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The evolution of the Dogger Bank, North Sea: A complex history of terrestrial, glacial and marine environmental change

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ABSTRACT

This paper presents a summary of the results of a detailed multidisciplinary study of the near surface geology of the Dogger Bank in the southern central North Sea, forming part of a site investigation for a major windfarm development undertaken by the Forewind consortium. It has revealed that the Dogger Bank is internally complex rather than comprising a simple “layer cake” of the Quaternary sediments as previously thought. Regional and high-resolution seismic surveys have enabled a revised stratigraphic framework to be established for the upper part of this sequence which comprises the Eem (oldest), Dogger Bank, Bolders Bank formations and Botney Cut Formation (youngest), overlain by a typically thin Holocene sequence. Detailed mapping of key horizons identified on the high-resolution seismic profiles has led to the recognition of a series of buried palaeo-landsystems which are characterised by a range of features including; glacial, glacifluvial and fluvial channels, a large-scale glacitectonic thrust-moraine complex with intervening ice-marginal basins, a lacustrine basin and marine ravinement surfaces. Interpretation of these buried landscapes has enabled the development of an environmental change model to explain the evolution of the Dogger Bank. This evolution was driven by the complex interplay between climate change, ice sheet dynamics and sea level change associated with the growth and subsequent demise of the British and Irish and Fennoscandian ice sheets during the Weichselian glaciation. Following the decay of these ice sheets the Dogger Bank entered a period of significant climatic and environmental flux which saw a terrestrial landscape being progressively inundated as sea levels rose during the Holocene.

1. Introduction

The North Sea has had a long and complex geological history with its present-day structural configuration largely being the result of rifting during the Jurassic–Early Cretaceous, followed by thermal cooling and subsidence (Glennie and Underhill, 1998; Zanella and Coward, 2003). Since the middle Cenozoic, up to 3000 m of Oligocene to Holocene sediments have accumulated in the central graben region of the North Sea, locally including more than 800 m of Quaternary sediments (Caston, 1977, 1979; Gatliff et al., 1994). Preserved within this sedimentary record is the evidence for several ice sheets having advanced into the North Sea at different stages during the Quaternary, contributing to the periodic erosion and infill of this sedimentary basin. The traditional view of the Pleistocene glacial history of the North Sea suggests that the region has encountered three major glacial episodes during the past 500 ka, referred to as the Elsterian Stage (oldest, Marine Isotope Stage [MIS] 12), Saalian Stage (MIS 10–6), and Weichselian Stage (youngest, MIS 5d–2) glaciations (Eisma et al., 1979; Jansen et al., 1979; Caston, 1979; Balson and Cameron, 1985; Sejrup et al., 1987, 1995, 2000, 2003; Cameron et al., 1987, 1992; Ehlers, 1990; Graham et al., 2007, 2011; Kristensen et al., 2007; Bradwell et al., 2008; Stoker et al., 2011; Stewart et al., 2013; Ottesen et al., 2014). The main criterion for this threefold subdivision are the discrete sets of tunnel valleys preserved offshore, which delimit the broad extents and submarginal drainage systems developed

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beneath these ice sheets during each phase of glaciation (Wingfield, 1990; Huuse et al., 2001; Praeg, 2003; Lonergan et al., 2006; Kristensen et al., 2007; Stewart and Lonergan, 2011; Stewart et al., 2013). However, in recent years, this simple three-stage model has come under considerable scrutiny and there is now growing body of evidence that there may have been many more glacial episodes (e.g. Lonergan et al., 2006; Stewart and Lonergan, 2011). The increasing geomorphological evidence for ice sheets having extended across the northwest European continental shelves (Graham et al., 2007, 2011; Bradwell et al., 2008), means that it is becoming increasingly apparent that the sedimentary record within the North Sea Basin is likely to contain the key evidence for the existence of these former Pleistocene ice sheets and intervening interglacials. Furthermore, the North Sea Basin is known to have been an important pathway for large-scale glacial transport to the deeper Atlantic Ocean, as shown by the presence of large glacial debris fans along the northwest European continental margin. These fans were fed by ice streams, comparable with those that drain the majority of ice from modern-day Greenland and Antarctica, and these were probably a key feature of the North Sea ice sheets. As a result, the North Sea Basin is an important site for understanding the discharge and stability of the major northern European palaeo-ice masses, including the British and Irish and Fennoscandian ice sheets.

A number of the current models for the Weichselian Stage glaciation of the North Sea (Graham et al., 2007, 2011; Bradwell et al., 2008; Sejrup et al., 2009, 2016) require the British and Irish and Fennoscandian ice sheets to have converged forming a "confluence zone" within the central part of the basin located to the north of, and between Dogger Bank and Denmark. However, the actual limits of these major ice masses within the southern North Sea are poorly understood and constrained (Catt, 1991; Sejrup et al., 2009). Consequently, establishing a robust model for the evolution of the Dogger Bank is critical to our understanding ice sheet dynamics in the southern central North Sea. However, until recently, very little was known about the sedimentary and structural architecture of the Quaternary and Holocene sediments of the Dogger Bank region.

