffness of clays. Overconsolidated clays (hosting laminae of silt to sand grade material and occasional gravel layers) are identified

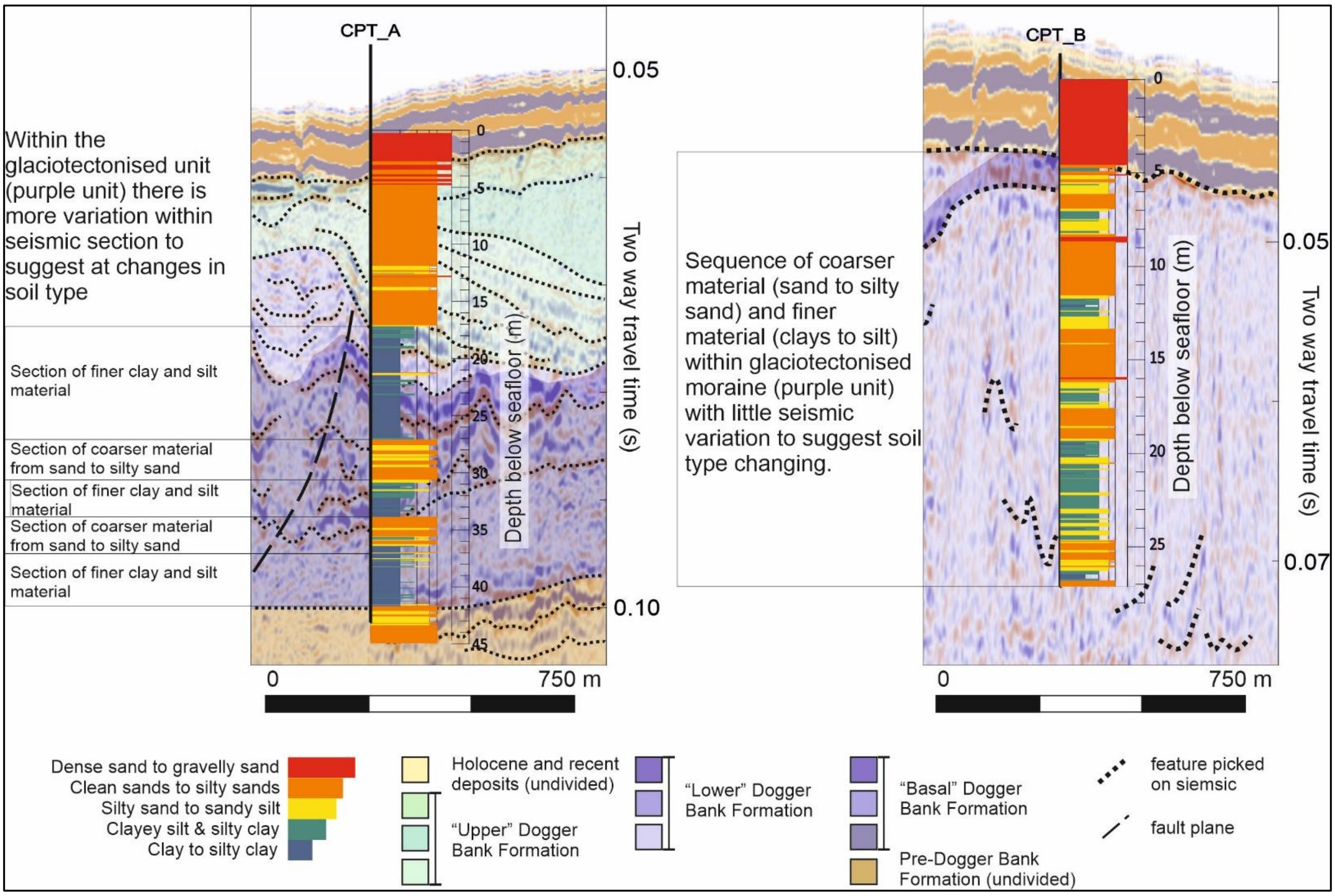

Figure 2. After Phillips et al 2022. Interpreted seismic sections from the Dogger Bank offshore windfarm area. Lower and Basal Dogger Bank Formation (Fm) in purple, Upper Dogger Bank Fm in green. Soil sticks generated from soil behaviour types obtained from cone penetration test (CPT) data. Figure shows the differing soil types that can be expected from glaciotectonised units (Lower and Basal Dogger Bank – purple). Seismic behind CPT_A shows amplitude changes that correspond to changes in the SBT curve, whereas the seismic behind CPT_B does not show very obvious amplitude changes or anomalies and remains uniformly transparent to low amplitude throughout. Seismic data is in two way travel time (seconds). CPT data has been time converted using a velocity of 1700 m/s.

