The mixed-bed glacial landform imprint of the North Sea Lobe in the western North Sea

Roberts, David H.; Grimoldi, Elena; Callard, Louise; Evans, David J. A.; Clark, Chris D.; Stewart, Heather A.; Dove, Dayton; Saher, Margot; O'Cofaigh, Colm; Chiverrell, Richard C.; Bateman, Mark D.; Moreton, Steven G.; Bradwell, Tom; Fabel, Derek; Medialdea, Alicia

Earth Surface Processes and Landforms

DOI:
10.1002/esp.4569

Published: 01/05/2019

Peer reviewed version

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[1], David J.A. Evans[1], Louise Callard[1], Chris D. Clark[2], Mark D. Bateman[2], Alicia Medialdea[2], Dayton Dove[3], Carol J. Cotterill[3], Margot Saher[4], Colm Ó Cofaigh[1], Richard C. Chiverrell[5], Steven G. Moreton[6], Derek Fabel[7], Tom Bradwell[8]

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

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 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 30 – 21.5 ka.

Analysing over 540km of sub-bottom profile data and forty vibro-cores, as well as deriving new optically stimulated luminescence and radiocarbon ages to constrain ice sheet history, this paper shows the core of the Dogger Bank to be composed glaciolacustrine sediment deposited between 31.6 – 25.8 ka. Following its initial 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. Ice override and retreat northwards back across the Dogger lake was rapid and complete by 23.1 ka, but resulted in widespread compressive glaciotectonism of the lake sediments and the formation of thrust moraine complexes and ice marginal deposits on both the southern and northern edges of the newly formed Dogger Bank. 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 new seismic data supports the previous notion that Dogger Bank is a thrust moraine complex and is a product of ice marginal instability promoted by ice sheet interaction with the Dogger Lake which would have initiated drawdown and provided ideal conditions for the development of a subglacial deforming bed and, hence, flow instability.

With the Dogger Bank acting as a positive relief feature, the shallow seafloor to the west and southwest 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 below an upper till 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 between 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 critical in influencing flow instability and rapid ice advance and retreat. Glaciotectonism of the 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.*

Keywords: Quaternary, Glaciation; Europe; Geomorphology; British-Irish Ice sheet; North Sea; Dogger Bank

1.0 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; De Conto 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/MIS2 (~ 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 30 – 19ka.

2.0 **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 metres 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 to -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 and 40 to 60 km in length trending NW to SE (Fig. 2). Water depths shallow to 5 to 10 m immediately offshore from Norfolk, which forms a low-elevation rolling landscape immediately onshore.

The ice sheet history of the southern North Sea has been pieced together over the last one hundred years but several key questions regarding ice sheet extent, dynamic behaviour and chronology still remain (see Graham et al., 2011 for a full review). During the last glacial cycle both the BIIS and FIS entered the North Sea. There is evidence for at least two major periods of basin-wide ice-sheet growth with early ice sheet build up in MIS 4 and a later MIS 2 event (Carr et al., 2006; Graham, 2007). The coupling and decoupling of these two ice sheets heavily influenced the imprint of glaciation in the North Sea basin (Sejrup et al., 2005; Bradwell et al. 2008; Clark et al., 2012; Graham et al; 2011). Erratic dispersal patterns and flow line reconstructions from Britain clearly show ice feeding into the North Sea from Scotland and Northern England (Harmer 1928; Raistrick 1931; Catt 1991; Davies et al., 2009; 2011; Roberts et al., 2013; Busfield, 2015). Ice streams sourced from major east coast catchments, such as the Moray Firth, Firth of Forth, Tweed, Tyne and Eden-Stainmore, funnelled ice into the western sector of the North Sea at different times between 30-15ka (Fig. 1) (Boulton et al., 1985; Boulton and Hagdorn, 2006; Hubbard et al., 2009; Livingstone et al., 2012; Hughes et al. 2014).

As a result of BIIS and FIS coalescence ice would have flowed north to a marine margin situated along the continental shelf margin between Shetland and Norway (Sejrup et al., 2000; Bradwell et al., 2008). In contrast, a terrestrial glacial margin formed in the southern the North Sea as a result of global eustatic drawdown (Straw, 1960). Our knowledge of the dynamic behaviour of the southeast sector of the BIIS during this time has been limited because the imprint of the ice sheet on the seafloor is largely unexplored, and while regional seismo-stratigraphic data provide a framework for Quaternary sedimentation in the North Sea (Fig. 3a), they do not provide detail on complex patterns of sediment distribution, lithofacies architecture or the timing of events (Cameron et al., 1987; Balson and Jeffrey, 1991; Cameron et al., 1992).

During the latter phases of the LGM, most reconstructions of ice extent in the North Sea point to BIIS/FIS coupling between 30-24 ka followed by decoupling and late stage re-advance of the NSL down the east coast of the UK between 21 - 17 ka (Rose, 1985; Carr et al., 2006; Sejrup et al., 2009; Evans and Thomson; 2010; Graham et al. 2011). More recently Clark et al. (2012) and Sejrup et al. (2016) have proposed that the BIIS and FIS were still coupled in the central North Sea until as late as 19 ka. At some point between 30-17 ka ice undoubtedly reached as far south as the Norfolk coast (Holkham Till Member/Bolders Bank Fm; Straw 1960; Brand et al., 2002), and the distribution of the BDK arguably suggests ice extended south of the Dogger Bank, but there is a lack of chronological control on those limits, other than provided by stratigraphic correlation based on lithological similarities to onshore sites. Radiocarbon and OSL ages along the east coast (predominantly Yorkshire) have shown that ice re-advances occurred as late as 21.6–18 ka (Skipsea Till Member) and ~16.8 ka (Withernsea Till Member; both Holderness Formation) (Bateman et al. 2018). Hence, there is compelling evidence from the central east coast of England to suggest that the BIIS was highly dynamic during the later stages of the LGM.

With the exception of a handful of papers (Carr et al., 2006; Davies et al., 2009; Graham et al., 2011; Clark et al., 2012; Sejrup et al., 2016; Dove et al., 2017), there has been no systematic assessment of the offshore extent of the BIIS or its dynamic behaviour in the southern North Sea during MIS 2. From early seismic records Cameron et al. (1992) described the internal properties of the Dogger Bank (Dogger Bank Fm; DBF) as composed of a tabular stratigraphic unit with predominantly sub-parallel internal reflectors and proposed it to be a proglacial, water-laid body, probably glaciolacustrine or glaciomarine. This would fit with several different strands of evidence or arguments that support the development of a large proglacial lake in the southern North Sea during several different glacial cycles (Belt, 1874, Gibbard, 1988; Ehlers and Gibbard, 2004; Clark et al., 2012; Murton and Murton, 2012; Cohen et al., 2014; Sejrup et al., 2016). Alternatively, based on micormorphological and palaeoontological work, Carr et al. (2006) proposed a glaciomarine origin for the DBF. Furthermore, Carr et al. (2006) demonstrated the sediments to have been deformed into a large push moraine complex; a concept previously put forward by Veenstra in 1965. There are no apparent glaciogenic surface features of significance on the current Dogger Bank, however, the push moraine concept has been developed further by Cotterill et al. (2017) and Phillips et al. (2018) who suggest the entire western sector of the bank is composed of glacial, glaciofluvial, glaciolacustrine and periglacial sediments, which are dissected by several palaeo-land and ravinement surfaces, but heavily glaciotectonised (Fig. 3b). However, the age of the bank and its association with regional grounded ice limits remain only partially understood.

Ice margin positions have been drawn both north and south of Dogger Bank, but it is not always clear how these limits have been formulated (e.g. Veenstra, 1965; Holmes, 1977; Sejrup et al., 2000; Fitch et al., 2005; Gibbard and Clark, 2011; Fig. 1). Sejrup et al. (2016) proposed that large sand ridges adjacent to the NW and SW sectors of the Dogger Bank originated as moraines recording an ice margin near the bank (Fig. 2), but such features have not been proven as glaciogenic, or shown to be related to the genesis of Dogger Bank itself. Neither have they been dated.

West and south of the Dogger Bank the BDK (subglacial), the Well Ground Fm (glaciofluvial) and Botney Cut Fm (deglacial/postglacial marine) are mapped on the seafloor between Yorkshire and the north Norfolk coast (Veenstra 1969; Long et al., 1988; BGS 1991; Cameron et al., 1992). The BDK clearly wraps around the western end of the Dogger Bank, suggesting the passage of an ice lobe that did not penetrate the Dogger Bank (if till limits are to be used to mark ice extents). It is often mapped as the southerly limit of the MIS 2 BIIS in the North Sea (Fig. 1; Jansen et al. 1997; Boulton et al., 1985; Ehlers and Gibbard, 2004) but the age of the BDK is unconstrained along its southern limit offshore.

The BDK limit may on-lap the Norfolk coast (Straw, 1960; Brand et al., 2002; Pawley et al., 2006), but marine processes have removed it from the seafloor close to shore making stratigraphic correlation untenable. Glacial sediments on the Norfolk coast were first described by Woodward (1884), Whitaker and Jukes-Browne (1899), Solomon (1932), Baden-Powell (1944) and Chatwin (1954) and a maximum ice limit reconstructed by Straw (1960). This was largely based on the distribution of the 'Holkham Till' and a subtle geomorphic assemblage of low-lying sand and gravel mounds and marginal meltwater features just inboard of the coast. Recent work has further defined the onshore extent of the ice between Stiffkey and Wells-next-the-Sea (Brand et al., 2002; Riding et al., 2003; Pawley et al., 2006), but the only dating control on the Holkham Till is the underlying raised beach at Morston, dated to MIS 5e by Gale et al. (1988). This has therefore led to a broad designation of the Holkham Till as a MIS 2 deposit. It has also been correlated with the Skipsea Till Member of the Holderness Fm (a correlative of the BDK), which was deposited after 22.3 -20.9 ka (Catt and Penny, 1966; Rose, 1985; Bateman et al., 2011, 2015).

Dove et al. (2017) identify at least four subtle moraine belts on the seafloor which mark punctuated northwards ice margin withdrawal from the Norfolk coast, but they have no direct dating control. Tunnel valleys (e.g. Inner Silver Pit, Sole Pit, Well Hole) associated with these moraine belts point to excessive meltwater discharge (Fig. 2), and several sandy areas on the seafloor along the southern edge of the BDK have been mapped as glaciofluvial deposits and outwash corridors (Well Ground Fm; BGS 1991; Gaffney et al., 2007) clearly denoting deglaciation in a terrestrial environment. Botney Cut Fm channels that dissect the BDK may be subglacial or proglacial in origin. Some are floored by BDK till, while others contain deglacial glaciolacustrine sediments. Many have upper sedimentary infills that denote a switch to shallow marine conditions during Early Holocene marine transgression (Cameron et al., 1992).

3.0 Methods

This study relies on data collected by the BRITICE-CHRONO project during cruise JC 123 on the RRS *James Cook* in summer 2015. It includes new geophysical and sediment core data collected across the seafloor north of the Norfolk coast and across the Dogger Bank, as well as onshore field investigations of ice marginal landforms and glacial sediments in North Norfolk carried out in 2015.

3.1 Seismic and bathymetric data

Co-registered sub-bottom profile and bathymetric data were collected using a hull-mounted Kongsberg SBP120 sub-bottom profiler system and EM710 multibeam system on the RRS James Cook. The EM710 is a 70-100 khz system and it is used for mapping in shallower waters (5-1500 m). Appanix POS-MV is used as primary positioning and motion sensor while Seapath200 is the secondary system. A Sonardyne Ranger USBL system provided underwater positioning during coring operations. Additional bathymetric was sourced from the UKHO Data Archive Centre website and is gridded to 25 m horizontal resolution. We present several seismic profiles (SP 1 - 9; Fig. 2) that were acquired across the Dogger Bank and south toward the north Norfolk coast and the Wash. Acoustic facies are characterised using both the stratigraphic architecture of the deposits and their internal characteristics (e.g. Dove et al., 2017). Interpretations are supported by sedimentological analysis on core material collected on the cruise JC 123 and from BGS archives (http://www.bgs.ac.uk/data/bmd.html).

3.2. Sediment cores and field logging

Coring operations utilised a 6 m long BGS vibrocorer. In all 40 cores were collected from the study area (Fig. 2). These were scanned through a multi-sensor core logger, split, and described sedimentologically (Evans and Benn, 2004). The sediments varied widely from over-consolidated diamicts, to laminated fines to coarse shelly sands and represent a wide range of glaciogenic and postglacial environments. Sediment descriptions were used to validate acoustic facies interpretations. Onshore sediment sections where excavated by mechanical digger. Several exposures were investigated in the vicinity of Garret Hill on the north Norfolk coast. Sedimentological analysis followed a lithofacies approach with sediments classified on the basis of colour, particle size, clastic lithologies and sedimentary structures (Evans and Benn, 2004). Shear vane measurements using a hand held Torvane was carried out on-board.

3.3 Radiocarbon and optically stimulated luminescence age determination

3.3.1 Radiocarbon dating

Samples for radiocarbon were collected from glaciomarine sediments overlying subglacial tills (in order to provide minimum ages deglaciation) and from estuarine and peat sediments to constrain later marine incursion. A mixture of paired bivalves, mixed benthic foraminifera samples, shell fragments and peats were collected for radiocarbon dating. Shell fragments and whole bivalves were cleaned with deionised water and dried at 40°C in an oven. Foraminifera were sieved through 500µm, 180µm and 63µm sieves and dried at 40°C. Foraminifera were picked dry from the 500-180 µm fraction. Only whole, unabraded specimens were picked. Conventional ages were calibrated using the Marine13 curve with an inbuilt marine reservoir correction of 400 years and a ΔR of 0 years (Calib v7.0 software; Reimer et al, 2013). It is likely the samples would be subject to large and variable local ΔR during the LGM and late glacial period. Marine reservoir values may have also varied as Holocene marine conditions stabilised. Ages are reported in the text as the calibrated 1σ median result (see Table 2).

3.3.2 OSL Sampling

Seven sand units from sediments interpreted to be glaciolacustrine or glaciofluvial were collected from the offshore Dogger Bank cores for optically stimulated luminescence (OSL) dating in order to constrain the age of ice marginal/proximal environments formed during glacial advance or retreat. These cores were collected in black core liners to avoid light exposure. Each core was cut longitudinally under red light and sand units were targeted for OSL dating. In addition, material ~20 cm above and below the OSL sample position was also taken to allow more accurate determination of the background dose-rate received by the OSL sample.

For these samples the background dose rate and elemental concentrations were measured by inductively coupled plasma mass spectroscopy (ICP). The material sampled for OSL was used to calculate the beta contribution. This material, in conjunction with that from adjacent sediments, provided the gamma contribution to dose rate. Sample moisture content, given the samples part of their burial history in a terrestrial environment and part in a marine environment, were calculated as an average by considering the two stages. For the pre-inundation period the moisture of the sediment was assumed partially saturated (17%) and for post-inundation burial time a fully saturated water content value was assumed to be representative (33%). The time of inundation was predicted using the GIA model of Bradley et al. (2011) and palaeotidal model of Ward et al. (2016) and the present-day positions and water depths of the cores. From this, an average moisture through time for each core was calculated. Calculated cosmic dose rates followed the expression of Prescott and Hutton (1994) taking into account both an assumed linear accumulation through time of sediments and the duration and depth of the water column as determined from the inundation model. Total dose rates were calculated using the conversion factors of Guerin et al. (2011) and attenuated for grain-size and the average moisture content (Table 1).

Additionally two samples were collected from freshly excavated vertical exposures onshore at Garret Hill. These were collected in opaque PVC tubes. For these samples beta dose rates are based on ICP measurements of U, Th and K concentrations and gamma dose rates are based on field measurements using an EG&G MicroNomad gamma spectrometer. Cosmic radiation contributions were based on the work of Prescott and Hutton (1994) and attenuation by moisture assumed a moisture content of 10% given the sites free draining situation.

For all OSL samples the palaeodose measurement (D_e), samples were sieved to extract the fraction 180-250 µm and prepared to isolate and clean the quartz fraction as per Bateman and Catt (1996). Measurement of the D_e was based on multiple replicates of small multigrain aliquots (SA, containing ~20 grains each) which have been shown to provide similar resolution to single grain measurements and are therefore appropriate to measure samples potentially affected by incomplete bleaching (Evans et al., 2017). All luminescence measurements were carried out at the University of Sheffield luminescence laboratory using the SAR protocol (Murray and Wintle 2003). Most of the Dogger samples had normal D_e distributions and low overdispersion (OD) suggesting they were well bleached before burial so ages are based on a D_e values derived from the Central Age Model (CAM, Galbraith, 1999). Samples, Shfd15177 and Shfd15178 along with those from Garret Hill (Shfd13033 and Shfd13034) had scattered D_e distributions and high OD values suggesting incomplete bleaching and so ages are based on a D_e values derived form a minimum age approach. Such an approach has been shown to be appropriate to estimate accurate ages for incompletely bleached glacial sediments (Bateman et al., 2017).

4.0 Ice extent in the southern North Sea

Three geographic areas are explored in order to reconstruct the nature of MIS 2 ice sheet activity in the region; 1) the seafloor in the vicinity of the Dogger Bank; 2) the seafloor between North Norfolk and Dogger Bank; and 3) the previously mapped ice limit for MIS 2 ice onshore in north Norfolk.

4.1 The Dogger Bank

Five sub-bottom profiles were gathered as part of cruise JC123 (SP 1 - 5) (Fig. 2). Reconstructed lithofacies associations based on acoustic and core data are given the prefix offshore *Dogger Bank* (*DB*) and visualised in Figures 4 - 11. High resolution images detailing the acoustic facies architecture for SP 1, 2 and 3 are provided in supplementary information.

SP1 covers the central Dogger Bank and runs NW to SE (Fig. 2). It captures the elevation change from the central Dogger Bank to the seafloor to the south (-20 to -50 m OD). There is a clear lower reflector approximately 40 m below the seafloor that undulates and has an indented surface with small indistinct channels (DB 1; Figs. 4 and 5). Above this there is an acoustically massive, semi-transparent unit that is 2 - 4 m in thickness to the south, but thickens substantially northwards to ~ 15 m (DB 3c). It has a sharp upper surface depicted by strong irregular reflector. Conformably overlying this is a sub-horizontally, stratified sediment package which exhibits higher acoustic energy, that is 20 - 25 m thick (DB 3b; *note DB 2 does not outcrop along SP1*). To the north the strata become folded (chevron folds) and upturned sub-vertically and the sequence is clearly truncated by an overlying sand sheet (DB 7) (Fig. 5). Between 23 and 47 km along SP1 a dark (high acoustic energy), opaque unit (DB 3a) with unusual transparent, lensoid packages up to 1 km long and 5 m thick is visible (Figs. 4 and 5b). Two cores (150 and 151VC; Fig. 5b) penetrated DB 3b at the north end of this transect where the internal bedding is up-turned and folded. In core 150VC, 171 cm of sediment was recovered. A lower sand unit (171-140 cm) is overlain by interstratified sandy silts and silty clays (140-80 cm), in turn overlain by 54 cm of shelly sand and capped by 23 cm of shell hash (Fig. 5c). The lower sand unit provided an OSL date of 29.5 ± 1.9 ka (Shfd15175). In 151VC, a slightly shorter core (148 cm) with similar stratigraphy provided a basal OSL date of 26.2 ± 2.1ka (Shfd15176). As these samples are taken from the upper part of DB 3b the OSL ages suggest DB 3c and DB 3b were deposited prior to 29.5 to 26.2 ka

SP 2 runs east to west linking SP1 and SP3 (see Fig. 2 plus supplementary information for full enlargement). It is not interrogated in detail herein but DB 3b + 3c can be traced acoustically and are clearly folded, inclined and disturbed in a number of areas. There are occasional surficial lenses of DB 4b, channel infills (DB 5) and DB 7 forms the top of the sequence.

Several acoustic facies can be traced northwards across Dogger Bank along SP3 (Fig. 2 for location; Fig. 6 seismic stratigraphy). Several sub-facies of DB 2 can be mapped (DB 2 a-d; Fig. 6). Unit DB 2b was sampled in cores 138VC, 139VC, 140VC and 141VC. It is a red/brown, over-consolidated, massive, matrix supported, fine grained diamict with distinctive chalk and flint clasts. Shear strengths range between 100-75 kPa. At 185- 186 km along the profile a large ridge formed in DB 2d is draped by an on-lapping sequence of stratified sediments with two phases of infill evident (one to the south and one to the north) (see Fig. 7a for enlarged image). On its southern edge the lower section of the ridge appears displaced laterally (a low angle failure plane) and overlies stratified sediments. Furthermore, there are a series of small ridges south of the main ridge (between 186 and 188 km) which may be rucked/folded sediment (Fig. 7a).

Four structureless, tabular unit associated with DB 2 can be seen in the profile between 155 and 190 km (DB 2a-d; Fig. 6). Deep channels often over 1 km in width cut down through all these sub-units. They are infilled with stratified sediment (DB 5a) that mainly represent a later depositional event postdating the deposition of DB 2, though occasional they are capped by sub-units of DB 2 suggesting synchronous deposition.