In 2008 The Crown Estate identified nine potential development zones for Round 3 windfarm development. In response to this call, RWE Npower Renewables, SSE, Statoil and Statkraft formed a consortium (Forewind) with a view to developing part of the Dogger Bank area (referred to as the Dogger Bank Zone) of the central North Sea (Fig. 1). The Dogger Bank lies in an area of shallow water approximately 100 km wide by 250 km long, and whilst the majority of the bank falls within the UK sector of the North Sea (Fig. 1a), it also extends into Dutch and German territorial waters. The Dogger Bank Zone (DBZ) is situated 125–290 km northeast of the Yorkshire coast and is the largest of the Round 3 zones, covering an area of 8660 km^2, with water depths ranging from 18 to 63 m Lowest Astronomical Tide (LAT). The Round 3 Zone covers the central and northern parts of the Dogger Bank, and is located entirely within the UK sector (Fig. 1b). The lack of understanding regarding the sedimentary and structural architecture of the Quaternary and Holocene sediments on Dogger Bank represented a major issue for the development of a windfarm in the DBZ. The stratigraphy and structure of the Dogger Bank was believed to be a relatively simple "layer-cake" with much of the upper 60 m (the foundation depth for the windfarm) of this unconsolidated sedimentary sequence being assigned to the Dogger Bank Formation (Balson and Cameron, 1985; Cameron et al., 1992). However, the acquisition of high-resolution data during the site investigation of the DBZ has proven that this is far from the case. This paper presents a summary of the results of the detailed multidisciplinary study undertaken by scientists from the Forewind consortium, the British Geological Survey and academia. Regional and high-resolution seismic survey data acquired during the site investigation are used to provide an updated interpretation of the stratigraphy of the DBZ, allowing the formulation of a robust palaeoenvironmental model which for the first time describes the evolution of this poorly understood region.

2. Regional setting and previous research

Dogger Bank is an isolated topographic high in the centre of the North Sea (Fig. 1a), and forms part of a sedimentary basin that has experienced long periods of rifting, sedimentation and glaciations over the last 300 million years. These processes have fundamentally influenced the nature, sedimentary architecture and geotechnical properties of the seabed and sub-seabed. It is well-established that much of the floor of the North Sea had been profoundly modified during the last Weichselian (Devensian) glaciation (Eisma et al., 1979), with the earlier Quaternary history of sedimentation having also been controlled by alternating glacial and interglacial conditions, with the associated sea level fluctuations (Jansen et al., 1979). However, Caston (1979) demonstrated that a significant thickness of Quaternary deposits throughout the North Sea Basin had accumulated through tectonic subsidence. Subsequent geological mapping in the southern North Sea has shown that the majority of the deposits are in fact early to middle Quaternary in age, and deposited in shallow water, distal and deltaic environments (Balson and Cameron, 1985). These sediments represent the continuation of a major delta system that extended into the area from the Netherlands which was fed not only by the Rhine but also several major rivers draining catchments in the area of the Baltic. These major fluvial systems eventually merged with smaller river systems flowing eastwards from the UK (Zagwijn, 1989, p. 114; Zagwijn and Doppert, 1978) in what is now the southern and central North Sea Basin. It was only during the middle to Late Quaternary that ice sheets eventually encroached into the southern part of the North Sea leading to deposition of locally thick sequences of proglacial and subglacial sediments. In the DBZ, Quaternary sediments can be up to 800 m thick - one of the thickest occurrences in the North Sea, comprising a mix of glacial, deltaic and shallow marine deposits.

The Quaternary Era represents a period of considerable global climatic instability, with repeated cycles of climate change. The base of the Quaternary is currently considered to occur at 2.6 Ma (http://www.geosociety.org/science/timescale/timescl.pdf), coinciding with a major change in the fauna of northwestern Europe which is considered to be the first signal in Europe of a major global cooling event. In the Dutch sector of the Dogger Bank, iceberg scars and palaeontological provide evidence for the presence of sea-ice dating back to about 2.2 Ma (Kuhlmann and Wong, 2008).

Regional mapping of the North Sea basin, completed by the late 1980's and early 1990's (BGS, 1989, 1991; Cameron et al., 1992), led to the recognition that the Quaternary geology of the Dogger Bank comprises a series of marine – intertidal – proglacial – subglacial – marine cycles, which record significant climatic changes during this period. Furthermore these cycles provide the key evidence for the influence of three main glaciations within the North Sea Basin; namely the Elsterian, Saalian and Weichselian. Onshore the subdivision of the Quaternary is based upon lithostratigraphic and biostratigraphic evidence, whilst offshore the stratigraphy is based on seismostratigraphic principals. Consequently a different set of names has been adopted for the main units (Table 1). Stoker et al. (2011) divided the entire Quaternary succession in the southern North Sea into three major groups: