Phased occupation and retreat of the last British–Irish Ice Sheet in the southern North Sea; geomorphic and seismostratigraphic evidence of a dynamic ice lobe

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Abstract

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

This paper presents analysis of a new, integrated set of extensive seabed geomorphological and seismo-stratigraphic observations that both advances the principles developed previously onshore (e.g. multiple advance and retreat cycles), and provides a more detailed and accurate reconstruction of the BIIS at its southern-most extent in the North Sea. A new bathymetry compilation of the region reveals a series of broad sedimentary wedges and associated moraines that represent several terminal positions of the NSL. These former still-stand ice margins (1-4) are also found to relate to newly-identified architectural patterns (shallow stacked sedimentary wedges) in the region's seismic stratigraphy (previously mapped singularly as the Bolders Bank Formation). With ground-truthing constraint provided by sediment cores, these wedges are interpreted as sub-marginal till wedges, formed by complex subglacial accretionary processes that resulted in till thickening towards the former ice-sheet margins. The newly sub-divided shallow seismic stratigraphy (at least five units) also provides an indication of the relative event chronology of the NSL. While there is a general record of south-to-north retreat, seismic data also indicate episodes of ice-sheet re-advance suggestive of an oscillating margin (e.g. MIS 2 maximum not related to first incursion of ice into region). Demonstrating further landform interdependence, geographically-grouped sets of tunnel

valleys are shown to be genetically related to these individual ice margins, providing clear insight into how meltwater drainage was organised at the evolving termini of this dynamic ice lobe. The newly reconstructed offshore ice margins are found to be well correlated with previously observed terrestrial limits in Lincolnshire and E. Yorkshire (Holderness) (e.g. MIS 2 maximum and Withernsea Till). This reconstruction will hopefully provide a useful framework for studies targeting the climatic, mass-balance, and external glaciological factors (i.e. Fennoscandian Ice Sheet) that influenced late-stage advance and deglaciation, important for accurately characterising both modern and palaeo-ice sheets.

1. Introduction

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

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

periods of glaciation, in particular the mid to late Devensian (Carr et al., 2006; Sejrup et al., 2009; Graham et al., 2011) (Fig. 1).

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

Location and Bathymetry

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

Glacial history of the study area

Much of our current understanding of the shallow geology of the southern North Sea originates from analysis and interpretation of data acquired during a systematic British Geological Survey (BGS programme of offshore geophysical surveying and ground-truthing) between the late 1970's and early 1990's (Long et al., 1988; Fannin, 1989; BGS, 1991; Cameron et al., 1992). Supported by the

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

The maximum extent of the last BIIS within the North Sea has been depicted in a wide range of reconstructions (Fig.1; Graham et al., 2011 and references therein). Carr et al. (2006), building upon the work of Sejrup et al. (1994; 2000), provides the most detailed account of Late Devensian North Sea glaciation, based on micromorphological analysis of tills combined with seismostratigraphy. They propose several phases of Devensian glaciation with two early episodes ('Ferder' c.70 ka; 'Cape Shore' c.29-20 ka) involving confluence of the BIIS and FIS in the North Sea, but not extending farther south than Holderness (Figs. 1, 2). During a final re-advance, termed the 'Bolders Bank Episode', ice extended southwards down the western side of the North Sea Basin between c.18-16kya, with the BIIS uncoupled from the FIS. The presence of this 'North Sea Lobe' (NSL) was originally inferred from the recovery of glacigenic deposits (Bolders Bank Formation) within the southern North Sea (e.g. Jansen et al., 1979; Balson and Jeffrey, 1991), and although discounted by some early ice sheet models of the BIIS (e.g. Boulton et al., 1977), ice sheet lobes such as the NSL are now understood to represent characteristic, if ephemeral, components of the palaeo-ice sheet system (e.g. Boulton and Hagdorn, 2006; Hubbard et al., 2009).

The interaction with the FIS is particularly important for understanding the behaviour of the BIIS within the North Sea, and while this has not always been the case, it is now broadly accepted that

the BIIS and FIS were coalescent within the North Sea basin at some point(s) during the mid-late Devensian (Boulton et al., 1985; Sejrup et al., 1994, 2009; Carr et al., 2006; Bradwell et al., 2008). While this coalescence likely peaked during the maximum extent of ice sheets (BIIS at ~(c.29-23 ka - e.g. Scourse et al., 2009), the time-varying confluence with the FIS may have also influenced the flow configuration of the NSL within the western North Sea. While Carr et al. (2006) did not invoke BIIS-FIS coalescence during this most recent glacial episode, the southerly flow trajectory of the NSL is more difficult to reconcile without some buttressing effect by the FIS (e.g. Graham et al., 2011; Busfield et al., 2015; Sejrup et al., 2016).

Accounting for the uncertainty in MIS 2 ice sheet reconstructions for the region, Clark et al. (2012) present two end-member reconstructions for the North Sea and east coast of Britain: 1) early (~27kya) and complete breakup of North Sea Ice with a later surge lobe into the southern North Sea and along the east coast at ~17kya; 2) persistent ice in the southern North Sea from 27 kya, with a re-advance farther south from ~19-17kya. Both Carr et al. (2006) and Clark et al. (2012) acknowledge that the maximum southern extent of the BIIS within the North Sea may not correspond to its maximum eastern advance. The primary observations conventionally used (though not always attributed) to define the LGM limit within the southern North Sea (and within this study area) are: 1) the extent of the Bolders Bank Formation (BGS, 1991), and 2) the southern limit of several incised deeps which are interpreted as glacial tunnel valleys (Ehlers and Wingfield, 1991). The tunnel valleys are common in the North Sea, and attributed to a number of discrete glacial episodes (Stewart and Lonergan, 2011; Van der Vegt et al., 2012). Those attributed to the Elsterian (MIS 12) are usually larger, and extend farther south than those attributed to the Weichselian/Devensian (MIS 2) (Huuse and Lykke-Anderson, 2000). Some of the MIS 2 tunnel valleys within this southern North Sea study area remain exposed at seabed whereas others have been infilled with post-glacial sediment (Wingfield , 1990; Praeg, 2003; Tappin et al., 2011; Moreau and Huuse, 2014).

Deposits relating to Late Devensian glaciation within the southern North Sea, and attributed to the NSL, are represented by the Bolders Bank Formation (BBF). First described by Veenstra (1965) in the area surrounding the Outer Silver Pit (Fig. 2), the BBF as a seismostratigraphic unit was subsequently mapped across the region by the BGS (e.g. BGS, 1991). In the south the formation extends to near the North Norfolk coast at c.53^{o} N, and in the north to c.55^{o}N, where it is considered laterally-contiguous with the Wee Bankie Formation (Fig. 1) (Gatliff et al., 1994; Davies et al., 2011). Sediment cores reveal that while variable, the BBF commonly comprises dense reddish-brown (or grey-brown) fine-grained diamicton, with sub-rounded to sub-angular clasts. Shallow seismic data show that the unit is c.5-20 m thick, acoustically homogenous, and exhibits a prominent generally flat basal reflector indicative of extensive erosion. The BBF is interpreted as a subglacial till

(Cameron et al., 1987; Carr, 1999; Davies et al., 2011). Clast petrology together with heavy mineral and derived palynomorphs suggest provenance from the Grampian Highlands and the Midland Valley of Scotland, northern England, and the margins of the western North Sea (Carr et al., 2006; Davies et al., 2011). At its eastern margin, the BBF has previously been thought to interdigitate with the Dogger Bank Formation (Cameron et al., 1992), though this relationship is being revised following recent research on Dogger Bank (Cotterill et al., in review).

The BBF comprises at least two distinct acoustic members separated by unconformities (e.g. Harrison, 1992), however the reason for this subdivision is not known and has not previously been investigated (i.e. process/origin of distinct members). Despite this knowledge gap, it has long been suggested that the BBF resembles, and is correlative with adjacent till sequences attributed to the Dimlington Stadial in East Yorkshire (Catt, 2007; Evans & Thomson, 2010; Roberts et al., 2013), Lincolnshire, and north Norfolk (Madgett and Catt, 1978; Cameron et al., 1992; England and Lee, 1991). Confined to a narrow belt along the coastal margin (Fig. 1), these sequences relate to the maximum onshore extent of the NSL and record complex patterns of ice marginal processes and dynamics (Evans et al., 1995; Pawley et al., 2006; Moorlock et al., 2008; Evans & Thomson 2010; Boston et al., 2010; Roberts et al., 2013). Recently published OSL dates indicate that the maximum onshore extent of the NSL in East Yorkshire was reached between 21-18 ka BP (Bateman et al., 2015), which is broadly comparable with the tentatively inferred age of the BBF (Carr et al., 2006). It is also worth noting that a large proglacial lake within the southern North Sea has been inferred by some researchers (e.g. Clark et al., 2012), pooled between the coalescent BIIS and FIS to the north and a shallow sill across the English Channel. While such a regional-scale lake appears topographically feasible, in situ data have yet to support this hypothesis.

The mapped occurrence of the BBF (constraining the maximum offshore extent of NSL) together with high-fidelity onshore stratigraphies provides an indication that the NSL was a dynamic component of the BIIS, extending down the western North Sea during the last glacial cycle (Jansen et al., 1979; Stokes and Clark, 2001; Carr et al., 2006; Graham et al., 2011). It is hypothesized that the NSL oscillated over time to produce the multiple tills and intervening stratified sediments that are now observed onshore (e.g. Evans and Thompson, 2010; Roberts et al., 2013), as well as impounded large proglacial lakes in the unglaciated Vale of Pickering (Kendall 1902; Evans et al. 2016), deglaciated Tees (Agar 1954; Plater et al. 2000), Wear (Smith 1981, 1994; Teasdale & Hughes 1999) and Vale of York (Bateman et al. 2008, 2015; Fairburn & Bateman 2015). Apart however from the first-order mapping of the BBF, these studies are almost entirely reliant on evidence from a narrow belt along the reconstructed NSL margins (Figs.1,2), leaving significant potential for improved

characterisation of the process-form regime responsible for BBF emplacement within the former NSL trunk zone, up-ice from the ice sheet termini. This evidence must necessarily come from the offshore environment where the full transition from the subglacial environment through to the deglacial terrain can be investigated, and in which potential features relating to the dynamic glacial evolution of the region may be placed in a robust stratigraphic and relative chronological framework.

2. Methodology

This study involved the integrated interpretation of bathymetry, shallow seismic, and sediment core data from various sources over a large study area (c.25,000 km^2) extending to 003° E in the east, and c.54° N in the north (Fig. 1). The study area is similar to that covered by the Humber Regional Environmental Characterisation (REC) report by Tappin et al. (2011), but has been expanded to incorporate further features of interest. It was in fact tentative, though un-reported observations (e.g. origin of regional bathymetric high and potential relationship with tunnel valleys) of a lower-resolution bathymetry dataset made during that work that inspired this more focussed glacial study.

2.1 Bathymetry

Existing bathymetry data have been compiled and re-gridded to produce a single bathymetric surface for geomorphological interpretation. The collated data were taken from multiple sources of varying age (late 1970's - late 2000's), lineage, and resolution (e.g. singlebeam vs multibeam swath bathymetry) to form a Digital Elevation Model (DEM) at 25 m horizontal resolution. Underlying datasets are open access and may be downloaded from the UK bathymetry Data Archive Centre (DAC) website. Applying glacial geomorphological principles that were originally developed in terrestrial settings to the submarine environment has become increasingly possible from the extensive bathymetric datasets now available (e.g. Todd et al., 2007; Bradwell et al., 2008; Dove et al., 2015). This approach is particularly applicable to the British Isles as it has been estimated that two-thirds of the BIIS (MIS 2) was situated in what is currently a submerged marine environment (Clark et al., 2012).

Approximately 10% of the area has been mapped using high-resolution (1-5 m) swath bathymetry, and these data have been incorporated into the 25 m bathymetric surface. These bathymetry datasets are mainly distributed along the coasts, as well as extending from the Humber Estuary to around the Inner Silver Pit (Figs. 2,). Where swath bathymetry data are not available, we rely upon older (1979-2005) single-beam echo-sounder data. These survey lines are sufficiently dense to support the regional 25m resolution bathymetry surface, but in a few places are spaced greater than 25 m and thus we have over-sampled the underlying data. While multiple smaller features (e.g.

sediment waves and ribbons) can only be adequately observed on the swath bathymetry data, the glacial features of interest in this study are well imaged at 25m resolution (Figs. 4,5).

2.2 Seismic

The shallow sub-seabed geology has been interpreted from digital scans of single-channel seismic data acquired by the BGS as part of the regional mapping programme from between the late 1970's and early 1990's (Fannin, 1989), as well as from a Regional Environmental Characterization (REC) funded by the Aggregates Levy (Tappin et al., 2011). There are significant volumes of 2D seismic (pinger, boomer, sparker, airgun) data of variable quality available in the region. Principally, the surface-towed boomer data from 1990/4, 1993/1, and 2008/5 surveys are most useful. Quaternary maps based on these data resulted in the published 1:250k maps of Spurn (e.g. BGS, 1991). The commissioned aggregates study, Harrison (1992), also provides a useful cross-reference for our seismic interpretations. Using the available seismic data in the region, we have developed a new (glacial) seismostratigraphic framework to more accurately characterise the sub-surface data (seismic and sediment cores) and its relationship to the glacial geomorphological features preserved at seabed. While we have examined a large proportion of the available data to confirm the validity of our interpretations, we have not systematically re-mapped the shallow geology of the region. Instead we present several representative profiles to demonstrate the revised seismic stratigraphy (Figs. 6-8). One final consideration is the navigational accuracy of data acquired prior to the use of Global Positioning System (GPS) in the mid 1990's. Data acquired prior to the mid 1980's were based on the Decca Navigator Main chain with accuracies of approximately ±100 m. From the mid 1980's through to the use of GPS, accuracies were nearer ±10 m using the Sydelis positioning system. Although it is important to acknowledge this navigational uncertainty in order to avoid over-interpreting correlations with seabed features, the landforms of interest in this study are sufficiently large (100's metres – kilometre scale) that such problems are effectively negligible.

2.3 Sediment cores

BGS-held sediment core records were used to cross-reference interpretation of the seismic data. While no new core analysis or re-interpretation was undertaken, existing core descriptions and classifications were used to validate our geomorphic and seismostratigrahic interpretations. Approximately 1800 sedimentary cores are distributed throughout the study area, 400 of which include sediment previously interpreted at subglacial till. Vibrocoring was the most common equipment type used in the region, although gravity and rock corers were also used (e.g. Fannin, 1989).

