Dogger Bank – A Geo Challenge

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Abstract
The Dogger Bank Zone is the largest of the Round 3 (R3) Offshore wind zones extending over ~8660 km^2. It is located between 125 and 290 kilometers northeast of Yorkshire on the Dogger Bank, a topographic high in the middle of the North Sea, with water depths of 18–63 m. The sheer size of this zone is considerably greater than that of standard shallow water oil and gas site investigations, leading to the generation of extremely large data volumes to manage, interpret and move between partners. This paper outlines the methodologies Forewind is utilising to prepare for the zone's development, including activities undertaken to date to develop a 3D model of the geology, stratigraphy and geotechnical conditions to assist in optimal selection of location and type of wind turbine foundations. Survey programmes and preliminary results are presented and discussed, illustrating experiences with ultra-high resolution multichannel sparker, shallow gas, glacial tectonics and fractured clays.

1. Introduction
In June 2008 The Crown Estate announced the opening of nine development zones within UK waters for offshore wind farm leasing, with a combined target energy output of 25GW. In January 2010, the successful "bidders" for each development zone were announced, with Forewind Limited, a consortium comprising Statoil, Statkraft, Scottish and Southern Energy (SSE) and RWE npower renewable, awarded the development rights for Dogger Bank.

Forewind is committed to securing the necessary Zone Appraisal and Planning (ZAP) consents for construction and development of the Dogger Bank Zone (DBZ). To achieve this end, Forewind has developed an intensive programme of geophysical, geological, geotechnical, metocean, biological and archaeological surveying which will encompass the entire zone (8660 km^2), undertaken in four Tranches. The planned programme of surveying each Tranche is as follows:

- Tranche A (2000 km^2) – identified and surveyed in 2010 / 2011. Data interpretation and model development in 2011 / 2012. Consent application to be made end 2012.
- Tranche B (1500 km^2) – identified and partially surveyed in 2011. Survey work to be completed in 2012, alongside data interpretation and model development. Consent application to be made in 2013.
- Tranche C (To be decided).
- Tranche D (To be decided).

2. Regional Setting
Dogger Bank exists as an isolated topographic high in the centre of the North Sea (Figure 1A). The high extends into both UK and Dutch territorial waters. However, the UK segment under consideration for a R3 windfarm is situated between 125–290 km northeast of Yorkshire, lying in both UK and Dutch waters, with water depths ranging from 18–63 m below Lowest Astronomical Tide (LAT). Regional mapping of the North Sea basin completed by the early 1990's (Cameron et al. 1992), describe the Quaternary geology across the Dogger Bank as comprising a series of marine – intertidal – pro-glacial – subglacial – marine cycles, representing the significant climatic changes of this period, and the influences of three main glaciations to affect the North Sea basin, being the Elsterian, Saalian and Weichselian. However, seismic stratigraphies developed by BGS relied on extrapolation from other areas with no stratigraphic boreholes being drilled to aid geological

