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Ice marginal dynamics of the last British-Irish Ice Sheet in the southern North Sea: Ice limits, timing and the influence of the Dogger Bank

David H. Roberts [a, *], David J.A. Evans [a], S. Louise Callard [a], Chris D. Clark [b], Mark D. Bateman [b], Alicia Medialdea [b], Dayton Dove [c], Carol J. Cotterill [c], Margot Saher [d], Colm Ó. Cofaigh [a], Richard C. Chiverrell [e], Steven G. Moreton [f], Derek Fabel [g], Tom Bradwell [h]

[a] Department of Geography, Durham University, Durham, DH1 3LE, UK
[b] Department of Geography, University of Sheffield, Sheffield, S10 2TN, UK
[c] British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK
[d] School of Ocean Sciences, Bangor University, Menai Bridge, LL59 5AB, UK
[e] Department of Geography, University of Liverpool, Liverpool, L69 7ZT, UK
[f] Natural Environment Research Council, Radiocarbon facility, East Kilbride, Scotland, G75 0QF, UK
[g] SUERC, Rankine Avenue, Scottish Enterprise Technology Park, East Kilbride, Scotland, G75 0QF, UK
[h] Biological and Environmental Sciences, University of Stirling, Stirling, Scotland, FK9 4LA, UK

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ABSTRACT

The southern North Sea is a particularly important area for understanding the behaviour of the British-Irish Ice Sheet (BIIS) during the last glacial cycle. It preserves a record of the maximum extent of the eastern sector of the BIIS as well as evidence for multiple different ice flow phases and the dynamic re-organisation of the BIIS. However, to date, the known ice sheet history and geochronology of this region is predominantly derived from onshore geological evidence, and the offshore imprint and dynamic history of the last ice sheet remain largely unknown. Using new data collected by the BRITICE-CHRONO project this paper explores the origin and age of the Dogger Bank; re-assesses the extent and age of the glaciogenic deposits across the shallow areas of the North Sea between the Dogger Bank and the north Norfolk coast and; re-examines the dynamic behaviour of the BIIS in the southern North Sea between 31.6 and 21.5 ka.

This paper shows the core of the Dogger Bank to be composed glaciolacustrine sediment deposited between 31.6 and 25.8 ka. Following its formation the western end of the Dogger lake was overridden with ice reaching ~54°N where the ice margin is co-incident with the southerly extent of subglacial tills previously mapped as Bolders Bank Fm. This initial ice override and retreat northwards back across the Dogger lake was complete by 23.1 ka, but resulted in widespread compressive glaciotectonism of the lake sediments and the formation of thrust moraine complexes. Along the northern edge of the bank moraines are on-lapped by later phase glaciolacustrine and marine sediments but do not show evidence of subsequent ice override.

The shallow seafloor to the west and southwest of the Dogger Bank records several later phases of ice advance and retreat as the North Sea Lobe flowed between the Dogger Bank and the Yorkshire/Lincolnshire coasts and reached North Norfolk. New optically stimulated luminescence (OSL) ages from Garrett Hill on outwash limit the arrival of the BIIS on the Norfolk coast to 22.8–21.5 ka. Multiple till sheets and chains of moraines on the seafloor north of Norfolk mark dynamic oscillation of the North Sea Lobe margin as it retreated northwards. This pattern of behaviour is broadly synchronous with the terrestrial record of deposition of subglacial, glaciofluvial and glaciolacustrine sediments along the Yorkshire coast which relate to post Dimlington Stadial ice marginal oscillations after 21.5 ka.

With respect to forcing mechanisms it is likely that during the early phases of the last glacial maximum (~30-23ka) the interaction between the southern margin of the BIIS and the Dogger Lake was

* Corresponding author.
E-mail address: d.h.roberts@durham.ac.uk (D.H. Roberts).

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critical in influencing flow instability and rapid ice advance and retreat. However, during the latter part of the last glacial maximum (22–21 ka) late-phase ice advance in the southern North Sea became restricted to the western side of the Dogger Bank which was a substantial topographic feature by this time. This topographic confinement, in addition to decoupling of the BIIS and the Fennoscandian Ice Sheet (FIS) further north, enabled ice to reach the north Norfolk coast, overprinting the seabed with late-phase tills of the Bolders Bank Fm.

1. Introduction

Investigating the external and internal forcing factors that control ice sheet behaviour is an important scientific and societal challenge if present and future changes to the cryosphere are to be understood and contextualised over decadal to millennial timescales (Sejrup et al., 2016; Bamber et al., 2009; DeConto and Pollard, 2016). During the Last Glacial Maximum (LGM; MIS2) the British-Irish Ice Sheet (BIIS) was a very dynamic ice sheet, being situated at low latitude and in close proximity of the North Atlantic, where oceanic and atmospheric changes could rapidly influence mass balance (McCabe et al., 1998; Hubbard et al., 2009). The eastern sector of the last BIIS was particularly important in influencing both the advance and retreat behaviour of the ice sheet (Carr et al., 2006; Davies et al., 2009; Graham et al., 2011). In the central and northern North Sea coalescence between the BIIS and the Fennoscandian Ice Sheet (FIS) radically changed ice sheet dynamics in the build-up to the LGM (~30–21 ka for BIIS; see Chiverrell and Thomas, 2010 for overview). Ice sheet coupling forced ice flow north into the Atlantic to a marine-terminating margin at the Norwegian shelf break (see Graham et al., 2011 for overview), whilst southerly directed flow terminated in the southern North Sea in a more stable terrestrial setting (global eustatic sea-level fall having produced a land-bridge between Europe and the UK). Furthermore, as the last glacial cycle waned decoupling between the two ice sheets triggered ice divide migration in the northern and central sectors of the BIIS inducing rapid flow re-organisation in the North Sea (Livingstone et al., 2012; Clark et al., 2012), though the timing of this remains uncertain (Sejrup et al., 2016).