within the younger, essentially undeformed soils (green colour on the seismic data) at the Dogger Bank site which rest upon the earlier formed moraines. Consequently, these undeformed soils were not subjected to loading by the ice. The clays, however, record undrained shear strengths of >100 kPa. It is believed that the unusually high undrained shear strengths of these clays may be due to subaerial exposure and periglacial weathering/alteration resulting in desiccation (Cotterill et al., 2017a, b). Further south, at the Dudgeon offshore windfarm site, variable shear strengths of clay material have been recorded within the Swarte Bank Fm (Elsterian, MIS 12) (Mellett et al., 2020). The Swarte Bank Fm is described as comprising a large variety of soil types, including chalk erratics, extremely hard and deformed sandy, silty and calcareous clays, as well as diamicton composed of clay and flint gravel to cobble sized clasts. The diamictons possess highly variable shear strengths, appearing to be unrelated to compaction associated with burial depth, with shear strength varying from 90 kPa to >250 kPa over depths of 16.5-50 m bsf. Mellett et al. (2020) concluded that this variation may be a result of repeated phases of subglacial deformation coinciding with multi-stage deposition of the channel infill sequence. Alternative explanations are also given, including differing pore-water pressures resulting from grain-size variations and/or hydraulic conductivities that may control the effective pressure. Additionally, clay beds within the channel-fill were seen to host variable amounts of calcium carbonate, which may have facilitated consolidation by cementation.

4 Gravel and Boulder distribution

Glacial sequences both onshore and offshore often contain discrete gravels and/or boulder sized clasts (erratics). A gravel lag may also mantle the surface of subglacial tills occurring immediately below the seabed. These may develop from the winnowing of the finer clays, silts, and sands forming the matrix to the diamictons, and can cause complications particularly during cable installation.