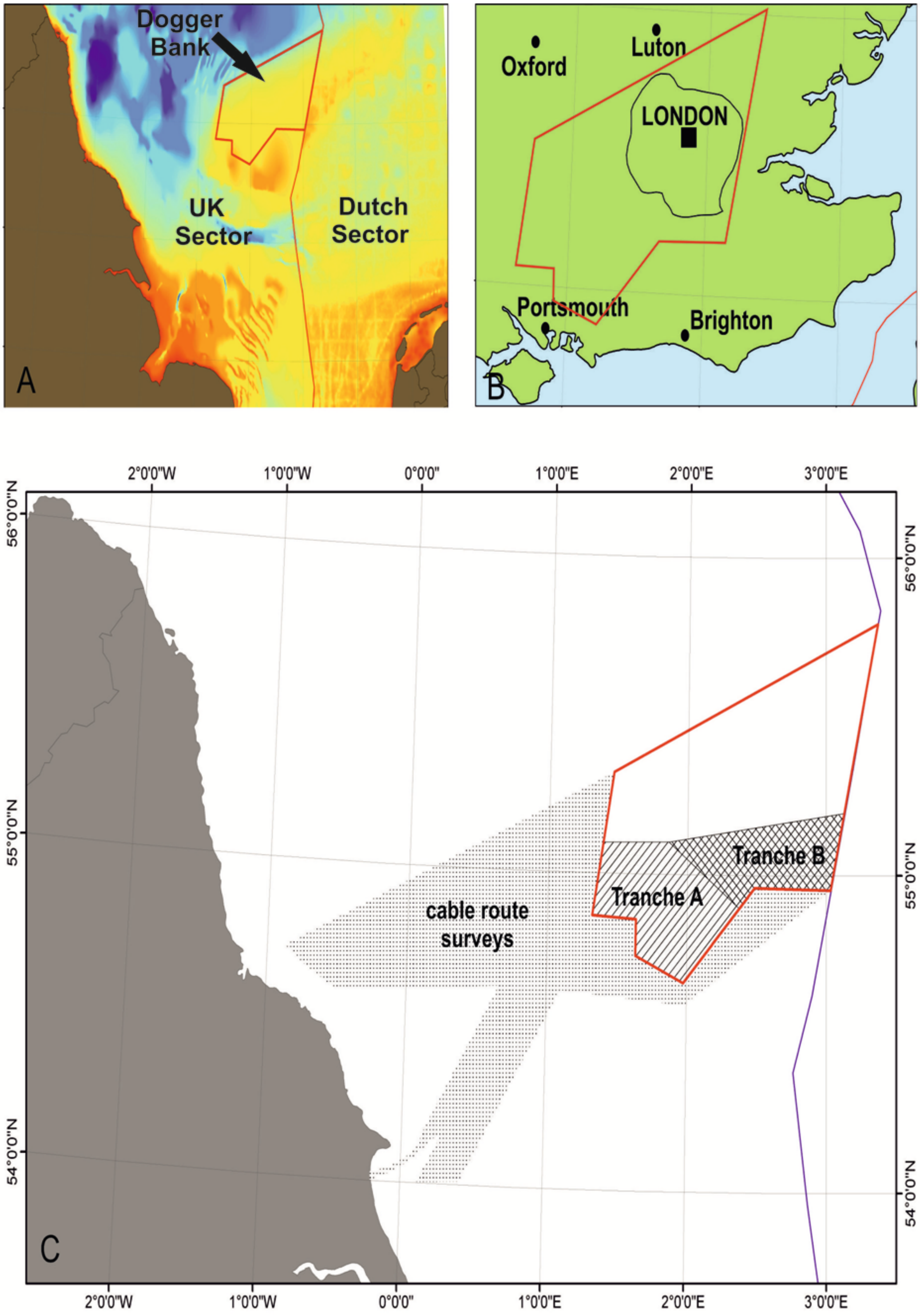

Figure 1: A) Gridded regional bathymetry showing the relative location of geomophological features with respect to Dogger Bank. The Dogger Bank Zone is outlined in red, with the UK median line marking the extent of UK waters. Data: DIGBath for UK waters, GEBCO for non-UK.; B) Dogger Bank R3 zone outline overlain onto the greater London and Home Counties region as an illustration of areal extent. Line surrounding London marks the location of the M25; C) Illustration of the areal extent of survey data acquired to date (February 2012), including connecting cable route surveys

descriptions, and little commercial investigation. In addition, the location of Dogger Bank at the juxtaposition between the southern and central North Sea led to inconsistencies in the correlation between the historically mapped BGS seismostratigraphies developed for each area (British Geological Survey 1986a, b and 1991a, b).

