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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

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A B S T R A C T

Along the terrestrial margin of the southern North Sea, previous studies of the MIS 2 glaciation impacting eastern Britain have played a significant role in the development of principles relating to ice sheet dynamics (e.g. deformable beds), and the practice of reconstructing the style, timing, and spatial configuration of palaeo-ice sheets. These detailed terrestrially-based findings have however relied on observations made from only the outer edges of the former ice mass, as the North Sea Lobe (NSL) of the British-Irish Ice Sheet (BIIS) occupied an area that is now almost entirely submarine (c.21–15 ka). Compounded by the fact that marine-acquired data have been primarily of insufficient quality and density, the configuration and behaviour of the last BIIS in the southern North Sea remains surprisingly poorly constrained.

This paper presents analysis of a new, integrated set of extensive seabed geomorphological and seismostratigraphic observations that both advances the principles developed previously onshore (e.g. multiple advance and retreat cycles), and provides a more detailed and accurate reconstruction of the BIIS at its southern-most extent in the North Sea. A new bathymetry compilation of the region reveals a series of broad sedimentary wedges and associated moraines that represent several terminal positions of the NSL. These former still-stand ice margins (1–4) are also found to relate to newly-identified architectural patterns (shallow stacked sedimentary wedges) in the region's seismic stratigraphy (previously mapped singularly as the Bolders Bank Formation). With ground-truthing constraint provided by sediment cores, these wedges are interpreted as sub-marginal till wedges, formed by complex subglacial accretionary processes that resulted in till thickening towards the former ice-sheet margins. The newly sub-divided shallow seismic stratigraphy (at least five units) also provides an indication of the relative event chronology of the NSL. While there is a general record of south-to-north retreat, seismic data also indicate episodes of ice-sheet re-advance suggestive of an oscillating margin (e.g. MIS 2 maximum not related to first incursion of ice into region). Demonstrating further landform interdependence, geographically-grouped sets of tunnel valleys are shown to be genetically related to these individual ice margins, providing clear insight into how meltwater drainage was organised at the evolving termini of this dynamic ice lobe. The newly reconstructed offshore ice margins are found to be well correlated with previously observed terrestrial limits in Lincolnshire and E. Yorkshire (Holderness) (e.g. MIS 2 maximum and Withernsea Till). This reconstruction will hopefully provide a useful framework for studies targeting the climatic, mass-balance, and external glaciological factors (i.e. Fennoscandian Ice Sheet) that influenced late-stage advance and deglaciation, important for accurately characterising both modern and palaeo-ice sheets.

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1. Introduction

The extent, pattern, and timing and dynamics of Late Devensian (Weichselian/Marine Isotope Stage (MIS) 2) glaciation in the southern North Sea has long been discussed, not least due to the classic terrestrial field sites located along the adjacent Norfolk, Lincolnshire, and eastern Yorkshire coasts (e.g. Catt and Penny, 1966; Madgett and Catt, 1978; Pawley et al., 2006, Catt, 2007; Evans and Thomson, 2010; Bateman et al., 2015), including the type site for the Last Glacial Maximum (LGM) within the British Isles at Dimlington (Penny et al., 1969; Rose, 1985; Bateman et al., 2011). Despite the abundance of onshore evidence, and conjectures on the offshore pattern/limits of glaciation (Valentin, 1957; Eyles et al., 1994; Boston et al., 2010), the dynamics of North Sea glaciation remain poorly constrained due to the relative lack of detailed observations from the modern marine environment, even for the Late Devensian (Graham et al., 2011; Clark et al., 2012). Increasing the evidence-base and our understanding of the offshore glacial geology will therefore: i) better constrain the regional history and behaviour of the former British-Irish Ice Sheet (BIIS) in the North Sea and its relationship with the Fennoscandian Ice Sheet (FIS); and ii) provide insight into the dynamics of recession of a major ice lobe during deglaciation. The latter has important implications for the potential collapse of contemporary ice lobes in response to future climate change.

Similar to many other mid and high-latitude regions, much of our current knowledge of the dynamics of glaciation within the North Sea basin has been inferred from neighbouring terrestrial sequences in the UK (Eyles et al., 1994; Evans et al., 1995; Catt, 2007; Boston et al., 2010; Evans and Thomson, 2010; Clark et al., 2012; Bateman et al., 2015; Busfield et al., 2015) and continental Europe (Houmark-Nielsen, 2007, 2011; Laban and van der Meer, 2011; Böse et al., 2012). Marine-acquired information only provides the basis for a crude model of the long-term glacial evolution of the southern North Sea (e.g. Veenstra, 1965; Cameron et al., 1987; Ehlers et al., 1984; Balson and Jeffrey, 1991; Laban, 1995; Sejrup et al., 2000; Laban and van der Meer, 2011; Lee et al., 2011). Furthermore, the relative lack of marine data has resulted in a range of disparate spatial reconstructions for specific periods of glaciation, in particular the mid to late Devensian (Carr et al., 2006; Sejrup et al., 2009; Graham et al., 2011) (Fig. 1).

