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A chronology for North Sea Lobe advance and recession on the Lincolnshire and Norfolk coasts during MIS 2 and 6

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ABSTRACT

During the last (MIS 2) and older glaciations of the North Sea, a North Sea Lobe (NSL) of the British-Irish Ice Sheet flowed onshore and terminated on the lowlands of eastern England, constructing inset sequences of either substantial ice-marginal deposits and tills or only a thin till veneer, indicative of complex and highly dynamic glaciological behaviour. The glaciation limit represented by the Marsh Tills and the Stickney and Horkstow Moraines in Lincolnshire is regarded as the maximum margin of the NSL during MIS 2 and was attained at ~19.5 ka as determined by OSL dating of overridden lake sediments at Welton le Wold. A later ice marginal position is recorded by the Hogsthorpe-Killingholme Moraine belt, within which ice-walled lake plains indicate large scale ice stagnation rapidly followed ice advance at ~18.4 ka based on dates from supraglacial lake deposits. The NSL advanced onshore in North Norfolk slightly earlier constructing a moraine ridge at Garrett Hill at ~21.5ka. In addition to the large ice-dammed lakes in the Humber and Wash lowlands, we propose that an extensive Glacial Lake Lymn was dammed in the southern Lincolnshire Wolds by the NSL ice margin at the Stickney Moraine. Previous proposals that older glacier limits might be recorded in the region, lying between MIS 2 and MIS 12 deposits, are verified by our OSL dates on the Stiffkey moraine, which lies immediately outside the Garrett Hill moraine and appears to be of MIS 6 age.

1. Introduction

The reconstruction of palaeo-ice sheets provides us with long-term records of ice-sheet behaviour which are useful analogues for understanding contemporary ice-sheets. The British Isles were repeatedly glaciated throughout the Quaternary, with the most recent British-Irish Ice Sheet (BIIS) coalescing with the neighbouring Scandinavian Ice Sheet (Sejrup et al., 2009,2015, 2016; Clark et al., 2012), a situation which likely occurred during prior glaciations (Gibbard et al., 2018; Rea et al., in press). During periods of North Sea glaciation, ice from Scotland, Northern England and potentially Scandinavia, flowed toward the southern margin of the BIIS over the dry land of the shallow marine basin, exposed due to global glacioesutatic sea level fall (cf. Perrin et al., 1979; Lee et al., 2002; Clark et al., 2004; Davies et al., 2011). From here this North Sea Lobe (NSL) flowed onshore and terminated on the lowlands of the east coast of England where it constructed substantial ice-marginal morainic deposits, subaqueous glacial lake grounding line fans and glacitectonic landforms (Fig. 1; Banham, 1975; Straw, 1979; Catt, 2007; Evans and Thomson, 2010; Gibbard et al., 2018). During the last glaciation, it appears that the behaviour of North Sea glacier ice fed by various source regions was complex and highly dynamic, with multiple advances or oscillations (Dove et al., 2017; Roberts et al., 2018, in press) and likely only advanced to altitudes <400 m OD on the high ground of Eastern England (Bateman et al., 2018; Fig. 1a).

The area comprising the Lincolnshire coastal lowlands, The Wash and the North Norfolk coast contains a record of multiple glaciations for which a definitive chronology has been difficult to establish (Preece et al., 2009; Lee et al., 2012; Figs. 1 and 2). The limit of the last (Devensian; Marine Isotope Stage (MIS) 2) laciation