It is likely that Dogger Bank formed during the last glaciation (Weichselian) to affect the North Sea basin, between 30 000 and 15 000 BP, in a pro-glacial tundra like environment. The bank is formed from a core of Pleistocene ice-proximal sediment, and is surrounded and covered by a veneer of variable thickness of mobile Holocene sediments, predominantly re-worked glacial sand and gravels. Kuhlmann and Wong (2008) describe iceberg scars and palaeontological evidence for sea-ice existing across the Dogger Bank in the Dutch sector, although no evidence of similar features had been recorded in the UK sector.

Dogger Bank is part of a larger landmass commonly termed “Doggerland” that formed a land bridge between mainland Europe and Great Britain during sea level lows associated with significant ice sheet build up, with the potential for both hominid and animal occupation (Gaffney et al. 2007). As sea levels rose at the end of the last glaciation, meandering fluvial systems initially cut down through Dogger Bank, followed by complete marine inundation sometime between 6000–10 000 BP (Shennan et al. 2000; Fitch et al. 2005). Dogger Bank therefore represents a topographic feature that has been subjected to numerous influences and environments, from fluvial to marine, aeolian tundra to lacustrine and pro-glacial to glaciated, thereby increasing the complexity associated with sedimentation processes and features.

3. Methods

The fundamental challenge faced by Forewind is that the area of study is incredibly large when compared to Round 1 or 2 offshore windfarm areas, or shallow water survey areas for the oil & gas industry – this is not a typical 3 km x 3 km site survey (Figure 1B). Geotechnical and geological data from samples and cone penetrometer tests (CPTUs) are used to extrapolate potential lithology and geotechnical properties of the soils across more than 10’s of kms. Although a number of boreholes have been drilled to ground truth the vast amount of seismic data acquired to date (Table 1), they represent an overall low density of data. This extrapolation challenge has become particularly relevant as preliminary results indicate that there are rapid lateral and vertical changes in the sediments and their geotechnical properties associated with deposition proximal to an ice margin, and subsequent ice driven deformation and compression.

To date, Forewind has commissioned 14 geophysical and geotechnical surveys. A reconnaissance geophysical survey over the entire Dogger Bank Round 3 zone commenced in May 2010 following field trials of shallow seismic sources and receivers. Detailed geophysical and bathymetric surveys comprising sub-bottom profiling with both Pinger and Sparker (providing penetration to 500 ms two way travel time), multibeam bathymetry (100% coverage across Tranches A and B and corridors across the regional area), dual frequency sidescan sonar and magnetometer data were designed to meet the seabed clearance, environmental baseline and ZAP requirements. In order to achieve data coverage without extensive infill due to the shallow water, a main line spacing of 100 m was adopted with 500 m spaced cross lines. Acquisition of Tranche A geophysical data took approximately 5 months using two vessels. Tranche B and cable export route surveys are currently due to recommence in spring 2012, mobilised across four vessels. These are augmented by borehole sampling, CPTU’s and downhole wireline log acquisition to aid tie-in between the geophysical and geotechnical aspects of the project. Table 1 and Figure 1C summarise the volume and areal extent of data collected to present (February 2012).

The 2010 geotechnical phase of the investigation was designed to explore as great a variety of interpreted seismic profiles as possible. Site operations were conducted from standard oil and gas industry specification dynamically positioned geotechnical drilling ships. Borehole sampling and testing was conducted through heave compensated drill pipe and comprised piston and push sampling to recover high quality 72mm diameter samples at 41 locations to maximum borehole depths of 47m. Downhole testing was conducted using 3m stroke CPTU units whilst seabed continuous push CPTU tests were conducted at 96 locations using a sea bed deployed 24 tonne unit to penetrations of up to 40m below sea bed. Offshore laboratory facilities enabled limited geotechnical analysis and reporting to be undertaken along with planning for the onshore phase of testing.