Between 164 and 169 km there is a second buried ridge complex beneath the seafloor (Figs. 6 and 7b for enlarged image). Five possible diamict units are evident in the stratigraphy (DB 2a - d and DB 4b). They are separated by DB 3b which is attenuated from the north (Fig. 6). At 167 km DB 3b and 2b and 2c are crosscut by a sub-vertical fault dipping north. The upper surface of DB 3b also clearly undulates (2 to 3 m high ridges; Fig. 7b). At this location (164-169 km) there are four identifiable acoustic units over DB 3b. DB 4a is composed of three units that have a fan-like geometry with flat tops (Fig. 7b). Between 165 and 168 km in particular there are very clear internal reflectors off-lapping and dipping south. Immediately to the north, and interleaved with DB 4a is a dark opaque unit (DB 4b) which has a sheet-like geometry and on-laps DB 4a (Fig 7b). DB 4b also outcrops above DB 2a between 153 and 162 km (Fig. 6). Importantly, between 155 and 163 km, the stratigraphic relationship between DB 2a, DB 3b and DB 4b can be discerned with DB 3b clearly originating from the north and being attenuated southwards above DB 2a and below DB 4b (Fig 6). Further north along SP3 between 140 and 150 km there are clear set of channels (DB 5a) incised into DB 3b (Fig.6). They are draped by overlying sand sheets (DB 7).

Between the 140 and 35 km in the sequence the acoustic signal is very poor and the stratigraphy becomes difficult to analyse (see SP 3 in supplementary information). There are perhaps three important stratigraphic features to note. Firstly, between 93 and 97 km the lower stratified unit (DB 3b) is contorted in a chevron-fold pattern. DB 3a can also be mapped. In some areas it is deformed, mimicking DB 3b below (Fig. 7c), but in other areas it is sub-horizontally stratified and infills surface depressions in DB 3b (see 80 – 85km along SP3 in supplementary information). Secondly, DB 4 may outcrop sporadically at the top of the sequence between 79 and 30 km, though cores 143VC-146VC failed to penetrate diamictic material. At times the exposed surface undulates, forming a series of low amplitudes broad ridges (e.g. 75 to 60 km; see SP 3 in supplementary information). Thirdly, at 98 km core 143VC recorded 244 cm of shelly sands with occasional reworked peat intraclasts resting over a channel infill. A sample of peat from 239cm has a calibrated radiocarbon age of 19395 ± 208 cal. yrs BP (SUERC-72882; Table 2).

At 38 km the upper surface of the Dogger Bank loses elevation and drops down from -30 m to -60 m OD. This surface appears to be composed mainly of DB 3 (with discontinuous pockets of DB 4) and forms low amplitude ridges between 35 - 20km m covered by surface sand (Fig. 8a). Two very large sand ridges at 30 and 26km have internal reflectors that suggest they sit over a core of material below (e.g. DB 3 or DB 4). There are also multiple smaller ridges between 20 - 25km along SP3 and a very clear buried ridge can also be seen at 11 -10 km (Fig. 8a). It is ~15-20 m high and 500 m wide and overlain by a thick sequence of interstratified sediments which conformably drape the northern edge of the Dogger Bank (DB 5b; Fig. 8). Core 155VC shows the sediments to be composed of brown/red, massive clays to interlaminated silts/clays and sands (Fig. 8b). This sediment is barren of forams. A single OSL date from 357cm down the core provided an age of 23.1 ± 2.3 ka (Shfd15178; Table 1).

To the west of the Dogger Bank, transect SP4 exhibits DB 3b, 4b, 5b and 7 (Figs. 2 and 9). DB 3b is heavily folded and its upper contact boundary forms a sharp, undulating contact to an overlying diamictic unit (DB 4b). DB 4b was cored in cores 171VC, 172VC and 174VC. It is a red/brown, massive diamict with distinctive chalk and flint clasts that occurs between 2.50 and 4.50 m below the sea-bed (Fig 9b). Shear strength values range between 80—150 kPa. Overlying the diamict in these cores is a dark grey, interlaminated clay, silt and sand unit containing well preserved marine gastropods (DB 5a). At this locality DB5a has a fan/delta – like geometry that off-laps to the south (Fig. 9a).

SP5 is situated 100 km southeast of the SP 3 (Fig. 2). The sub-bottom profile data shows five acoustic facies (Fig. 10). The lowest acoustic facies is denoted as faint lower horizontal reflector above which is a sub-horizontally stratified sediment ~ 8 m in thickness (DB 1a, 1b). DB 1b can be traced over 16 km along the survey line. It could be equivalent to DB 1 as seen in SP1 but this is uncorroborated. DB 1b is overlain by two acoustically structureless, tabular units that vary in their degree of opaqueness and in thickness between 2-4 m. The upper unit was recovered in cores 176VC and 177VC. It is a brown, massive diamict with distinctive chalk and flint clasts (Fig. 10b). These two units are designated as DB 2d and 2c. Between 24 and 22 km along the transect two channels incise through DB 2d but are capped by DB 2c. The internal reflectors in these channels are sub-horizontal. The upper diamict (DB 2c) is also dissected in places by shallow, broad, transparent channels. Larger, deeper channels ~15 – 20 m deep and over 1 km wide also crosscut the entire sediment pile (e.g. 19 km; Fig. 10a). They exhibit conformable interstratified sediment fills (DB 5a).

The seafloor is capped by a coarse shelly sand (DB 7) and several sand ridges up to 6 m high are evident from SP5 data (e.g. 23- 21 km; 28.5-27km). Several cores have thin peats (DB 6) recorded just below the upper sand (DB 7). In core 178VC DB 7 and DB 6 are underlain by a lower brown/grey laminated clay silt with sandy inclusions (30-259 cm) (Fig. 10c). The peat is truncated by 23 cm of shelly sands. An OSL date from 145 cm (beneath the peat) yielded an age of 25.8 ± 2.4 ka (Shfd15179; Table 1; Fig. 10c). From the acoustic data the OSL sample overlies a diamict (DB 2c). The same can be said for core 179VC where 240 cm of shelly sands overlay 12 cm of well sorted medium sand at the base of the core which is devoid of shell material or marine microfossils and which in turn overlies a diamictic unit (DB 2c) (Fig 10c). The lower 12 cm sand unit yielded an OSL age of 31.6 ± 2.1 ka (Shfd15180). These sediments lie in small hollows on the surface of DB 2c (Fig. 10a).

Peats from the uppermost sections of cores 175, 176 and 178VC yielded Early Holocene ages (~ 9.9 - 9.7 ka) with the exception of the lowest sample in core 175VC which provided a bulk radiocarbon date of 20,190 ± 229 cal. yrs BP (Table 2).

4.1.1 The Dogger Bank: key interpretations

In Figure 11 we summarise the above observations into a model of the lithofacies architecture of the Dogger Bank. From our observations DB 1 clearly underlies the eastern the Dogger Bank (e.g. Fig. 5b). The upper surface of DB 1 forms a strong acoustic reflector incised by small channels, but it has few distinctive internal characteristics. A strong lower reflector also characterises parts of the southern end of SP3 (Fig. 6), and in other localities in western Dogger Bank this reflector is mapped as a decollement surface (Cotterill et al., 2017; Phillips et al., 2018). DB1 was not cored during this research but various deposits have been reported from this stratigraphic position in the vicinity of the Dogger Bank (Cameron et al. 1992; Laban 1995, Busschers et al. 2008; Moreau et al. 2012). DB1 could be either the Cleaver Bank or Egmond Ground Formations given the lateral continuity and tabular geometry of the deposit. The other possible options include Swarte Bank deposits though these usually occur in channels (see Cotterill et al. 2017), or the Eem and Brown Bank Fms (shallow marine and brackish environments (Cameron et al., 1992).

In the east (SP1) DB 3 directly overlies DB 1 (Fig. 5), as DB 2 is restricted across the study to the west. The lower sub-unit, DB 3c has faint stratification and a sharp, but conformable upper contact boundary with DB 3b. DB 3b is sub-horizontally stratified but becomes more deformed towards the northern and western part of the Dogger Bank. This can be clearly seen in SP1 where the sediment becomes folded and upturned at cores sites 150 and 151VC (Fig. 5b). There are also several places along SP 2 and SP 3 where DB 3b appears to exhibit open, chevron folding (e.g. Figs. 6 and 7; plus see high resolution images in supplementary information). This is indicative of compressive stress in interstratified sediments of high rheological contrast (alternating sands and clays) (Ramsey, 1974). DB 3b can be traced laterally and continuously through the core of the Dogger Bank (i.e. comprises the main element of relief to the Bank) from north to south. In cores 150VC and 151VC, the upper strata in DB 3b are characterised by interstratified sands and clays, which are barren of forams and dated to 26.2 and 29.5 ka (Table 1). Therefore, DB 3b is interpreted as an interstratified glaciolacustrine deposit that has been glaciotectonised from the north sometime after 26.2ka. This assessment concurs with the recent work of Cotterill et al. (2017) who classify the DB 3 c-a as the Basal, Older and Younger sub-facies of the Dogger Bank Formation (DBF) and separate these elements into glaciolacustrine and glaciofluvial sediments. The Basal and Older subfacies are mapped as stiff to very stiff clay/silt which fits a glaciolacustrine origin. DB 3b in particular (Older DBF), can be traced across SP1, SP 2 and SP3 which makes this a regionally extensive glaciolacustrine sub-facies (>150 km). In the western Dogger Bank area in particular the Basal and Older DBF are intensely folded and thrust into multiple thrust moraine complexes (Fig. 11) and this concurs with the recent work of Phillips et al. (2018) (Fig. 3b).

At the southern end of SP1, DB 3a is tabular, partially stratified and has several transparent lenses (Fig. 5b). In places, DB 3a is 4-5 m thick and the lenses hundreds of meters in width. Where it occurs over the central Dogger Bank it is often deformed (Fig.7c). The lateral and vertical conformability of DB 3b and DB 3a point to continued shallow glaciolacustrine conditions, though Cotterill et al. (2017) and Phillips et al. (2018) note a transition in DB 3a to conformable outwash sediments, particularly in low-lying areas between moraines (Fig. 3b). The transparent lenses in DB 3a could mark gas pockets or potentially areas of patterned ground. Eisma et al. (1979) have suggested that the southern North Sea was an extensive periglacial surface or tundra plain during the LGM, hence the lenses could represent patterned ground if the shallow lake dried out. Cotterill et al. (2017) suggest that periglacial and tundra-like conditions were common in subaerially exposed areas adjacent to the ice margin across the Dogger region, and hypothesise that bright seismic reflectors within the Dogger Bank Formation are indicative of desiccated, subaerial surfaces.

During this investigation no diamicts where recognised above or below DB 3 in the east part of the Dogger Bank (Fig. 5). However, diamicts both underlie and overlie DB 3 to the west (along SP 3, 4 and 5) suggesting the BIIS was pushing over the Dogger area from west to east (Fig. 11). Importantly, cores 178 and 179VC along SP5 (Fig. 10) have OSL ages which limit the deposition of subglacial tills to the south of Dogger to before 25.8 and 31.6ka. These fit broadly with the OSL ages from cores 151/150VC which suggest proglacial lake formation was coincident with ice margin advance and retreat (26.2 and 29.5 ka; Table 1).

These relationships can be seen best at 165 - 167 km in SP 3 where several tills and a buried moraine complex sit just beneath the seafloor (Figs. 6 and 7b). The axis of the buried moraine runs approximately southwest to northeast. The lower two till units are clearly faulted and relate to compressional stress transfer through the sediment pile from northwest to southeast. The undulating upper surface of DB 3b at this locality suggests a series of small moraines formed in its upper surface (Fig 7b). Above this, a series of coalesced fans (DB 4a) are interpreted as ice-contact outwash fans fed from an ice margin retreating sequentially to the north. The most southerly fan clearly off-laps the moraine to the south, with bedding angle becoming less steep to the south as the fan aggrades (Fig. 7b). DB 4b is interpreted as a (re)advance till deposited on the proximal side of the moraine. Small shallow surface channels in the surface of DB 4b are interpreted as proglacial channels marking the passage of meltwater streams as ice retreated northwards. However, deep channels that underlie tills sheets more likely represent subglacial channels cut beneath active ice.

DB 4b is most clearly expressed in cores 171, 172 and 174VC on SP 4 which record a brown, chalk-rich, consolidated diamict across the upper part of the central southwest Dogger Bank area (Fig. 9) DB 4b therefore overlies, not underlies DB 3 (Fig. 11). Along SP 4 the base of 171VC shows a downward transition from diamict to massive clays, hinting at the emplacement of a subglacial till over glaciolacustrine deposits. This interpretation is further corroborated by the acoustic stratigraphy as DB 4b clearly overlyies folded and deformed DB 3b (Fig. 9).

Given these stratigraphic relationships we equate DB 2 with the previously reported BDK tills. Cores 138-141VC sit within the mapped limits of the BDK (Fig. 1) and these brown, chalk-rich subglacial diamicts are known to occur close the seabed to the southwest Dogger Bank (Cameron et al., 1992;

Dove et al., 2017). The presence of diamict relatively high up on the SW Dogger Bank in cores 171-174VC is also important. Again, DB 4b is a brown/red, over consolidated, chalk/flint rich diamict which we assign to a younger sub-unit of the BDK, but its occurrence over the upper surface of the western Dogger Bank points to ongoing, dynamic, and episodic oscillation of ice moving in and out of the western Dogger region and sourced from the British mainland. DB 2 and DB 4 are essentially the same lithofacies (BDK) but they represent different phases of subglacial till deposition as the NSL oscillated across the region. This would fit the assertion that the Humber area and Dogger Bank were subjected to numerous re-advances from the northwest and underwent significant glaciotectonism and moraine formation during the late MIS 2 (Boulton et al., 1985; Rose, 1985; Long et al., 1988; Cotterill, et al., 2017; Dove et al., 2017; Phillips et al., 2018).

Along SP3 the north half of the Dogger Bank appears to show either DB 3 or DB 4 at the seabed (Fig. 11), except where there is mobile sand (DB 7). On the northern flank of the Dogger Bank there are two important morphostratigraphic relationships. The first is that a series of ridges can be seen in the acoustic profiles (Figs. 8a and 11). These ridges could not be cored but are composed of either DB 3 or DB 4 based on their acoustic properties. They are therefore interpreted as moraines. Several of them are one or two kilometres wide and 10-20 m in amplitude. Where they are close to the seafloor they undoubtedly act as anchor points for sand ridges (DB 7) as suggested in Sejrup et al. (2016), and are best manifested in the acoustic record between 0 and 30 km in line SP3 (Fig. 8a).

On-lapping the north sector of the Dogger Bank and the moraines described above is DB 5b (Fig. 11). This red/brown interlaminated fine sediment is undoubtedly a low energy waterlain deposit that on-laps the northern edge of the Dogger Bank. The sediments mapped previously as Botney Cut Fm (BGS - Dogger Bank Quaternary Sheet). Their basinal geometry in between the moraines and lack of foraminifera strongly suggest a glaciolacustrine origin. The upper part of the sequence is dated by OSL in core 155VC to 23.1 ± 2.2 ka. From the acoustic and core data adjacent to 155VC this lithofacies does not have an overlying diamictic unit indicative of overriding by ice.

To the western end of the Dogger Bank, further evidence for the late phase draping of sediment across the bank can be seen in SP 4 (Fig. 9). At this locality DB 3 is highly deformed due to folding and is overlain by DB 4 (subglacial till; sub unit of BDK). Capping the sequence is DB 5a; a dark grey, interlaminated clay, silt and sand unit which coarsen upwards. The shells within the sediments suggest they are shallow marine/estuarine sediments of the Botney Cut Fm, deposited in a surface hollow in the upper surface of the Dogger Bank thrust moraine complex during Holocene marine transgression. Peats and shallow marine sands (DB 6 and 7) above the outwash sands from cores 175, 176 and 178 mark the switch to shallow estuarine and marine conditions at the opening of the Holocene (9.7 – 9.9 cal. yrs BP; Table 2).

In summary, DB 1 is a pre MIS 2 stratigraphic unit. In the Dogger region it is most likely to be Egmond Ground or the Cleaver Bank Fm. DB 2 is interpreted as a series of subglacial tills (early sub units of BDK) that outcrop mainly to the south and west of Dogger Bank. They were deposited prior to 31.6 - 25.8 ka. DB3 is glaciolacustrine in origin, with an upper sub-facies of glaciofluvial sediments in places. In some acoustic sections it is over 40 m thick. The areal extent and depth of this lithofacies points to a large, regional, ice dammed lake. It was formed prior to 29.5 - 26.2 ka. In the east it becomes progressively deformed to the north. To the west DB 3 has been intensively proglacially glaciotectonised and subsequently overrun. An upper till (DB 4; later sub unit of the BDK) and moraine complexes mark as ice retreat northward across Dogger Bank (Fig. 11). Glaciolacustrine sediments (DB 5b) that on-lap the northern edge of the western Dogger Bank were deposited prior to 23.1 ka. Importantly, core 155VC demonstrates that DB 5b is not capped by a till, inferring Dogger Bank was not directly over run by ice post 23.1ka

4.2 The imprint of the BIIS on the seafloor between North Norfolk and Dogger Bank

Four geophysical survey lines are presented from the area off shore from Norfolk (Fig. 2). SP6 and SP7 run north/south and east/west close to the Inner Silver Pit. SP8 runs northwest/southeast terminating ~20 miles north of the Norfolk coast. Further east, SP9 also runs northwest/southeast close to the Sole Pit. This shallow area was targeted to provide correlation between glacial deposits onshore in Norfolk, Lincolnshire and Yorkshire and offshore sediments previously mapped as relating to MIS 2 glaciation (BGS, 1991; Cameron et al., 1992; e.g. Bolders Bank Fm; Well Ground Fm).

The lithofacies from this area are given the prefix *Offshore North Norfolk* (*ONN*) (Fig.12). Sub-bottom profile data from SP6 clearly shows Cretaceous chalk (ONN 1) at the base of the Inner Silver Pit (Figs. 12 and 13a). At this location it is overlain by a conformable, on-lapping stratified sedimentary unit. In core 164VC this is a brown/beige/black, interlaminated, clay/silt deposit with occasional black organic laminae (ONN 2). This deposit was restricted in areal extent to the base of the Inner Silver Pit. Along SP 7 and SP 8, the chalk surface varies from flat and to irregular, and is often incised. It is overlain in many places by a brown/red, massive, matrix-supported, fine grained, over-consolidated diamict with distinctive chalk and flint clasts (ONN 3; Figs. 12 and 13b, c). In a number of locations there are at least two layers visible in the sub-bottom profile data (e.g. Fig. 13b between 29 - 32 km).

Just north of 159VC the sub-bottom profile data shows a ‘ridge’ and a ‘wedge’ structure on the seafloor. They are labelled Moraine 1 and 2 respectively (Fig. 13 b). Acoustically, Moraine 1 displays a distinctive, triangular cross section associated with a complex set of attenuated sediment units. Two diamict units (ONN 3e + 3f) can be traced from core 159VC beneath the ridge. They become attenuated folded beneath moraine 1 and overlain by two acoustically stratified units (ONN 3c + d) that are also heavily attenuated and boudinaged (See Fig. 14a for interpretation panel). The ‘wedge’ (Moraine 2) has a lower, truncated boundary overlying a least five acoustic units (Figs. 13b and 14b). ONN 3c to 3f are relatively sub-horizontal and tabular in form. They are crosscut by three channels with weak internal acoustic stratification. ONN 3c + 3d thin out northward and are truncated below the wedge. A small discontinuous, tabular, transparent unit which forms a very strong reflector lies along the bottom of the wedge 3 - 4 km along the section (ONN 3b; Fig. 14b). Internally the wedge is folded to the south and has high angle dipping reflectors along its northern edge. Several other ridge or mound structures can be seen in the acoustic stratigraphy on survey lines SP 8 and SP 9. They include simple diamictic ridges or mounds, and more complex ridges that can be mapped across the seafloor (Fig. 14c).

Cores 156 and 157VC contain two other important acoustic facies that outcrop in the region (Fig. 13b). Above ONN 3 in both cores there is a dark grey, massive to interlaminated sequence of sandy silts and clays (ONN 4; Fig. 12). These are best shown acoustically at core site 157VC along SP8 where a channel cuts through the upper diamicts to the chalk below (Fig. 13b). Clearly this is an erosional feature, but the sedimentary infill (ONN 4) is draped and conformable. Channels are common along transect SP8, often dissecting ONN 3 into the chalk below. They range from <100m to >2000 m wide and ~ 5 to 40 m deep. Core 166VC from SP 9 recovered 5.2 m of grey interlaminated sands, silts and clays infilling one such channel (Fig. 15). In places rhythmic bedding is very clear but it is noticeable that laminae thickness decreases while frequency increases up core. Forams within the whole sediment sequence are predominantly estuarine with an increasing marine influence (e.g. *Ammonium aberdoveyensis/beccarri/batavus; Elphidium williamsoni/magellanicum excavatum/incertum; Quinqueloculina*). Several *Littorina Littorae* shells were also recovered from the lower part of the core (Fig 15; 589 and 593 cm) and provide radiocarbon ages of 9535 ± 82 and 9141 ± 129 cal. yrs BP respectively (Table 2). The upper unit in many of the cores along SP8 and SP9 is a moderately to poorly sorted, brown/orange/grey, shelly sand often with a cap of shell hash. It varies in depth between 0.5 to 1.0 m and is clearly visible on the sub-bottom data as a transparent, upper unit across much of the seafloor (ONN 5; Figs. 12 and 13b).