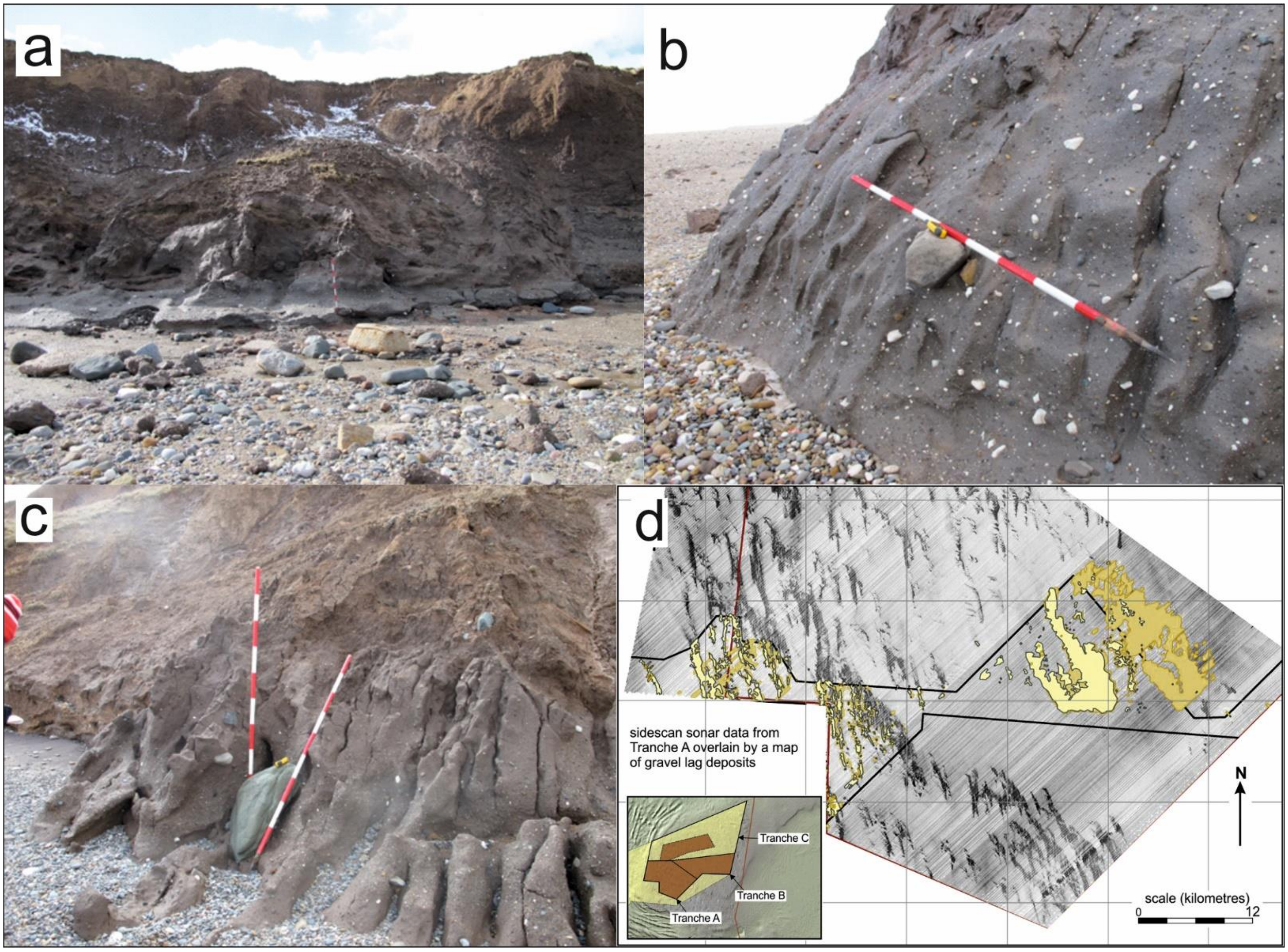

Figure 3. a, b, c. Boulder distribution along coastal section of the Yorkshire coast. Boulders originate from Skipsea and Withernsea tills, the onshore equivalent of the Bolders Bank Formation which is present within the Westermost Rough OWF area. A. Boulder and gravel distribution on ground, compared to observable boulders and gravel within the cliffside. B, C. In situ boulders and gravel within cliffside. Note the large size difference between clasts. D. Map of gravel lag within a section of the Dogger Bank OWF, from Cotterill et al (2017a). Figure shows extent of gravel lag seen at and near seabed using Sidescan Sonar and pinger seismic data. Gravel mapped at seabed – yellow, potential buried gravel deposits – orange.

Offshore, the Bolders Bank Fm was deposited during the Late Weichselian and comprises a sequence of diamictons, sands and muds (Mellett et al., 2020, Cotterill et al., 2017a). Onshore, the equivalent of the Bolders Bank Fm diamictons are the Withernsea and Skipsea Tills (Dove et al, 2017) which crop-out in the coastal cliffs in East Yorkshire at Easington and Aldbrough. These sites were investigated during the siting of the Westermost Rough offshore windfarm (OWF) with a focus on understanding the distribution of large (>1 m) boulders within these deposits as an analogue for the Bolders Bank Fm (Figure 3a, b and c). The westernmost Rough OWF is located ~8km off the Yorkshire Coast, ~8km and ~20km from Aldbrough and Easington, respectively and its export cable routes are in areas where the Bolders Bank Fm is situated beneath a surficial layer (<0.2m thick) of gravelly sand to sandy cobbly gravel. The coastal survey found the tills to be relatively boulder-rich, suggesting the high probability for increased boulder density where the Bolders Bank Fm occurs at or near seabed offshore.

Alongside this study, investigations into ground conditions for the Westermost Rough OWF and cable export route further highlighted the extent of boulder distribution particularly at, and near to seabed (Nordh et al., 2013). Side scan sonar (SSS), multibeam echo sounder (MBES) and sub bottom profiler (SBP) data was utilized by Nordh et al. (2013) to classify surface geology and seabed features and establish the density of boulders within the deposits; low 10-50 boulders per 10000m^2, to high >100 boulders per 10000m^2. The areas of higher boulder density were identified and predominantly mapped as sandy cobbly gravel. Point source reflectors seen in SBP data, interpreted as single large boulders, were present throughout the cable routes across all interpreted Bolders Bank Fm layers. These boulders ranged in size from 0.4-6m across, and in total, across the array cable routes of the Westermost Rough OWF, 1166 boulders larger than 1m were identified using SSS (Nordh et al., 2013).