3. Results

3.1 Seabed Geomorphology

The large-scale morphology of the seabed is characterized by a broad, arcuate, low-relief bathymetric high extending eastwards from the Holderness and Lincolnshire coasts and a series of large valleys incised approximately perpendicularly into this high (Fig. 2). Water depths generally increase eastward away from the Lincolnshire coast, but also north and south of the regional bathymetric high. Over the high, water depths are commonly ~15 m in the west, increasing to 20-30 m in the east. Water depths over the coastal platforms (shallow bedrock and/or tidal flats) and within The Wash, are very shallow at <10 m. For example, water depths of less than 5 m extend nearly 20 km north of the Norfolk coast on the Burnham Flats (Fig. 2). The deepest parts of the study area are found within the incised deeps, with water depths reaching nearly 100 m in the Inner Silver Pit. Results sections 3.1 - 3.3 describe the physical characteristics of several glacial features observed in the bathymetry (Section 3.1), sediment core (3.2), and shallow seismic stratigraphy (3.3) data. An interpretation of these glacigenic features is given in section 3.4, based on the integration of observations and analysis of the three data types.

3.1.1 Arcuate ridge complexes

Regional bathymetric high and broad sediment wedges (BBSWs)

The regional bathymetric high extends c.170 km eastward from the Holderness and Lincolnshire coasts towards Dogger Bank with a variable width up to 90 km (Figs. 2,4). It is arcuate in plan-view, oriented NW-SE adjacent to Holderness in the west, turning SW-NE in the east. The high comprises several smaller bathymetric highs, hereby called broad sediment wedges (BBSW), which are also elongate and arcuate in plan-view. These features range in width from approximately 10-25 km, are approximately 10-20 m in height. They exhibit a broad wedge-like morphology in cross-section (i.e. subtle changes in vertical relief over large geographic areas), with relatively steep-dipping southward-facing margins and gently-dipping northward slopes (Figs. 2,4). South-dipping slopes descend locally into shallow, elongate depressions that separate the broad sediment wedges. Apart from the more-pronounced southern margins, the boundaries of the sediment wedges are generally diffuse and irregular, becoming particularly difficult to identify in the west where coastal sedimentation and mobile sediment bedforms progressively obscure their seabed expression.

Narrow Ridges (NR)

Narrow ridges, c.500 m – 2 km wide, commonly delineate the southern terminus of the BSWs described above (Fig. 4) forming a series of discontinuous ridge-chains across the study area. Individual ridges exhibit a sinuous to saw-tooth plan-view morphology, are up to 10 m in height (though more commonly 1-2 m). They are frequently interrupted at seabed by other geomorphic

features such as Holocene sediment bedforms and the incised deeps. They exhibit no consistent asymmetry, but rest on the southern edge of the BSWs such that bathymetric relief on the southern slopes of the ridges is often greater where descending into the shallow depressions. Defining a distinct northern edge is often difficult as the ridges appear morphologically contiguous with the underlying BSWs.

The mapped location of the NRs is shown in Fig. 9, which collectively form four separate ridge-chains, ordered NR1-4 from south to north. The two northerly ridges (NR3 and NR4) are more distinctive and continuous than NR1 and NR2 which are more diffuse. A notable characteristic of NR3 is that several isolated loop-shaped (convex southward) ridge elements occur situated to the south of the main ridge (Fig. 4).

3.1.2 Incised deeps

Across the study area several large deeps (ID) are incised into the seabed and are up to 100m deep (c.80m below surrounding seabed), 45km length and 5km width (Fig. 2). The most prominent deeps, the Inner Silver Pit and Sole Pit, are eroded into bedrock. Several of these deeps are depicted within the seabed bathymetry whilst others can be recognised within shallow seismic data (Cameron et al., 1992; Tappin et al., 2011). All of the incised deeps exhibit U-shaped cross-sectional profiles and scoop-shaped longitudinal profiles with reverse slopes at both the northern and southern ends (Figs. 2,3). In plan-view the incised deeps are linear-to-curvilinear in shape.

The orientation of these deeps is roughly perpendicular to the local orientation of the BSW into-which they are incised. As such, incised valleys radiate to the south fanning out to the west and east (Fig). The northern and southern rims of the incised deeps are broadly coincident with the respective northern and southern margins of the BSWs, though it is notable that the deeps commonly extend a further 2-5 km south of the BSWs, and the NRs that delimit their southern margin. For example, the Inner Silver and Sole Pits are incised into the northern-most BSW, with their southern rims extending just beyond NR4. This apparent landform association is repeated and clear for the northerly two BSWs (NR3 & 4), and potentially for the more subtle BSW associated with NR2. The narrow ridges also commonly turn northwards as they near the incised deeps (Figs. 2, 4).

3.1.3 Coast-parallel offshore ridges

Observed along ~50km of the Holderness coast, and extending up to ~20km offshore, we observe a large number of sharp-relief, thin ridges (commonly 100-150 m wide, 1-3 m high) which are oriented ~parallel to the adjacent coast (Fig. 5). Due to the small height and width of these features, they have primarily been mapped from high-resolution swath bathymetry data from just offshore, although they are coarsely visible on the 25m DEM where swath bathymetry data are not available. Individual ridges are commonly spaced ~500m apart, and although on a regional scale discontinuous, there are single continuous ridge lengths of up to ~8km. At the kilometre-scale the ridges are linear

to curvilinear in plan-view, but at a higher-resolution are seen to be zig-zag to sinuous. The ridges typically are asymmetric, with the steeper western-facing scarp slopes of up to 25^{0}. The orientation of the offshore ridges broadly parallels the coast as well as the moraine ridges on Holderness (Fig. 10a) (Evans & Thomson, 2010), although there is some variation in the orientation of separate groupings of ridges (NW-WE switching to NNW-SSE in northeast corner of Fig. (5)). These divergent orientation groups also appear to be pre-disposed by an underlying geomorphic fabric.

3.2 Sediment Cores

Where Holocene mobile sediments are thin, shallow cores located on the BSWs sample firm-to-stiff diamicton, interpreted as a subglacial till and attributed to the Bolders Bank Formation (BBF) (Figs. 9,10) (Veenstra, 1965; Long et al., 1988, BGS 1991; Carr et al., 1999; Davies et al., 2011). The core samples reveal a clear boundary extending ENE from North Norfolk with till recovered in cores north of this boundary. This apparent boundary (together with seismostratigraphic observations) was previously used to map the regional extent of the BBF (BGS, 1991). This till limit (i.e. extent of BBF) also corresponds to the southern margin of the regional bathymetric high and its BSWs, suggesting a relationship between the BBF and the bathymetric relief of the region.

Few cores are located on the NRs (1-4), although where significant penetration (>50 cm) was achieved, till (i.e. BBF) was recovered. As a note however, this is one circumstance in the study where the navigational uncertainty (~10-100m) associated with legacy core records may lead to interpretation errors, especially as the NRs themselves are only ~500m – 2 km wide. Because of this uncertainty, the lithological interpretation of the NRs remains tentative. The BBF has previously been described as an overconsolidated reddish-brown (or grey-brown) fine-grained matrix-supported diamicton with sub-rounded to sub-angular clasts of local and far-travelled provenance (e.g. BGS, 1991; Carr et al., 1999, Davies et al., 2011), and this is confirmed by a preliminary review of legacy core records. A webGIS of the BGS-held sedimentary cores and scans of core description sheets can be found here: http://mapapps2.bgs.ac.uk/geoindex_offshore/home.html.

3.3 Seismic Stratigraphy –shallow stacked till complex

Within this section shallow seismic data are investigated to establish links between the shallow seismic stratigraphy and the geomorphic observations presented above. Several representative cross-sectional profiles (A-A' – Fig. 6; B-B' – Fig. 7; C-C' – Fig. 8) are presented which are orientated broadly perpendicular to the observed seabed geomorphic trends. While these cross-sections cannot capture every detail and stratigraphic variation that occurs in the area, they portray the common architectural trends which are consistently observed across the area. It is also worth emphasizing that like the seabed geomorphological record, subtle vertical relief is spread across

large geographic distances (10's kms), thus the data examples and cross-sections are presented with significant vertical exaggeration to clearly demonstrate the stratigraphic relationships.

Profile A-A' presents a long (57 km) interpreted profile (Fig. 6a) and subset data example (Fig. 6b) from a BGS boomer survey (1990/4 - 1). It serves as our 'type-section', and is broadly representative of the Quaternary succession within the study area (Fig 2). This N-S oriented profile crosses the northerly-most BSW and NR4. as well as NR3 that converges on NR4 in this location. Further south, profile A-A' partly crosses the BSW associated with NR2 (Fig. 9). There are several Holocene features (mobile sediment-wave fields, prominent sediment bank) that partially obscure the glacial record causing attenuation of the acoustic signal, thereby masking the underlying stratigraphy, and partially inhibiting a continuous interpretation north and south of the bank (Fig. 6). There are also several shallow channels which are eroded into the seabed and interpreted as Holocene channels formed by fluvial incision prior to marine transgression (Fitch et al., 2005; Gaffney et al., 2007)). Pre-MIS 2 stratigraphic units are also present in the form of Egmond Ground (light brown) and Sand Hole (dark brown) formations, both inferred as interglacial (Holstenian/Hoxnian) deposits (BGS, 1991; Harrison, 1992; Cameron et al., 1992).

While the BBF was previously mapped as a single seismic unit across the region (e.g. BGS, 1991; Harrison, 1992), here we provide evidence that the BBF can be subdivided into multiple seismostratigraphic units (SU), separated by unconformities. Where the BBF SUs outcrop at/near seabed, sediment-core data indicate they comprise till previously interpreted as BBF (undivided) (Fig. 9). Along profile A-A' we observe five clear SUs that are shallowly and progressively stacked (predominantly) from south to north, younging northwards. In other words, BBF tills outcropping at/near seabed in the south are mostly stratigraphically deeper and older than those farther to the north. The acoustic character of the five SUs is typically homogenous/massive with few internal laterally-continuous reflectors, with only isolated examples of conformable/bedded stratigraphy. Acoustic reflectors separating 5 SUs are high-amplitude and are typically planar where the underlying SU is not topography-forming (e.g. ridge). Four or five generations of channels (defined by stratal position and cross-cutting relationships) can be identified which are eroded into and below these stacked BBF SUs along A-A'. As with the SUs themselves, the channels observed in the south occur at lower stratal levels than those observed farther north, indicating that the southerly buried channels are predominantly older than those in the north, which include the northern tip of a seabed incised deep (Figs. 6,9).

Before describing the SUs (I-V) observed along profile A-A' in detail, it is important to note that acoustic character alone cannot be used to discriminate between SUs (e.g. correlating across broad lateral distances), as they don't exhibit uniquely identifiable characteristics. This may be due to the

age and quality of the data, and/or the variability of the physical properties of the remotely-sensed sediment. Across the region, the BBF exhibits stratigraphic variability and local-scale complexity, and for this reason we do not assume that each of SUs I-V observed on profile A-A' can be individually traced across the study area. Instead, what usefully characterises the SUs (and where pattern can be found) is the aggregated stratal architecture of the BBF across broader scales (>10-20 km), and as we'll shortly describe, their association with seabed geomorphological features. Despite that individual BBF SUs variably exhibit irregular, to tabular, to buried-ridge morphologies (Fig. 2), the combined stack of BBF SUs consistently form low-relief wedges along regional cross-sectional profiles oriented perpendicularly to the arcuate ~E-W bathymetric trends. These broad wedges are relatively thicker and more acutely tapered/pinched-out towards their southern limit (e.g. Fig. 6).

3.3.1 Seismostratigraphic Units (SUs) – Profiles A-A' and B-B'

Five seismic units (SUs) are observed along our type-section, profile A-A' (Fig. 6). The shorter profile B-B' presents a portion of BGS seismic line 1990/4 -21 approximately 9 km east of profile A-A' (Fig. 7), and is included here to reveal the southern projection of structures (i.e. buried wedge) comprising SUs I & II which are truncated at the southern end of profile A-A' (Figs. 2, 9).

The stratigraphically deepest **SU I** is observed along the southern portion of profile A-A', overlying the Egmond Ground Formation (Fig. 6). One channel is observed descending from the basal reflector of Unit I, suggesting channel incision either pre-dates or is broadly contemporaneous with the formation of the unit. The majority of the unit is tabular with thicknesses averaging between 3-5 m (c.4-7 ms two-way travel time; 1700 m/s assumed). The unit includes some irregular and discontinuous reflectors suggestive of lithologic and/or structural heterogeneity (Fig. 6 – south). One of these reflectors separates the fill in the channel from that of the overlying unit. In the far south the unit thickens and exhibits a ridge/wedge-like structure, rising up to where it is truncated at sea bed. Profile B-B' shows the southern extension of this thickened feature. The data along profile B-B' also suggest that this feature is a buried wedge (comprising SUs I & II) which has been slightly truncated/eroded at seabed, presumably by Holocene/modern marine erosion. This buried wedge corresponds to the subtle bathymetric high which is associated with NR2 observed on regional bathymetry data (Fig. 9).

Overlying SU I, **SU II** is a broadly tabular lens of sediment (c.4-8 m thick). Locally, a deep channel is incised from the basal reflector of SU II, and this channel appears to have been further exploited by later Holocene fluvial action (Fig. 6) (e.g. Fitch et al., 2005). SU II exhibits a highly chaotic/transparent, low-acoustic energy character which is interpreted to reflect a predominantly homogeneous deposit such as a diamicton (Stewart and Stoker et al., 1990; Ó Cofaigh et al., 2005). South of the large sand bank (yellow), SU II outcrops at/near seabed, underlying mobile seabed sediments. Profile B-B' suggests that Unit II mantles, and builds upon SU I's wedge-like structure in

the south, and is also truncated at seabed. SU II also extends farther south than SU I, which appears to pinch out just south of the wedge (Fig. 7). SU II extends to the north beneath the sediment bank where its stratigraphic association with the overriding/abutting SUs III & IV is difficult to assess due to the acoustic masking effect, and seabed multiple of the sediment bank (Fig. 6).

SU III does not appear to directly overlie SU II (Fig. 6) and appears to persist only in the northern half of profile A-A',overlying the Egmond Ground Formation. SU III is thin and roughly tabular (2-3 m thick) but thickens southward to form a buried wedge structure (up to c.12 m thick) which is exposed and truncated at/near seabed. As with SU II, SU III exhibits a highly-chaotic/transparent acoustic character. The wedge-shaped seismostratigraphic unit is interpreted as a constructional landform rather than an erosive feature because the irregular top surface is more suggestive of a constructional origin than incision. This feature also exhibits a similar morphology to the buried ridge within SU I at the southern end of profile A-A' and B-B'. This apparent buried ridge corresponds to, and sub-crops just north (c.2 km) of NR4 on the northern-most BSW (Fig. 9). Towards its southern limit, the stratigraphic boundary between SU III and the overriding SU IV is not entirely clear, with a channel incised into both units. SU III however appears to pinch-out against its flat basal reflector, atop the Egmond Ground Formation.