4.2.1 The seafloor between North Norfolk and Dogger Bank: key interpretations

The sedimentary sequence in this region of the seafloor is underlain by ONN 1, which is The Chalk (Cameron et al., 1992). This is most clearly seen in the base of the Inner Silver Pit (Dove et al., 2017), but it also outcrops on the seafloor towards the Norfolk coast, or is overlain by a thin veneer of sediment. ONN 2 is an interlaminated, clay/silt/sand, conformable, on-lapping stratified sedimentary unit. This unit it has been previously mapped as Egmond Ground Fm; a shallow marine sediment indicative of cool temperate seas following MIS 12 glaciation (Cameron et al., 1992) which fits with the observations made herein.

The diamict facies and associated deposits (ONN 3) reported from many boreholes has the typical hallmarks of subglacial tills assigned to BDK which almost on-laps the Norfolk coast (Long et al., 1988; BGS, 1991 – Spurn Sheet; Cameron et al., 1992; Carr et al., 1999; Davies et al., 2011). This diamictic facies is a red/brown, massive, fine-grained diamict with small clasts (sub-rounded to sub-angular). It has abundant locally derived chalk and flint clasts with a far travelled erratic, and palynological and heavy mineral assemblages from Northern England and Scotland (Carr et al., 1999; Davies et al., 2011). Dove et al. (2017) note that it exhibits a prominent reflector over the chalk, perhaps denoting erosion, and that multiple till units are recognisable from seismic data. These characteristics are duplicated in the offshore data presented here.

The stratigraphic architecture of ONN 3 becomes complex in areas associated with ice sheet still stand or re-advance. Dove et al. (2017) report on the occurrence of over-lapping till wedges/sheets associated with subtle moraines across this sector of the seafloor and the moraine complexes identified in the JC123 seismic data coincide with the many of moraine ridges mapped by Dove et al. (2017) (Fig. 14c). The 'ridge' structure (Moraine 1) to the north of 159VC is a thrust moraine complex exhibiting deformed lower till units (ONN 3) and attenuated/boudinaged stratified sediments (Fig. 14a; van der Wateren 1995, 2003; Benn & Evans 2010). It is defined geomorphologically by a prominent well defined ridge up to 10 m in altitude with dipping reflectors. The 'wedge' (Moraine 2) displays a different geometry and is a possible hill-hole pair and/or large glaciotectonic raft (Aber et al. 1989; Rise et al. 2016 Fig. 14b). The geomorphology of the seafloor immediately north of Moraine 2 has a depression indicative of a hill-hole pair, and rafts of chalk and glacial sediment several kms long and ~10 to 15 m thick have been reported from MIS 12 glacial sections along the North Norfolk coast (Banham, 1988, Roberts and Hart; 2005; Phillips et al., 2008; Burke et al. 2011). These moraines thus relate to distinct standstill or re-advance limits of the NSL and the deposition of discrete stacked/overprinted sheets of BDK till layers.

The interlaminated sediments reported from the channel fills (ONN 4) in both the core and seismic data are interpreted as low energy, shallow, temperate marine sediments of the Botney Cut Fm (Cameron et al. 1992). Many channels in this region clearly dissect glacial sediments and chalk below (Fig. 13b). This most likely infers a subglacial origin (Ehlers and Wingfield; Gaffney et al., 2007). Some authors have hypothesised the low energy sediment infill in many channels may have originated in glaciolacustrine or lacustrine settings following deglaciation, inferring ponding in freshly exposed over-deepened channels but the upper sequences are characterised by a switch to marine sedimentation as the southern North Sea became inundated in the early Holocene (Cameron et al. 1992). The foraminifera and marine shell assemblage in core 166VC support a marine origin for the upper component of these channel infills. The increasing, high frequency of the sand/silt/clay laminae and their clear rhythmicity suggest an inter- or subtidal environment (Daidu et al. 2013). The radiocarbon dates of 9.5 and 9.1 ka are compatible with the estimated time of submergence of the land bridge in this sector of the North Sea (Sturt et al., 2013) and shallow estuarine environments have been widely reported from this region during Holocene marine transgression. Many of the channel infills mapped as DB 5a relate to this phase of deposition.

The upper unit across the seabed (ONN 5) is interpreted as the contemporary, active seafloor. Mobile sand waves and ridges are common in this region of the southern North Sea (Tappin et al., 2011) due to strong tidal current and shallow water depths which bring the seafloor above storm wave base (-5 to -20 m OD). Many of the cores show a shelly sand/shell hash that has truncated the underlying BDK, indicating strong scour by current and wave activity.

4.3 The MIS 2 limit in North Norfolk

Pawley et al. (2006) described the MIS 2 limit at Garret Hill near Stiffkey where a NE-SW trending sand and gravel ridge forms one of a chain of ice marginal landforms adjacent to the Stiffkey valley. Of the four lithofacies identified within the ridge, two were assigned a pre MIS 2 origin (LFA 1 and 2 ^{Paw}) but an upper diamict (LFA3^{Paw}) and outwash sediment (LFA4^{Paw}) were interpreted as representing MIS 2 glaciation. This section reports briefly on the results of a re-investigation of the Garret Hill site in order to derive a new geochronology for the putative 'MIS 2' ice limit in Norfolk.

Five sections were exposed in the SW side of Garret Hill (Fig. 16). Lithofacies associations mapped at this site are assigned the prefix "GA". GA 1 forms the base of the sequence and is a chalky, massive, matrix-supported diamict containing abundant chalk and flint clasts. Overlying this is a variably stratified sand and gravel deposit (GA 2) that appears to form the core of the ridge and coarsens upward. In Logs 1-5 the stratigraphy of this unit tends to vary between sub-horizontally stratified sands (with gravelly lags and lenses) and coarser matrix-supported, tabular gravel units that are massive to weakly stratified. Palaeo-current directions on fluvial bedforms suggest flow to the NW. In Log1 the lower sands are well sorted and sub-horizontally stratified, with occasional laminated fines and ripples. Two OSL dates from GA 2 in Log1 returned dates of 21.5±1.3 (shfd15033) and 22.8±1.8 ka (Shfd15034) at 9.0 m and 8.6 m OD respectively (Fig. 16; Table 1). GA 3 caps the sequence and is a brown, massive, poorly consolidated, silty/sandy diamict (pedogenically altered in the top 20-30 cm). Pawley et al. (2006) report a range of local and far travelled erratics in this diamict that included low-grade schist, basaltic/andesitic porphyries, dolerites, Devonian Old Red Sandstone, granite, acid porphyry, Carboniferus Millstone grit, crystalline limestone, coal, Triassic red/green mudstones, Jurassic sandstones and Lower Cretaceous glauconitic sandstone and Carstone.

4.3.1 Garret Hill: key interpretations

GA 1 is interpreted as a subglacial till similar to the lithofacies reported by Pawley et al. (2006), who suggested it was a correlative of the MIS 12 Weybourne Town Till because of its chalky content and deformation structures. GA 2 is interpreted as a glaciofluvial outwash deposit. The coarsening upward of the sequence suggests increasing ice proximity to the site, but palaeo-current data contradicts this with current flow towards the northwest. As this unit is dated to 22.8 – 21.5 ka it cannot relate to a pre MIS 2 glacial environment as proposed by Pawley et al. (2006). Instead, it represents a proglacial fluvial system operating in advance of the arrival of an ice sheet on the Norfolk coast shortly after 22.8 – 21.5 ka with meltwater draining west/northwest following the local topography. GA 3 is interpreted as a subglacial till predominantly because it bears all the hallmarks of the Holkham Till previously reported by Straw (1960) and Pawley et al. (2006); being brown, massive, poorly consolidated, silty/sandy, and pedogenically altered. The assemblage of erratics indicate emplacement by British-sourced ice (Pawley et al., 2006). Taking the new OSL ages into account the arrival of the BIIS on the Norfolk coast during MIS 2 is thus constrained to immediately after 22.8 – 21.5 ka. This suggests that it was deposited at around the same time as the Skipsea Till in Yorkshire (Bateman et al., 2011, 2015; 2017).

5.0 Discussion

5.1 The Dogger region and the nature of the BIIS ice sheet margin during early MIS 2

In transects SP1, SP2 and SP3 a tabular, stratified unit (DB 3) can be seen to form the core of the Dogger Bank and off-laps to the south. DB 3 has also been recognised by in other areas of the central Dogger Bank (Tranche A and B in Cotterill et al. 2017; Basal/Lower/Upper Dogger Bank Fm). The lateral continuity of this acoustic facies supports the notion that it represents a regional lake in the central North Sea as hypothesied previously (Veenstra, 1965; Cameron et al., 1992; Laban, 1995).

In order to form a lake in this region of the North Sea, ice must have been damming the regional drainage to the north (e.g. Fig. 17). In addition, the southern North Sea was located in the peripheral depression of a regional forebulge with respect to both the FIS and BIIS (Lambeck et al. 2006; Brooks et al., 2008; Bradley et al. 2011). A large regional lake is hypothesised to have formed south of the Dogger area in previous glacial periods (e.g. MIS 12 and MIS 6; see Murton and Murton; 2011; Cohen et al., 2014) and across the Dogger region in the last glaciation but its extent is very poorly constrained (Clark et al. 2012; Sejrup et al. 2016). The extensive glaciotectonism of the lake sediments (inclined, open folding; upturned strata; thrusts) indicates that ice advanced into the lake. Our work demonstrates that DB3 is undeformed to the southeast, but becomes progressively more deformed in the central, northern and western parts of the bank. Cotterill et al. (2017) and Phillips et al. (2018) identify several separate phases of glaciotectonism in response ice advance and retreat in the vicinity of SP3. In the central part of the Dogger Bank, OSL samples from cores 151 and 150VC indicate lake formation pre-dated 29.5 ka inferring the impedance of regional drainage during the switch from MIS 3 to MIS 2, though BIIS and FIS coalescence in the North Sea at this time is unsubstantiated (Hijma et al. 2012; Cohen et al., 2014; Patton et al., 2017).

Underlying the south western Dogger Bank lake sediments there are subglacial tills (DB 2) indicative of ice advance into the region prior to lake formation (Fig. 11). These lower tills (DB 2) can be traced close to the mapped limit of the BDK south of Dogger Bank (Fig. 1) and in cores 179VC and 178VC OSL ages suggest that these two tills where deposited prior to 31.6 – 25.8 ka. These age estimates overlap with the dates for lake deposition from 150VC and 151VC and suggest that early glaciolacustrine environments (DB 3) developed as ice first retreated from close to the BDK limit. Hence, the later till that overlies the Dogger Bank to the west (DB 4), and the moraine/fan complex near core 142VC (Figs. 6 and 11), demonstrate ice re-advanced across western Dogger at a later stage. That re-advance event is limited by the OSL date from core 155VC, because DB 5b (a later phase of glaciolacustrine sedimentation), is dated to 23.1 ± 2.3 ka and clearly drapes the upper till (DB 4) that forms moraines along the northern edge the Dogger Bank (Fig. 11). Therefore, based upon the OSL dates, ice advance/retreat/re-advance/retreat across Dogger appears to have been in a window between 31.6 and 23.1 ka (Fig. 17).

Wide, deep channels infilled with sediments to the south of Dogger Bank have a polygenetic origin. Many are subglacial in origin and capped by till pointing to contemporaneous deposition during glaciation (e.g. channels between 191 and 193 km on SP3; Fig. 6). In contrast, other channels are infilled to the seabed by interstratified sediment (e.g. 180 - 185 km km along SP3; Fig. 6). Many such examples across the region have been shown to be filled with Holocene marine sediments (and designated as Botney Cut Fm (DB 5a). The Botney Cut Fm is mapped across the seafloor in many areas across Dogger Bank and the seafloor to the west (Cameron et al., 1992). Some authors have suggested that lower sedimentary infills can contain BDK tills, which would be compatible with a subglacial channel hypothesis for their origin (Ehlers and Wingfield, 1991; Dove et al., 2017). However, glaciolacustrine sediments may be present in the lower parts of some channels, representing early deglacial proglacial conditions. This is the case for DB 5b which on-laps the northern edge of the bank and drapes near surface moraines formed as ice retreated northwards (Fig. 8). Other shallow channels in the surface of DB 4b along SP3 may represent surface meltwater streams (Figs. 6 and 11) and similar channels at the seabed have been interpreted as proglacial, glaciofluvial outwash and mapped as Well Ground Fm (Cameron et al., 1992; Fitch et al, 2005; Gaffney et al., 2007). The sands sampled for OSL ages in cores 178VC and 179VC originated in such glaciofluvial settings. An outwash model is further reinforced by Cotterill et al. (2017) who identified several phases of glaciofluvial activity related to ice retreat across the Dogger Bank. Hence, as the BIIS retreated its margin switched between glaciolacustrine and glaciofluvial conditions as the interplay between ice margin configuration, morainic topography and drainage pathways controlled patterns of sedimentation.

5.2 Late stage re-advance of the BIIS and the MIS 2 limit

North of the Norfolk coast the lower sequence of sediments above the chalk is dominated by multiple tills. Both this study and that of Dove et al. (2017) demonstrate the stacked and discontinuous geometry of these till units with ice marginal thickening, glaciotectonism and thrusting producing moraine complexes (Fig. 14).

The age of these limits can be bracketed using the onshore information from Garret Hill and further OSL deglacial dates from the Yorkshire coast. The arrival of ice on the Norfolk coast during MIS 2 must post date 22.8 - 21.5 ka (Table 1). This broadly supports OSL ages along the eastern England coast, which indicate a post Dimlington Stadial southward advance of the NSL after 21.6 ka (Bateman et al., 2017). The retreat limits mapped herein and reported by Dove et al. (2017) immediately north of the Norfolk coast therefore provisionally match the retreat and marginal oscillation behaviour described from the Yorkshire coast, with dynamic marginal oscillations reconstructed after 21.7 ka (Skipsea Till and Withernsea Tills/Holderness Formation)(Bateman et al., 2017). This clearly postdates ice advance and retreat across the Dogger Bank, which occurred in a time window of ~31.6 - 23.1 ka, and therefore suggests that the BDK 'tills' cannot be a contiguous till sheet stretching from west to east across the region as they are often mapped. The BDK is a series of overlapping and off-lapping till sheets that mark several generations of ice advance and retreat across the southern North Sea between ~ 30 and 22ka; it does not solely represent the late phase imprint of the NSL after 21.5 ka.

5.3 Understanding the behaviour of the BIIS in the southern North Sea during MIS2

The OSL dates in cores in cores 179 and 178VC and the tills beneath constrain initial ice advance into the central North Sea prior to 31.6 and 25.8 ka; around the onset of MIS2 (Fig 17; Phase 1). The window between 31.6 and 25.8 ka is rather earlier than many previous reconstructions which tend to show the BIIS ice reaching its maximum extent between 25-24 ka (Sejrup et al. 2005; 2015; Hubbard et al., 2009), though alternative models do consider pre MIS2 ice sheet build up, and there is evidence that the FIS reached the eastern edge of the North Sea between 36-33 ka and 31-29 ka (Houmark and Kjaer 2003; Hijma et al. 2012). OSL dates from the Dogger Bank lake sediments suggest lake formation started at some time prior 29.5 to 26.2 Ka BP. Hence, it is feasible that Dogger Lake developed and extended as BIIS ice moved westwards and coalesced with the FIS (Fig. 17; Phase 2). BIIS/FIIS coalescence and glacioisotatic depression of the central/southern North Sea would have facilitated Dogger lake development during this time but delimiting the exact extent of the lake is beyond the scope of this paper. For simplicity, lake extent is restricted to the edge of Dogger Bank in areas where DB 3 has been mapped.

Sejrup et al. (2016) have recently suggested that there was no coupling over the Fladen ground between 26-23 ka, but our study partially refutes this and demonstrates the western Dogger Bank region was in contact with the ice margin between 25.8 and 23.1 ka (Fig. 17; Phase 3). Moraine complexes composed of folded and thrust Dogger lake sediment (DB3) and subglacial till (DB 4) over the lake sediments mark the active oscillation and recession of ice across western Dogger as proposed by Phillips et al. (2018). The OSL date on lakes sediments on-lapping the north edge of Dogger Bank (core 155VC; Table 1) suggest ice underwent a significant step back by 23.1 ± 2.3 ka (Table 1; Fig. 17; Phase 3), and at this point a ribbon lake would have developed between the ice margin and the newly formed Dogger Bank push moraine complex.

Taken together, the OSL ages and widespread glaciotectonism of the lake sediments suggest marked periods of advance and retreat and pronounced ice marginal instability. This may have been promoted by ice sheet interaction with the Dogger lake which would not only have initiated drawdown and ice marginal calving (cf. Stokes & Clark, 2004) but also would have been characterized by saturated, fine grained, unconsolidated sediments, thereby providing ideal conditions for the development of a subglacial deforming bed and potential flow instability (Evans and O Cofaigh, 2003). Similar ice-marginal oscillations have been reported by Bateman et al. (2018) for the NSL where it contacted Glacial Lake Humber in the Humber Estuary (see Fig. 1). The position of the ice margin to the west between Dogger Bank and the Yorkshire/Lincolnshire coast between 31.6 and 23.1 ka (Fig. 17; Phases 1-3) cannot be constrained accurately, though there are several locations along the east coast where on-going stratigraphic work and new OSL ages point to till deposition post MIS 5e but pre 23ka. The Basement Till, which sits stratigraphically below the Sewerby raised beach (MIS 5e) on the Yorkshire coast predates these MIS 2 ice advances (Catt, 2007).

The OSL ages from Garret Hill confirm that the ice limit on the Norfolk coast represents a much later phase of BIIS advance than that reconstructed for Dogger Bank. This later advance occurred after 22.8 - 21.5 ka (Table 1; Fig. 17; Phase 4). There are several reasons why the NSL may have been restricted to the western side of the North Sea during this late phase re-advance. Firstly, the Dogger Bank was a substantial moraine complex by this time (Phillips et al., 2018) standing ~30 - 50 m above the surrounding ground surface and, therefore, could have deflected a low gradient ice sheet southwestwards. This suggests that ice was thin and had a very low profile, supporting previous assertions that the NSL was an over-extended, surge-type glacier lobe during the end of the last glacial cycle (Eyles et al, 1994; Evans et al 1995; Boston et al, 2010; Evans & Thomson 2010; Roberts et al., 2013; Fairburn and Bateman, 2016; Bateman et al., 2017). A key trigger for ice advance in the southern North Sea at this time may been have the decoupling of the BIIS and FIS around 22 – 21ka due to a catastrophic outburst flood from Dogger Lake. The ice sheet wide feedbacks of such an event would have generated regional scale flow re-organisation of the BIIS. However, 22 – 21ka is earlier than recently suggested by Sejrup et al. (2016) and Hjelstuen et al. (2018) who fix this event at ~18.7 ka. The stacked tills and marginal retreat positions on the seafloor immediately north of Norfolk relate to the NSL margin stepping back towards the Lincolnshire and Yorkshire coast (Fig. 14; Dove et al., 2017), and moreover, these fit well with extensive onshore stratigraphic and geomorphic evidence that demonstrates phased retreat of the NSL after 21.5 ka along the Yorkshire coast (Bateman et al., 2008; 2011; Evans et al. 2017; Fig 17; Phase 5)

The character of the NSL as it retreated from the Norfolk coast post 21.5 ka was likely a result of several major controls: i) ice divide migration over northern Britain prompted by decoupling between BIIS and the FIS; ii) flow re-organisation of the main ice streams entering the North Sea, particularly the Forth Ice Stream (the major feeder for the NSL) nourished from central and eastern sectors of the Scottish Highlands, and; iii) marine inundation of the BIIS margin in the northern and central North Sea, causing grounding line and flow instabilities. Indeed, Roberts et al. (submitted) track the final retreat of the NSL northwards passed the Durham and Northumberland coast and into the Firth of Forth between 19 - 17 ka under glaciomarine conditions, marking the cessation of MIS 2 terrestrial glaciation in the southern North Sea.

6.0 Conclusions

New acoustic, bathymetric and geochronological data from the southern North Sea casts fresh light on the dynamic history of the eastern sector of the BIIS. Offshore mapping of several acoustic facies shows the core of the Dogger Bank to be composed glaciolacustrine sediment deposited between 31.6 and 23.1 ka. In the east these sediments are not overlain by subglacial tills, but to the west ice overrode the Dogger Lake and deposited subglacial tills as far south as ~ 54°N. Both advance and retreat northwards back across the Dogger lake was rapid and complete by 23.1 ± 2.3 ka, but resulted in widespread compressive glaciotectonism of the lake sediments and the deposition of several off-lapping subglacial till sheets and smaller moraine complexes on both the southern and northern edges of the newly formed Dogger Bank. Along the northern edge of the Dogger Bank several moraines point to temporary stabilisation of the ice margin on the shallow bank, but these are draped by later phase glaciolacustrine and marine sediments which reflect topographic damming of ice marginal drainage and later the Holocene sea-level transgression. These interpretations support the previous notion that Dogger Bank is a large thrust moraine complex and is a product of ice marginal instability promoted by drawdown and calving as well as a slippy, deforming bed provided by the lake floor.

Following formation of the Dogger Bank, the seafloor to the west and southwest of the Dogger Bank records several later phases of ice advance and retreat as the NSL flowed between the Dogger Bank and the Yorkshire/Lincolnshire coasts and reached Norfolk. New OSL ages from Garrett Hill now date the deposition of the Holkham Till on the Norfolk coast to after 22.8 - 21.5ka, and while a direct stratigraphic correlation with the Holkham Till onshore and the tills offshore is not possible, it does appear that as the ice retreated northwards from the coast it deposited several distinct till sheets and chains of moraines that signify temporary standstills and minor re-advances. This pattern of behaviour is broadly synchronous with the deposition of subglacial and ice marginal sediments along the Yorkshire coast which relate to ice sheet activity post-dating 21.5 ka.