Table 1: Summary of geophysical and geotechnical datasets acquired to February 2012 across the Dogger Bank Round 3 wind farm zone

Area	Instrument	Coverage / Number	~ Data volume (GB)
Regional	Multibeam Bathymetry & AGDS	16% coverage (1431km^2)	575
Regional	Dual Frequency Sidescan sonar	16% coverage (1431km^2)	1230
Regional	Sparker, Pinger, Magnetometer	7152 line kms	295
Regional 2010	CPTU's / Boreholes	96 CPTU's / 41boreholes	1
Tranche A	Multibeam Bathymetry	100% coverage (2020 km^2)	820
Tranche A	Dual Frequency Sidescan sonar	100% coverage (2020 km^2)	1850
Tranche A	Sparker, Pinger, Magnetometer	22,000 line kms	780
Tranche A 2011	Boreholes / wireline logs	14 boreholes / 13 logs	1
Tranche A	Environmental sampling & camera	103	150
Tranche B	Multibeam Bathymetry & AGDS	70% coverage (1090 km^2)	450
Tranche B	Dual Frequency Sidescan sonar	70% coverage (1090 km^2)	1140
Tranche B	Sparker, Pinger, Magnetometer	10900 line kms	450
Export Cable Route	Multibeam Bathymetry & AGDS	95% coverage (430 km^2)	173
Export Cable Route	Dual Frequency Sidescan sonar	80% coverage (325 km^2)	620
Export Cable Route	Pinger / sub-tow Boomer	7275 line kms	154
Export Cable Route	Environmental sampling & camera	76	70
Reports			10

Onshore laboratory testing commenced in November 2010 and was completed in April 2011. A 2011 geotechnical borehole campaign was undertaken to investigate seismic anomalies and the potential for shallow gas within the very shallow soils of Dogger Bank. This investigation mobilised the standard drilling, sampling and testing spread with additional safety systems. Specialist equipment included the Bengt Arne Torstensson (BAT) probe and wireline logging. The BAT probe was used to obtain pore fluid samples and give near real-time information on the presence of any free gas and the concentration of any gas in solution within the pore fluids. Wireline logging of pilot holes was utilised to provide information on the presence of free gas prior to conducting sampling and testing boreholes. The wireline tools also aided stratigraphic interpretations, and enabled targeted soil testing and sampling and BAT sampling.

4. Results

Preliminary interpretations of the regional dataset, when combined with the detailed work undertaken on the high-resolution datasets from Tranches A and B, have revealed many unexpected findings. These new interpretations have highlighted the impact of high-resolution data coverage and the recent developments in remote sensing technologies on historical interpretations and lithological designations that were based on the best available datasets, often from decades ago. Our findings indicate that there is a significant improvement in many fields of study with the current data resolutions that the Forewind surveys are acquiring:

- the core of Dogger Bank comprises pro-glacial / terrestrial soils deposited in a fresh water system and is not considered to be a marine deposit;

- geological formations can now be sub-divided into different sub-units, each having slightly different lithologies and geotechnical properties;
- previously undetectable geohazards can be identified, such as complex shallow channelling and small sand bodies where there is a potential for shallow gas to accumulate;
- different sequences of channel infill and bed-form development can be established;
- thin, laterally variable units that might prove hazardous to foundation installation jack-up platforms can be recognised;
- effect of glacio-tectonism on the soils of Dogger Bank;
- intense glacially derived deformation can now be mapped and the resulting impacts on soil conditions, shear strengths and associated properties assessed.

These are amongst a few examples of how radically our understanding of the Dogger Bank has improved. The following sections highlight some of the most significant areas where the improvement in data resolution has aided our development of a comprehensive, yet continually evolving, 3D model.