SU IV is somewhat distinct from the other units in its variability of geometry and acoustic character. Unit IV broadly mimics the form of the underlying Unit III, but is interpreted to extend both farther to the north and south. Towards the north, SU IV drapes SU III, and while thin, the irregular top-surface forms a series of ridge or mound-like structures. Where SU III thickens, SU IV shows onlapping reflector terminations. Several channels are part of the basal reflector of SU IV which are cut into SU III (and deeper units) in the north, potentially infilled with the type of sediment which constitutes the overlying Unit V. In the south, the stratigraphic relationships with SUs II and III are more ambiguous because attenuation of the acoustic signal by an overlying sand bank. SU IV comprises more laterally-continuous reflectors than other units, exhibiting a higher-amplitude acoustic character. There are several channels eroded into and from its base. Just south of bathymetrically-interpreted NR3 and underlapping SU V (NR4) (Fig. 6), a large infilled channel (c.12 m deep) exhibits bedded, conformable reflectors (marked by G.C. on Fig. 9). We interpret the acoustic character of this channel infill to reflect water-lain deposits. The location of this infilled channel corresponds with a narrow bathymetric depression, which just south of NR3 extends discontinuously to the east of profile A-A'. Other seismic data that cross this depression (and similarly, south of NR4) reveal further infilled channels, suggestive of connected channel networks between the upstanding bathymetric wedges (Fig. 9)

SU V is the highest seismostratigraphic unit within the assemblage and occasionally crops-out within the seabed where not covered by a veneer of active seabed sediments (Tappin et al., 2011). Along profile A-A' SU V is broadly tabular in form, ranging in thickness from 6-10 m, and exhibits a complex/transparent acoustic character suggestive of massive, structureless diamicton. In the north, several erosional channels are cut from its base and into the underlying stratigraphy. In the north, a partly-infilled channel is exposed at seabed, and is the northern tip of one of the large seabed incised deeps, which is oriented oblique to this seismic profile (Fig 2). The southern margin of SU V is characterised by a pronounced southerly-dipping bathymetric slope. The top of this slope marks the position of NR4 and the southern edge of a BSW (Fig. 9).

Collectively, SUs III-V together form a wedge-like structure in profile, thinning and shallowly-dipping northwards, with a relatively steep and abrupt slope in the south. On this basis, and as observed elsewhere (e.g. SUs I & II corresponding to NR2 (Figs. 7, 9) we infer that the broad, arcuate sediment wedges observed on the bathymetry data are entirely formed by the sequential stacking of seismostratigraphic units (e.g. units III-V), which cores confirm comprise BBF till. A further observation is that along profile A-A', the wedge-like package of SU V thins over buried ridge of SU III and IV, extending c.2 km farther to the south where it is marked by NR4. Bathymetry data reveal that NR4 locally intersects NR3 near profile A-A', providing an indication that the depositional regime responsible for formation of SU V (NR4), encroached on the pre-existing wedge associated with SU III (NR3).

3.3.2 Profile C-C'

Profile C-C' is included here to demonstrate that the architectural trends (stacked till wedges) apparent along profiles A-A' and B-B' are not geographically confined, but are representative of the whole study area (Fig. 8). The data along profile C-C' (2008/5 line 9rev) are of poorer quality (acquired in winter), but still reveal the southern margin of the till wedge associated with NR3. In the subsurface it is clear that the broader wedge is a composite feature comprising at least two SUs, both of which comprise till (Fig. 9). The lower most SU exhibits a broad ridge-like cross-sectional profile, and incorporates some internal structure as well as several reflectors. Ramping up onto the lower SU, the overlying SU exhibits a similar acoustic character (massive/transparent) and extends farther north to where it is cut by a seabed incised deep ('Sole Pit'). Farther north (c. 2 km) along the seismic line from which profile C-C' is extracted, the lower SU thins and pinches out against the planar basal reflector.

3.4 Interpretation of geomorphic and shallow geological record

On the basis of the bathymetric evidence we identify close morphological affinities between several distinctive positive-relief landforms, together with the incised deeps across the region. This new

geomorphological record has drawn attention to previously unrecognised seismostratigraphic relationships in the subsurface. Below we combine observations of the bathymetry, seismic, and sediment core data to produce an integrated interpretation of glacial features preserved at seabed and in the shallow subsurface.

3.4.1 Till wedges and moraines – Record of glacier sub-marginal processes

Listed in decreasing size, the positive-relief features (of non-marine origin) observed in the bathymetry data are: i) the regional-scale bathymetric high extending E-W across the study area; ii) several BSWs that together make-up the regional high; and iii) the NRs that delimit the southern margins of the arcuate BSWs (Figs. 2, 9, 10). Sediment cores (Fig. 9) reveal that these arcuate BSWs comprise Bolders Bank Formation (BBF) which has been interpreted as subglacial till, and that the NRs 1-4 also comprise glacigenic deposits, altogether demonstrating a glacial origin for this landform assemblage. Re-analysis of BGS shallow seismic data reveal that the sub-surface unit previously mapped singularly as the BBF (e.g. BGS, 1991; Cameron et al., 1992) can be divided into at least five separate seismostratigraphic units (SUs), that have been progressively and shallowly stacked from south to north over large lateral distances (10's kilometres), indicating younging to the north (Fig. 10b).

Critically, the architecture (e.g. stacked strata and buried wedges) and extent of these seismostratigraphic units correspond to the position and character of the landform assemblages observed on the seabed (Figs. 6, 9, 10b). For example, NR 1 corresponds very well with the previously mapped seismostratigraphic extent of the BBF and the southern distribution of cores comprising BBF. The shallow south-to-north stack of SUs over large lateral distances (> 10-20 km) forms composite sub-surface (cross-sectional) wedges that also fully account for the extent and morphology of the broad arcuate wedges observed at seabed. Along profiles A-A'(Fig. 6) and B-B' (Fig. 7) the stacked succession of SUs I and II corresponds to the broad sediment wedge (IM 2 – Fig. 10b) which has NR2 along its southern margin (Fig. 9). Similarly, SUs III-V account for the wedge (IM 4 – Fig. 10b) associated with NR4 (Figs. 6, 9), and the stacked SUs on profile C-C' comprise the wedge (IM 3- Fig. 10b) associated with NR3 (Figs. 8, 9).

Based on the morphological, sediment core and seismic evidence, together with reference to findings from other glaciated basins, including the northern North Sea (e.g. Bradwell et al., 2008), we interpret that the broad sediment wedges (BSWs) and narrow ridges (NRs) (1-4) relate to subglacial and ice marginal processes acting along several terminal positions of the former North Sea Lobe of the BIIS (cf. Boulton 1996a, b; Evans & Thomson 2010; Boston et al. 2010; Evans et al., 2012; Eyles et al., 2011). We interpret the NRs (1-4) delimiting the southern edge of the BSWs as terminal moraines, which mark successive ice-marginal still-stands (e.g. Colgan et al., 1999, 2003; Shaw et al.,

2007; Dowdeswell et al., 2008). Several isolated loop-shaped moraines mapped south of moraine-ridge 3 are interpreted as evidence of either a localized marginal re-advance, or a general saw-tooth pattern that is common to lobate ice sheet margins within enclosed basins and piedmont settings (i.e. radial crevassing) (Fig. 9) (e.g. Price 1970; Evans & Twigg 2002; Kalm, 2012; Lee et al., 2013; Evans et al., 2015; Eyles et al., 2015).

The BSWs, and by extension the shallow stacked SUs (e.g. SUs I, II, III, V), are interpreted as sub-marginal till wedges formed by complex accretionary processes that resulted in the accumulation and thickening of glacigenic sediment inboard of the separate ice margins (Figs. 6,9) (Boulton et al., 1996b; Evans and Hiemstra, 2005; Eyles et al., 2011; Evans et al., 2012; Lee et al., 2016). We suggest that each of the BBF SUs, with the exception of SU IV, which incorporates a high proportion of channels, relate to individual still-stand episodes where incremental till thickening occurred towards the ice margin (thinning up-glacier), producing the BSWs now apparent at seabed (Ice-margins 1-4: Figs. 6, 9, 10) (Leysinger-Vieli & Gudmundsson 2010; Eyles et al. 2011; Evans et al., 2012).

3.4.2 Tunnel valleys

Consistent with previous investigations in the region, we interpret the large seabed incised deeps (U-shaped in cross-section; scoop-shaped in longitudinal profile) as glacial tunnel valleys (e.g. Donovan, 1972; Tappin et al., 2011; Van der Vegt et al., 2011), and that these features were likely formed due to erosion by over-pressurized subglacial meltwater (e.g. Kehew et al., 2012). What has not been previously recognized is that the northern and southern limits of individual tunnel valleys are coincident with the equivalent northern and southern edges of the BSWs (i.e. discrete ice sheet margins) into which they are incised (Figs. 9, 10). Because of this association, tunnel valleys are geographically grouped, and are found incising three of the four arcuate wedges. Tunnel valleys associated with the northern two ice margins 3 and 4 demonstrate this relationship most clearly, with only one smaller, apparently connected channel system relating to ice margins 1 and 2.

We interpret that this landform association demonstrates a clear genetic relationship between the emplacement of the till wedges at ice margins 2-4, and the meltwater erosion that led to the formation of the tunnel valleys. As such the landform assemblage forms a sub-marginal glacial landsystem similar to those of modern active temperate glacier lobes and not unlike of ancient terrestrial ice sheet margins.

3.4.3 Coast-parallel offshore ridges

The presence of small moraine ridges in Holderness (Evans & Thomson, 2010) originally drew our attention to a potentially related series of thin ridges observed offshore of the Holderness coast (Figs. 5, 9, 10a). The similar orientation and dimensions of these offshore ridges hints at a near seamless continuation of the terrestrial moraine belt, providing a high-resolution record of ice sheet retreat in the region. Several factors however suggest that these features are unlikely to be primarily

of glacial origin: 1) The offshore ridges exhibit a very 'fresh' geomorphic character with slopes up to 25°. Such excellent preservation seems unlikely in this shallow, wave-influenced high-energy hydrodynamic environment, where mean tidal current velocities reach nearly 2 m/s (Tappin et al., 2011); 2) Several offshore ridge specimens are observed immediately adjacent to the modern coast (within c.200 m) (Google Earth satellite imagery also suggests they are also found in the intertidal zone where not directly mapped acoustically). Intense coastal erosion and sediment bar migration is known to occur along this coastline (e.g. Pringle, 1985) suggesting that ridge formation is more likely linked to modern, or perhaps relict Holocene coastal processes.

Despite their probable marine origin, these ridges still may reflect a glacial influence, albeit indirectly. Fig. (5) shows that the crisp narrow ridges sit atop a broader, more diffuse fabric of c.NW-SE oriented ridges with intervening lows. This underlying fabric appears to control the location and orientation of the narrow ridges (i.e. sitting atop the rugged, broader ridges), and this pre-existing topography itself may reflect former glacial processes. In other words the more modern marine bedforms have preferentially formed over relative bathymetric highs, and therefore mimic the orientation of the underlying topography (e.g. potential moraine belt). This offshore record may help understand the topographic evolution of Holderness, but focussed and direct sampling of these features is required to better inform interpretations of their origin.

4 Discussion

Despite the amount of published literature from adjacent onshore sequences in East Yorkshire and Norfolk (e.g. Catt, 2007; Moorlock et al., 2008; Evans & Thomson, 2010; Bateman et al., 2015; Evans et al., 2016), comparatively little is known about the equivalent offshore record of the last glacial cycle. The accumulated evidence derived from *in situ* marine data in the southern North Sea has largely precluded MIS 2 glaciation from being characterised with any greater specificity than as a single event. The extensive BGS programme of geophysical surveying and coring during the 1970's through early 1990's provided a coarse (though broadly accurate) characterisation of the Quaternary sediments in the region (e.g. Cameron et al., 1992), but inadequate dating of core material combined with an insufficiently detailed seismostratigraphic model on which to hang existing dates has inhibited progress. There has been some effort to consider the existing offshore record in reference to the more nuanced onshore evidence (e.g. Boston et al.,2010), but there has been surprisingly little work conducted to re-analyse the offshore data (e.g. provenance -Davies et al., 2011). One important exception to this is the work by Carr et al. (2006) (described in greater detail within Introduction), who through provenance and micromorphological analysis found evidence of at least two stages of glaciation impacting this part of the southern North Sea (Fig. 1). Our results are broadly compatible with this work (i.e. more than one incursion of ice into the region), but through

611 the identification of new geomorphological and stratigraphic relationships, we are able to describe
612 and map a more detailed and spatially accurate record of glaciation within the southern North Sea.

613 ## 4.1 Offshore landform associations, ice sheet dynamics, and relative event
614 ## chronology

615 The series of broad arcuate till wedges (BSWs) and associated moraines (NRs) observed on the
616 bathymetry data represent several terminal positions of the former North Sea Lobe of the British
617 and Irish Ice Sheet (BIIS) (Figs. 9, 10a). Supporting this, and providing relative chronological control,
618 shallow stacked seismostratigraphic units (SUs) within the BBF are observed to directly correspond
619 to the position and extent of specific arcuate wedge/moraine complexes (ice-margins 1-4) (Figs. 6-8,
620 10b). These discrete ice margins also show clear affinities with the region's tunnel valleys in that
621 their location and orientation is correlated with (and bracketed by) the position of the BSWs,
622 suggesting a formational interdependence between the landforms as a sub-marginal glacial
623 landsystem (e.g. Colgan et al., 2003; Jørgensen and Sanderson, 2006). The arcuate till
624 wedge/moraine complexes indicate that the former ice margins were lobate in plan-view, with the
625 tunnel valleys radiating out from the centre trunk of the ice stream and intersecting the
626 reconstructed margins approximately perpendicularly (Fig. 10). This inferred association, together
627 with the maturity of the observed landforms (i.e. the extent and thickness (up to c.15 m) of
628 individual till wedges; size of tunnel valleys up to c.80 m deep below surrounding seabed), indicates
629 that these landform assemblages (till wedges and corresponding groups of tunnel valleys) were
630 formed during separate still-stand episodes of the North Sea Lobe as the ice margin was stationary
631 for several periods of time before retreating and stepping back to the north. As such they represent
632 inset sequences of sub-marginal glacial landsystems similar to those recognized in a variety of
633 ancient terrestrially-based ice sheet marginal settings (e.g. Colgan et al. 2003; Evans et al., 2006,
634 2014; Jennings, 2006; Ó Cofaigh et al. 2010; Eyles et al. 2011).
635 Glacier sub-marginal thickening of subglacially deforming sediment, acting in tandem with other
636 subglacial advection processes (cf. Alley et al. 1997), to produce incrementally stacked till wedges
637 has been demonstrated by empirical-based theory (Boulton, 1996a, b), modern process observations
638 (Evans & Hiemstra 2005) and numerical modelling (Leysinger-Vieli & Gudmundsson 2010). Such
639 studies reveal a clear linkage between moraine construction and subglacial till emplacement
640 processes, wherein the stratigraphic architecture of repeated ice-marginal oscillations during slow
641 recession or dynamic oscillations of quasi-stable glacier lobes is manifest as superimposed, lobate-
642 shaped till wedges. This model of till emplacement has been applied to the landform-sediment
643 associations of the southern margins of the Laurentide Ice Sheet by Boulton (1996a, b), Patterson
644 (1997, 1998), Jennings (2006), Evans et al. (2008, 2012, 2014) and Ó Cofaigh et al. (2010) as well as