Investigations into potential gravel lag deposits at, or near seabed within the Dogger Bank area of the North Sea identified extensive areas of medium to coarse gravel (6.3-63 mm long). These gravel bodies were found to be typically flint-rich and often were found to form gravel lag buried up to 4 m below seafloor (bsf), with occasional fine gravels (2-6.3 mm long) and large cobbles (63-200 mm long) and expressed typically at areas where glacial diamicton of the Dogger Bank Formation is exposed at seabed (Cotterill et al., 2017a, Figure 3d). Similar deposits are identified in the southwestern Baltic Sea, where coarser material (gravel to boulder grade) is found above morainic deposits (Diesing and Schwarzer, 2006). The gravel lag deposits described above were, again, most likely to be formed due to winnowing of the fines from the glacial diamicton deposits (Cotterill et al., 2017a, Diesing and Schwarzer, 2006).

Gravel-rich deposits are not just restricted to eroded and weathered glaciotectonised diamicton deposits. The Quaternary sequence at Glen Roy (Monadhliath Mountains, Scotland) includes gravel fans which prograded into rhythmically laminated glaciolacustrine deposits. These fans are found to have a total combined volume of c.6,000,000 m^3 and were potentially deposited over the period of about 200 years, with deposition reducing drastically by 85% once the glaciers damming the lake began retreating (Cornish, 2017). This example highlights the potential for large amounts of coarse-grained soils to accumulate across glaciated terrains, which have the capability for causing challenges during offshore infrastructure siting and installation (e.g. installation issues for suction caisson, and cable trenching challenges associated with plough deviation).

5 Organic soils

Peats developing prior to and during early Holocene transgression are common particularly within the southern North Sea (Waller and Kirby, 2021, Stoker et al., 2011, Cameron et al., 1992). Peats can be difficult to identify using seismic data and aren’t always obvious on CPTs, as they can cause either~~both~~ a drop or~~and~~ an increase in cone tip resistance. Peat and other organic soils can be associated with biogenic gas, which may be pressurised, causing gas kicks or even blowouts. Additionally, when planning linear infrastructure routes, peat must be taken into account as it can be difficult to trench through due to its fibrous nature and can cause cable hot-spots to develop due to the relatively low thermal conductivity of peats (Brown et al., 2015, Callender et al., 2020). Another engineering risk associated with peat is the occurrence of ground compression during loading.

Boreholes encountering the Elbow and Nieuw Zeeland Gronden Formations (Holocene, MIS 1) within the Dogger Bank OWF area found peats, as well as wood and tundra bog soils (Cotterill et al., 2017a, Emery et al., 2019b). These formations include post-glacial to transgressive (estuarine, intertidal, and marine) deposits (Cameron et al., 1992, Stoker et al., 2011, Cotterill et al., 2017a). These sequences typically occur at a shallow level within the stratigraphy and close to seabed, thereby causing challenging conditions for cable burial activities.

6 Discussion and Conclusions

There are numerous hazards associated with glaciated to post-glaciated terrains when siting offshore infrastructure. Here the authors focus on depth of weathering, particularly in chalk, soil anisotropy, boulder and gravel distribution and organic soils. In the examples listed above, onshore geological analogues, as well as integrated multidiscipline site investigations, can provide key insights into expected ground conditions. Where investigating depth of weathering of bedrock for chalk encountered during siting of the Sheringham Shoal OWF, onshore analogues provided valuable insight regarding age indicating likely ground conditions based on units encountered onshore. From this information, site investigations could be planned according to expected ground conditions, and geological, geophysical and geotechnical studies could be planned in an integrated and holistic manner. Similarly, regarding boulder distribution and gravel lag deposits, initial studies focussing on conditions along coastal outcrops of equivalent till units encountered offshore can be utilised to give a preliminary assessment of likely boulder distribution that may be expected offshore. Ultimately, when siting offshore infrastructure, a well-rounded and multidisciplined approach to site investigation has proved to be the most efficient way of assessing potential hazards. This allows for integration of onshore analogues, site specific and regional analysis of geological, geotechnical, and geophysical data.

- Integration between all available datasets is key in producing a scientifically robust ground model.
- Initial investigation into onshore analogues can be key in informing possible hazards and challenges that may be encountered during site investigation and installation.
- Both regional and site-specific studies will always be necessary to assess unexpected hazards and challenges at different levels, and put these into the broader geological perspective, allowing for a more robust ground model.