5. Discussion

5.1 Seismic Stratigraphy

The regional sub-bottom dataset appeared to correlate fairly well, (with some localised discrepancies), with the Quaternary succession interpretation from BGS presented by Cameron et al. (1992) and refined by Stoker et al. (2011). However, the high-resolution Tranche surveys revealed that Dogger Bank has a far more complex geological story than previously thought, showing multiple sub-units within previously recognised formations. Numerous cycles of channelling became evident within multiple formations. The deepest set of channels mapped are believed to be the Swarte Bank tunnel valleys formed by sub-glacial melt water during the Elsterian glaciation (e.g. Praeg, 2003). Above the Elsterian glacial surface there are at least two further surfaces each containing channels. These surfaces are sub-horizontal and comprise predominantly sandy sediments. It is upon this that the Dogger Bank Formation is deposited, the base of which is cut by multiple meandering channel systems, proposed to have formed through the actions of pro-glacial outwash channels running across a relatively flat tundra landscape prior to building of the Dogger Bank feature itself. Within the Dogger Bank Formation are a number of cyclical clay-rich to sand-rich sub-units, also with multiple channel systems, some of which stop at the base Dogger Bank horizon and some of which incise into the underlying formation. The cyclicity of the sub-units within the glacially derived Dogger Bank Formation suggest seasonal fluctuation or possibly ice-front advance and retreat drivers are linked to the style of sediment deposition across Tranche A. There are also significant buried, and later in-filled, fluvial channels that appear to be lie seismo-stratigraphically within the period generally assigned to represent the marine transgression and flooding of Dogger Bank, again with clear sequences of infill. However, recent C^{14} dating of organic material obtained by Wessex Archaeology (6190 years BP) suggest that the inundation is closer to the predicted dates (7000 – 6000 years BP) of Shennan et al. (2000) as opposed alternative published transgression dates of 10 000 – 7500 years ago (Fitch et al. 2005), placing inundation as being more recent than previously believed.

5.2 Glacio-tectonics and deformation

A significant degree of sediment deformation was observed in the high-resolution Tranche A sub-bottom profiles. The deformation ranged from soft sediment deformation of the upper 30-40 m that predominantly terminated at a laterally continuous, high amplitude reflector believed to be the base of the Dogger Bank Formation, although locally the deformation could be seen to punch through this horizon. Within this deformation, there was a combination of short wavelength (5-20 m) folding, some minor thrusting and large areas where all internal stratigraphy had been destroyed, resulting in a chaotic seismic character. However, the western and north-western area of Tranche A showed a very different style of deformation, with the effects reaching up to 120 m below sea bed. The deformation here was a combination of soft, large wavelength (50-100m) folding and more brittle faulting, with thrusting causing lateral and vertical over-riding of older sediments onto younger by up to 500 m on, presumably, the glacial downstream side, and listric faulting on the upstream side. In addition, there is a distinct seismic character associated with this zone of multiple thrust planes, whereas the listric faulting is associated with a band of acoustically blank sediments immediately to the west of the thrusts that is in turn followed by a zone where clear, laterally continuous laminated sediments were mapped. The thrusts originate on a decollement zone at ~100-120 m depth below seabed. This configuration indicates a combination of (glacial) vertical loading and horizontal shear leading to failure.

As the majority of the deformation is associated with the Dogger Bank Formation itself, it is proposed that this represents glacio-tectonic deformation as a result of fluctuating ice sheet margins in proximity to this region during the Weichselian glacial period. The high-resolution nature of the data has given an unprecedented insight into the formation of this feature, which is proposed to be a push-moraine sitting at the leading edge of an ice sheet in a pro-glacial environment. One possible hypothesis is that proximity to the leading edge of the ice sheet resulted in freezing to depth of sediments and the more brittle style of deformation, with the zone of acoustic blanking potentially representing an area where the ice load gradients (steep near the ice margin) caused downward listric movements that tilted and fragmented the under-lying sediments, resulting in the destruction of internal laminations combined with scattering of acoustic energy due to the inclination of the reflectors. The ice may have over-ridden the thrust zone, flattening any surface expression of faulting, and advance into zones where deformation was softer due to presence of glacial outwash and the possible proximity of pro-glacial lakes.