645 the onshore till sequences in eastern England by Boston et al. (2010), Evans & Thomson (2010) and
646 Lee et al. (2016). Importantly, these zones of incremental thickening and marginal till wedges involve
647 net vertical accretion of subglacial deposits, which is critical to the preservation of meltwater
648 sediments in canal fills, which are observed to thicken towards eskers and/or ice-contact
649 subaqueous fans or grounding line fans on Holderness (Evans et al., 1995; Evans & Thomson 2010)
650 and the Durham coast (Davies et al. 2009). Evidence for the preservation of similar discontinuous
651 meltwater features appears to be manifest in the few internal laterally-continuous reflectors in what
652 otherwise are homogenous diamictons. Additionally, as the seabed tunnel valleys are observed to
653 incise into and below respective till wedges, e.g. the uppermost unit of the BBF (seismic unit V) (Fig.
654 6), we infer that valley incision and till deposition occurred pene-contemporaneously.
655 Seismostratigraphic evidence demonstrates that the till wedge/moraine complexes in the south are
656 predominantly associated with stragraphically deeper and presumed older glacial deposits. We
657 interpret therefore that the four observed till wedge/moraine complexes visible in the bathymetry
658 data (Figs. 6, 9, 10) record the phased occupation and retreat of the North Sea Lobe from south to
659 north, with the oscillating ice margin holding at least four major still-stand positions before
660 retreating north out of the study area. In the south, SU II overlies and appears to extend farther
661 south than SU I (Figs. 6, 7). This suggests that the oldest stratigraphic member (SU I) is in fact
662 associated with Ice-margin 2, and that SU II potentially records a significant re-advance that brought
663 the oscillating margin of the NSL to its most southerly extent (e.g. encroaching on North Norfolk;
664 Roberts et al. in prep). Higher quality, and more densely distributed seismic data will be required to
665 confirm this potential re-advance signature in the south. Isolated loop-shaped moraines extending
666 south beyond Ice-margin 3 indicate transient and minor re-advance, but the seismic data presented
667 in Figs. (6, 7) provide evidence of what appears to be another significant re-advance associated with
668 the youngest glacial episode and related to Ice-margin 4. Along profile A-A', the buried sediment
669 wedge of SU III is truncated and overlain by sediments of SU V, which corresponds with Ice-margin 4
670 and the northern-most assemblage of tunnel valleys (Fig. 9). Elsewhere in the offshore environment,
671 Ice-margin 3 is located farther south than Ice-margin 4, but at the crossing of profile A-A' the two
672 landform assemblages are convergent. In accordance with this geomorphic configuration and the
673 stratigraphic observations, we interpret that SU III is associated with Ice-margin 3. With SU V over-
674 riding and extending farther south than SU III along profile A-A', this provides evidence of ice-sheet
675 re-advance, which at least locally overrode the deposits of the previous ice sheet margin.
676 The combined stratigraphic and geographic position of tunnel valleys provides further constraint on
677 the relative age of these landform assemblages. Like the seabed incised deeps, we interpret deeply
678 incised channels buried in the subsurface as tunnel valleys because they are cut from stratigraphic

679 units comprising BBF subglacial till (Fig. 6). One exception is observed along profile A-A' where the
680 channels incised from SU IV appear (laminated, conformable) more to be likely associated with ice-
681 marginal/proglacial erosion from the still-stand positions marked by Ice-margins 3 or 4. For those
682 interpreted as tunnel valleys, we find that the valleys eroded from the deeper SUs (I & II) are
683 observed in the south, whereas channels in the north are eroded from the higher (and younger) SUs
684 (III-V), including the northern reach of the seabed-exposed tunnel valley eroded into seismic-unit V
685 (Figs. 6, 9, 10). This argument that the stratigraphic position of the tunnel valleys is indicative of
686 relative age and retreat direction is dependent on the assumption that subglacial meltwater
687 conduits would have been concentrated near the ice margin (cf. Hooke and Fastook, 2007; Storrar et
688 al., 2014), and the close association between the tunnel valley groups with Ice-margins 2-4, together
689 with observations from other terrestrial lobate ice margins (e.g. Colgan, 1999; Colgan et al., 2003),
690 appear to support this hypothesis.
691 The largest tunnel valleys are found within the northern-most assemblage (e.g. Inner Silver Pit and
692 Sole Pit), which notably coincides with the largest and most morphologically pronounced (and
693 stratigraphically youngest) Ice-margin 4 (Figs. 6, 9, 10). This may indicate longer residence time at
694 this margin allowing for increased thickening and erosion (e.g. Boulton et al., 2001), better
695 preservation potential, or alternatively that sediment accumulation and meltwater production at
696 this northern-most position were for some reason greater at this time. With respect to individual
697 margins we also observe that the spacing between tunnel valleys appears to be proportionate to
698 their size, and by inference, meltwater discharge. To investigate whether this apparent dependency
699 is valid, we measured the cross-sectional area (measured 5 km up-glacier from moraine) as well as
700 the distance between tunnel valleys along the northern-most moraine 4 (Fig. 11). We utilised the
701 smallest distance measured between each tunnel valley to assess the relative influence of each
702 meltwater conduit (i.e. catchment). There are seven mapped tunnel valleys along this till
703 wedge/moraine complex, but we only analysed the inner five as the Sand Hole and Well Hole tunnel
704 valleys are unconstrained in the far west and east respectively (Fig. 2). A simple regression analysis
705 demonstrates a positive linear relationship (R^2 = 0.986) between tunnel valley spacing and cross-
706 sectional area (i.e. discharge). While acknowledging that the small sample population requires that
707 these results are treated with some uncertainty, this analysis does suggest a correlation and
708 proportional relationship between the two variables, which is consistent with theoretical predictions
709 of meltwater drainage and the spacing of associated landforms (e.g. Boulton et al., 2007; Hewitt,
710 2011; Dowdeswell et al., 2015).
711 The southern rims/outlets of the tunnel valleys commonly extend 2-5 km beyond the till
712 wedge/moraine complexes, suggesting that subglacial meltwaters were strongly focussed towards

(and confined by) individual tunnel valleys until reaching the ice margin, where they were released (Figs. 9, 10). It is anticipated that this mid-latitude palaeoglaciological system would have produced significant volumes of meltwater (e.g. Toucanne et al., 2010), and indeed the large size of the tunnel valleys suggests that it did. However, because of the study area's submarine setting, the preservation potential for other glacifluvial landforms (e.g. fans) and glacifluvial deposits is low, and few are found regionally (Cameron et al., 1992). Due to the shallow nature of the seabed and proximity to the coast, the study area is characterised by very high-energy hydrodynamic conditions (e.g. ubiquitous mobile sediment waves) and has since been drowned during the Holocene marine transgression (Uehara et al., 2006; Sturt et al. 2013; Ward et al., 2016). However, one consequence of this study is that the shallow depressions between the till wedges may have hosted glacifluvial pathways, and the channels observed in seismic unit IV seem to indicate that such deposits may be preserved here (Fig. A-A'). Despite the relative absence of depositional landforms and glacifluvial deposits, the apparent correlation between tunnel valley size and spacing indicates that they served as the primary control on regulating meltwater drainage (Fig. 11), and suggests that the till wedge/moraine complexes served as an effective dam to meltwater escape, with meltwaters being routed towards tunnel valleys within catchments that were proportional to the size of each valley (e.g. Boulton et al., 2007).

Due to the unambiguous link between the tunnel valleys and the till wedge/moraine complexes associated with the BBF, we infer that the location, pattern, and morphology of the tunnel valleys may be satisfactorily attributed to Late Devensian (MIS 2) glaciation alone. However, whether the valleys are multi-generational features and pre-disposed by previous valley incision from older glacial periods (e.g. MIS 12) is not immediately clear.

In order to significantly improve the geomorphological and stratigraphic record of the region, higher-resolution swath bathymetry and better quality 2D and/or 3D seismic data over extensive areas will be required. Further to this, targeted absolute dating will be necessary to tie this combined reconstruction of sub-marginal ice sheet dynamics and evolving spatial configurations of the NSL, to the broader activity of the BIIS. There is existing evidence however, that the incursion of the NSL into the region was a relatively late phenomenon, bracketed between about 21 ka and 15 ka (Batemen et al., 2015). Central to accounting for this diachronous event will be to understand the interaction between the BIIS and the Fennoscandian Ice Sheet (FIS) in the southern North Sea, as is becoming clearer in the northern North Sea (e.g. Bradwell et al., 2008; Sejrup et al., 2016). An important next step towards this aim will be to characterise the relationship of the NSL with the Dogger Bank (e.g. Cotterill et al., in review). The study presented here demonstrates the dynamic nature of the NSL when it was at or near its maximum southern extent; but what did it encounter in the Dogger Bank

747 area; how far did it extend when it first impinged on the region; and how did it interact with the
748 Dogger Bank as it actively retreated back to the North and West?

749 ## 4.2 Stratigraphic correlation with the onshore record

750 The age and dynamics of the Late Devensian glaciation in Eastern England are relatively poorly-
751 constrained but the chronology of regional glaciation is the focus of significant recent and ongoing
752 research (Bateman et al. 2011, 2015; Evans et al., 2016; Roberts et al. in prep.). This study however
753 provides a crucial link between the offshore record and onshore successions in East Yorkshire (Catt &
754 Penny, 1966; Catt, 2007; Boston et al., 2010; Evans & Thomson, 2010; Roberts et al., 2013; Bateman
755 et al., 2015) and north Norfolk (England and Lee, 1991; Pawley et al., 2006; Moorlock et al., 2008),
756 enabling the first regional-scale interpretation of the North Sea lobe of the Last British-Irish Ice Sheet
757 within the Southern North Sea (Clark et al., 2012).
758 The southern-most extent of this ice advance is indicated by Ice-margin 1 (SUII) and is tentatively
759 correlated with the onshore occurrence of the Holkham Till in north Norfolk (Pawley et al., 2006;
760 Roberts et al. in prep.) and the oldest ("advance till") units of the Skipsea Till in East Yorkshire (Figs.
761 9, 10) (Catt 2007; Evans & Thomson 2010). Onshore deposits in north Norfolk include thin beds of
762 diamicton and outwash sand and gravel locally forming morainic landforms and kame mounds, on
763 the northern flanks of low Chalk hills (England and Lee, 1991; Pawley, 2006; Pawley et al., 2006;
764 Moorlock et al., 2008; Roberts et al. in prep). Ice damming of northward-draining chalk rivers,
765 including the Stiffkey and Heacham rivers, led to the development of several impounded lake basins
766 and localised drainage diversions (Brand et al., 2002; Moorlock et al., 2008). The position of the ice
767 margin in the modern area of the Wash and Fen basins between northwest Norfolk and Lincolnshire
768 remains unclear, with evidence presumably, having been either buried beneath Holocene deposits
769 or removed by fluvial and/or marine processes. Alternatively, the clay-rich substrate (Kimmeridge
770 Clay – Jurassic bedrock) within the Wash (as opposed to the chalk substrate in adjacent areas) may
771 have promoted ice-bed decoupling and southward ice flow. Therefore, the ice margin may have
772 been situated to the south of the modern coastline within the Wash.
773 Combined seismostratigraphic and geomorphic evidence presented in this study suggests however
774 that this most laterally-extensive episode of glaciation, does not coincide with the first ice advance
775 into the region (i.e. SUII overlaps SUI and extends farther south to Ice-margin 1). The
776 stratigraphically deeper and presumed older SUII is instead associated with Ice-margin 2 (Figs. 6, 9),
777 indicating that deposits associated with this first encroachment of Devensian glaciation into the
778 region did not reach the north Norfolk coast. Projecting Ice-margin 2 towards the East Yorkshire
779 coast demonstrates good alignment with a previously mapped moraine belt in East Yorkshire (Figs.
780 9, 10), and is also potentially associated with the various advance and retreat till wedges of the

781 Skipsea Till which crops-out extensively across the region (Boulton 1996a, b; Evans and Thompson,
782 2010; Boston et al., 2010). An alternative hypothesis is that this oldest Late Devensian glacial
783 episode (SUI; Ice-margin 2) is associated with the Basement Till (e.g. Catt et al., 2007), which
784 underlies the Skipsea Till in the north of Holderness (Evans and Thompson, 2010). This hypothesis is
785 also considered viable due to: i) the correlation between the seismostratigraphic framework
786 presented here with the glacial depositional model presented by Evans & Thompson (2010), and ii)
787 the interpreted extent of the Basement Till (based on borehole analysis) broadly corresponds with
788 the landward projection of Ice-margin 2 (Figs. 9, 10). Previously, Eyles et al. (1994) presented amino
789 acid dates that supported a Late Devensian origin for the Basement Till, and Evans and Thompson
790 (2010) indicated that this could be accommodated within their depositional model for East
791 Yorkshire. The stratigraphic position of the Basement Till, via its relationship to the Sewerby (MIS 5e)
792 raised beach, remains to be elucidated (Catt, 2007).
793 Ice margins 3 and 4 record a stepped northwards retreat of the ice margin. In East Yorkshire, Ice-
794 margin 3 likely further corresponds to the “retreat till” units of the Skipsea Till (Evans & Thomson
795 2010). Ice Margin 4 records the final known offshore position of the ice margin and correlates
796 onshore with the deposition of the Withernsea Till and formation of the onshore morainic ridges
797 (Figs. 9, 10) (Evans & Thomson, 2010). The maximum onshore ice limit is situated on the reverse
798 dip-slope of the north-south striking Chalk bedrock which forms the Lincolnshire and Yorkshire
799 Wolds (Catt, 2007; Evans and Thomson, 2010). To the north of the Humber Estuary in Holderness,
800 the glacial succession thickens, comprising a complex sequence of diamictons, ice-contact lacustrine
801 and proglacial outwash sediments (Catt and Penny, 1966; Madgett and Catt, 1978; Evans et al.,
802 1995; Catt, 2007; Evans and Thomson, 2010; Boston et al., 2010; Roberts et al., 2013). Detailed
803 lithological analyses demonstrate that the diamictons were deposited by ice flowing down the east
804 coast of England from southern and eastern Scotland (Busfield et al., 2015) with variations in bulk
805 composition reflecting spatial changes in the predominant source of substrate entrainment along
806 the ice flow-tract (Boston et al., 2010). Eastwards retreat of the ice margin led to the formation of a
807 succession of morainic ridges (Evans and Thomson, 2010) which may continue offshore into the
808 Coast-parallel offshore ridges (Figs. 9, 10). In fact, combining the previously mapped terrestrial
809 record (e.g. moraines) with the newly-mapped seabed geomorphology, suggests that the entire
810 landscape of Holderness itself may be a large moraine complex. Ice-margin 3 can be extrapolated to
811 project up the Humber Estuary, and Ice-margin 4 onto Holderness, providing a credible origin for its
812 position, topography, and orientation (e.g. causes River Humber to deflect southeast). Recently
813 published OSL dates from coastal sections in Holderness indicate that the area was initially glaciated
814 between 21 and 19 ka but was ice-free by about 15 ka (Bateman et al., 2015). Further absolute

chronological data is anticipated from the recent BRITICE-CHRONO sampling campaign, providing useful dated reference points with which to constrain the spatiotemporal reconstruction presented here (e.g. Roberts et al., in prep).