7 References

Bennett, M.M. and Glasser, N.F. eds., (2011). Glacial geology: ice sheets and landforms. John Wiley & Sons.

Brown, M. J., Bransby, M. F., Knappett, J., Tovey, S., Lauder, K. D., & Pyrah, J. (2015). The effect of buried fibres on offshore pipeline plough performance. Ocean Engineering, 108, 760-768.

Burke, H., Phillips, E., Lee, J.R., Wilkinson, I.P. (2009). Imbricate thrust stack model for the formation of glaciotectonic rafts: an example from the Middle Pleistocene of north Norfolk, UK, Boreas, Volume 38, Issue 3, Pages401-646

Callender, G., Ellis, D., Goddard, K. F., Dix, J. K., Pilgrim, J. A., & Erdmann, M. (2020). Low computational cost model for convective heat transfer from submarine cables. IEEE Transactions on Power Delivery, 36(2), 760-768.

Cameron, T., Crosby, A., Balson, P., Jeffery, D. H., Lott, G. K., Bulat, J., et al. (1992). United Kingdom Offshore Regional Report: The Geology of the Southern North Sea. London: HMSO.

Clarke, B. G., Hughes, D. B. & Hashemi, S. (2008). Physical characteristics of subglacial tills. Geotechnique 58, No. 1, 67–76

Clarke, B. G. (2018) The engineering properties of glacial tills. Geotechnical Research, Vol 5, issue 4, pp. 262 – 277

Cornish, R. 2017. The gravel fans of upper Glen Roy, Lochaber, Scotland: their importance for understanding glacial, proglacial and glaciolacustrine dynamics during the Younger Dryas cold period in an Atlantic margin setting, Proceedings of the Geologists' Association, Volume 128, Issue 1, 2017, Pages 83-109

Cotterill, C., Phillips, E., James, L., Forsberg, C.F., Tjelta, T.I., Carter, G., Dove, D. (2017a), The evolution of the Dogger Bank, North Sea: A complex history of terrestrial, glacial and marine environmental change, Quaternary Science Reviews, Volume 171, Pages 136-153

Cotterill, C., Phillips, E., James, L., Forsberg, C.-F. and Tjelta, T.I. (2017b), How understanding past landscapes might inform present-day site investigations: a case study from Dogger Bank, southern central North Sea. Near Surface Geophysics, 15: 403-414

Diesing, M., and K. Schwarzer. 2006. Identification of submarine hard-bottom substrates in the German North Sea and Baltic Sea EEZ with high-resolution acoustic seafloor imaging. In Progress in marine conservation in Europe, ed. H. von Nordheim, D. Boedeker, and J.C. Krause, 111–125. Berlin, Heidelberg: Springer.

Dove, D., Evans D.J.A., Lee, J.R., Roberts, D.H., Tappin D.R., Mellett, C.L., Long, D., Callard, S.L., (2017) Phased occupation and retreat of the last British–Irish Ice Sheet in the southern North Sea; geomorphic and seismostratigraphic evidence of a dynamic ice lobe, Quaternary Science Reviews, Volume 163, 2017, Pages 114-134

Emery A.R., Hodgson D.M., Barlow N.L.M., Carrivick J.L., Cotterill C.J., Phillips E., (2019a) Left High and Dry: Deglaciation of Dogger Bank, North Sea, Recorded in Proglacial Lake Evolution. Frontiers in Earth Science, 7, art. no. 234

Emery A.R., Hodgson D.M., Barlow N.L.M., Carrivick J.L., Cotterill C.J., Mellet C.L., Booth A.D., (2019b) Topographic and hydrodynamic controls on barrier retreat and preservation: An example from Dogger Bank, North Sea, Marine Geology, Volume 416

Emery A.R., Hodgson D.M., Barlow N.L.M., Carrivick J.L., Cotterill C.J., Richardson J.C., Ivanovic R.F., Mellett C.L., (2020) Ice sheet and palaeoclimate controls on drainage network evolution: An example from Dogger Bank, North Sea. Earth Surface Dynamics, 8 (4), pp. 869 - 891

Fugro (2006) Sheringham Shoal offshore wind farm and cable route: Factual report on ground investigation for Scira Offshore Energy Limited. Report no. NEA051012, part 2. Accessed via the Marine Data Exchange Portal.