There are many hypothesised locations for the southernmost edge of ice during the Weichselian (e.g. Jelgersma, 1979; Huuse and Lykke-Andersen 2000; Shennan et al. 2000; Hubbard et al. 2009; Boston et al. 2010). It is hoped that future mapping of thrust and fold orientations will help decipher the story of which ice masses (British and Irish Ice Sheet or Fennscandian Ice Sheet), coming from which orientation, resulted in the formation of Dogger Bank, the nature of the resulting ice / sediment interaction, ice sheet fluctuations and compressional forces that drove internal deformation, and the relationship between the mode of glacial tectonism and encountered geotechnical properties of the Dogger Bank sediments. Comparison will be made with terrestrial examples such as the north Norfolk coast and with active glacial settings to improve the deformation aspect of the 3D model.

5.3 Seismic anomalies and shallow gas

Following the initial appraisal of regional seismic data, the proximity and connectivity of seismic anomalies to seabed and the known presence of peats in the Dogger Bank area, the presence of shallow gas within 40m of seabed was not considered the likely explanation of the numerous bright spots seen in the seismic data. However, drilling operations in 2010 were disrupted by a shallow gas blowout. A drilling campaign in 2011 was devised to assess and sample all types of seismic anomalies encountered within the top 50m of Dogger Bank, specifically to investigate the potential for shallow gas. The seismic anomalies were deliberately drilled with pilot holes, well logging and in situ pore water sampling to investigate the operational hazard of shallow gas. Interpretation of results from this campaign have concluded that there is no free gas present at the seismic anomalies tested but various gases are dissolved in the pore water. The 2011 campaign has confirmed that the blowout was probably caused by depressurization induced by sampling procedures. This has led to improved operating procedures for the recovery of samples.

A number of prominent sand units have been identified across the area during the investigation phases which have subsequently been proven to be associated with the seismic anomalies identified. On-going evaluation of wireline logs has shown the presence of ‘low density, low velocity’ clean sand units which correlate with the seismic anomalies and the depths where the largest volumes of dissolved gas were sampled in the in situ pore water. Further analyses of the results from this survey are currently ongoing to establish the precise material and behavioural relationships.

5.4 Physical Properties

The main unit into which any foundation will be emplaced is the Dogger Bank Formation which has been shown to be lithologically variable, reflecting the irregularity of reflectors mapped in the seismic profiles, as described in section 5.1. Shear strengths are typically firm to very stiff or hard but often show decreases with depth. This may reflect permafrost conditions during deposition or desiccation of sediments. Lateral geotechnical continuity can be limited, based on results from closely spaced boreholes and CPTUs.

Examination of borehole and CPTU data indicates the presence of distinct layers of high plasticity soils occupying two zones within the Dogger Bank Formation. The shallowest zone occurs immediately beneath sea bed sediments or equivalent; the second appears to coincide with the basal part of the Dogger Bank Formation whilst the deepest equates to a separate clay unit below the base of the Dogger Bank Formation. Plasticity values within these cohesive soils are recorded in the upper region of high plasticity through very high plasticity, (LL 50– 90, PI 35–55). A small number of profiles have high to very high plasticity material throughout the profile, preliminary assessments of which indicate that these characteristics may be associated with area specific structural evolution, deformation and subaerial exposure. Conversely, significant numbers of clay profiles exhibit very low liquid and plastic responses, (LL 20–40, PI 10–25), more typical of traditional North Sea glacial material. The precise relationships of these materials will be established in the course of ongoing and future analysis.

Several recovered cores show evidence of fabric with slickensides and fracturing. This has resulted in discrepancies in the shear strengths between undisturbed and remoulded triaxial results with remoulded tests giving apparent increases in strength and sensitivities of less than 1. The presence of potential weak, pre-sheared planes reflects large scale fault thrusts evident in the seismic record suggestive of a component of lateral stress from an active ice front at or close to the site. Ongoing work is aimed at understanding soil strength and the detectable extent of sample disturbance from sampling and gas coming out of solution and how this has impact on the anomalous undrained shear strengths encountered.