Conclusions

The southern North Sea serves as an interesting 'marine' setting to study glaciation, as not only did the region lie above sea-level during the last MIS 2 glaciation, but ice was directed away from the ice-sheet centre within an epicontinental basin, rather than directly towards the marine margin. In this regard, the southern North Sea palaeoglaciological system is more analogous to terrestrial ice lobes than marine-based ice masses.

Within this study, new bathymetry data have been used to identify and describe an extensive series of glacial landforms relating to the phased occupation and retreat of the North Sea Lobe (NSL), the southern-most component of the last British-Irish Ice Sheet east of Britain. Mapping these landforms has in-turn drawn attention to related, and previously unrecognized, broadscale architectural patterns within existing shallow seismic data. Characterising this combined landform and seismostratigraphic assemblage has led to the following observations:

- Apart from superficial Holocene sediment banks and waves, glacial landforms are responsible for the conspicuous variation in the region's seabed morphology. Extending ~E-W across the study area, a series of broad arcuate wedges are delimited at their southern margins by relatively narrower moraines. Together, these landforms represent several terminal positions (lobate in plan-view) of the former NSL (Ice-margins 1-4);
- Sediment cores and shallow seismic data reveal that each of the broad arcuate wedges comprise subglacial till of the Bolders Bank Formation (BBF), which has here (for the first time) been subdivided into at least five separate seismo-stratigraphic units. Importantly, the architecture of these units (i.e. shallow stacked wedges) is consistent across the study area, and corresponds to the position and character of the arcuate wedge/moraine complexes observed at seabed;
- These broad sediment wedges (observed at seabed and in the sub-surface) are interpreted as sub-marginal till wedges, formed by complex accretionary processes inboard of several still-stand ice margins (e.g. Ice-margins 1-4). This glacial landsystem is similar to examples previously recognized in terrestrially-based ice sheet marginal settings (e.g. southern Laurentide);
- Discrete groups of subglacial tunnel valleys are incised ~perpendicularly into the lobate till wedge/moraine complexes, with the northern and southern rims of the tunnel valleys coincident with the northern and southern margin of the respective till wedge/moraine

complexes. This close and repeated correlation indicates a clear genetic relationship between the position of individual ice margins and the origin of the tunnel valleys. Further to this, we observe a significant relationship between the size (i.e. inferred discharge) of the tunnel valleys and the spacing between them, suggesting that meltwater was organised within catchments that were proportional to the size of each tunnel valley, conforming with theoretical predictions of meltwater routing in mid-latitude glaciological systems;

- Seismic data provide constraint on the relative event chronology of the NSL, with the subdivided BBF seismostratigraphic units progressively and shallowly stacked from south to north (generally younging to the north). There are also however, several clear examples of ice sheet re-advance; for example, the oldest stratigraphic unit (Seismic-unit I) corresponds to the position of Ice-margin 2, which was over-ridden to the south by an ice lobe recorded by Seismic-unit II (southern-most ice-margin 1). Overall this is indicative of an oscillating ice sheet margin that occupied several lobate still-stand positions prior to its retreat from the region;
- We demonstrate that the more detailed, and spatially accurate reconstruction presented here (based on in situ data from within the southern North Sea) is compatible with existing, more disparate terrestrial records of MIS 2 glaciation. Ice margins mapped offshore are geographically well correlated to the fragmentary onshore limits, and further to this, offshore seismostratigraphic associations place these terrestrial limits into a clearer regional-scale event chronology.
- This new reconstruction of the NSL provides an important new framework for understanding the late-stage behaviour of the BIIS in the North Sea. Using this framework, future efforts to date and model the ice sheet can more specifically target the climatic, mass-balance, and external glaciological factors (i.e. Fennoscandian Ice Sheet) that influenced deglaciation, important for better characterising both modern and palaeo-ice sheets.
- Lastly, this study provides an important demonstration of how improved bathymetry data and geomorphological interpretation over extensive areas enables the identification of greater detail within shallow seismic data, which in turn allows for more nuanced and accurate interpretations of ice sheet dynamics and relative event chronologies.

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Figure Captions

1- North Sea bathymetry and study area. Gray lines show generalized LGM reconstruction of BIIS and FIS extent and flow configuration (Graham et al., 2011). Three reconstructions of MIS 2 maximum are shown in white (contrasting line styles reflect different studies; see legend). Contrasting reconstructions of later-stage glaciation (uncoupled BIIS and FIS) shown in yellow (Carr et al., 2006) and blue (Sejrup et al., 2016). Terrestrial LGM limit in southern Britain taken from BRITICE (Clark et al., 2004). Source of bathymetry data: EMODnet. Northern MIS 2 margin adapted from Clark et al. (2012) and Bradwell and Stoker (2015).

2- Study area bathymetry with figure inset locations and feature names. Bathymetry data are compiled from the UK Bathymetry Data Archive Centre (DAC), and gridded to 25m horizontal resolution. Terrestrial topography: NEXTMap.

3- Oblique view, looking south down the Inner Silver Pit. The glacial tunnel valley exhibits significant vertical relief, exposes outcrops of deformed bedrock, and incorporates discontinuous Holocene sediment cover. High-resolution swath bathymetry from within the tunnel valley were acquired for the Silver Pit Marine Conservation Zone (MCZ), Defra, and made available under Open Government License Copyright.

4- Zoomed-in view of bathymetry, demonstrating glacial landform assemblage i.e relationship between till wedges, moraines, and tunnel valleys. Inset (top left) shows interpretation of glacial landforms.

5- Zoomed-in view of coast-parallel ridges offshore Holderness. These ridges may relate in part to the moraines mapped on Holderness (Evans and Thompson, 2010). These are shown within the bottom-left inset, together with newly-mapped offshore ridges. Swath bathymetry data were acquired by the Channel Coastal Observatory (CCO)-nearshore, and for recommended Marine Conservation Zones (MCZ)-offshore, Defra, and made available under Open Government License Copyright.

6- Revised seismostratigraphic model of the Bolders Bank Formation (blue fill). Panel A) shows seismic interpretation along our type section A-A'. Yellow fill indicates mobile and/or sand-rich deposit. Orange fill indicates mud-rich Holocene channel infill. Profile location shown in Fig. (2). Panel B) shows an extract of the seismic data highlighting key stratigraphic features that correspond to the seabed geomorphology (boomer; BGS survey 1990/4).

7- A) Seismic and B) interpreted sections along profile B-B', an offset boomer line from the southern end of profile A-A'. Seismic data reveal southern extent of buried wedge that is truncated on profile A-A', and the same seismostratigraphic nomenclature applies (i.e. seismic units I and II) as in Fig. 6.

8- A) Seismic and B) interpreted sections along profile C-C' (boomer data; BGS-held survey 2008/5). Similar colour scheme used as along profiles A-A' and B-B' (Figs. 6,7) to demonstrate that similar seismic architectural patterns are observed across the study area (e.g. stacked till wedges). Seismostratigraphic units are not labelled however because it's not clear whether individual seismic sequences persist over large lateral distances (10's kms).

9- Interpreted glacial geomorphology of the study area. Observed glacial landforms used to infer approximate positions of four arcuate ice margins, numbered from south to north (1-4). White dots indicate the locations of BGS-held cores where Bolders Bank till was

recovered in shallow sediment cores (note that these do not persist south of Ice-margin 1).'G.C.' indicates the location of the infilled Glacifluvial Channel on Fig. (6).

10- A) Regional extent (Bolders Bank Formation (BBF) and ice flow configuration (white arrows) of the North Sea Lobe. Arcuate ice margins are projected away from observed landforms and outwidth the study area. These projected ice margins suggest good agreement with previously observed terrestrial limits e.g. Ice-margin (I.M.) 1 and the LGM maximum in north Norfolk (Clark et al., 2004), and moraine ridges in Lincolnshire and Holderness. Previously mapped seismostratigraphic extent of the Bolders Bank Formation (BBF) superimposed on regional hillshade bathymetry. B) Simplified conceptual diagram demonstrating the relationships between the glacial landforms present at seabed (broad wedges, moraines, tunnel valleys), and the revised stratigraphy of the BBF (shallow stacked till wedges). This combined landform and sub-surface stratigraphic assemblage elucidates the phased still-stand occupation of the North Sea Lobe at an oscillating southern margin, prior to final retreat from the region .

11- Tunnel valley spacing vs. drainage (i.e. cross-sectional area). Regression analysis suggests a proportional relationship between the lateral spacing and inferred discharge of the tunnel valleys distributed along Ice-margin 4. This suggests that subglacial meltwater is strongly focussed towards individual tunnel valleys, in which the size of the tunnel valley corresponds to its broader catchment area.