The central and southern North Sea is a particularly important area because its geomorphic and sedimentary archives preserve a record not only of the maximum extent of the eastern sector of the BIIS (Fig. 1), but critically, a record of multiple ice streams draining the centre of the BIIS which were thought to be sensitive to both external and internal forcing (Livingstone et al., 2012). For many years it has been known that stratigraphic sequences along the coast of the western North Sea basin contain a record of an ice sheet prone to rapid, dynamic marginal instabilities and possible surges (Eyles et al., 1994; Evans et al., 1995; Boston et al., 2010; Evans and Thomson, 2010; Roberts et al., 2013; Dove et al., 2017), and more recent onshore mapping and optically stimulated luminescence (OSL) chronologies confirm notions of a dynamic, complex ice sheet margin oscillating on sub-millennial timescales (Bateman et al., 2011, 2015; Evans et al., 2017).

However, despite these recent research efforts, key aspects of the offshore imprint and dynamic history of the eastern sector of the BIIS are largely unknown. The BIIS limit is poorly defined and the multiphase, flow history of the ice sheet, particularly the North Sea Lobe (NSL), has only been partially reconstructed onshore. The maximum extent of ice during MIS 2 has been mapped along the North Norfolk coast and inferred to extend offshore to link with the Bolders Bank Fm (BDK) (based on stratigraphic correlation) (Long et al., 1988; Cameron et al., 1992), but these hypotheses have never been tested by chronometric dates. Enigmatic offshore features such the Dogger Bank (Carr et al., 2006), tunnel valleys (Ehlers and Wingfield, 1991) and large ridges of possible morainic origin (Sejrup et al., 2016) lack clear morpho-stratigraphic integration with the onshore glacial history of the east English coast (Boston et al., 2010). Only recently have Dove et al. (2017) made a significant step forward in identifying broad moraine arcs and BDK till sheets on the seafloor north of Norfolk, whilst Cotterill et al. (2017) have demonstrated that the Dogger Bank is composed of series of glacitectonised glaciolacustrine and outwash sediments (Dogger Bank Formation). Hence, there are stratigraphic and geomorphic indicators from the offshore record that point to dynamic and complex BIIS behaviour during the last glacial cycle, but they remain largely unintegrated with current ice sheet reconstructions.

Using new onshore and offshore geophysical, sedimentological and geochronological data collected by the BRITICE-Chrono project this paper aims to investigate the offshore glacial history of the southern North Sea to provide an integrated model for ice sheet advance and retreat in the region. It specifically explores the origin and age of the Dogger Bank; re-assesses the extent, age and diachroneity of the MIS 2 limit and associated BDK tills in the southern North Sea and; re-examines the dynamic behaviour of the BIIS in the southern North Sea between 31.6 and 21.5 ka.

2. Setting and BIIS history in the North Sea during MIS 2

The southern North Sea is a subsiding, tectonic basin. Throughout the Plio-Pleistocene it was a major depo-centre becoming infilled with deltaic, prodeltaic, glacial and marine deposits by the Middle Pleistocene (Rea et al., 2018). In the southwest, Jurassic and Cretaceous strata forming the edge of the basin outcrop close to the seabed with only a thin veneer of Quaternary sediments in places. Further east in the central basin, ~1200 m of Neogene and Quaternary sediments make up the seafloor (Cameron et al., 1992). The Dogger Bank lies just north of 54°N and runs SW to NE from ~1°E to 5°E. It is almost 300 km long and 130 km wide and forms a marked geomorphic high on the seabed. It is located in 50 to 15 m water depth (Fig. 1). Large sand ridges up to 25 m in amplitude and several 10's kilometres in length mark the NW and SW edges of the Dogger Bank, before the seafloor drops off to between −80 and −40 m OD toward the Durham and Yorkshire coasts.

To the south of the Dogger Bank, toward the Norfolk coast and the Wash, the seafloor has several features of note. A large depression, the Outer Silver Pit, runs west to east immediately south of the western end of the Dogger Bank. South of this, several arcuate-shaped depressions/channels cross cut the seafloor trending N/NW to S/SE (e.g. Inner Silver Pit, Sole Pit; Well Hole; Coal Pit, Markhams Hole; Figs. 1 and 2). In places, the southern ends of these channels coincide with subtle, discontinuous, linear ridges (3–5 m amplitude) on the seafloor that trend west to east and which mark the southern edges of till sheets and subtle moraines (Dove et al., 2017). The most prominent positive topographic features of the southern North Sea are large sand ridges up to 40 m in amplitude