5.5 Salinity

In a number of boreholes, low salinities were measured during the in-situ BAT tests. Some laboratory testing of recovered sediments was then undertaken by Fugro, with the results ranging from 0.002–0.024 kg/kg indicating fresh to brackish water (seawater is commonly 0.035 kg/kg), so replicating the low salinities observed during the geotechnical acquisition. The geological model has clearly shown that although the site is currently located in the middle of an epi-continental sea, this has not always been the case. The area was exposed to a terrestrial, potentially tundra-like, environment for the majority of the time that sediments from the foundation zone depths were being deposited. This depositional environment, combined with the presence of freshwater proglacial lakes and outwash channels might explain the presence of low salinity pore water lenses, captured between clay seals. However, other hypotheses have also been proposed, including migration of fresh to brackish water along the fracture and thrust plains observed in the seismic dataset. Further analysis is required to define the exact source and age of these fresh to brackish water lenses, but what is certain is that their presence must be considered when undertaking future geotechnical testing of samples.

6. Conclusion

The large acreage covered by the Dogger Bank windfarm zone, combined with the vast number of turbines to be installed (~2000), means that untraditional methods have been adopted for its development. The data acquired on the 2.5 km grid is too ambiguous for use in the 3D model and it reinforces the need to acquire a 100 m-line spaced data for sufficient horizontal resolution for the 3D model. The results of all the various investigations are being collated in a GIS database that will ultimately allow site specific queries and provide the various geophysical, geological and geotechnical parameters as depth profiles, so that preliminary factors which would impact on the design parameters needed for the turbine foundations will be readily available for any location. It is also planned to develop a model that will present surfaces and suitable parameters in 3-dimensions. The predicted parameters will then be checked on a site by site basis before final installation.

The scale and evolving complexity of this project has demanded input from numerous groups and companies. A multidisciplinary team, all with different areas of expertise and skill sets, has been gathered over the last two-years to assist Forewind. What has become very evident is that there has to be clear communication and direction between the numerous companies and personnel involved in order to coordinate the interpretation and management of vast quantities of data, information and results, and synthesise them into a format that is easily understandable for the licensing process team and the foundation design engineers, within the tight time scale set by the overall project development deadlines. These requirements necessitate regular communications, workshops, a large, secure FTP site readily accessible by all parties and a clear method for QA/QC'ing the many technical notes being produced as a result of data interpretation.

The survey findings to date have proven beyond doubt the absolute necessity for a fully calibrated engineering-focused 3D understanding of the Dogger Bank development area. Results of studies pursued thus far have confirmed the perceived 3D complexity of the area, from both a geotechnical and geological point of view, and will ultimately enable the area to be categorised in the full geotechnical context required for engineering development. This categorisation will permit geotechnical or engineering provinces to be defined and refined, enabling selected project areas to be optimised and providing engineering data for the most cost effective foundation solution possible. Without the ongoing and proposed processes, overall development and construction costs for the Dogger Bank area would be significantly higher.

It is clear that the 3D model being developed for Tranche A and part of Tranche B is a continually evolving model that will develop as our understanding of the geo-complexities of Dogger Bank broadens. With further high-resolution datasets still to be acquired, the project partners will continue assessing all new data against the current model, refining the seismo- and lithostratigraphies, developing our comprehension of the relationship between the glacially derived sediment deformation and the resulting changes in geotechnical properties of the soils, assessing the different depositional environments for their effect on the physical properties of the soils and generally better understanding the overall complexities that are the "Geo Challenge" of Dogger Bank.

7. Acknowledgements

The authors would like to thank GEMS, Gardline and Fugro for their assistance in acquiring the geophysical and geotechnical datasets, and the above companies, and NGI, RPS, BGS and Wessex Archaeology for the work undertaken so far in processing and interpreting the preliminary results.
Above all, the authors would like to thank Forewind (Statoil, Statkraft, SSE and RWE npower) for the funding that has made this work possible. For C. Cotterill, D. Dove and D. Long, this paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

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