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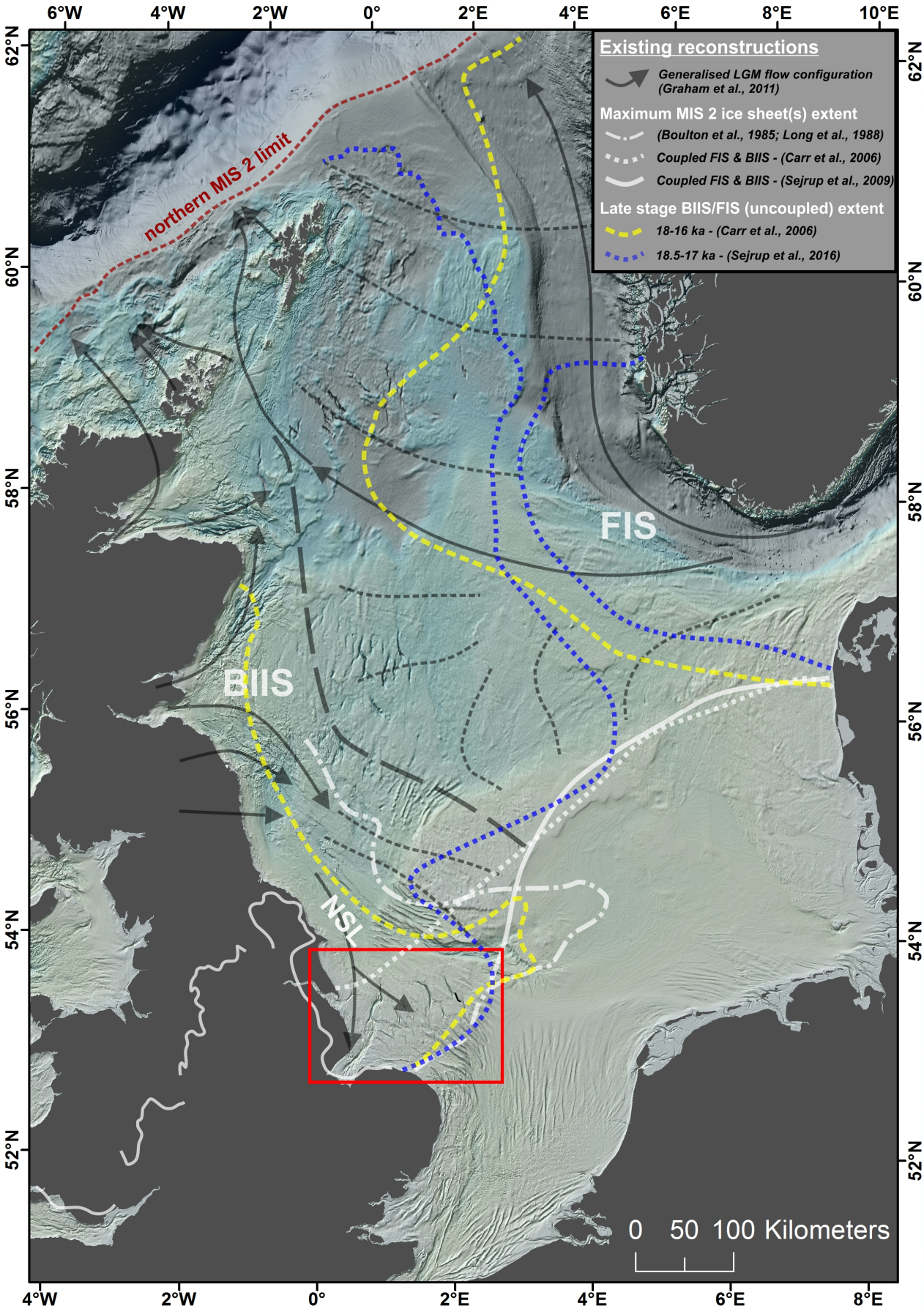
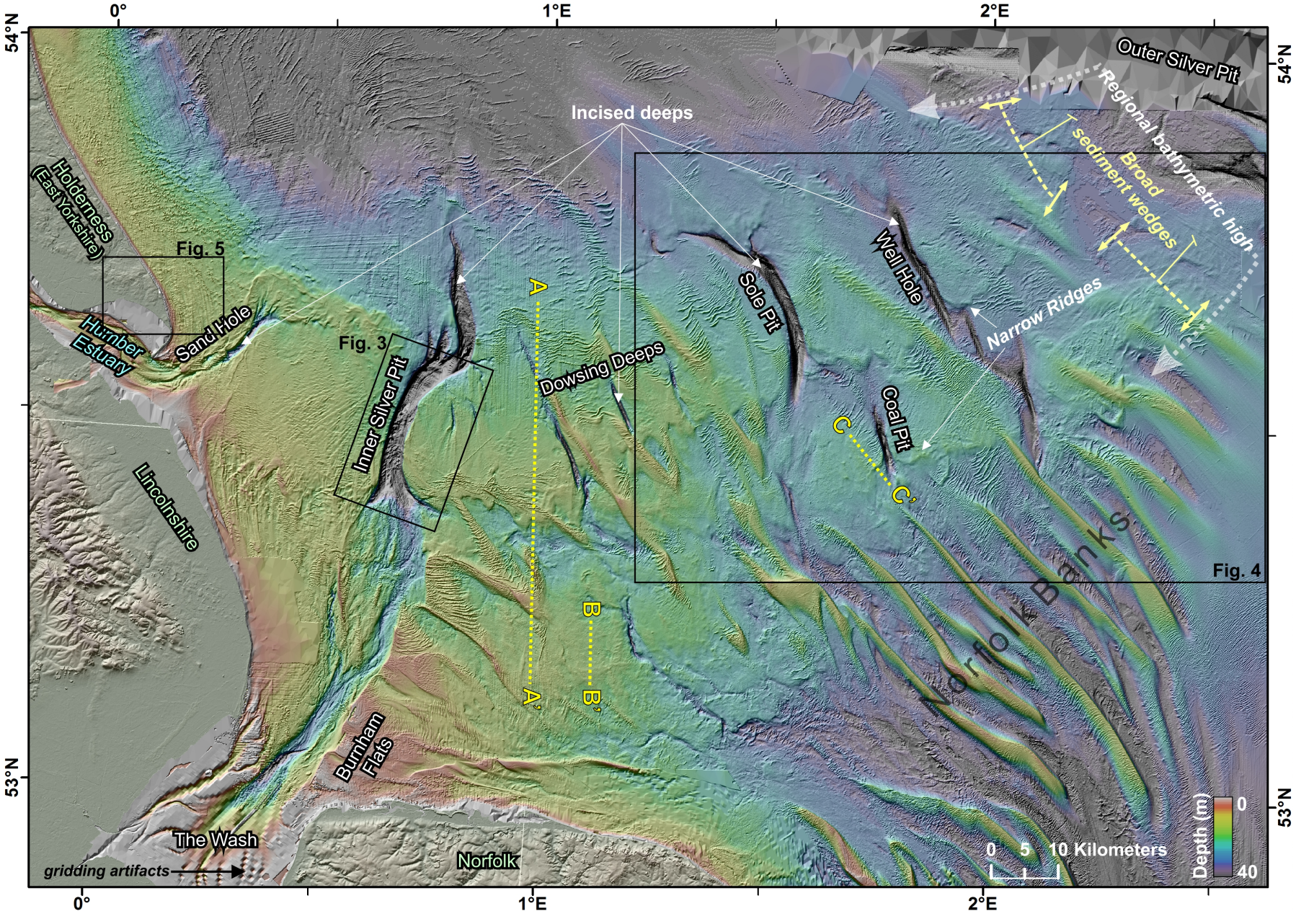
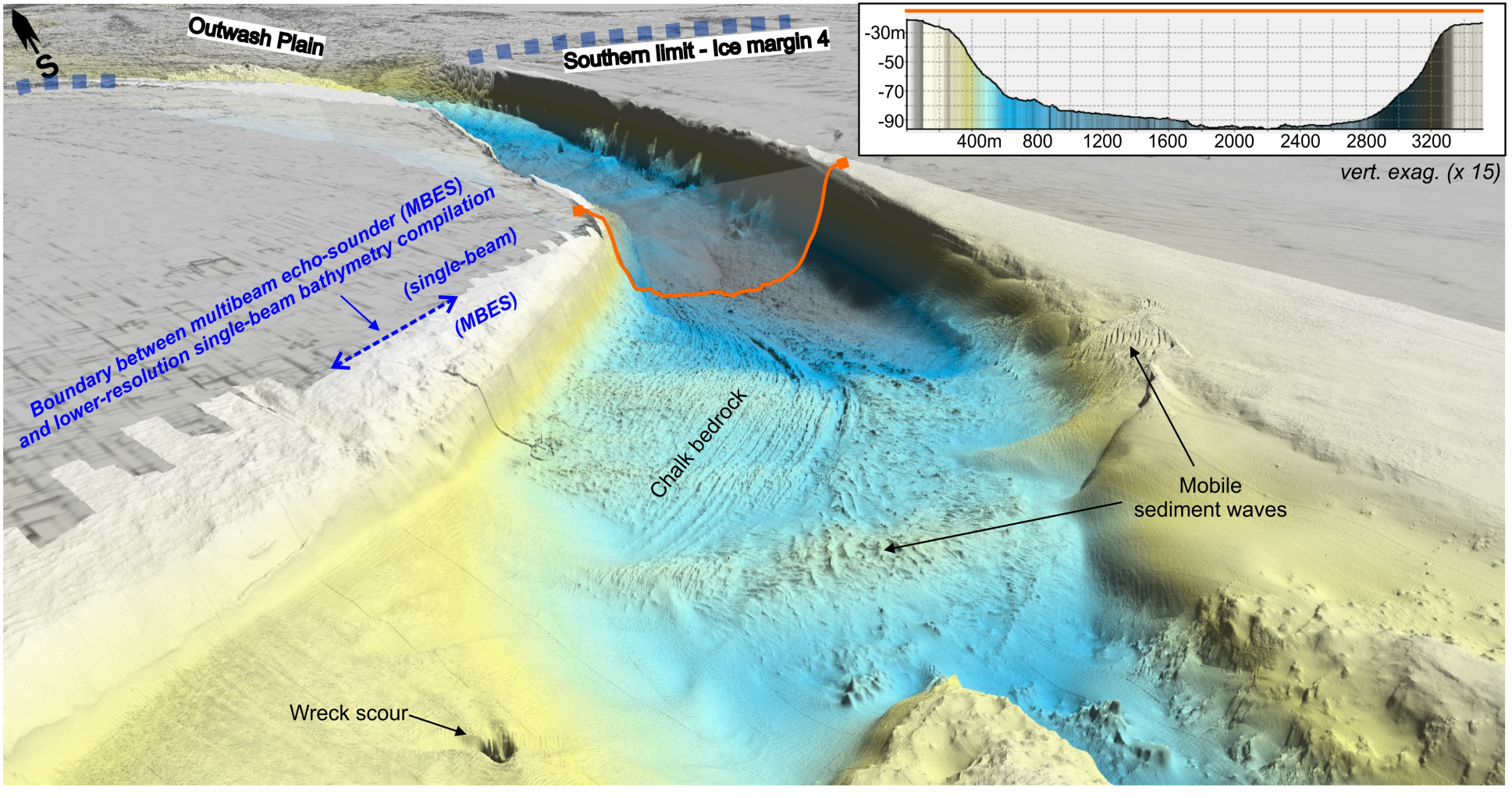
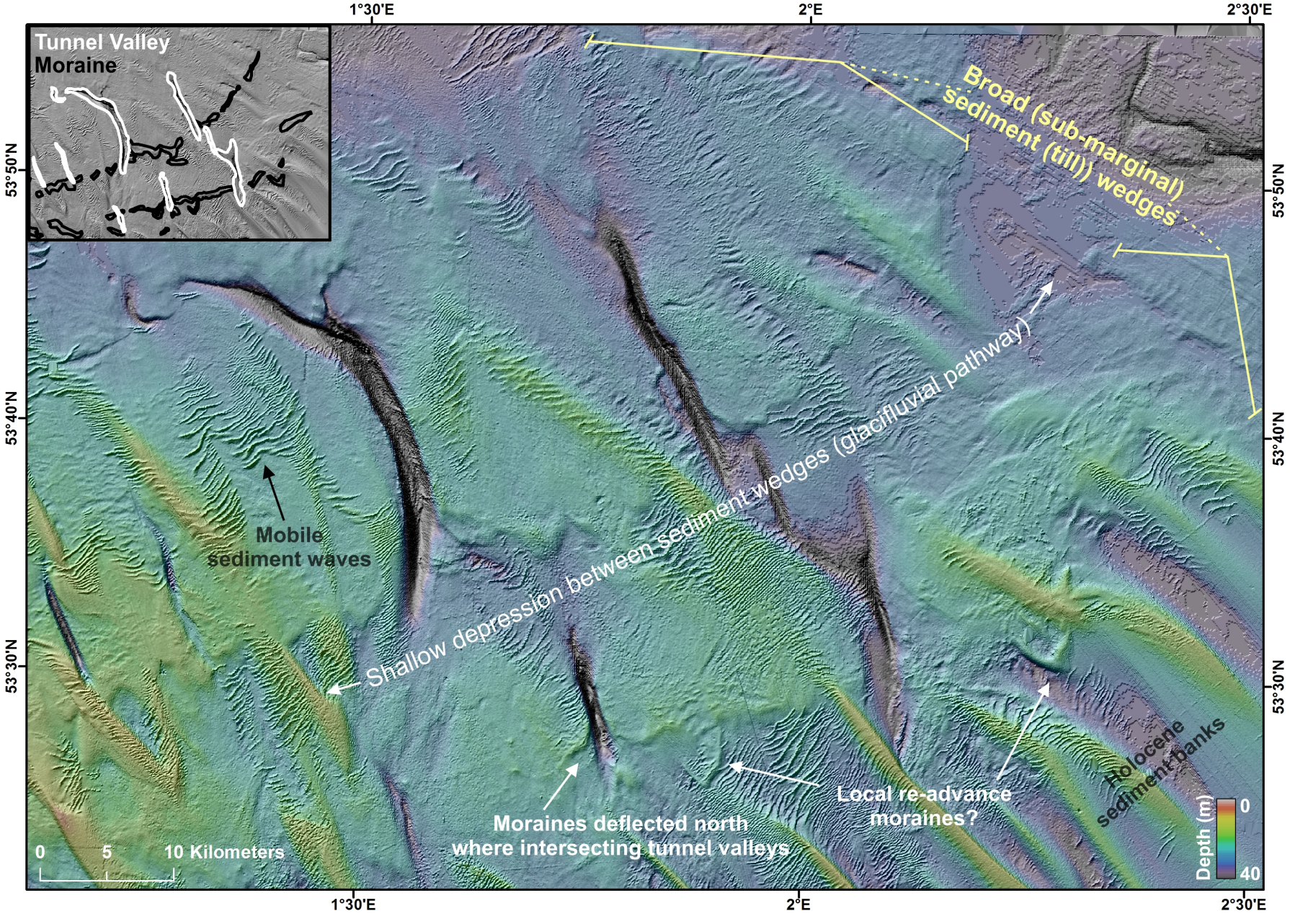
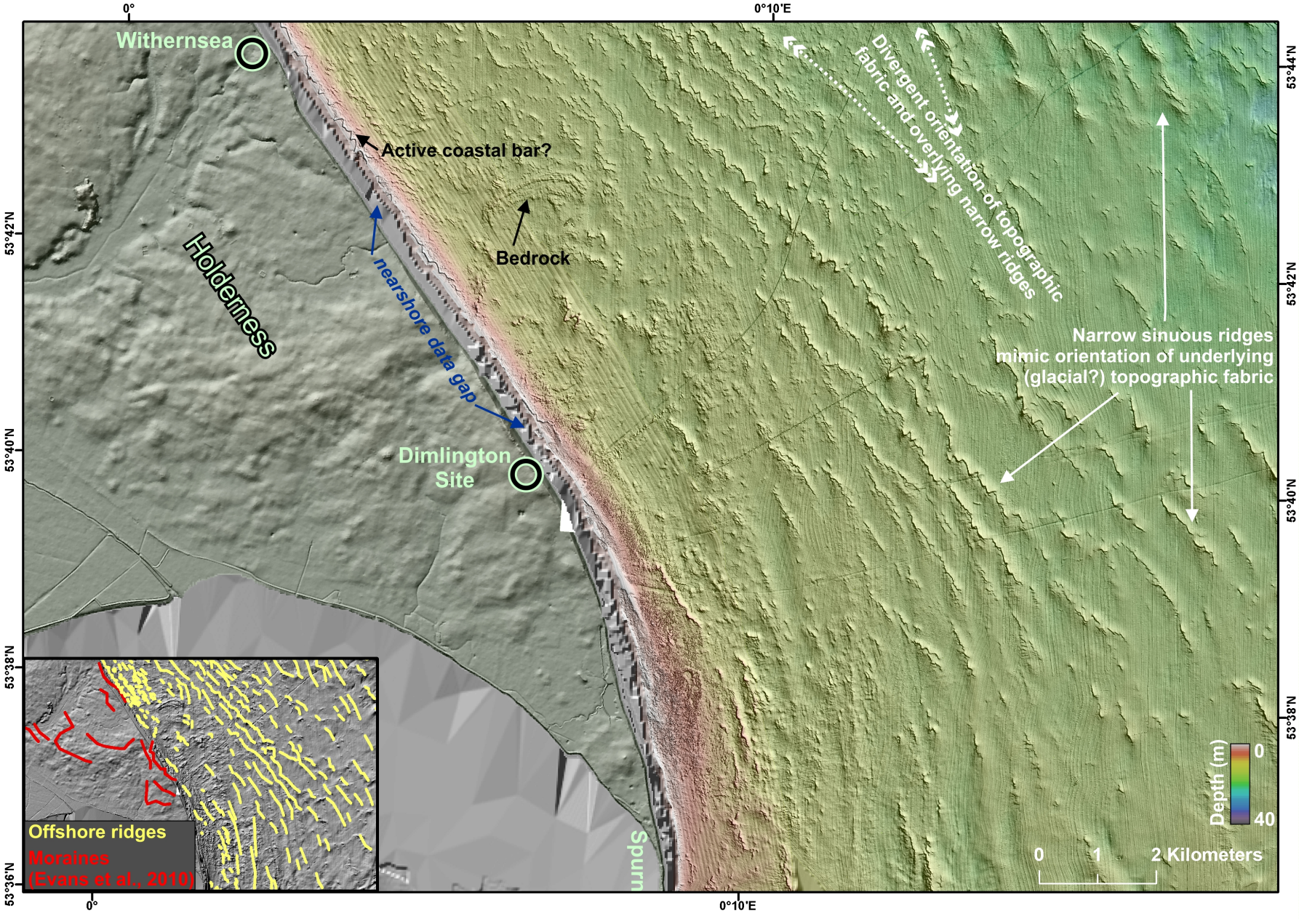
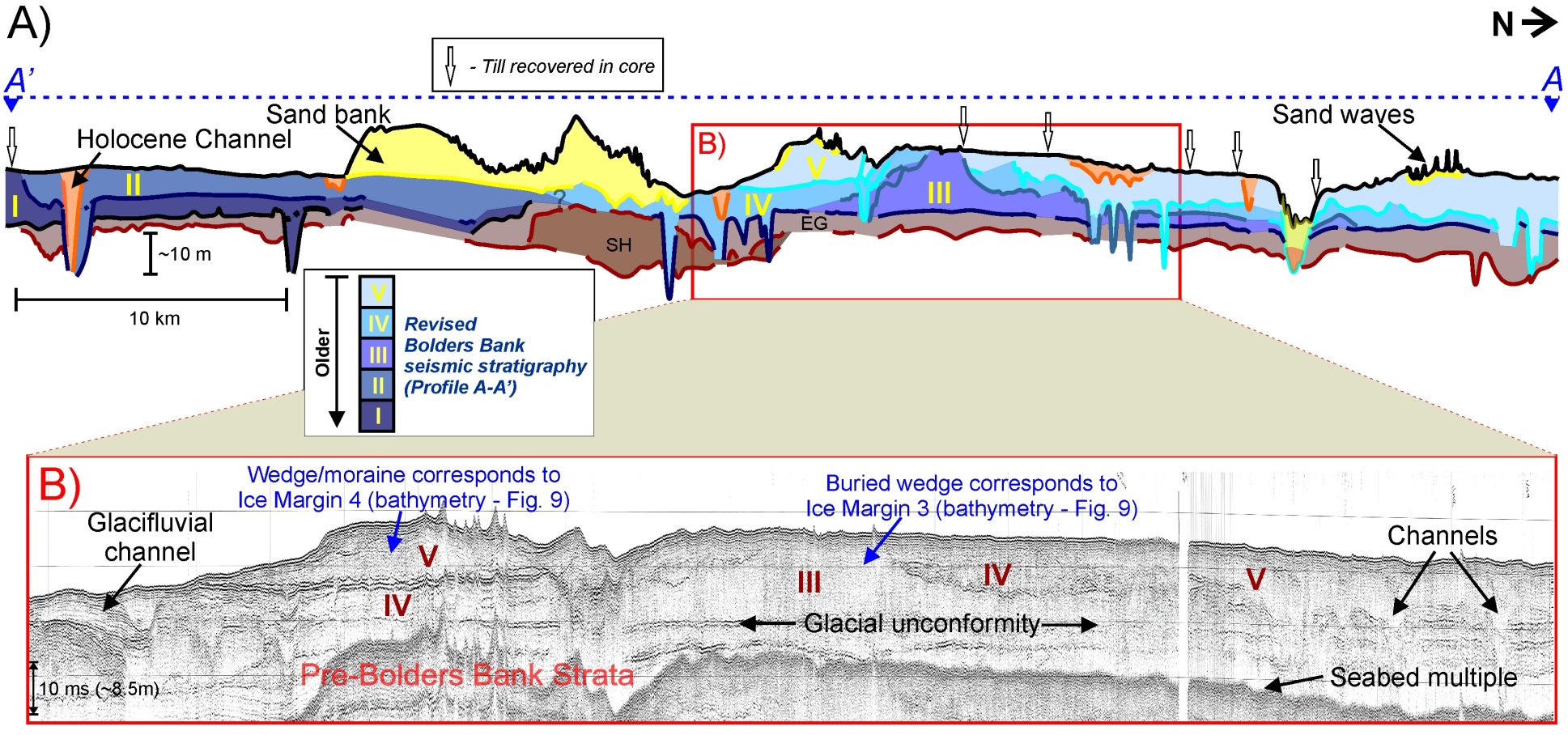