During the early phases of MIS 2 galciation (~30 to 23 ka) it is clear that interaction between the southern margin of the BIIS and the regionally extensive Dogger lake was important in influencing flow instability and rapid ice advance and retreat. Glaciotectonism of the Dogger lake bed was pivotal in the formation of the moraine complex now referred to as Dogger Bank. Following its formation it is apparent that 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 standing some 30-50m above the terrestrial land surface. The topographic influence of the Dogger Bank and the potential squeezing of the NSL between the Yorkshire coast and the bank potentially enabled it to overextend and reach the north Norfolk. It was also a control on the spatial 'footprint' of the BDK which extends southeast around the Dogger Bank. It should be noted that this final phase of NSL expansion was only one of many that deposited a till attributed to the BDK during the last glacial cycle.

Acknowledgements

This work was supported by the Natural Environment Research Council consortium grant; BRITICE-CHRONO NE/J009768/1. Data was collected during cruise JC 123 in summer 2015. The authors would like to extend their thanks the crew of the ship and the BGS and Britice-Chrono science teams who supported the planning and execution of this work.

References

Aber, J.S., Croot, D.G., Fenton, M.M., 1989. Glaciotectonic landforms and structures. Kluwer, Dordrecht.

Baden-Powell, D. F.W., Moir J.R., 1944. On the Occurrence of Hessle Boulder Clay at Happisburgh, Norfolk, containing a Flint Core. Geological magazine 81, 207-215.

Balson, P.S., Jeffrey, D.H., 1991. The glacial sequence of the southern North Sea J. Ehlers, P.L. Gibbard, J. Rose (Eds.), Glacial Deposits of Great Britain and Ireland, Balkema, Rotterdam (1991), pp. 245–253.

Bamber, J.L., Riva, R.E.M., Vermeersen, B.L.A., LeBrocq, A.M., 2009. Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet. Science 324, 901-903.

Banham, P.H., 1988. Polyphase glaciotectonic deformation in the contorted drift of Norfolk. In: Croot, D. (Ed.), Glaciotectonics: Forms and Processes. Balkema, Rotterdam, pp. 27–32.

Bateman, M. D., Catt, J.A., 1996: An absolute chronology for the raised beach deposits at Sewerby, E. Yorkshire, UK. Journal ofm Quaternary Science 11, 389–395.

Bateman, M.D., Buckland, P.C., Chase, B., Frederick, C.D., Gaunt, G.D., 2008. The Late-Devensian proglacial Lake Humber: new evidence from littoral deposits at Ferrybridge, Yorkshire, England. Boreas 37, 195–210.

Bateman, M.D., Buckland, P.C., Whyte, M.A., Ashurst, R.A., Boulter, C., Panagiotakopulu, E.V.A., 2011. Re-evaluation of the Last Glacial Maximum type site at Dimlington, UK. Boreas 40, 73-584.

Bateman, M.D., Evans, D.J.A., Buckland, P.C., Connell, E.R., Friend, R.J., Hartmann, D., Moxon, H., Fairburn, W.A., Panagiotakopulu, E., Ashurst., R.A. 2015. Last glacial dynamics of the Vale of York and North Sea Lobe s of the British and Irish Ice Sheet. Proceedings of the Geologists' Association 126, 712-730.

Bateman, M.D., Evans, D.J.A., Roberts, D.H., Medialdea, A., Ely, E., Clark C.D., 2018. The timing and consequences of the blockage of the Humber Gap by the last British-Irish Ice Sheet. Boreas 47, 41-61.

Belt, T., 1874. Glacial Period. Nature 10, 62-63.

Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation. Arnold, London

Boston, C.M., Evans, D.J.A., ÓCofaigh, C., 2010. Styles of till deposition at the margin of the Last Glacial Maximum North Sea lobe of the British-Irish Ice Sheet: an assessment based on geochemical properties of glacigenic deposits in eastern England. Quaternary Science Reviews 29, 3184-3211.

Boulton, G.S., Smith G.D., Jones A.S., Newsome, J., 1985. Glacial geology and glaciology of the last mid-latitude ice sheets. Journal of the Geological Society 142, 447-74.

Boulton, G., Hagdorn, M., 2006. Glaciology of the British Isles Ice Sheet during the last glacial cycle: form, flow, streams and lobes. Quaternary Science Reviews 25, 3359-3390.

Bradley, S.L., Milne, G.A., Shennan, I., Edwards, R., 2011. An improved glacial isostatic adjustment model for the British Isles. Journal of Quaternary Science 26, 541–552

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G., 2008. The northern sector of the last British Ice Sheet: maximum extent and demise. Earth-Science Reviews 88, 207-226.

Brand, D., Booth, S.J., Rose, J., 2002. Late Devensian glaciation, ice-dammed lake and river diversion, Stiffkey, north Norfolk, England.Proceedings of the Yorkshire Geological Society 54, 35-46.

British Geological Survey, 1991. Dogger Sheet 55 N - 02 E Quaternary. 1:250,000 Map Series. British Geological Survey, Keyworth, Nottingham.

British Geological Survey, 1991. Spurn Sheet 53 N - 00 Quaternary. 1:250,000 Map Series. British Geological Survey, Keyworth, Nottingham.

Brooks, A.J., Bradley S.L., Edwards, R.J., 2008. Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. Journal of Quaternary Science 23, 175–192.

Burke, H., Phillips, E., Lee, J. R., Wilkinson, I. P. 2009. Imbricate thrust stack model for the formation of glaciotectonic rafts: an example from the Middle Pleistocene of north Norfolk, UK. Boreas 38, 620–637.

Busfield, M.E., Lee, J.R., Riding, J.B., Zalasiewicz, J., Lee, S.V., 2015. Pleistocene till provenance in east Yorkshire: reconstructing ice flow of the British North Sea Lobe. Proceedings of the Geologists' Association 126, 86-99.

Busschers, F.S., Kasse, C., van Balen, R.T., Vandenberghe, J., Cohen, K.M., Weerts, H.J.T., Wallinga, J., Johns, C., Cleveringa, P., Bunnik F.P.M., 2007. Late Pleistoceneevolution of the Rhine-Meuse system in the southern North Sea basin: Imprints of climate change, sea-level oscillation and glacio-isostacy, Quat. Sci. Rev. 26, 3216–3248,

Cameron, T.D.J., Stoker, M.S., Long, D., 1987. The history of Quaternary sedimentation in the UK sector of the North Sea Basin. Journal of the Geological Society 144, 43-58.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J., Harrison, D.J., 1992. The geology of the southern North Sea. United Kingdom offshore regional report. British Geological Survey and HMSO, London.

Carr, SJ., 1999. The micromorphology of Last Glacial Maximum sediments in the Southern North Sea. Catena 35, 123–145.

Carr, S.J., Holmes, R.V.D., Van der Meer, J.J.M., Rose, J., 2006. The Last Glacial Maximum in the North Sea Basin: micromorphological evidence of extensive glaciation. Journal of Quaternary Science 21, 131-153.

Catt, J.A., 1991. The Quaternary history and glacial deposits of east Yorkshire. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial deposits in Great Britain and Ireland. Balkema, Rotterdam, pp. 185–191.

Catt, J.A., 2007. The Pleistocene glaciations of eastern Yorkshire: a review. In Proceedings of the Yorkshire Geological and Polytechnic Society (Vol. 56, No. 3, pp. 177-207). Geological Society of London.

Catt, J.A., Penny, L.F., 1966. The Pleistocene deposits of Holderness, East Yorkshire. Proceedings of the Yorkshire Geological Society 35, 375-420.

Chatwin. C. P. 1954 East Anglia and Adjoining Areas. British Regional Geology. London (H.M.S.O.)

Chiverrell, R.C., Thomas, G.S.P. 2010. Extent and timing of the Last Glacial Maximum (LGM) in Britain and Ireland: a review. Journal of Quaternary Science 25, 535-549.

Clark, C.D., Hughes, A.L., Greenwood, S.L., Jordan, C., Sejrup, H.P., 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. Quaternary Science Reviews 44, 112-146.

Cohen, K.M., Gibbard, P.L., Weerts, H.J.T., 2014.North Sea palaeogeographical reconstructions for the last 1 Ma: Geologie en Mijnbouw 93, 7–29.

Cotterill, C.J., Phillips, E., James, L., Forsberg, C.F., Tjelta, T.I., Dove, D., 2017. The evolution of the Dogger Bank, North Sea: a complex history of terrestrial, glacialand marine environmental change. Quat. Sci. Rev. 171, 136-153.

Daidu, F., Yuan, W., Min, L., 2013. Classifications, sedimentary features and facies associations of tidal flats. Journal of Palaeogeography 2, 66-80.

Davies, B.J., Roberts, D.H., Ó Cofaigh, C., Bridgland, D.R., Riding, J.B., Phillips, E.R., Teasdale, D.A., 2009. Interlobate ice-sheet dynamics during the Last Glacial Maximum at Whitburn Bay, County Durham, England. Boreas 38, 555-578.

Davies, B.J., Roberts, D.H., Bridgland, D.R., Cofaigh, C.Ó.,Riding, J.B., 2011. Provenance and depositional environments of Quaternary sediments from the western North Sea Basin. Journal of Quaternary Science 26, 59-75.

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591-597.

Dove, D., Evans, D.J.A., Lee, J.R., Roberts, D.H., Tappin, D.R., Mellett, C.L., Long, D., Callard, S.L. 2017. 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. Quaternary Science Reviews 163, 114-134.

Eisma, D., Jansen, J.H.F., Weering, T. C. E. Van., 1979. Sea-floor morphology and recent sediment movement in the North Sea. In *The Quaternary history of the North Sea*, Oele-Schotenhelm, R. T. E. and Wiggers, A.J. (editors). Acta Universitatis Upsaliensis: Symposium Universitatis Upsaliensis AnnumQuingentesimum Celebrantis.

Evans, D.J.A., ÓCofaigh, C., 2003. Depositional evidence for marginal oscillations of the Irish Sea ice stream in southeast Ireland during the last glaciation. Boreas 32, 76–101.

Ehlers, J., Wingfield, R., 1991. The extension of the late Weichselian/late Devensian ice sheets in the North Sea basin. Journal of Quaternary Science 6, 313-326

Ehlers, J., Gibbard, P., 2004. Quaternary Glaciations –Extent and Chronology. Part I: Europe. Cambridge University Press

Evans, D.J.A., Owen, L.A., Roberts, D.H. 1995. Stratigraphy and sedimentology of Devensian (Dimlington Stadial) glacial deposits, east Yorkshire, England. Journal of Quaternary Science 10, 241-265.

Evans, D.J.A., Benn, D.I., 2004. A practical guide to the study of glacial sediments .Arnold.

Evans, D.J.A., Thomson, S.A., 2010. Glacial sediments and landforms of Holderness, eastern England: a glacial depositional model for the North Sea Lobe of the British–Irish Ice Sheet. Earth-Science Reviews 101, 147-189.

Evans D.J.A., Bateman, M.D., Roberts, D.H., Medialdea, A., Hayes, L., Duller, G.A., Fabel, D., Clark, C.D., 2017.Glacial Lake Pickering: stratigraphy and chronology of a proglacial lake dammed by the North Sea Lobe of the British–Irish Ice Sheet. Journal of Quaternary Science 32, 295–310.

Eyles, N., McCabe, A.M., Bowen, D.Q., 1994. The stratigraphic and sedimentological significance of Late Devensian ice sheet surging in Holderness, Yorkshire, UK. Quaternary Science Reviews 13, 727-759.

Fairburn, W.A.,Bateman, M.D., 2016. A new multi-stage recession model for Proglacial Lake Humber during the retreat of the last British and Irish Icesheet. Boreas, 45, 133-151.

Fitch, S., Thomson, K., Gaffney, V., 2005. Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. Quaternary Research 64, 185-196.

Galbraith, R. F., Roberts,R.G., Laslett,G. M., Yoshida, H., Olley, J.M., 1999: Optical dating of single andmultiple grains of quartz from Jinmium rock shelter, northern Australia. Part 1. Experimental design and statistical models. Archaeometry 41, 339–364.

Gale, S.J., Hoare, P.G., Hunt, C.O., Pye, K. 1988. The middle and upper Quaternary deposits at Morston, North Norfolk, UK. Geological Magazine 125, 521-533.

Gaffney, V.L., Thomson, K., Fitch, S., 2007.Mapping Doggerland: the Mesolithic landscapes of the southern North Sea. Archaeopress.

Gibbard, P.L., 1988. The history of the great northwest European rivers during the last three million years. Philosophical Transactions of the Royal Society of London, Series B, 318, 559–602.

Gibbard, P.L., Clark, C.D., 2011, Pleistocene glaciation limits in Great Britain: Developments inm Quaternary Science 15, 75–93.

Graham, A.G.C., Lonergan, L., Stoker, M.S., 2007. Evidence for Late Pleistocene ice stream activity in the Witch Ground basin, central North Sea, from 3D seismic reflection data. Quaternary Science Reviews 26, 627–643.

Graham, A.G.C.; Stoker, M.S., Lonergan, L.; Bradwell, T.; Stewart, M.A., 2011 The Pleistocene glaciations of the North Sea Basin. In: Ehlers, J.; Gibbard, P.L.; Hughes, P.D., (eds.) Quaternary glaciations : extent and chronology : a closer look. Elsevier, 261-278. (Developments in Quaternary Science 15).

Guerin, G., Mercier, N., Adamiec, G., 2011: Dose-rate conversionfactors: update. Ancient TL 29, 5–8.

Harmer, F.W., 1928. On the distribution of erratics and drift. Proceedings of the Yorkshire Geologists and Polytechnic Society 21, 79–150.

Hijma, M.P., Cohen, K.M., Roebroeks, W., Westerhoff, W.E., Busschers, F.S., 2012. Pleistocene Rhine–Thames landscapes: geological background for hominin occupation of the southern North Sea region. Journal of Quaternary Science 27, 17–39

Hjelstuen, B.O., Sejrup, H.P., Valvik, E.,Becker, L.W.M., 2018. Evidence of an ice-dammed lake outburst in the North Sea during the last deglaciation. Marine Geology 402, 118–130.

Holmes, R., 1977. The Quaternary geology of the UK sector of the North Sea between 56° and 58°N. Report of the Institute ofGeological Sciences, No. 77114.

Houmark-Nielsen, M., Kjær, K.H. 2003. Southwest Scandinavia 40-15 ka BP: Plaleogeography and environmental change. Journal of Quaternary Science 18, 769–786.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M., 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. Quaternary Science Reviews 28, 758-776.

Hughes, A.L.C., Clark, C.D., Jordan, C.J., 2014. Flow-pattern evolution of the last British Ice Sheet. Quaternary Science Reviews, 89, 148-168.

Jansen, J.H.F., Van Weering, T.C., Eisma, D., 1979. Late Quaternary sedimentation in the North Sea. In The quaternary history of the North Sea. Acta Universitatis, Symposium Universitatis Usaliensis Annum Quingentesinum Celebrantis (pp. 175-187).

Laban, C., 1995. The Pleistocene Glaciations in the Dutch Sector of the North Sea. Ph.D. thesis, Universiteit van Amsterdam.

Lambeck, K., Purcell, A., Funder, S., Kjaer, Larsen, E., Moller, P., 2006. Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from field data and rebound modelling. Boreas 35, 539-575.

Livingstone, S.J., Evans, D.J., Cofaigh, C.Ó., Davies, B.J., Merritt, J.W., Huddart, D., Mitchell, W.A., Roberts, D.H., Yorke, L., 2012. Glaciodynamics of the central sector of the last British–Irish Ice Sheet in Northern England. Earth-Science Reviews 111, 25-55.
Long, D., Laban, C., Streif, H., Cameron, T.D.J., Schuttenhelm, R.T.E., 1988. The Sedimentary Record of Climatic Variation in the Southern North Sea [and Discussion]. Philosophical Transactions of the Royal Society of London, Series B, 318, 523-537.
McCabe, A.M., Knight, J., McCarron, S., 1998. Evidence for Heinrich Event 1 in the British Isles. Journal of Quaternary Science 13, 549–568.
Moreau, J., Huuse, M., Janszen, A., Van Der Vegt, P., Gibbard P.L., Moscariello A., 2012., The glaciogenic unconformity of the southern North Sea. Geol. Soc. Spec. Publ. 368, 99–110,
Murray, A.S., Wintle,A.G., 2003. Thesingle aliquot regenerative dose protocol: potential for improvements in reliability. Radiation Measurements 37, 377–381.
Murton D.K., Murton J.B., 2012. Middle and Late Pleistocene glacial lakes of lowland Britain and the southern North Sea Basin. Quaternary International 260, 115–142
Patton, H., Hubbard, A.L., Andreassen,K., Auriac, A., Whitehouse, P.L., Stroeven, A.P., Shackleton, C., Winsborrow, M., Heyman, J., Hall, A.M., 2017. Deglaciation of the Eurasian ice sheet complex. Quaternary Science Reviews 169, 148 – 172.
Pawley, S.M., Candy, I., Booth, S.J., 2006. The Late Devensian terminal moraine ridge at Garrett Hill, Stiffkey valley, north Norfolk, England. Proceedings of the Yorkshire Geological Society 56, 31-39.
Phillips, E., Lee, J.R., Burke, H., 2008. Progressive proglacial to subglacial deformation and syntectonic sedimentation at the margins of the Mid-Pleistocene British Ice Sheet: evidence from north Norfolk, UK. Quaternary Science Reviews 27, 1848–1871.
Phillips, E., Cotterill, C., Johnson, K., Crombie, K., James, L., Carr, S., Ruiter , A., 2018. Large-scale glacitectonic deformation in response to active ice sheet retreat across Dogger Bank (southern central North Sea) during the Last Glacial Maximum. Quaternary Science Reviews 179, 24-47.
Prescott, J. R., Hutton, J.T., 1994: Cosmic ray contributions to dose rates for luminescence and ESR: large depths and long-term time variations. Radiation Measurements 23, 497–500.
Raistrick, A., 1931. The glaciation of Northumberland and Durham. Proceedings of the Geologists' Association 42, 281–291.
Ramsay, J 1974. Development of chevron folds. Geological Society of America Bulletin 85, 1741-1754.
Rea, B.R., Newton, A.M.W., Lamb, R.M., Harding, R., Bigg, G.R., Rose, P., Spagnolo, M., Huuse, M., Cater, J.M.L., Archer, S., Buckley, F., Halliyeva, M., Huuse, J., Cornwell, D.G., Brocklehurst, S.H., Howell, JA. 2018. Extensive marine-terminating ice sheets in Europe from 2.5 million years ago. Science Advances 4, eaar8327.
Reimer, P., Bard, E., Bayliss, A., Beck, J., Blackwell, P., Ramsey, C., Van der Plicht, J. (2013). IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. Radiocarbon, 55, 1869-1887.
Riding, J., Rose, J., Booth S.J., 2003. Allochthonous and indigenous palynomorphs from the Devensian of the Warham Borehole, Stiffkey, north Norfolk, England; evidence for sediment provenance. Proceedings of the Yorkshire Geological Society 54, 223-237
Rise, L., Bellec, V.K., Ottesen, D., Bøe R., Thorsnes T., 2016. Hill–hole pairs on the Norwegian continental shelf. Geological Society, London, Memoirs 46, 203-204.
Roberts, D.H., Hart, J.K., 2005. The deforming bed characteristic of a stratified till assemblage in north East Anglia, UK: investigating controls on sediment rheology and strain signatures. Quaternary Science Reviews 24, 123–140.
Roberts, D.H., Evans, D.J.A., Lodwick, J., Cox, N.J., 2013. The subglacial and ice-marginal signature of the North Sea Lobe of the British–Irish Ice Sheet during the Last Glacial Maximum at Upgang, North Yorkshire, UK. Proceedings of the Geologists' Association124, 503-519.
Roberts, D.H., Grimoldi, E.Callard, S.L., Evans, D. J.A ., Clark, C.D., Stewart, H.A., Dove, D., Saher, M., Cofaigh, C.O., Chiverrell, R., Bateman, M.R., Moreton, S.G., Bradwell, T., Fabel, D., Medialdea. A. submitted). The mixed-bed glacial landform imprint of the North Sea Lobe in the western North Sea. Earth surface Process and Landforms.

Rose, J., 1985. The Dimlington Stadial/Dimlington Chronozone: a proposal for naming the main glacial episode of the Late Devensian in Britain. Boreas 14, 225-230.

Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Haflidason, H., Nesje, A., 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. Quaternary Science Reviews, 19, 667-685.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason,H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin: Marine and Petroleum Geology 22, 1111–1129.

Sejrup, H.P., Nygård, A., Hall, A.M., Haflidason, H., 2009. Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK: Quaternary Science Reviews 28, 370–380.

Sejrup, H.P., Hjelstuen, B.O., Nygård, A., Haflidason,H., Mardal, I., 2015. Late Devensian ice-marginal features in the central North Sea - Processes and chronology: Boreas 44, 1–13.

Sejrup, H.P., Clark, C.D., Hjelstuen, B.O., 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea. Geology 44, 355-358.

Solomon, J.D., 1932. The glacial succession on the north Norfolk coast. Proc. Geol. Association 43, 241-271.

