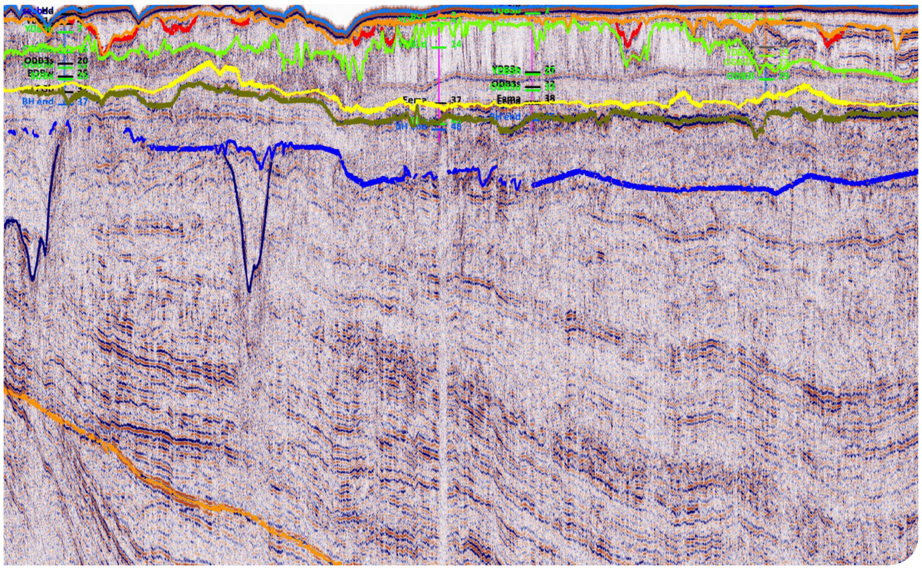


The geology of Dogger Bank
April 2015

Geological factsheet

16,000 B.C.
8,000 B.C.
7,000 B.C.
Land area today

Map of how Doggerland flooded and the changing landscape, National Geographic Magazine

Forewind and Dogger Bank

Forewind is a consortium of four leading international energy companies – RWE, SSE, Statkraft and Statoil – committed to securing all the necessary consents required for offshore wind energy development in the Dogger Bank Zone. The zone was awarded to Forewind as part of The Crown Estate's third leasing round.

The Dogger Bank Zone is in the North Sea, located between 125 and 290 kilometres (77 to 180 miles) off the east coast of Yorkshire. It is the largest of The Crown Estate's Round 3 zones, extending over approximately 8660 square kilometres (3343 square miles), which is about the same size as North Yorkshire. It is also one of the shallowest with water depths ranging from 18 to 63 metres (59 to 206 feet), making it ideal for wind turbine placement.

Through the offshore surveys and subsequent data analysis, Forewind has started to piece together a rich knowledge of the geology and history of the Dogger Bank itself.

Right: Worked flint dredged from Dogger Bank.

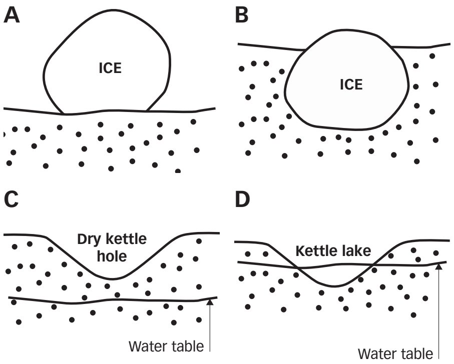
Doggerland

Dogger Bank sits as an isolated topographic high within the central to southern North Sea spanning UK, German, Danish and Dutch waters. The movement of water, or hydrodynamic processes, can explain many of the features surrounding Dogger Bank, however Dogger Bank itself sits as a geological anomaly, with no other similar large features observed in the North Sea Basin.