Existing reconstructions
Generalised LGM flow configuration (Graham et al., 2011)
Maximum MIS 2 ice sheet(s) extent
(Boulton et al., 1985; Long et al., 1988)
Coupled FIS & BIIS - (Carr et al., 2006)
Coupled FIS & BIIS - (Sejrup et al., 2009)
Late stage BIIS/FIS (uncoupled) extent
18-16 ka - (Carr et al., 2006)
18.5-17 ka - (Sejrup et al., 2016)
northern MIS 2 limit
FIS
BIIS
NSL
0 50 100 Kilometers
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

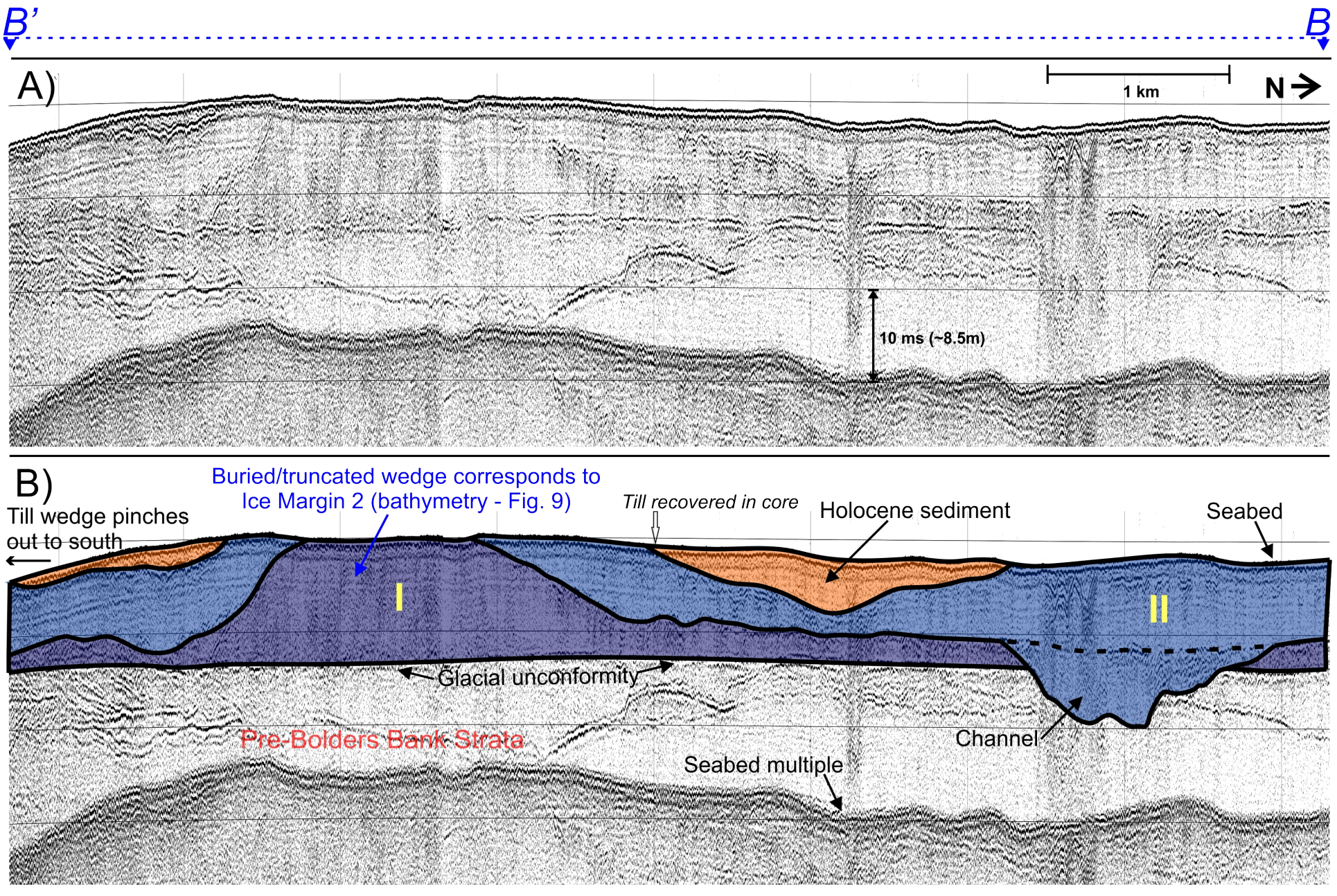

0°
1°E
2°E
54°N
53°N
Outer Silver Pit
Regional bathymetric high
Broad sediment wedges
Incised deeps
Holderness (East Yorkshire)
Fig. 5
Humber Estuary
Sand Hole
Fig. 3
Inner Silver Pit
Dowsing Deeps
Sole Pit
Well Hole
Narrow Ridges
Coal Pit
Fig. 4
Norfolk Banks
Lincolnshire
A
A'
B
B'
C
C'
Burnham Flats
The Wash
Norfolk
gridding artifacts
0 5 10 Kilometers
Depth (m)
0
40

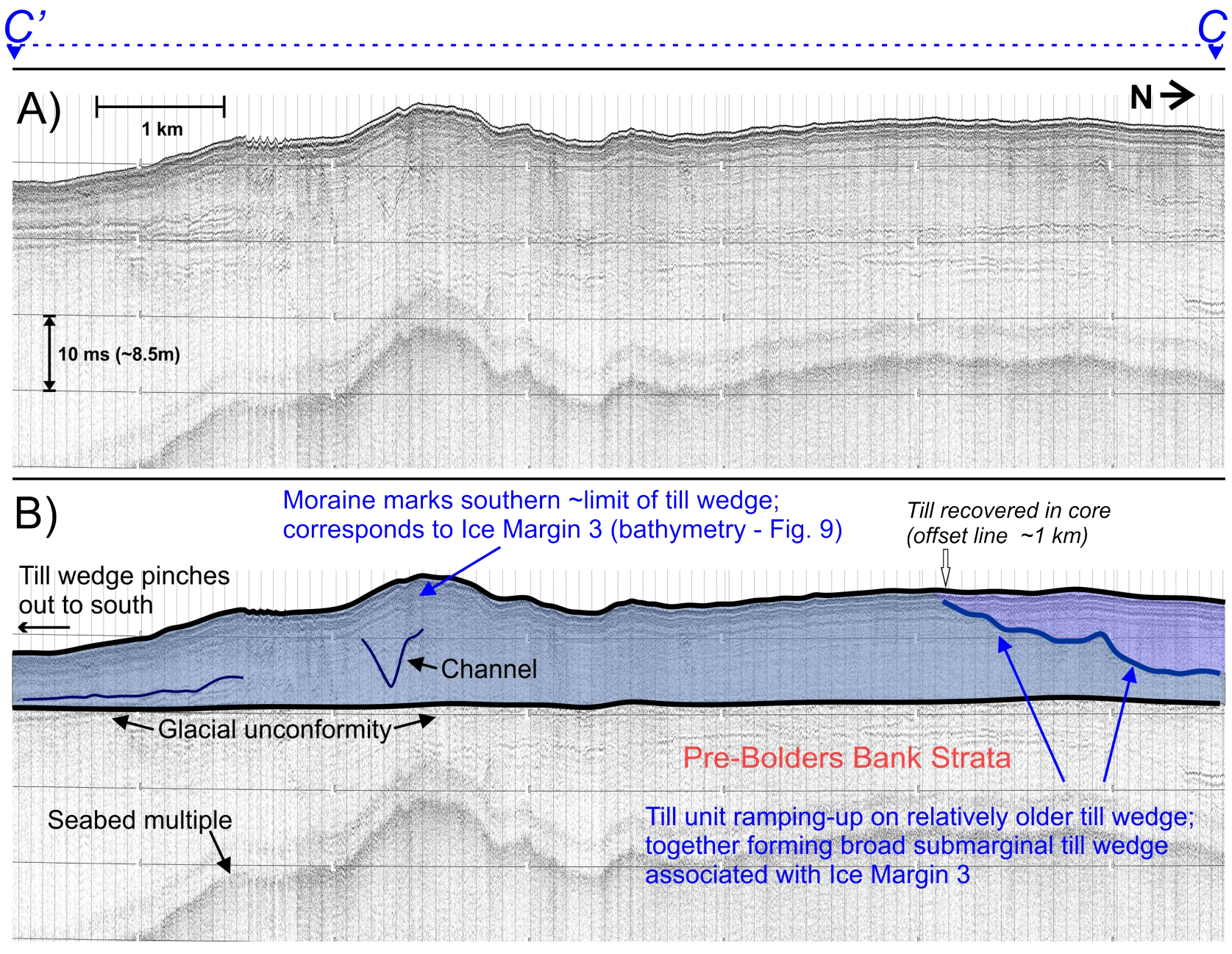

S
Outwash Plain
Southern limit - Ice margin 4
-30m
-50
-70
-90
400m
800
1200
1600
2000
2400
2800
3200
vert. exag. (x 15)
Boundary between multibeam echo-sounder (MBES) and lower-resolution single-beam bathymetry compilation
(single-beam)
(MBES)
Chalk bedrock
Mobile sediment waves
Wreck scour

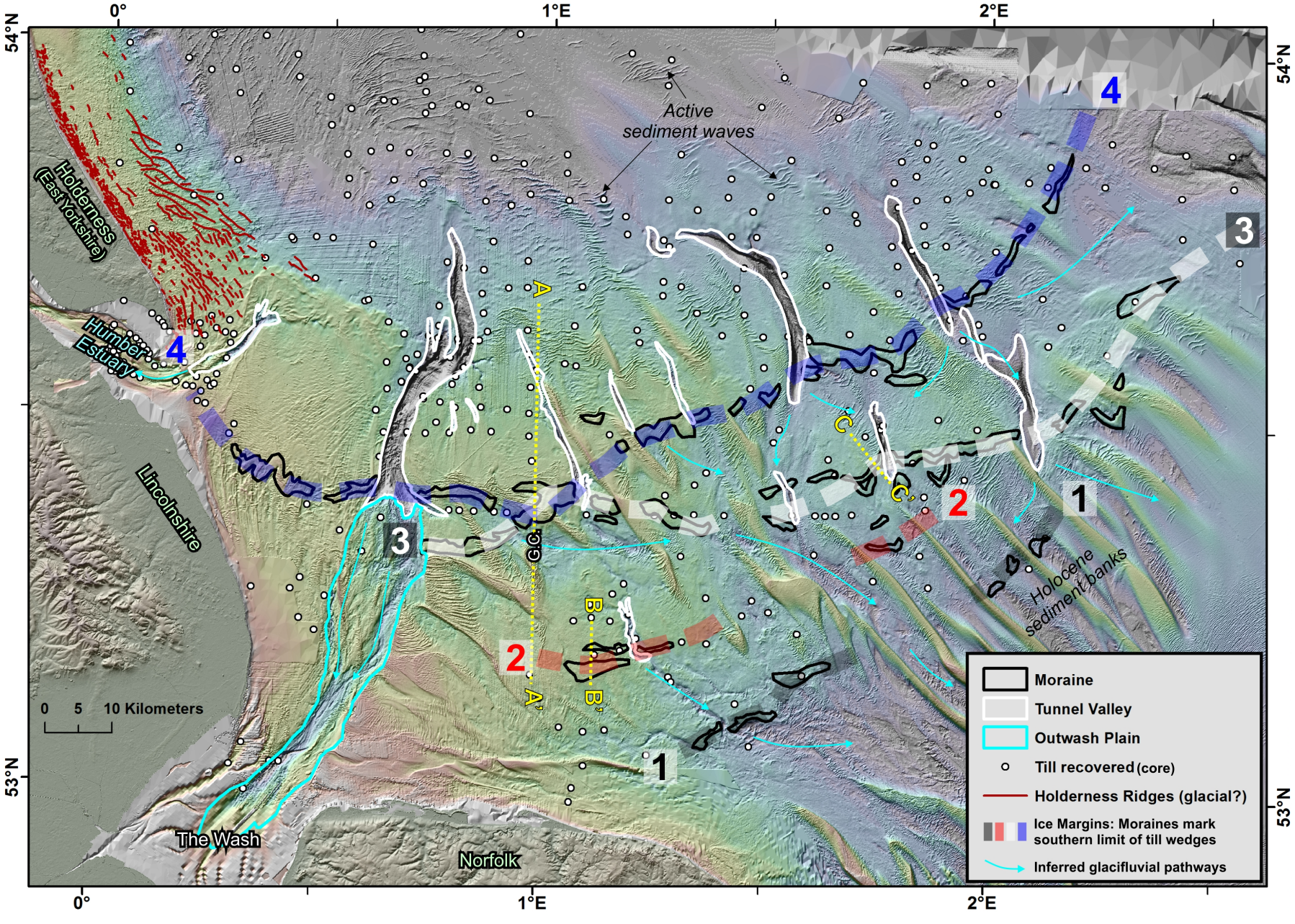

1°30'E
2°E
2°30'E
53°50'N
53°40'N
53°30'N
Tunnel Valley
Moraine
Broad (sub-marginal)
sediment (till)) wedges
Mobile
sediment waves
Shallow depression between sediment wedges (glacifluvial pathway)
Moraines deflected north
where intersecting tunnel valleys
Local re-advance
moraines?
Holocene
sediment banks
Depth (m)
0
40
0
5
10 Kilometers