Stokes C.R., Clark C.D., 2004. Evolution of late glacial ice-marginal lakes on the northwestern Canadian Shield and their influence on the location of the Dubawnt Lake palaeo-ice stream. Palaeogeography, Palaeoclimatology, Palaeoecology 215, 155–171.

Straw, A., 1960. The limit of the 'Last' Glaciation in North Norfolk.Proceedings of the Geologists' Association 71, 379-390.

Sturt, F., Garrow, D., Bradley, S., 2013. New models of North West European Holocene palaeogeography and inundation. Journal of Archaeological Science 40, 3963-3976.

Tappin, D.R., Pearce, B., Fitch, S., Dove, D., Gearey, B., Hill, J.M., Chambers, C., Bates, R., Pinnion, J., Diaz Doce, D., Green, M., 2011. The Humber regional environmental characterisation. Marine Aggregate Levy Sustainability Fund.

van der Wateren, F.M., 1995. Structural geology and sedimentology of push moraines: Mededelingen Rijks Geologische Dienst, 54.

van der Wateren, F.M., 2003. Ice marginal terrestrial landsystems: southern Scandanavian ice sheet margin. In Evans D.J.A. (ed.), Glacial Landsystems. Arnold, London. 166-203

Veenstra, H.J., 1965. Geology of the Dogger Bank area, North Sea. Marine Geology 3, 245-262.

Ward, S., Neill, S., Scourse, J., Bradley, S.L., Uehara, K., 2016, Sensitivity of palaeotidal models of the northwest European shelf seas to glacial isostatic adjustment since the Last Glacial Maximum. Quaternary Science Reviews 151, 198-211.

Whitaker, W., Jukes-Brownw, A.J., 1899. Geology of the Borders of the Wash. Memoirs Geological Survey, U.K.

Woodward, H.B., 1884. Geology of the country around Fakenham, Wells and Holt. Memoir of the Geological Survey, England and Wales, Old Series Quarter Sheets 68NW and 68SW.

Fig Captions

Figure 1: The physiographic setting of the North Sea with previous mapped ice limits for the LGM (coupled and uncoupled FIS/BIIS). The Dogger Bank sits in the central/southern North Sea. The coast lines on Norfolk, Lincolnshire and Yorkshire are situated south and west of the DB respectively. Major drainage basins feeding ice streams into the North Sea include the Moray Firth, Firth of Forth, Tweed (Tw), Tyne Gap (Ty) and the Eden-Stainmore (Ed-St) gap. The Humber Gapis also marked. (Image based on reconstruction of Dove et al., 2017).

Figure 2: Seismic profiles and core locations collected from the southern North Sea for BRITICE-CHRONO on cruise JC123 in 2015. The Dogger Bank is covered by seismic lines SP 1 – 4. SP5 is south of the Dogger Bank. The blue line denotes the position of a regional-scale BGS seismic survey line (Cameron et al., 1992; see Fig 3a). The yellow line denotes the location of Line 12

from Philips et al. (2018; see Fig. 3b). The shallow coastal areas north of the Norfolk coast and the Wash are covered by SP 6- 9. Garret Hill on the Norfolk coast is marked GH.

Figure 3: a) The Quaternary geology of the southern North Sea and the Dogger Bank (Cameron et al., 1992). b) The internal stratigraphy of the Dogger Bank (re-drawn from Phillips et al. 2018). Note sediments of the Dogger Bank Formation is split into three units (Basal, Lower and Upper). They are described as glaciolacustrine and glaciofluvial deposits. The Basal and Lower units are folded and thrust due to glaciotectonics.

Figure 4: Acoustic facies associated with the Dogger Bank sub-bottom profiles (SP 1- 3). DB 1 to DB 7 are identified using both geophysical acoustic properties and sediment properties from gravity cores.

Figure 5: a) Fence diagram of SP 1 - 3 across Dogger Bank. High resolution versions of SP 1, 2 and 3 are available in the supplementary information. b) The acoustic stratigraphy of SP1. Note the preglacial unit (DB 1) overlain by three sub-units of DB 3. DB5 represent channels infills and the sequence is capped by DB 7. c) Core logs 150 and 151VC. The basal sediments in both cores are interpreted as folded glaciolacustrine (DB 3b) and provided OSL ages of 29.5±1.9 and 26.2±2.1ka respectively (Shfd15175 and Shfd15176).

Figure 6: Acoustic facies mapped along the southwestern end of SP3 between (see Figure 2 for location). A high resolution image of the complete line is available in supplementary information. A series of lower diamicts (DB 2) can be traced above the preglacial sediments. These are overlain in turn by deformed clays (DB 3b) and upper diamicts and sands (DB 4) that coincide with a buried moraine/outwash fan at 165 - 168 km. Multiple, infilled channels dissect the sequence (DB 5) and the seafloor is capped by a shelly, sand (DB 7).

Figure 7: Specific geomorphic and stratigraphic relationships along SP3. a) A buried moraine composed of DB 2 is draped by overlying interstratified sediments (DB5) with low angle thrust inferring north to south displacement. There are also ssmaller moraines to the south of the main moraine. b) A moraine complex with faulted and stacked/deformed tills (DB 2) which are overlain by an outwash/fan complex and upper tills (DB 4a and b). c) Well developed folds (chevron) in the core of the Dogger Bank with DB 3b clearly having undergone compressional glaciotectonics. A sub-unit of DB 3a is also highlighted; its bedding aspect is more sub-horizontal and less deformed.

Figure 8: a) Moraines underpinning sand ridges on the northern edge of the Dogger Bank. b) Core 155VC: A 6m core of interlaminated silts/clays (DB 5b) from a basin on-lapping the moraines on the northern edge of Dogger Bank. An OSL sample from 357cm down core returned an age for 23.1±2.3 ka. No till was recorded over DB 5b at this site.

Figure 9: a) SP4 on the western edge of the Dogger Bank showing deformed and folded DB 3b, and overlying till (DB 4b) and an on-lapping infill of stratified silts and clayst (DB5b). b) Cores 171 – 174VC record a red/brown, massive, matrix-supported, diamict with chalk and flint erratics (DB 4b) sitting above DB 3b inferring ice override of this area of western Dogger Bank.

Figure 10: a) Acoustic facies mapped along SP5 Dogger Bank where diamicts are overlain by localised pockets of outwash/glaciolacustrine sediments. b) Brown, red diamicts interpreted as subglacial tills of the Bolders Bank Fm. c) Well sorted sands sitting above DB 2 are pockets of outwash sediment that were dated in cores 178 and 179 VC provided OSL ages of 31.6±2.1 and 25.8±2.4 ka respectively (Shfd15179 and Shfd15180). Upper peats in core 178VC returned ages of 9.7 and 9.8 ka respectively.

Figure 11: A schematic model of the acoustic stratigraphy of the eastern and western Dogger Bank. North is to the left and the plots are vertically exaggerated. To the east (SP1) there is evidence for proglacial glaciotectonism of the northern part of the Dogger Bank and associated lake sediments, but a lack of till suggests the bank was not overrun. To the west (SP3, 4, 5) there is evidence for ice advancing/retreating over the area and depositing multiple subglacial tills and as well as causing widespread proglacial glaciotectonism.

Figure 12: Individual acoustic facies from the seafloor north of the Norfolk coast found along transects SP 6-9.

Figure 13: a) Seafloor acoustic stratigraphy from SP 6 and SP 8. Several acoustic facies can be mapped with pre MIS2, subglacial, glaciolacustrine and marine sediments covering chalk bedrock which is very close to the seafloor. b) Multiple cores retrieved acoustic facies ONN 3. Whci recovered a brown/red, massive, matrix-supported, fine grained, over-consolidated diamict with distinctive chalk and flint clasts. It is mapped across the seafloor as Bolders Bank Fm and the same type of diamict is observed further north around the western Dogger Bank (DB 2; see Figure 9b).

Figure 14: a) High resolution seafloor bathymetry from the area north of the Norfolk coast. Moraines are clearly distinguishable in the bathymetric data (marked in yellow) and can be mapped acoustically in the seismic data (collected on cruise JC 123). Tunnel valleys (orange) and ice marginal/proglacial channels (red) are also be mapped. This geomorphic pattern relates to an oscillating ice margin migrating northwards (image sourced from Dove et al., 2017). b and c) Moraine 1 is a thrust moraine complex exhibiting deformed lower till units (ONN 3) and attenuated and boudinaged stratified sediments. Moraine2 further to the north displays a different geometry and is interpreted as a possible a hill-hole pair.

Figure 15: Core 166VC exhibiting interlaminated sands, silts and clays. Note decreasing laminae thickness and increase laminae frequency up core. Rhythmites are particularly clear between 200 - 500cm in the core. Two *Littorina Littorae* samples from the base of the core (589 and 593cm) provide a minimum date of deposition at 9.5 and 9.1 ka.

Figure 16: a) Location of Garret Hill, North Norfolk. The MIS 2 ice limit is marked running west to east (Straw, 1962). b) Sediments sections from the northwest side of the Garret Hill showing gravelly diamict separated by stratified sand and gravels. OSL dates from the lower sands provide ages of 21.5±1.3 and 22.8±1.8 ka (Shfd15033 and Shfd15034; Table 1).

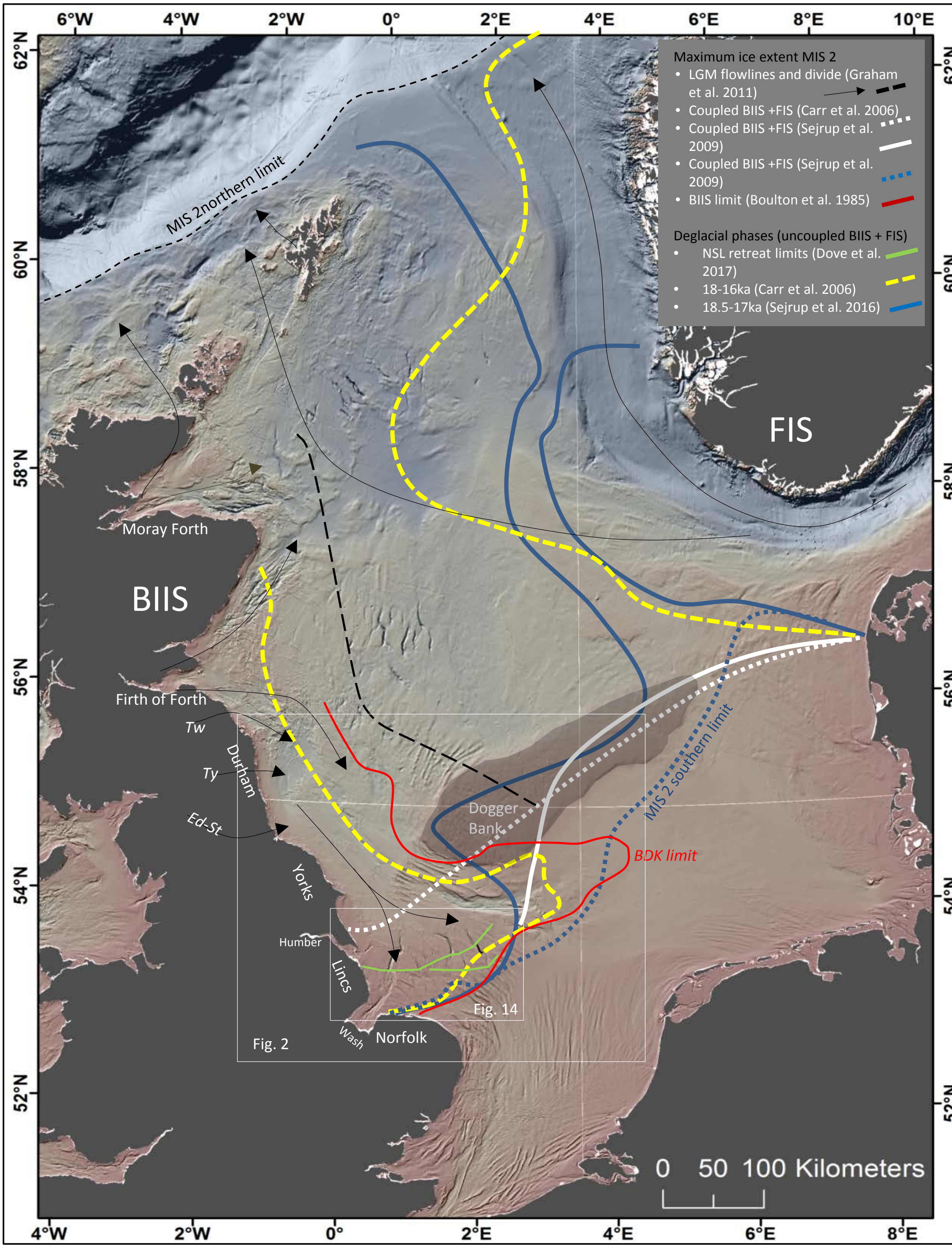
Figure 17: ***Phase 1***: The advance of the BIIS at the MIS3/2 transition? Ice margin position poorly constrained. ***Phase 2:*** Coalescence of the BIIS and FIS blocks regional drainage and the Dogger lake forms west to east along the southern edge of the ice sheet. An unstable, oscillatory ice margin would have triggered multiple minor advance/retreat cycles over western Dogger between 30 - 23 ka leading to widespread glaciotectonism of lake sediments. ***Phase 3:*** A single OSL age of 23.1ka and on-lapping gl'lacusrine sediments in core 155VC constrains ice retreat to the northern edge of Dogger and infers ribbon lake development behind the Dogger bank thrust moraine complex. ***Phase 4:*** The later phase advance of the NSL was restricted to the western side of the North Sea basin after 22 to 21 ka. Ice dynamics in the southern North Sea at this time may have been influenced by decoupling of the BIIS and FIS triggered by Dogger lake outburst flood to the north. Estimates on decoupling vary widely from 23 - 22 ka (Patton et al. 2017) to 18.7 ka (Hjelsstuen et al. 2018). ***Phase 5:*** Ice retreat along the east coast toward NE England between 21 - 19ka. Marine inundation of the central North Sea would have aided deglaciation, while areas to the south of Dogger Bank remained terrestrial until the opening of the Holocene.

Table 1: OSL age data including total dose rate, number of aliquots measured (in brackets) and accepted, the derived estimated equivalent doses (D_e) and resulting ages.

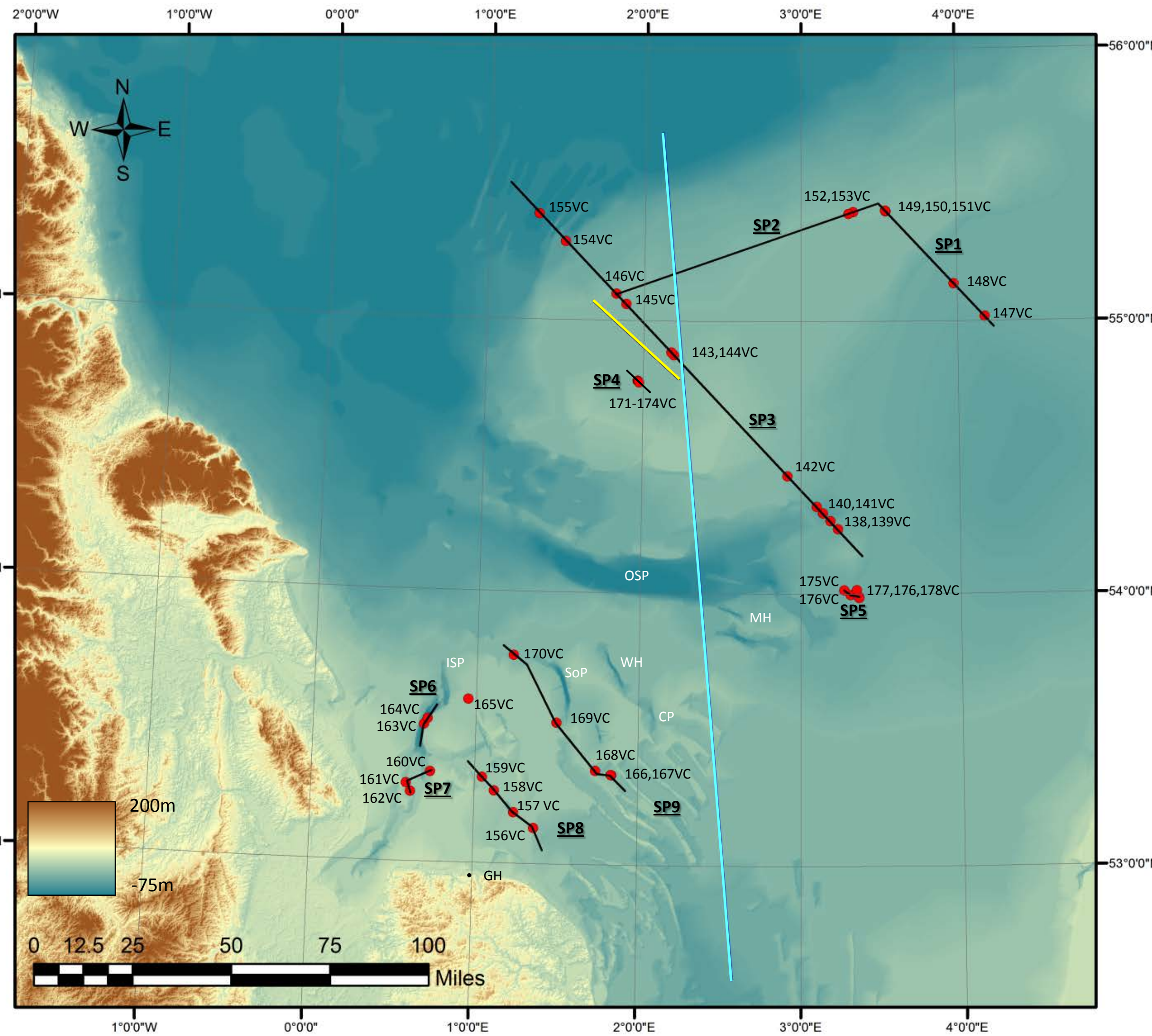
Region	Lab code	Core	Total dose rate (Gy/ka)	$n_{measured}$ (n_{total})	OD (%)	D_e (Gy)	Age (ka)
Dogger	Shfd15174	142VC	1.14±0.06	72 (80)	16	11.3±0.2	9.9±0.6
	Shfd15175	150VC	1.23±0.07	70 (72)	21	36.2±1.0	29.5±1.9
	Shfd15176	151VC	1.28±0.07	48 (50)	29	33.5±1.9	26.2±2.1
	Shfd15177	154VC	1.12±0.08	43 (50)	42	117.5±8.0	105.0±7.2
	Shfd15178	155VC	3.1±0.15	47 (55)	51	71.6±6.2	23.1±2.3
	Shfd15179	178VC	1.67±0.09	41 (52)	27	43.1±3.3	25.8±2.4
	Shfd15180	179VC	2.06±0.11	42 (50)	22	65.1±2.5	31.6±2.1
Norfolk	Shfd15033	GAR14-1-1	1.52±0.07	80 (41)	41	32.7±1.2	21.5±1.3
	Shfd15034	GAR14-1-2	1.20±0.05	70 (47)	55	27.4±1.8	22.8±1.8

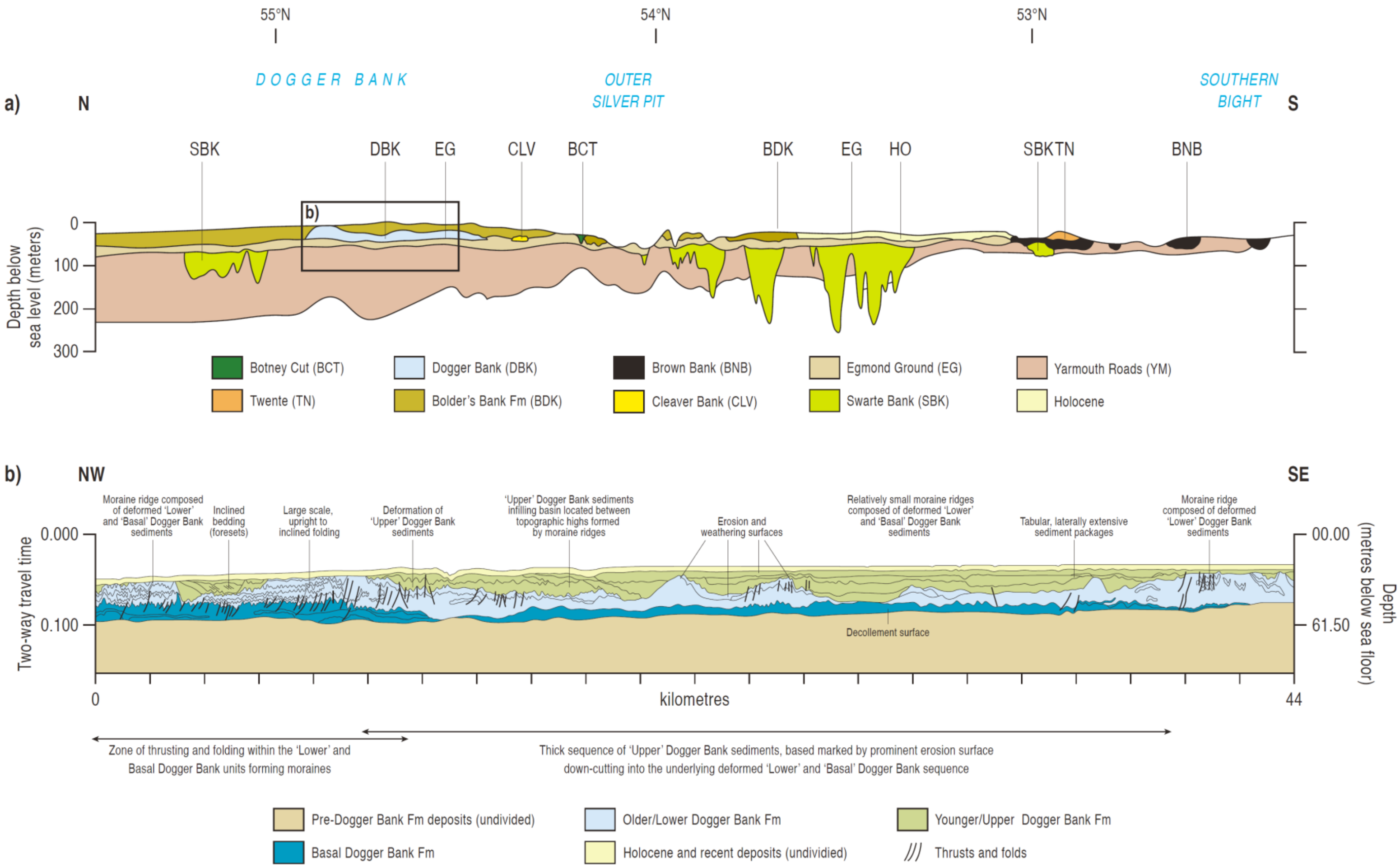
Table 2: Radiocarbon ages form cores 143, 166, 175, 176 and 178VC