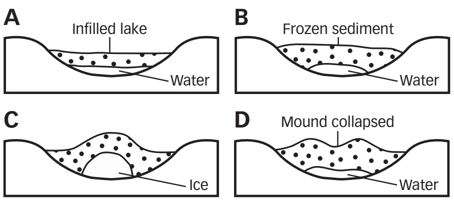
The remains of mammals, evidence of human activity and vegetation from sites to the south of the Dogger Bank Zone have told archaeologists that the general area was, for a period of time, a land mass connecting the UK to mainland Europe, known as Doggerland[1]. As the sea level rose after the last glaciation (ice age), it gradually became an island, until it was completely covered by water some time between 8000 and 5500 years ago.

Prior to Forewind's work, the geological and geographical maps of the area were based on sparse, widely spaced (tens of kilometres apart) data acquired in the late 1960s and 1970s. Now there is a growing understanding of the geology of Dogger Bank that has enabled geologists to add significant detail to the maps.

1. http://theconversation.com/doggerlands-lost-world-shows-melting-glaciers-have-drowned-lands-before-and-may-again-26472



Formation of a kettle hole



Formation of a closed system pingo

Gathering the data

To identify the sites for the wind farm locations on Dogger Bank, Forewind spent four years accumulating a huge amount of data via detailed geophysical (seabed and sub-seabed) surveys; seabed sampling and video traverses; geotechnical testing; wind resource data, other meteorological parameters, and oceanographic data. As well as surveying, the results have been interpreted and 3D models created to integrate the geology with geophysical and geotechnical data, and with subsequent foundation design parameters and layout.

Forewind carried out more than 170 cone penetration tests (CPT) to assess the properties of the seabed and sub-seabed soils, and 71 boreholes, to collect soil and water samples.

Surveyors also undertook nearly 60,000 kilometres of line surveys using a multibeam echosounder (to paint a picture of the seabed using sound, determine the depth of the seabed and detect objects lying on the seafloor); a side scan sonar (to take images of the seafloor); a marine magnetometer (to look for magnetic anomalies such as wrecks) and seismic profiles (using sound to image the geological layers beneath the seabed).

Through this work, it has been found that the Dogger Bank has a complex geology, both vertically and laterally, as a result of the many different environments that have helped to form it over the last 100,000 years.

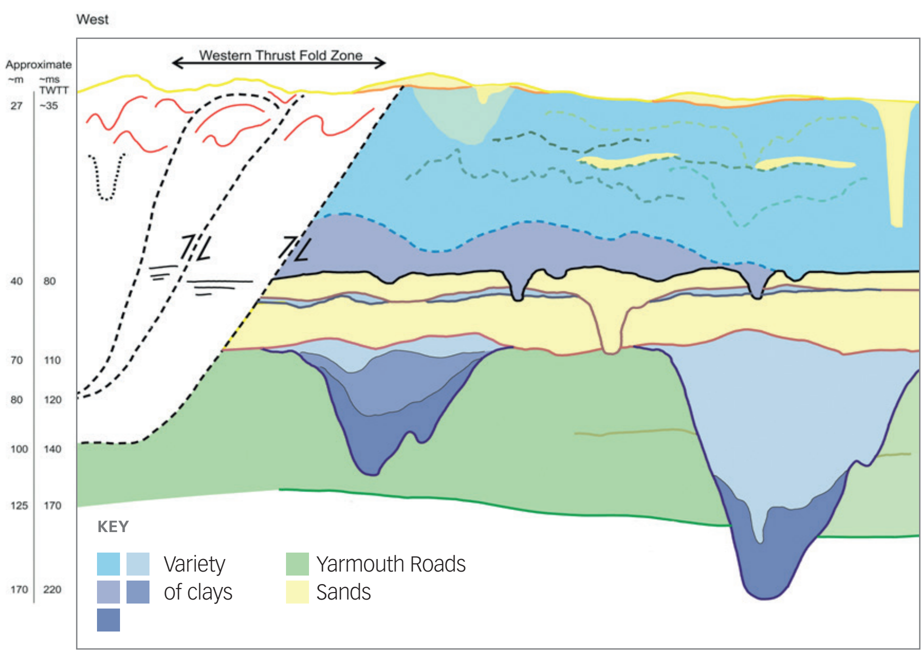
Formation of Dogger Bank

Dogger Bank is now generally accepted to be a highly deformed glacial till, created as the ice sheets advanced southwards, bringing eroded soils with them that were often left in ridges (terminal moraines) at the front of the ice. As the ice moved backwards and forwards these soils were "rucked up" forming features known as push-moraines, which were then overridden and eroded. Between these ridges shallow lakes developed. This earliest environment has been compared to the current tundra in Canada and Russia.