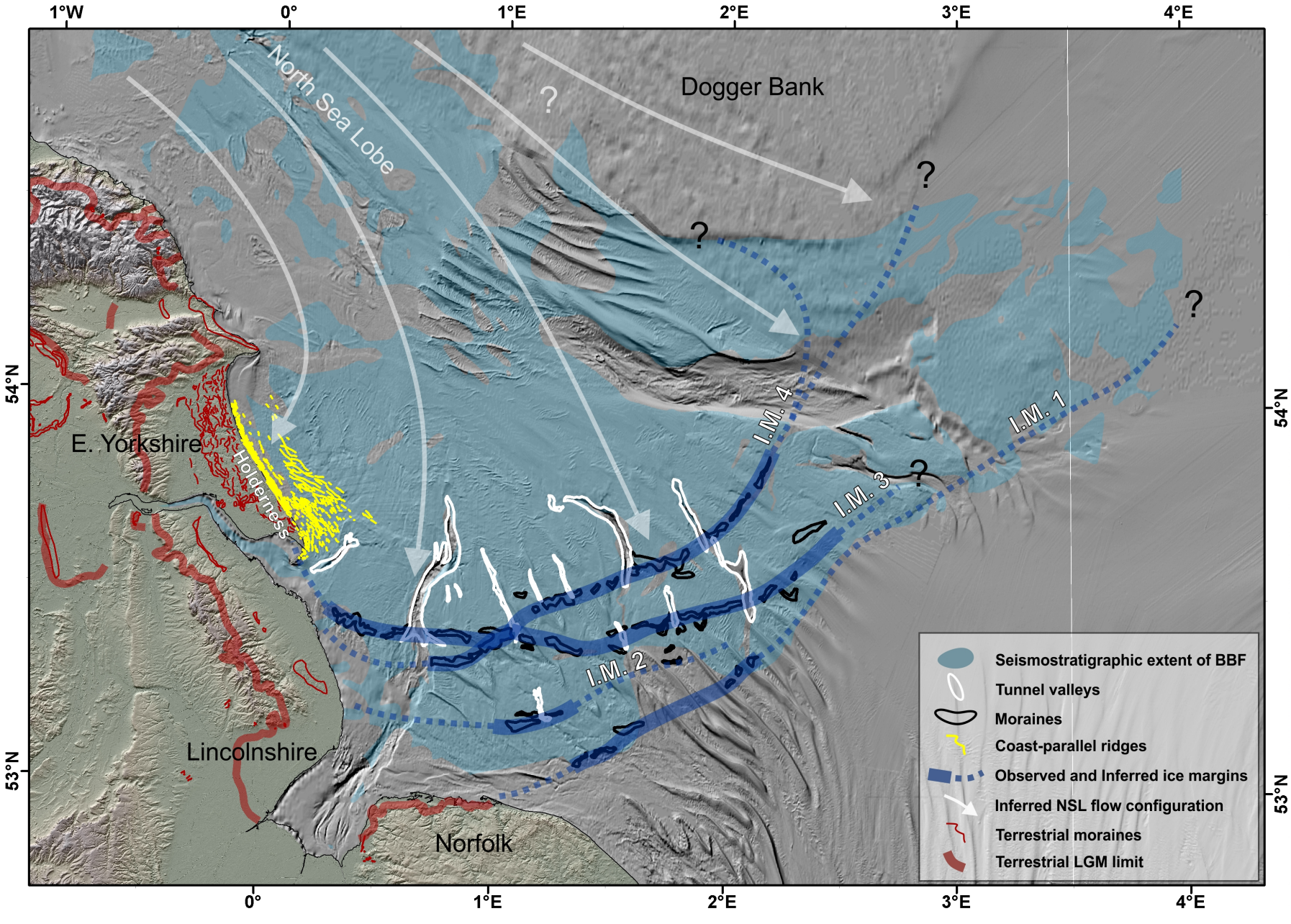

0°
0°10'E
53°44'N
53°42'N
53°40'N
53°38'N
53°36'N
Withernsea
Active coastal bar?
Holderness
Bedrock
nearshore data gap
Dimlington Site
Divergent orientation of topographic fabric and overlying narrow ridges
Narrow sinuous ridges mimic orientation of underlying (glacial?) topographic fabric
Depth (m)
0
40
0
1
2 Kilometers
Offshore ridges
Moraines (Evans et al., 2010)
Spurn

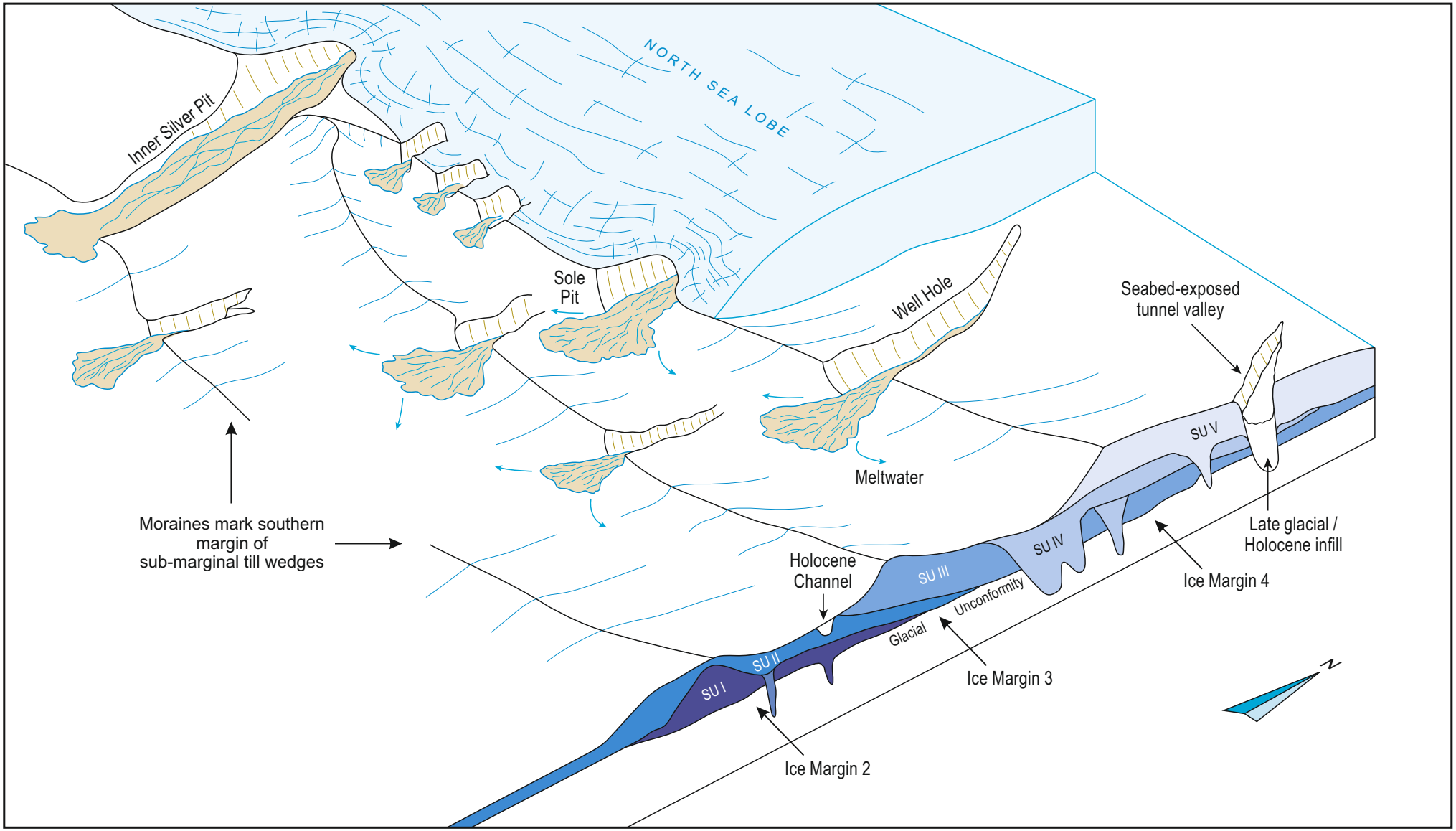

A)
N
A'
A
- Till recovered in core
Holocene Channel
Sand bank
Sand waves
B)
I
II
III
IV
V
EG
SH
~10 m
10 km
Older
Revised
Bolders Bank
seismic stratigraphy
(Profile A-A')
B)
Wedge/moraine corresponds to
Ice Margin 4 (bathymetry - Fig. 9)
Buried wedge corresponds to
Ice Margin 3 (bathymetry - Fig. 9)
Glacifluvial
channel
Channels
Glacial unconformity
Pre-Bolders Bank Strata
Seabed multiple
10 ms (~8.5m)


B'
B
A)
1 km
N
10 ms (~8.5m)
B)
Buried/truncated wedge corresponds to
Ice Margin 2 (bathymetry - Fig. 9)
Till wedge pinches
out to south
Till recovered in core
Holocene sediment
Seabed
I
II
Glacial unconformity
Pre-Bolders Bank Strata
Channel
Seabed multiple

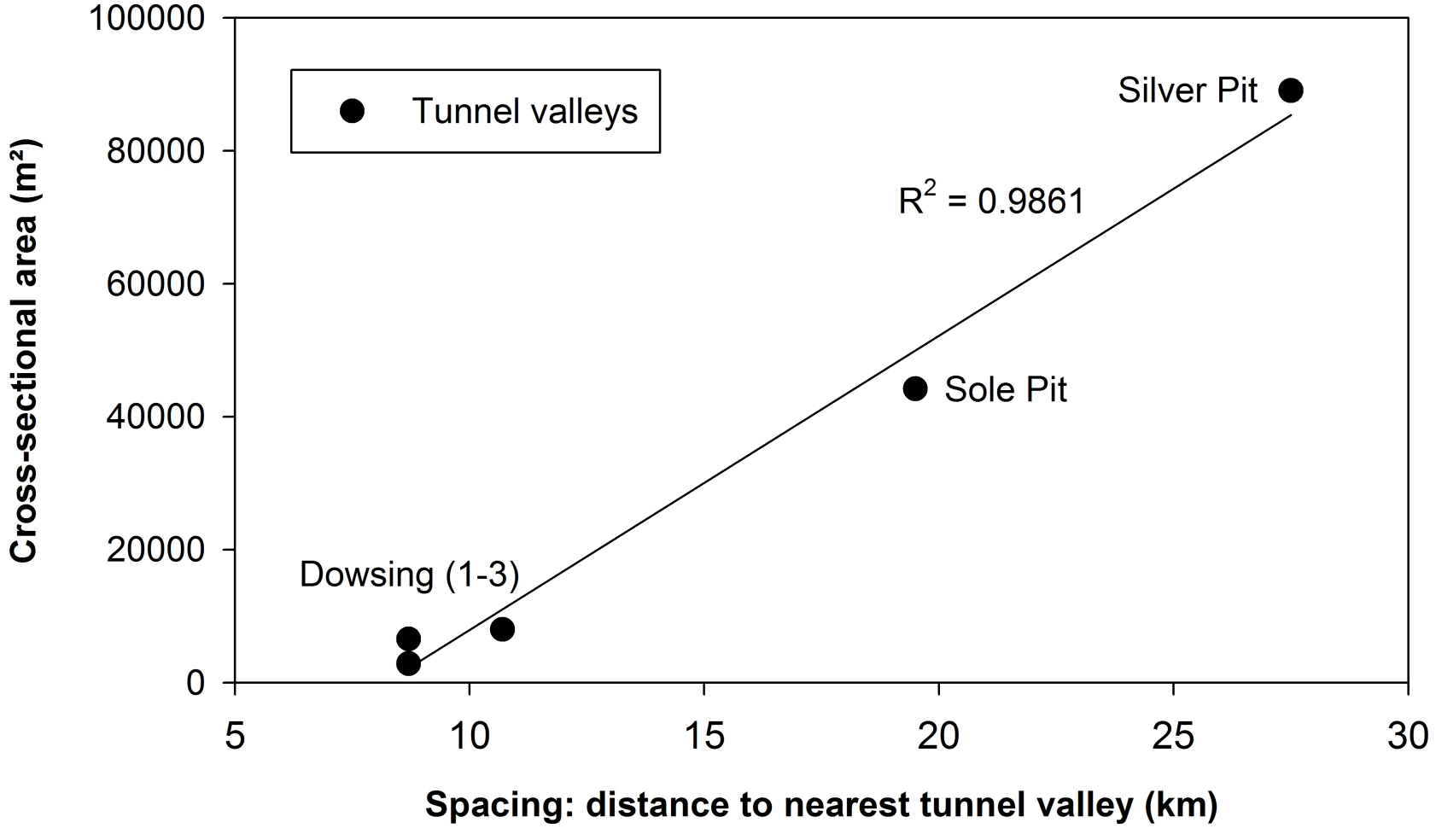

C'
C
A)
1 km
N
10 ms (~8.5m)
B)
Moraine marks southern ~limit of till wedge;
corresponds to Ice Margin 3 (bathymetry - Fig. 9)
Till recovered in core
(offset line ~1 km)
Till wedge pinches
out to south
Channel
Glacial unconformity
Pre-Bolders Bank Strata
Seabed multiple
Till unit ramping-up on relatively older till wedge;
together forming broad submarginal till wedge
associated with Ice Margin 3


0°
1°E
2°E
54°N
53°N
Active
sediment waves
Holderness
(East Yorkshire)
Humber
Estuary
Lincolnshire
The Wash
Norfolk
Holocene
sediment banks
A
A'
B
B'
C
C'
1
2
3
4
0 5 10 Kilometers
Moraine
Tunnel Valley
Outwash Plain
Till recovered (core)
Holderness Ridges (glacial?)
Ice Margins: Moraines mark
southern limit of till wedges
Inferred glacifluvial pathways


1°W
0°
1°E
2°E
3°E
4°E
54°N
53°N
North Sea Lobe
Dogger Bank
?
E. Yorkshire
Holderness
I.M. 4
I.M. 1
I.M. 3
I.M. 2
Lincolnshire
Norfolk
Seismostratigraphic extent of BBF
Tunnel valleys
Moraines
Coast-parallel ridges
Observed and Inferred ice margins
Inferred NSL flow configuration
Terrestrial moraines
Terrestrial LGM limit


NORTH SEA LOBE
Inner Silver Pit
Sole Pit
Well Hole
Seabed-exposed tunnel valley
Meltwater
Moraines mark southern margin of sub-marginal till wedges
Holocene Channel
SU V
SU IV
SU III
SU II
SU I
Unconformity
Glacial
Late glacial / Holocene infill
Ice Margin 4
Ice Margin 3
Ice Margin 2
N

Tunnel Valley (Spacing vs. Drainage)					
	Silver Pit	**Dowsing-1**	**Dowsing-2**	**Dowsing-3**	**Sole Pit**
Spacing (nearest valley) (km)	27.5	10.7	8.7	8.7	19.5
Cross-sectional area (m²)	89054.0	8010.1	6577.0	2855.0	44179.4



Highlights for Manuscript:

"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"

- Detailed reconstruction of MIS 2 glaciation in S. North Sea based on marine data;
- Extensive bathymetry data reveal terminal positions of former North Sea Lobe (NSL);
- Seabed landforms relate to previously undetected seismostrat. architecture;
- Landform/subsurface assemblage constrains relative chronology, fits onshore record;
- Tunnel valley origin linked to discrete ice margins; size proportional to catchment.