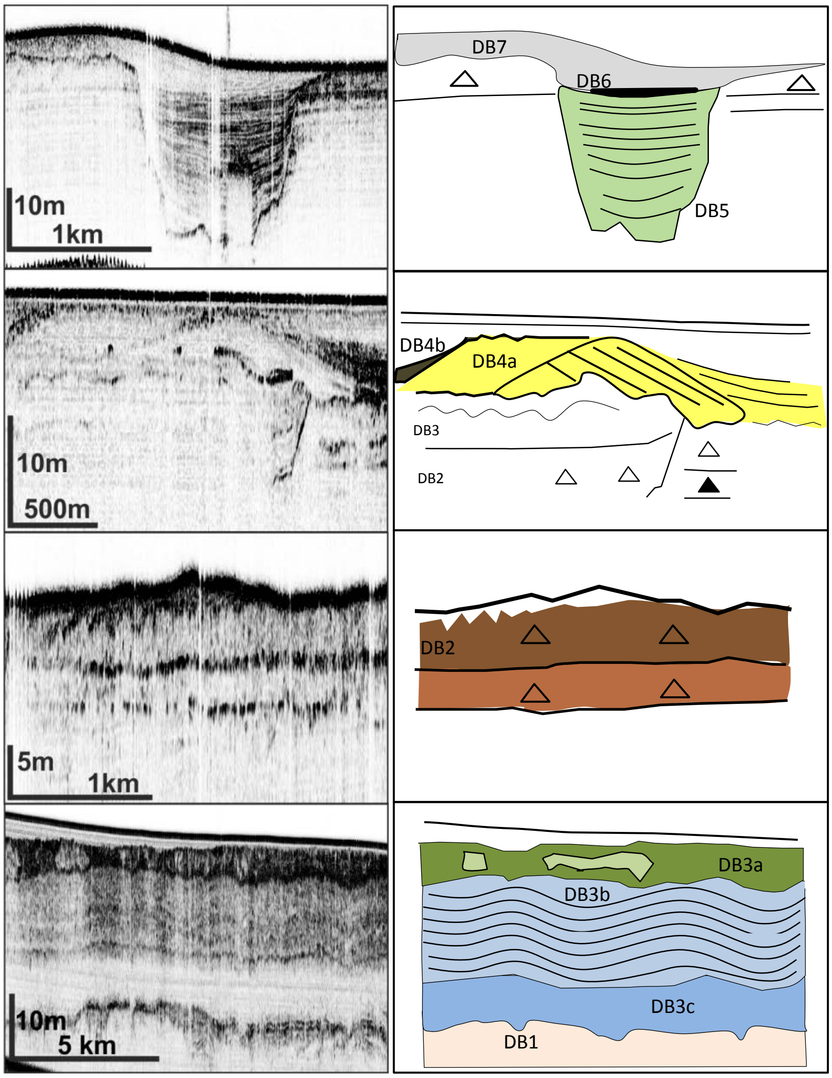
Lab code	Transect No/core/ sample depth	Conventional Radiocarbon Age (years BP)	Error ± 1α (radiocarbon yrs BP)	Calibrated C14 age (cal yrs BP)	Error ± 1α (cal yrs BP)
SUERC-72882	T2-143VC-239	16477	66	19395	208
SUERC-72162	T2-175VC-44	9084	40	9801	171
SUERC-72884	T2-175VC-52	9143	45	9917	202
SUERC-72885	T2-175VC-80	17138	74	20190	229
SUERC-72886	T2-176VC-83	9151	40	9934	188
SUERC-72887	T2-178VC-28	9025	40	9705	161
SUERC-72891	T2-178VC-47	9089	39	9809	171
SUERC-68002	T2-166VC-589	8887	35	9535	82
SUERC-68003	T2-166VC-593	8515	37	9141	129



6°W
4°W
2°W
0°
2°E
4°E
6°E
8°E
10°E
62°N
60°N
58°N
56°N
54°N
52°N
Maximum ice extent MIS 2
LGM flowlines and divide (Graham et al. 2011)
Coupled BIIS +FIS (Carr et al. 2006)
Coupled BIIS +FIS (Sejrup et al. 2009)
Coupled BIIS +FIS (Sejrup et al. 2009)
BIIS limit (Boulton et al. 1985)
Deglacial phases (uncoupled BIIS + FIS)
NSL retreat limits (Dove et al. 2017)
18-16ka (Carr et al. 2006)
18.5-17ka (Sejrup et al. 2016)
MIS 2northern limit
FIS
BIIS
Moray Forth
Firth of Forth
Tw
Durham
Ty
Ed-St
Yorks
Humber
Lincs
Wash
Norfolk
Dogger Bank
BDK limit
MIS 2 southern limit
Fig. 14
Fig. 2
0 50 100 Kilometers
4°W
2°W
0°
2°E
4°E
6°E
8°E


2°0'0"W
1°0'0"W
0°0'0"
1°0'0"E
2°0'0"E
3°0'0"E
4°0'0"E
56°0'0"N
55°0'0"N
54°0'0"N
53°0'0"N
N
W
E
S
155VC
154VC
146VC
145VC
143,144VC
152,153VC
149,150,151VC
148VC
147VC
SP1
SP2
SP3
SP4
171-174VC
142VC
140,141VC
138,139VC
OSP
175VC
176VC
177,176,178VC
SP5
MH
170VC
ISP
SoP
WH
SP6
164VC
163VC
165VC
169VC
CP
160VC
161VC
162VC
SP7
159VC
158VC
157 VC
156VC
SP8
168VC
166,167VC
SP9
200m
-75m
GH
0
12.5
25
50
75
100
Miles


a)
N
S
55°N
54°N
53°N
DOGGER BANK
OUTER SILVER PIT
SOUTHERN BIGHT
SBK
DBK
EG
CLV
BCT
BDK
EG
HO
SBK
TN
BNB
b)
Depth below sea level (meters)
0
100
200
300
Botney Cut (BCT)
Twente (TN)
Dogger Bank (DBK)
Bolder's Bank Fm (BDK)
Brown Bank (BNB)
Cleaver Bank (CLV)
Egmond Ground (EG)
Swarte Bank (SBK)
Yarmouth Roads (YM)
Holocene
b)
NW
SE
Moraine ridge composed of deformed 'Lower' and 'Basal' Dogger Bank sediments
Inclined bedding (foresets)
Large scale, upright to inclined folding
Deformation of 'Upper' Dogger Bank sediments
'Upper' Dogger Bank sediments infilling basin located between topographic highs formed by moraine ridges
Erosion and weathering surfaces
Relatively small moraine ridges composed of deformed 'Lower' and 'Basal' Dogger Bank sediments
Tabular, laterally extensive sediment packages
Moraine ridge composed of deformed 'Lower' Dogger Bank sediments
Decollement surface
Two-way travel time
0.000
0.100
00.00
61.50
Depth (metres below sea floor)
0
kilometres
44
Zone of thrusting and folding within the 'Lower' and Basal Dogger Bank units forming moraines
Thick sequence of 'Upper' Dogger Bank sediments, based marked by prominent erosion surface down-cutting into the underlying deformed 'Lower' and 'Basal' Dogger Bank sequence
Pre-Dogger Bank Fm deposits (undivided)
Basal Dogger Bank Fm
Older/Lower Dogger Bank Fm
Holocene and recent deposits (undividied)
Younger/Upper Dogger Bank Fm
Thrusts and folds



Acoustic facies description

DB7: Transparent draped unit with sand waves (Holocene; active seafloor)

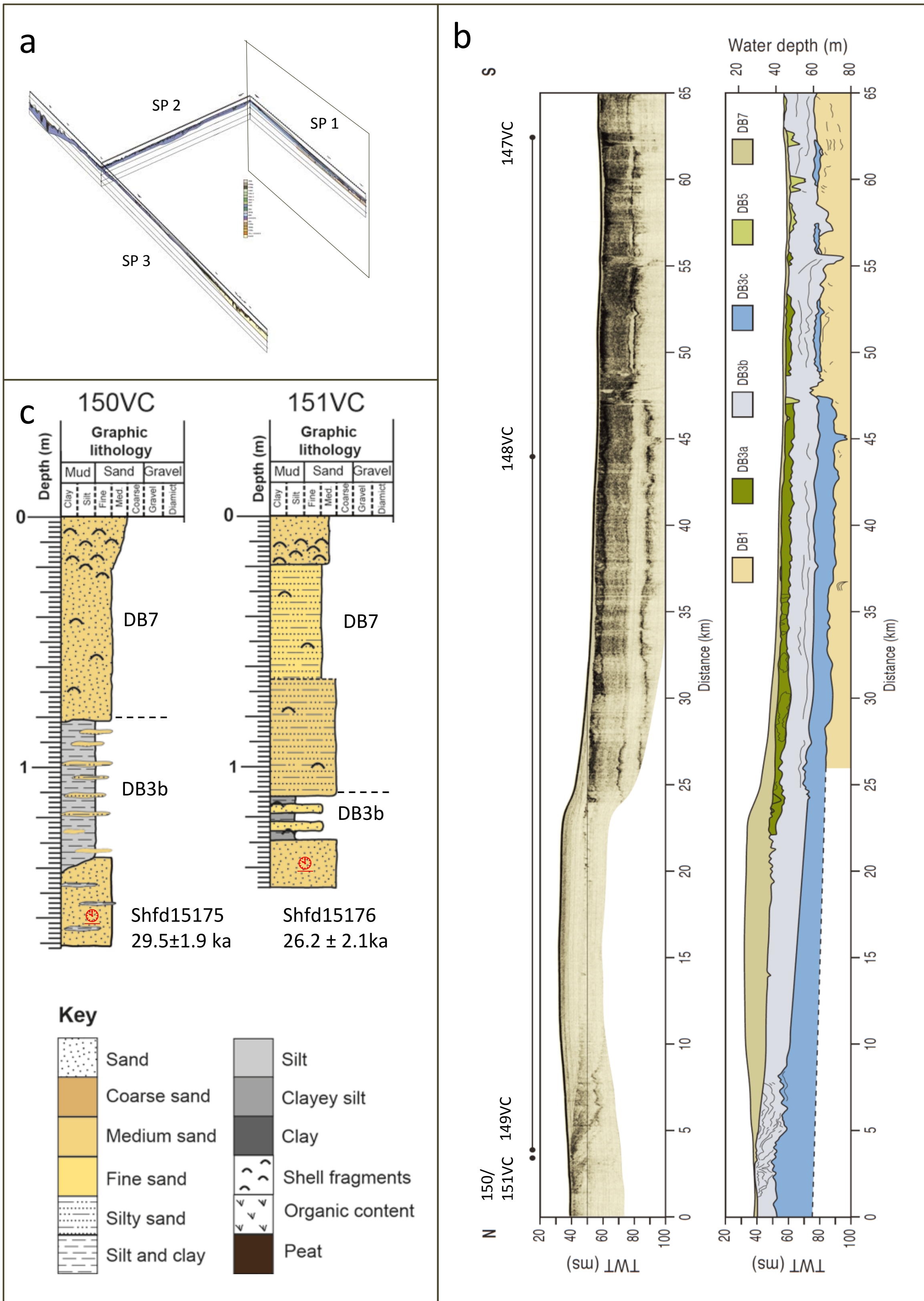
DB6: peat (Holocene; terrestrial/estuarine)

DB5(a-b): Stratified channel infills (subglacial channels with glaciolacustrine and postglacial marine infill; Botney Cut Fm)

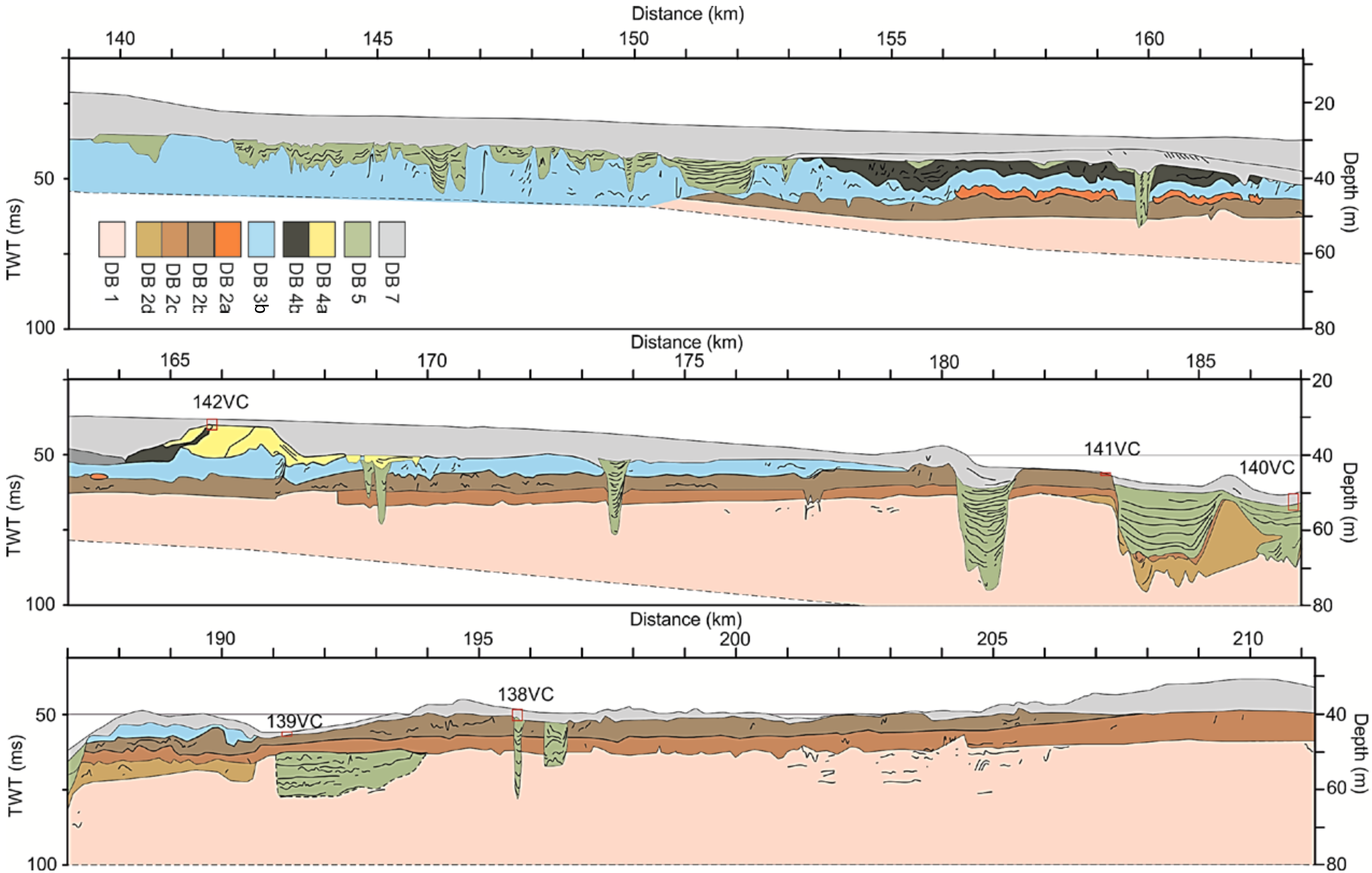
DB4a: Dipping, off-lapping, semi-transparent sand units over glaciotectonitised sediments (DB3) and diamict (DB2)
(Ice marginal fan/delta; Bolders Bank Fm)
DB4b: massive, opaque, structureless, stacked units (Subglacial till; Bolders Bank Fm)

DB 2(a-d): massive, opaque, structureless, stacked diamict units
(Subglacial till; Bolders Bank Fm)

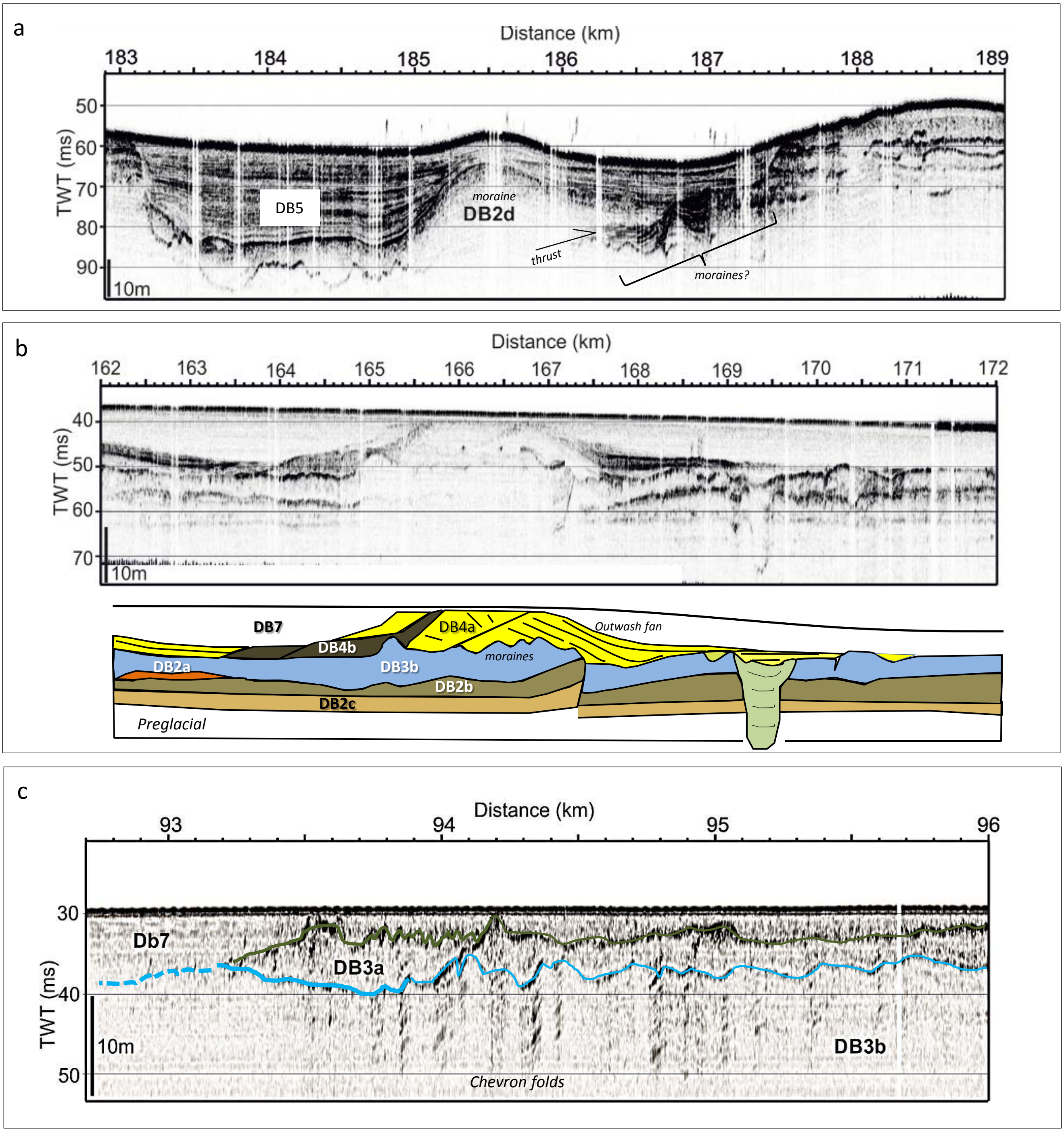
DB3a: Massive unit with distinctive lenses (Glaciolacustrine/outwash; Younger/Upper DB Fm)
DB3b: Sub-horizontal stratified fines. Folding. (Glaciolacustrine; Older/Lower DB Fm)
DB3c: Transparent, structureless, tabular unit (Glaciolacustrine/outwash?; Basal Dogger Bank (DB) Fm;
DB1: Transparent, structureless, tabular unit; Incised upper surface (Marine; Egmond Gr'd Fm)