It is called "deformed" because the soils that were originally deposited horizontally, like layers in a cake, are now often folded over, disturbed and sometimes even faulted, due to a combination of processes that have been active over the past 130,000 years, in this highly dynamic environment.

The more the area has been investigated, the more evidence for deformation has been found. This is due to the fact Forewind's data was collected at a much finer resolution than previously, combined with integrating the various disciplines from the start. Work is ongoing to attempt to differentiate the types of deformation and depths affected, mapping zones of defined thrusting and faulting. However, in addition to the faulting, other features found included evidence of past lakes, complex channel systems and glacial features such as pingos and kettle holes, which formed as ice grew in the tundra or fell from the front of an ice sheet and then melted away over thousands of years.

Geological cartoon of Dogger Bank Tranche A



Forewind chose to develop the zone sequentially in stages, known as tranches, from within which the project boundaries were identified. This geological cartoon is from the first tranche, Tranche A, and was constructed to explain the seismic stratigraphy. (Not drawn to scale)

Clay samples taken from across Dogger Bank have different geotechnical properties and responses

The ongoing research and analysis will continue in a circular fashion through various iterations as the understanding of the impacts of the many environments on the sediments increases. However, it is clear that sediments have been deposited and reshaped by a number of different environments from glacial activity – tundra, permafrost, sub-glacial (under ice), pro-glacial (in front of ice) – through to lakes, rivers and estuaries or lagoons, as a terrestrial landmass exposed to wind and weather, and to later changes as the sea level rose and flooded Dogger Bank.

Environmental analysis

The datasets collected as part of Forewind's environmental impact assessments enabled experts to far better define the geological strata, or layers, and also to introduce an environmental aspect to the analysis. That is, they can assess if the sediments were deposited when the area was marine or terrestrial, covered by ice or part of a river delta. Many processes can then act on those sediments, from drying out (desiccation), freezing/ thawing cycles, loading and flooding, all of which can make a large impact on the geotechnical properties of the soils, altering them from their original properties. This can help explain why soils of the same origin and age can have different properties across an expansive area.

For example, clay samples taken from across Dogger Bank had varied geotechnical properties and behaviours. This may be because they were formed from different minerals or because some had been covered by ice and loaded while others had not. The challenge was to be able to distinguish one sample of clay from another, and find any patterns that could be confidently extrapolated across the area.

Visual observations, seismic character and test results were used, in combination with the potential soil stress histories, to see what factors determined the geotechnical properties of each clay sample or layer. The environmental process of desiccation and the freeze and thaw cycles that happened across the southern North Sea during much of the last ice age are likely to have had the most significant impact.

Glacial activity

Ice is assumed to be key to the development of today's Dogger Bank. Huge amounts of sediment were eroded from hinterlands in Scandinavia and the UK and carried by ice sheets to be deposited into the North Sea over at least three ice ages during the Quaternary Period (~2.5 million years).

Identifying the origins of the sediment is complicated as not only is the possible source area expansive, but the sediment may have been re-worked by different ice sheets moving in different directions. However, varying minerals within the clays can indicate whether the soils originally came from the UK or Scandinavia.

It is thought that the maximum extent of ice sheets during the last glacial period was just south of Dogger Bank. During pulses of activity, ice would have fluctuated around this point, sometimes retreating and sometimes advancing, mirroring changes in the climate, before finally decaying and disappearing from the area. Over time, as the Dogger Bank built up, it would start to become a significant obstacle to later ice movements in the North Sea.