Lee, J R, Rose, J, Hamblin, R J, Moorlock, B S, Riding, J B, Phillips, E, Barendregt, R W, And Candy, I. 2011. The Glacial History of the British Isles during the Early and Middle Pleistocene: Implications for the long-term development of the British Ice Sheet. 59-74 in Quaternary Glaciations–Extent and Chronology, A Closer look. Developments in Quaternary Science. Ehlers, J, Gibbard, P L, And Hughes, P D (editors). 15. (Amsterdam: Elsevier.)

Macdonald C., Carter G.D.O., Johnson K.R., Augarde C.E., Coombs W.M., Bird R.E., Brown M.J., Sharif Y.U., Depth of Lowering and layered soils; a case study from across the North Sea. Proceedings of the 9th International Conference, held 12–14 September 2023 at the Royal Geographical Society, London. vol. 1-2

Martin C.J., Morley, A.L., and Griffiths, J.S. (2017). Introduction to engineering geology and geomorphology of glaciated and periglaciated terrains in: Griffiths, J.S., Martin, C.J (eds) 2017. Engineering geology and geomorphology of glaciated and periglacial terrains – Engineering Group Working Party

Report. Geological Society, London, Engineering Geology Special Publications, 28

Mellett, C. L., Phillips, E., Lee, J. R., Cotterill, C. J., Tjelta, T. I., James, L. & Duffy, C. (2020): Elsterian ice-sheet retreat in the southern North Sea: antecedent controls on large-scale glaciotectonics and subglacial bed conditions. Boreas, Vol. 49, pp. 129– 151

Mortimore, R.N., (2021). The Chalk of the South Downs of Sussex and Hampshire and the North Downs of Kent. Geologists' Association.

Mortimore, R.N., James, L. (2015) The search for onshore analogues for the offshore Upper Cretaceous Chalk of the North Sea, Proceedings of the Geologists' Association, Volume 126, Issue 2, Pp 188-210

Mortimore R.N. (2014) Logging the Chalk. The Definitive Chalk Handbook. Whittles Publishing, pp357

Mortimore, R.N. (2012) Making sense of the chalk: a total-rock approach to its Engineering Geology. Quarterly Journal of Engineering Geology and Hydrogeology, Volume 45, Pages 252 - 334

Murton, J and Ballantyne, C K (2017) Periglacial and permafrost ground models for Great Britain. In: Griffiths, J S and Martin, C J (eds.) Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains – Engineering Group Working Party Report. Engineering Geology Special Publications, 28 . Geological Society, London, pp. 501-597

Nordh, D., Hanslik, D., Sundberg, T., (2013), MMT Doc. No: 101266-DON-MMT-SUR-REP-GEOPHINT Geophysical Report: Geophysical Survey and Anomaly Inspection Inter Array Cables, Project 101266, Doc. No: 101266-DON-MMT-SUR-REP-GEOPHINT. Client: Dong Energy, Accessed via the Marine Data Exchange Portal

Phillips, E., Cotterill, C., Johnson, K., Crombie, K., James, L., Carr, S., Ruiter, A. (2018), Large-scale glacitectonic deformation in response to active ice sheet retreat across Dogger Bank (southern central North Sea) during the Last Glacial Maximum, Quaternary Science Reviews, Volume 179, Pages 24-47

Phillips, E., Johnson, K., Ellen, R., Plenderleith, G., Dove, D., Carter, G., Dakin, N., Cotterill, C., (2022) Glacitectonic evidence of ice sheet interaction and retreat across the western part of Dogger Bank (North Sea) during the Last Glaciation, Proceedings of the Geologists' Association, Volume 133, Issue 1, Pages 87-111

Prins, L.T., Andresen, K.J. (2021), A geotechnical stratigraphy for the shallow subsurface in the Southern Central Graben, North Sea, Engineering Geology, Volume 286

SEtech (Geotechnical Engineers) Limited (2007), Scira Offshore Energy Ltd, Sheringham Shoal Wind Farm: Geotechnical Integration Study. Report no. 8495-1. Accessed via the Marine Data Exchange Portal.

Stoker, M. S., Balson, P. S., Long, D., Tappin, D. R. (2011). An Overview of the Lithostratigraphical Framework for the Quaternary Deposits on the United Kingdom Continental Shelf. Nottingham: British Geological Survey, 48.

Waller M, Kirby J, 2021, Coastal peat-beds and peatlands of the southern North Sea: their past, present and future. Biological Reviews, Vol 96, Issue 2, Pp 408-432