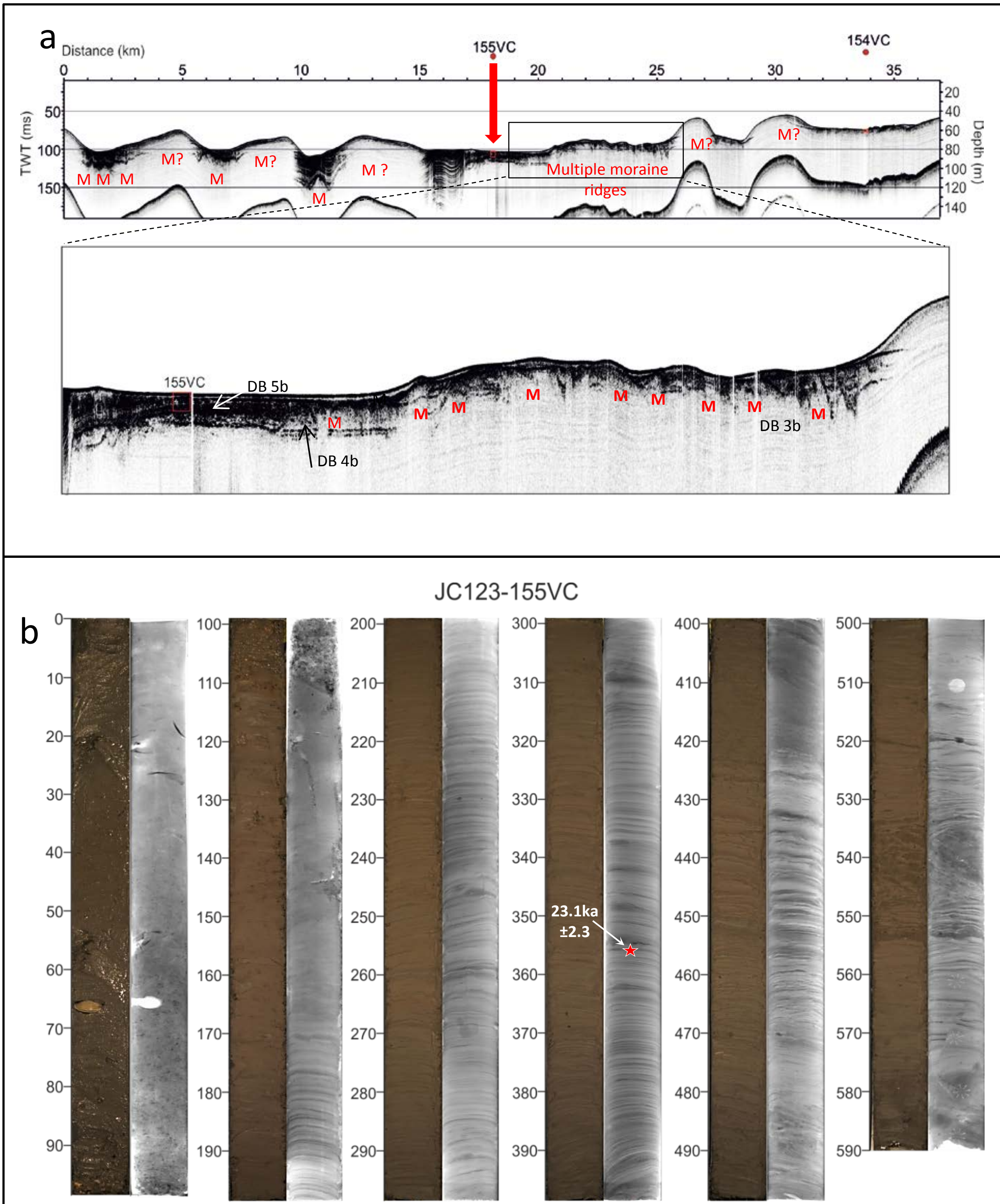
a
SP 2
SP 1
SP 3
b
Water depth (m)
S
N
147VC
148VC
149VC
150/ 151VC
Distance (km)
TWT (ms)
DB7
DB5
DB3c
DB3b
DB3a
DB1
c
150VC
151VC
Graphic lithology
Depth (m)
Mud
Sand
Gravel
Clay
Silt
Fine
Med.
Coarse
Gravel
Diamict
DB7
DB3b
Shfd15175
29.5±1.9 ka
Shfd15176
26.2 ± 2.1ka
Key
Sand
Coarse sand
Medium sand
Fine sand
Silty sand
Silt and clay
Silt
Clayey silt
Clay
Shell fragments
Organic content
Peat

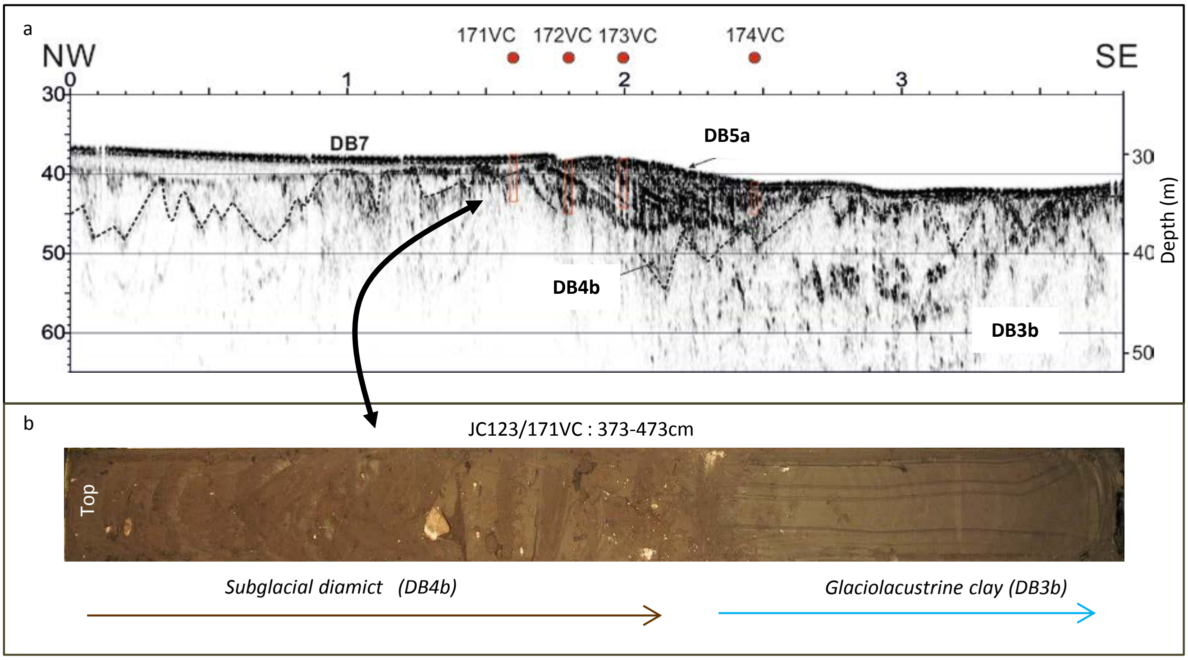


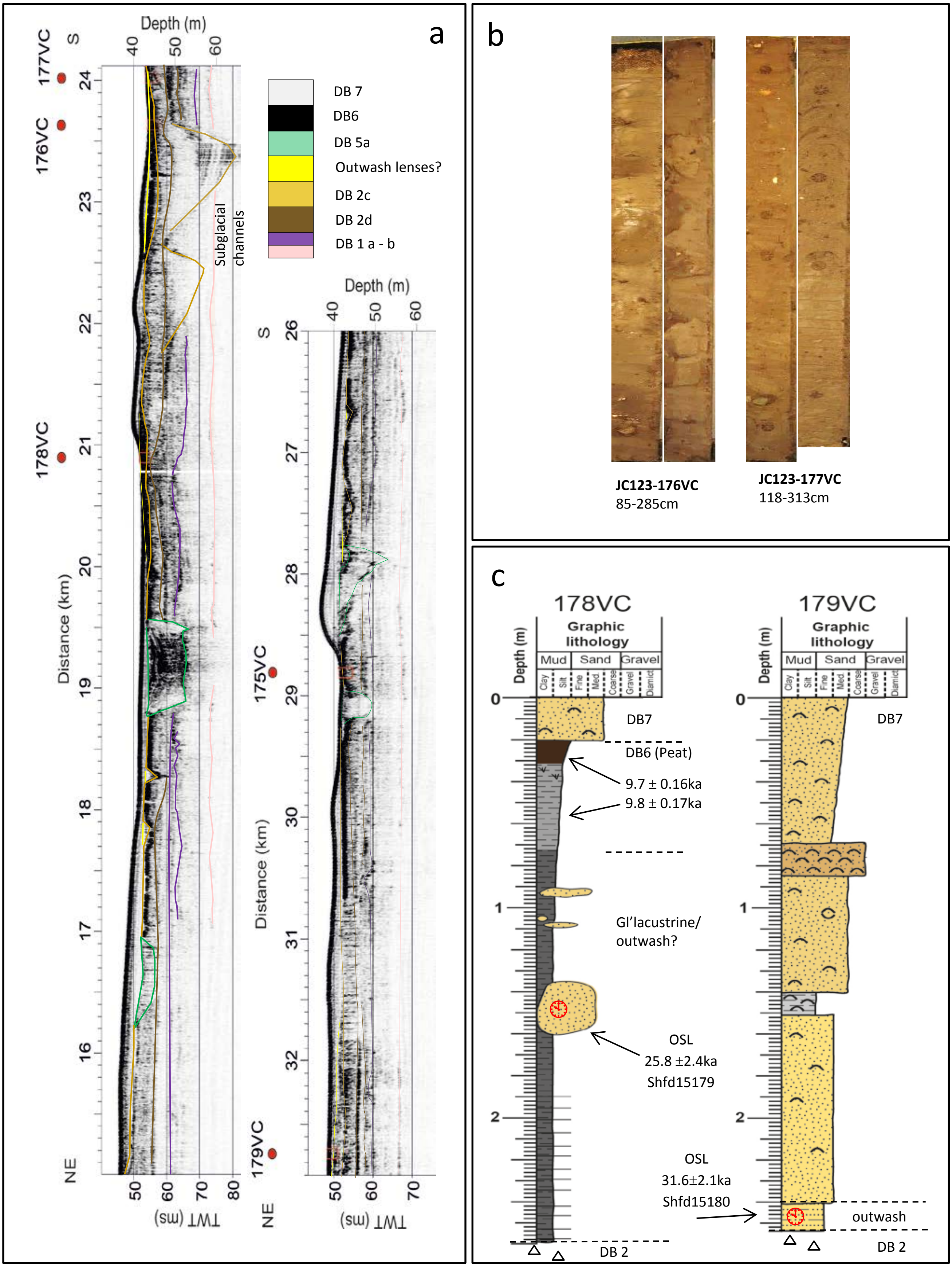
Distance (km)
TWT (ms)
Depth (m)
DB 1
DB 2d
DB 2c
DB 2b
DB 2a
DB 3b
DB 4b
DB 4a
DB 5
DB 7
142VC
141VC
140VC
139VC
138VC



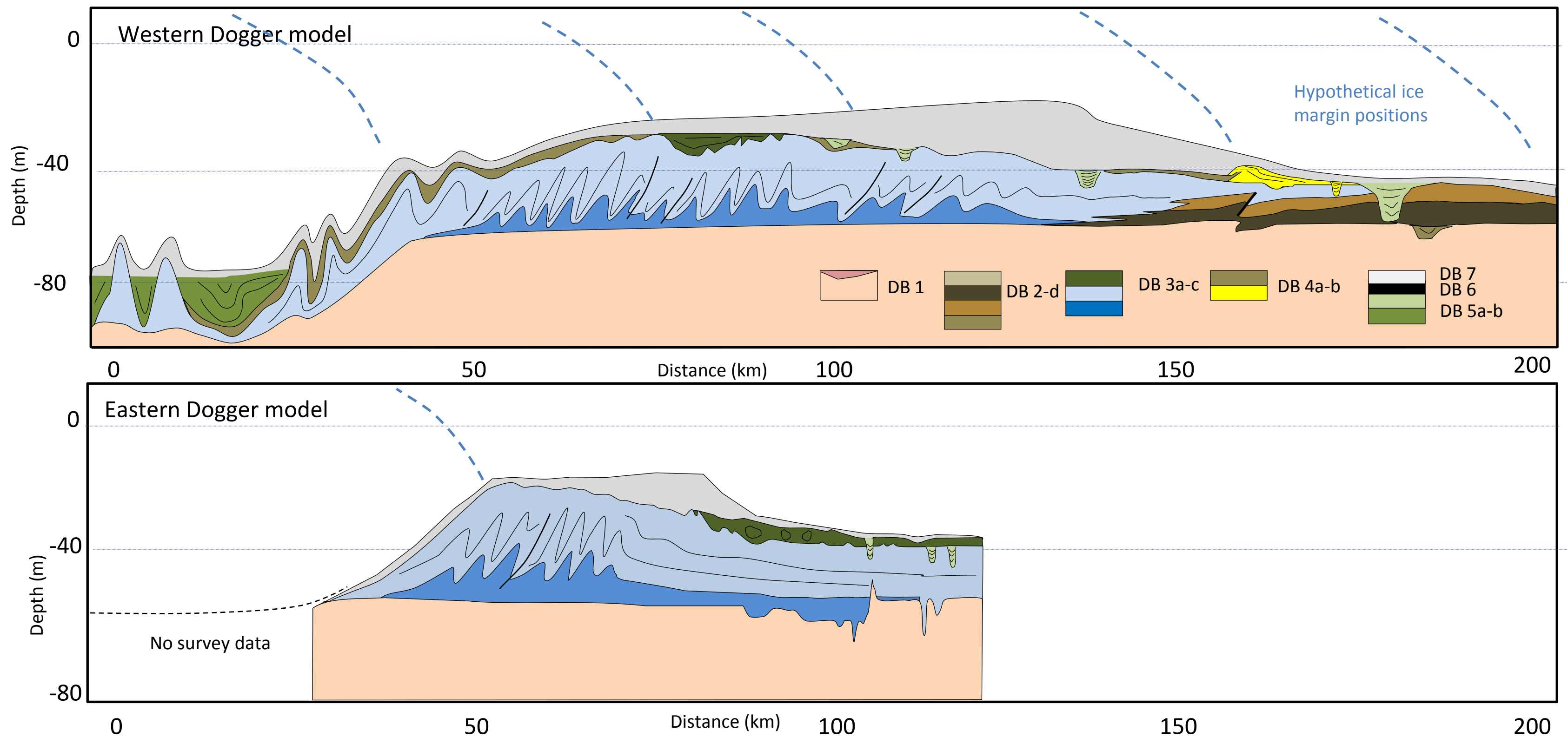
a
Distance (km)
183
184
185
186
187
188
189
TWT (ms)
50
60
70
80
90
10m
DB5
moraine
DB2d
thrust
moraines?
b
Distance (km)
162
163
164
165
166
167
168
169
170
171
172
TWT (ms)
40
50
60
70
10m
DB7
DB4a
Outwash fan
DB4b
moraines
DB2a
DB3b
DB2b
DB2c
Preglacial
c
Distance (km)
93
94
95
96
TWT (ms)
30
40
50
Db7
DB3a
10m
DB3b
Chevron folds


a
Distance (km)
0
5
10
15
20
25
30
35
155VC
154VC
TWT (ms)
50
100
150
Depth (m)
20
40
60
80
100
120
140
M M M
M?
M
M?
M
M ?
M?
M?
Multiple moraine ridges
155VC
DB 5b
DB 4b
M
M
M
M
M
M
M
M
M
DB 3b
JC123-155VC
b
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
340
350
360
370
380
390
23.1ka
±2.3
400
410
420
430
440
450
460
470
480
490
500
510
520
530
540
550
560
570
580
590

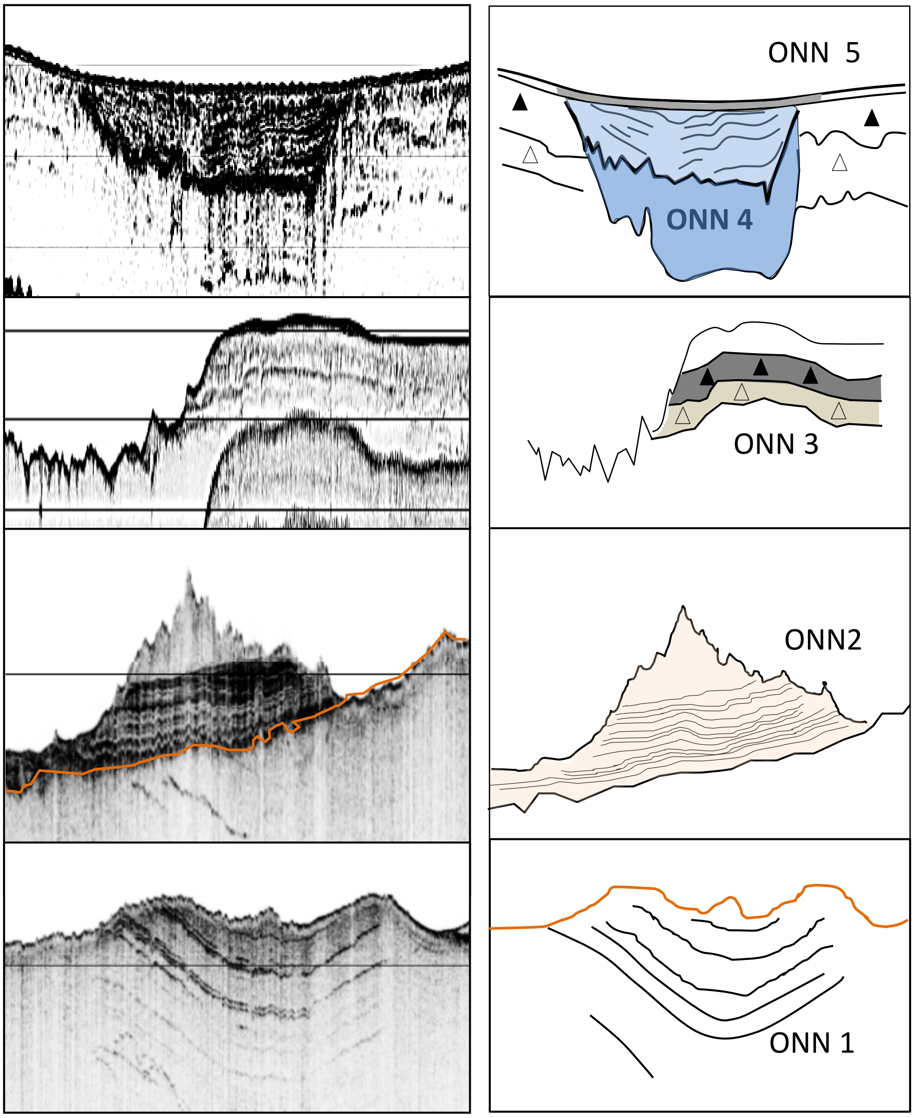

a
171VC 172VC 173VC 174VC
NW
SE
0
1
2
3
30
40
50
60
DB7
DB5a
DB4b
DB3b
30
40
50
Depth (m)
b
JC123/171VC : 373-473cm
Top
Subglacial diamict (DB4b)
Glaciolacustrine clay (DB3b)



a
177VC
176VC
178VC
S
NE
Depth (m)
Distance (km)
TWT (ms)
Subglacial channels
DB 7
DB6
DB 5a
Outwash lenses?
DB 2c
DB 2d
DB 1 a - b
175VC
179VC
b
JC123-176VC
85-285cm
JC123-177VC
118-313cm
c
178VC
179VC
Graphic lithology
Depth (m)
Mud
Sand
Gravel
Clay
Silt
Fine
Med
Coarse
Gravel
Diamict
DB7
DB6 (Peat)
9.7 ± 0.16ka
9.8 ± 0.17ka
Gl'lacustrine/ outwash?
OSL
25.8 ±2.4ka
Shfd15179
OSL
31.6±2.1ka
Shfd15180
outwash
DB 2



Western Dogger model
0
-40
-80
Depth (m)
Hypothetical ice
margin positions
DB 1
DB 2-d
DB 3a-c
DB 4a-b
DB 7
DB 6
DB 5a-b
0
50
Distance (km)
100
150
200
Eastern Dogger model
0
-40
-80
Depth (m)
No survey data
0
50
Distance (km)
100
150
200