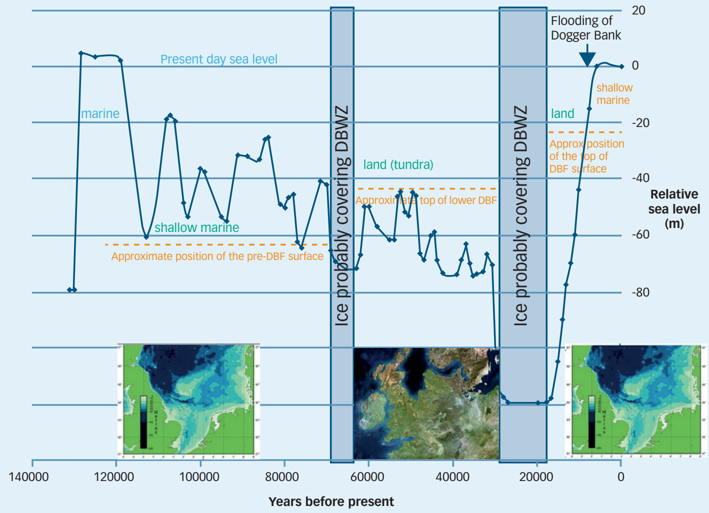
The scale of the lateral variations in rock texture, grain size and composition can be attributed to glacial activity, although it is still not known exactly how long ice may have covered the area or how often it fluctuated across the Dogger Bank.

Analysis of core material collected during the Forewind surveys indicated that parts of the area had experienced numerous sedimentary environments during the last ice age. These included breaks in deposition when glacial processes shaped the landscape; covering and loading of the sediments; erosion and lateral compression of the sediments; localised formation of freshwater lakes and carving of channels. Many of these processes occurred over tens of thousands of years, changing the nature and behaviour of the soils.

Changing sea level

It is accepted that Dogger Bank was land well into the Holocene period (the past 10,000 years), becoming an island before finally being flooded 8000 to 5500 years ago. It has been possible to track the "evolutionary" stages of its development (for example from artefacts, mammal remains and pollens), and see signatures of a changing climate and sea level.

When the core sample data was combined with the Forewind seismic data, it suggested there were multiple transgressions – with the sea level rising and falling again – before Dogger Bank was finally flooded.



ABBREVIATIONS: DBF – Dogger Bank Formation DBWZ – Dogger Bank Wind Zone

The possible impacts of changing sea levels

Sample donations

The borehole core samples collected from Dogger Bank will be donated to the National Geological Repository (NGR) in Nottingham for use by universities and students to further their understanding of the geology, archaeology, sea level rise information and chemical signatures that act as proxies (indicators) for past climate change.

The NGR is part of the British Geological Survey and maintains the UK's largest core storage examination facility. The donation of these samples will help develop our understanding of the Dogger Bank area through continued research, with dissemination of the knowledge gained to the wider community.

Next steps

As the wind farms progress post-consent, the information gleaned to date will help the operators to design the projects and define feasible foundation types. Preliminary work shows that Dogger Bank is suitable for a range of foundation types such as monopiles, gravity base and jacket structures, and monopods (those with steel skirts penetrating the seabed). While there are differences across the zone, each location surveyed appears to be appropriate for at least one foundation type.

Studies and analysis will continue right up until construction, and most likely beyond, gradually expanding the knowledge about the geology and history of this well-known geographical feature.

Timeline

Time period	Land / Sea	Environment
130,000 to 114,000 years ago (Eemian)	Water depth slightly deeper than today at around 50 metres	Marine
~80,0000 to 60,000 years ago (Early Weichselian)	Water depth around 10 metres	Marine
~40,000 years ago (Middle Weichselian)	25 metres above sea level	Land/tundra
~20,000 years ago (Late Weichselian)	Ice covered land	Ice/glacial
10,000 to 8500 years ago (Holocene Shorelines)	Sea level rises and slowly covers the land. Dogger Bank goes from being an extension of the European landmass to an isolated island	Tundra to temperate to marine
~5500 years ago	Sea level rise finally floods the area	Marine

Contact

For more information about Forewind and the Dogger Bank development visit the website www.forewind.co.uk or contact us via:

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