To address these contrasting interpretations this paper presents a series of new marine observations, which in combination with terrestrial evidence, enables an enhanced model for the occupation and retreat of the BIIS in the southern North Sea. We utilise an extensive new compilation of bathymetry data together with legacy 2D seismic data to constrain the pattern, style, and relative chronology of glaciation during the last glacial cycle. Linkages are drawn between seabed geomorphology and seismic stratigraphy to provide a more detailed model of the offshore glacial geology. Until now, regional bathymetry data have not been of sufficient resolution to identify and describe glacial landforms and landform assemblages, and the area's legacy seismic data have not been exploited to investigate the regional-scale glacial stratigraphy. The updated model enables an improved correlation between marine and terrestrial glacigenic features associated with the North Sea lobe of the BIIS.

1.1. Location and bathymetry

The study area lies in the southern North Sea, bordered by the East Yorkshire (Holderness) and Lincolnshire coasts to the west, and the Norfolk coast to the south (Figs. 1 and 2). Bathymetry data records a number of features unrelated to past glacial processes, including mobile sediment bedforms associated with the Holocene marine transgression and modern hydrodynamic processes, as well as exposed pre-Quaternary bedrock (e.g. Tappin et al., 2011). Sedimentary bedforms of marine (current-induced) origin are ubiquitous at seabed across the study area and include large-scale sediment banks (up to 40 m in height), sediment waves (up to 10 m in height), fields of small sand waves (megaripples), as well as sand ribbons, patches, and sheets (e.g. Tappin et al., 2011) (Figs. 2–4). Quaternary sediments are relatively thin and bedrock is commonly present within c.20 m of the seabed (Harrison, 1992; Cameron et al., 1992). Within seabed-incised deeps, Quaternary sediments are commonly absent revealing bedrock composed of folded Cretaceous-age Chalk (Inner Silver Pit) (Fig. 3), and Jurassic/Triassic sand- and mudstones (Sole Pit) (Donovan, 1972; Cameron et al., 1992; Tappin et al., 2011; Mortimore and James, 2015). A broad and elongated channel-system extends from the Inner Silver Pit southwards towards the Wash in-which Cretaceous (Chalk) and Jurassic (mudstone) bedrock crop-out (Gallois, 1994).

1.2. Glacial history of the study area

Much of our current understanding of the shallow geology of the southern North Sea originates from analysis and interpretation of data acquired during a systematic British Geological Survey (BGS programme of offshore geophysical surveying and ground-truthing) between the late 1970's and early 1990's (Long et al., 1988; Fannin, 1989; BGS, 1991; Cameron et al., 1992). Supported by the existing, but sparse literature (e.g. Jansen et al., 1979), this survey activity led to the establishment of a coherent regional seismostratigraphic framework calibrated from shallow cores and boreholes (Stoker et al., 2011). The glacial component of the Quaternary succession has conventionally been partitioned into three glacial stages (separated by interglacial marine deposits) and, based upon correlation with the Dutch succession, ascribed to the following stages of glaciation: MIS 12 (Anglian/Elsterian), MIS 10-6 (Saalian), and MIS 5d-2 (Devensian/Weichselian) (Cameron et al., 1987; Balson and Jeffrey, 1991; Laban, 1995). However, recent work has indicated additional stages of glaciation both pre- and post-dating the Middle Pleistocene (Ekman, 1998; Carr et al., 2006; Graham et al., 2011; Lee et al., 2011, 2016; Dowdeswell and Ottesen, 2013). Farther north, at least 7 stages of glaciation have been proposed using multiple generations of cross-cutting tunnel valleys observed in 3D seismic data (e.g. Stewart and Lonergan, 2011). This increased sub-division of glacial episodes in the Quaternary has become broadly accepted, and looks increasingly tenable given the time-transgressive behaviour of the BIIS and the neighbouring FIS during the late glacial stage (c.32–11.5 ka) (Scourse et al., 2009; Böse et al., 2012; Kalm, 2012; Hughes et al., 2016). The emerging picture from both empirical reconstructions and model results is of a highly-dynamic last BIIS, exhibiting complex behaviour through binge-purge cycles, migrating ice divides and flow regimes, as well as interaction with the neighbouring FIS (Hubbard et al., 2009; Clark et al., 2012; Livingstone et al., 2012).

The maximum extent of the last BIIS within the North Sea has been depicted in a wide range of reconstructions (Fig. 1; Graham et al., 2011 and references therein). Carr et al. (2006), building upon the work of Sejrup et al. (1994, 2000), provides the most detailed account of Late Devensian North Sea glaciation, based on micromorphological analysis of tills combined with seismostratigraphy. They propose several phases of Devensian glaciation