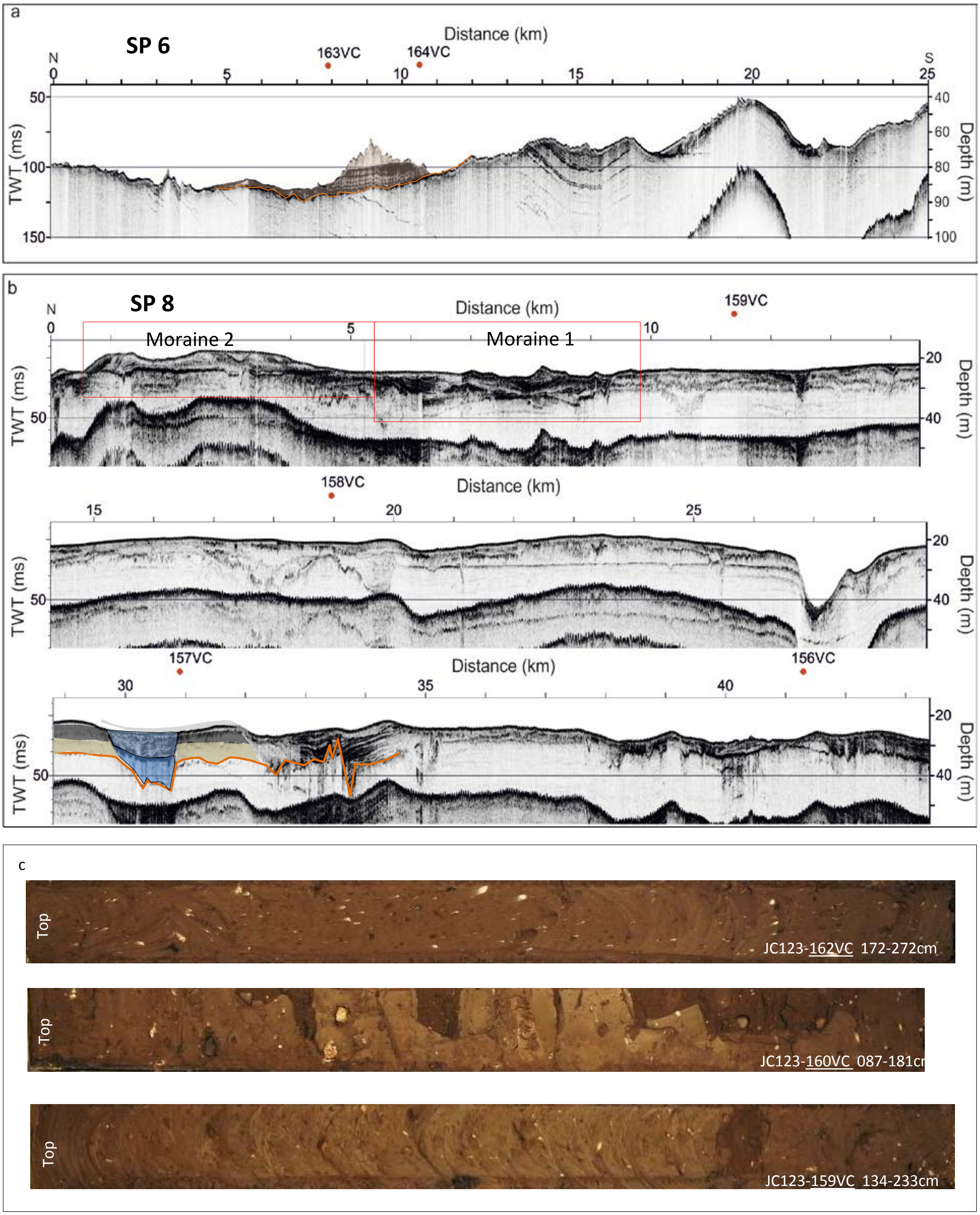
ONN5: Transparent, draped sand unit (Holocene; active seafloor)

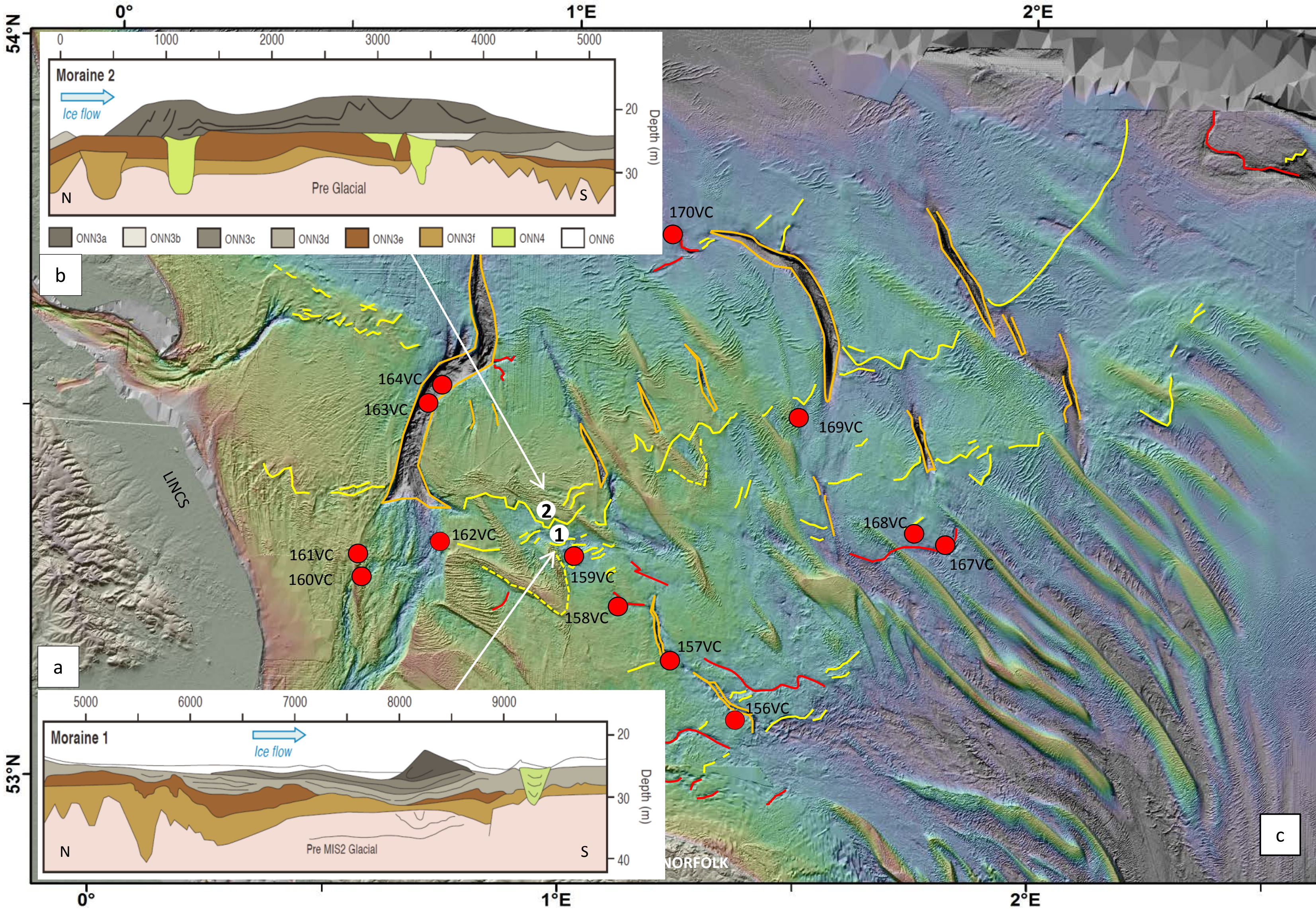
ONN4: Stratified channel infills (Sub/proglacial channels with glaciolacustrine and marine + postglacial infill; Botney Cut Fm)

ONN3: Massive, structureless, semi opaque diamict units; (Subglacial till; Bolders Bank Fm)

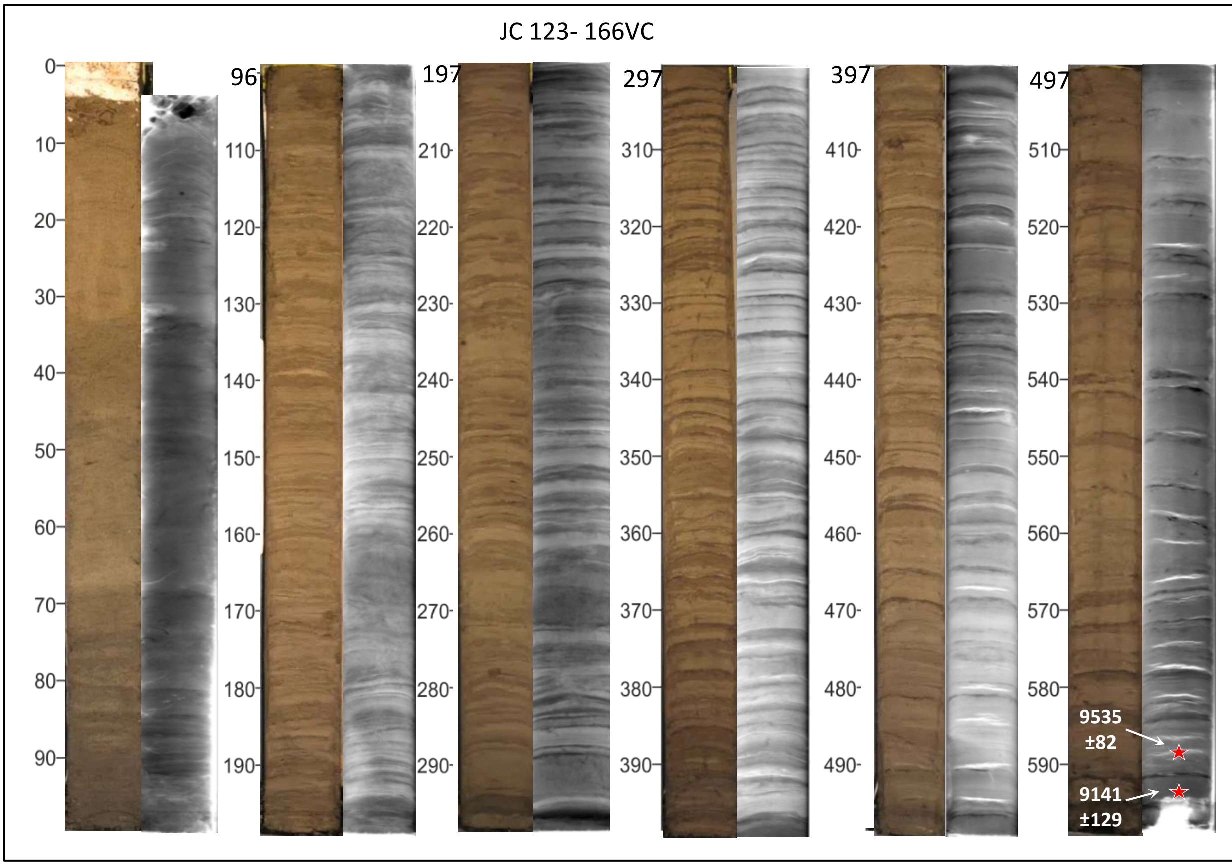
ONN2: Stratified fines draping Chalk bedrock (Egmond Grd Fm)

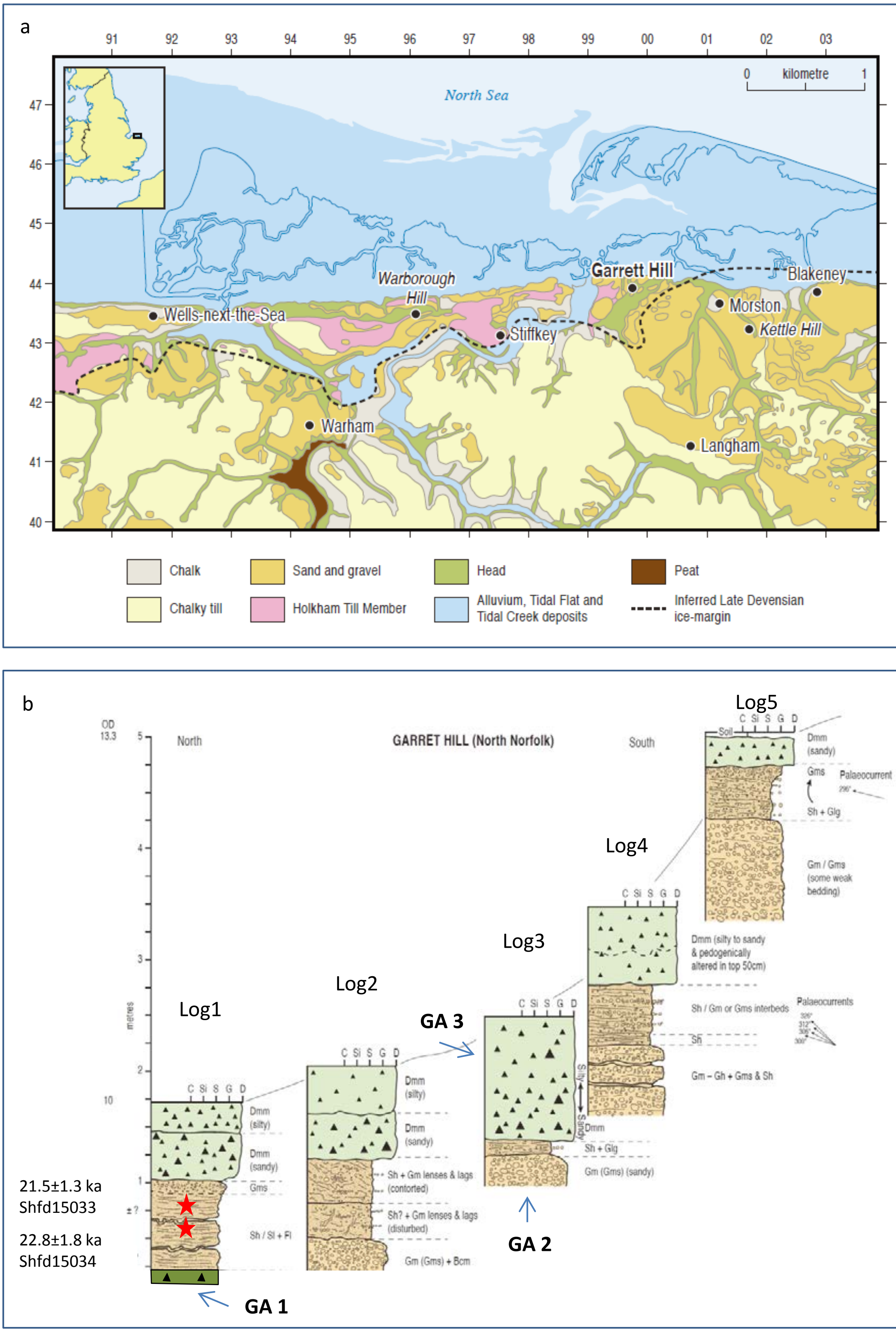
ONN1: Chalk bedrock


a
SP 6
Distance (km)
N
S
163VC
164VC
0
5
10
15
20
25
TWT (ms)
50
100
150
Depth (m)
40
60
80
90
100
b
SP 8
N
Distance (km)
159VC
Moraine 2
Moraine 1
0
5
10
TWT (ms)
50
Depth (m)
20
40
158VC
Distance (km)
15
20
25
157VC
Distance (km)
156VC
30
35
40
c
Top
JC123-162VC 172-272cm
Top
JC123-160VC 087-181cm
Top
JC123-159VC 134-233cm

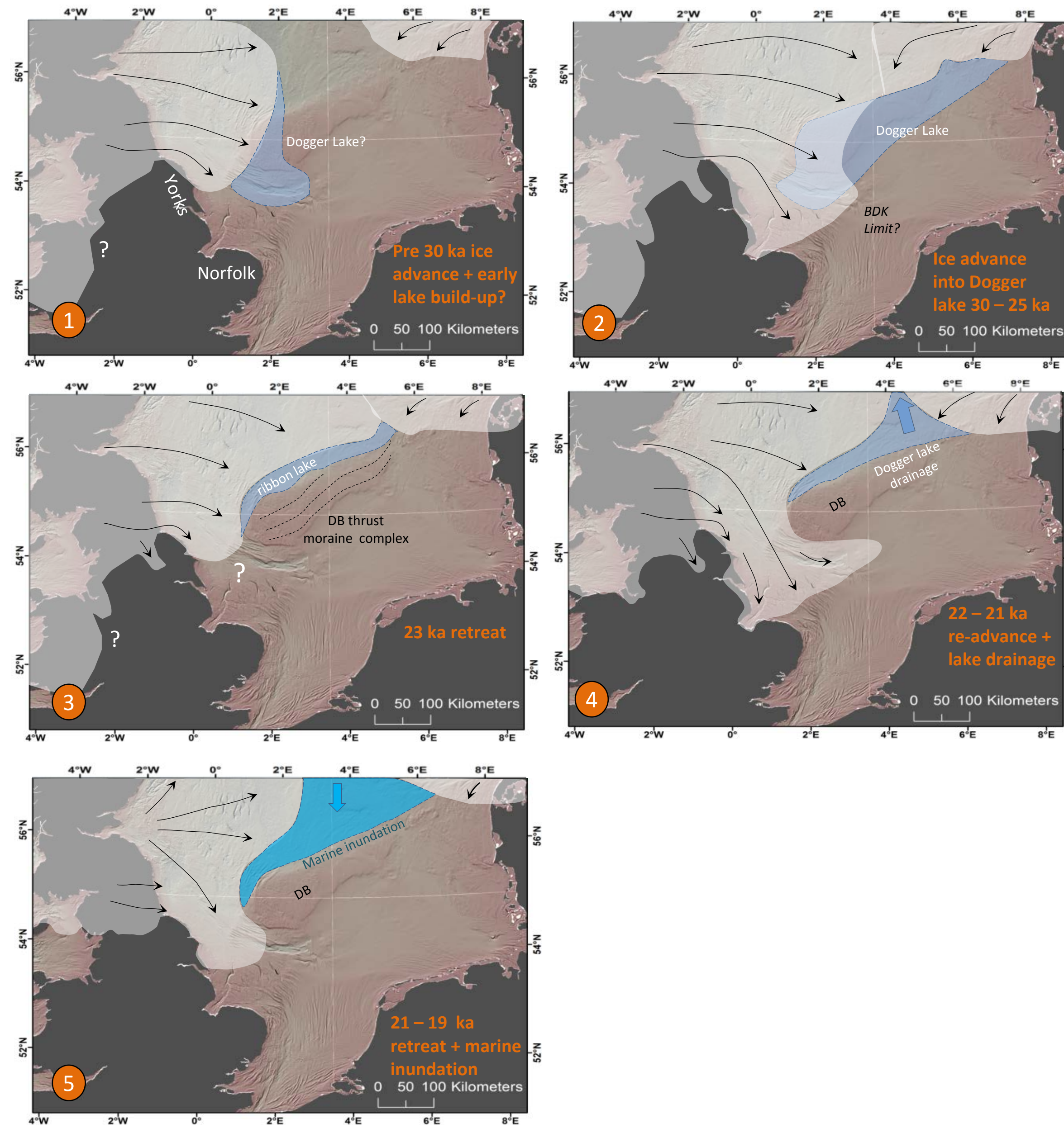


0°
1°E
2°E
54°N
53°N
0
1000
2000
3000
4000
5000
Moraine 2
Ice flow
20
30
Depth (m)
Pre Glacial
N
S
ONN3a
ONN3b
ONN3c
ONN3d
ONN3e
ONN3f
ONN4
ONN6
b
170VC
164VC
163VC
169VC
LINCS
2
1
168VC
167VC
161VC
162VC
160VC
159VC
158VC
157VC
156VC
a
6000
7000
8000
9000
Moraine 1
40
Pre MIS2 Glacial
NORFOLK
c


JC 123- 166VC
0
10
20
30
40
50
60
70
80
90
96
110
120
130
140
150
160
170
180
190
197
210
220
230
240
250
260
270
280
290
297
310
320
330
340
350
360
370
380
390
397
410
420
430
440
450
460
470
480
490
497
510
520
530
540
550
560
570
580
590
9535
±82
9141
±129



a
91
92
93
94
95
96
97
98
99
00
01
02
03
47
46
45
44
43
42
41
40
0
kilometre
1
North Sea
Warborough Hill
Garrett Hill
Blakeney
Morston
Kettle Hill
Wells-next-the-Sea
Stiffkey
Warham
Langham
Chalk
Chalky till
Sand and gravel
Holkham Till Member
Head
Alluvium, Tidal Flat and Tidal Creek deposits
Peat
Inferred Late Devensian ice-margin
b
OD 13.3
North
GARRET HILL (North Norfolk)
South
metres
Log1
Log2
Log3
Log4
Log5
C Si S G D
Soil
Dmm (silty)
Dmm (sandy)
Gms
Sh / Sl + Fl
Sh + Gm lenses & lags (contorted)
Sh? + Gm lenses & lags (disturbed)
Gm (Gms) + Bcm
Dmm
Sh + Glg
Gm (Gms) (sandy)
Silty
Sandy
Dmm (silty to sandy & pedogenically altered in top 50cm)
Sh / Gm or Gms interbeds
Sh
Gm – Gh + Gms & Sh
Palaeocurrents
Palaeocurrent
Gm / Gms (some weak bedding)
21.5±1.3 ka
Shfd15033
22.8±1.8 ka
Shfd15034
GA 1
GA 2
GA 3



4°W 2°W 0° 2°E 4°E 6°E 8°E
56°N 54°N 52°N
1
Dogger Lake?
Yorks
?
Norfolk
Pre 30 ka ice advance + early lake build-up?
0 50 100 Kilometers
2
Dogger Lake
BDK Limit?
Ice advance into Dogger lake 30 – 25 ka
0 50 100 Kilometers
3
ribbon lake
DB thrust moraine complex
?
?
23 ka retreat
0 50 100 Kilometers
4
Dogger lake drainage
DB
22 – 21 ka re-advance + lake drainage
0 50 100 Kilometers
5
Marine inundation
DB
21 – 19 ka retreat + marine inundation
0 50 100 Kilometers