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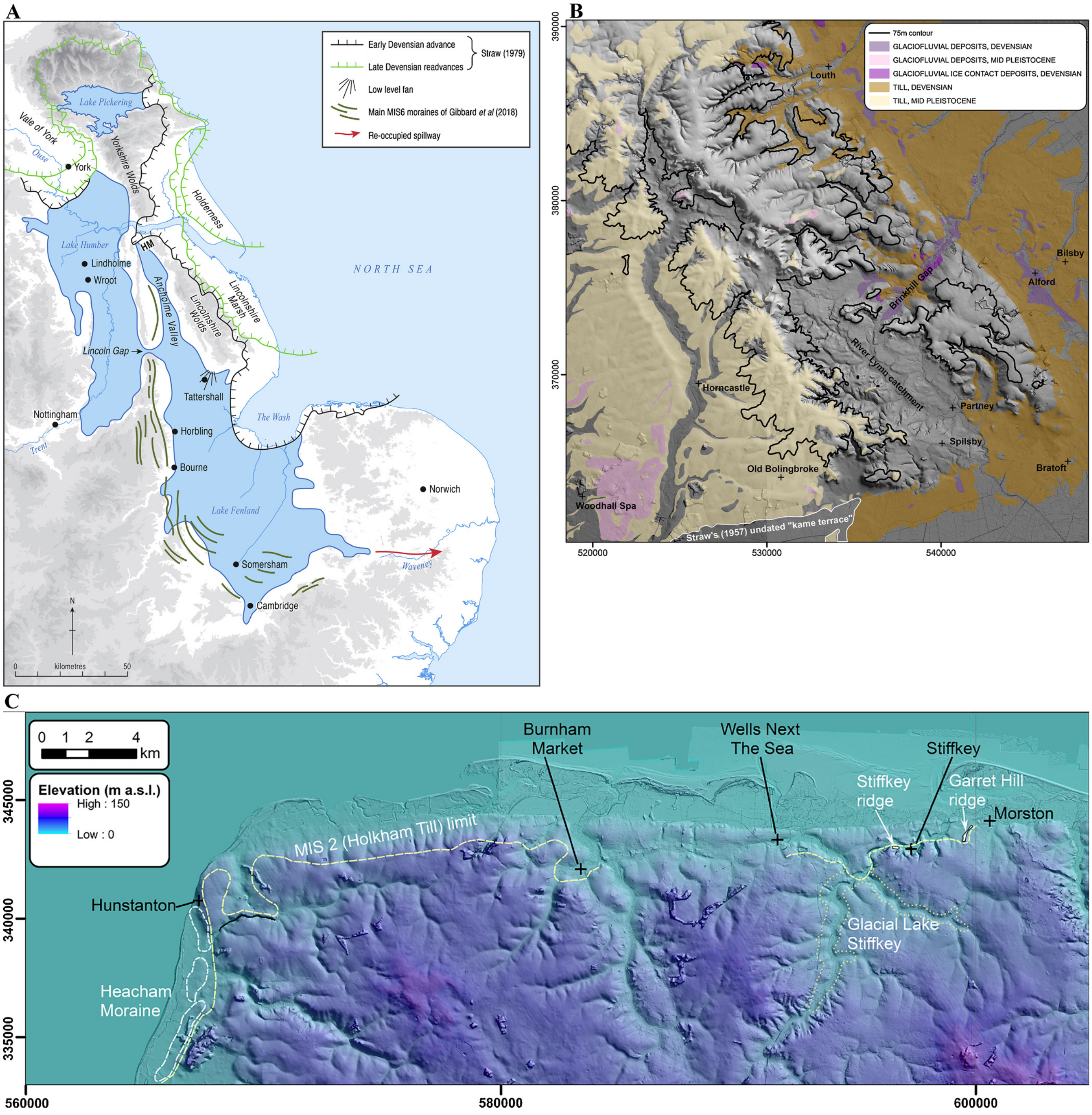

Fig. 1. Location maps and LiDAR imagery for eastern England with proposed ice margins and major landform-sediment assemblages pertinent to the reconstruction of former limits of the North Sea Lobe of the British-Irish Ice Sheet: a) map of eastern England showing proposed early and late Devensian ice limits of Straw (1979) and proglacial lakes (HM = location of Horkstow Moraine). Details of the Fenland/Wash ice limits and landforms are from Gibbard et al. (2018); b) LiDAR based topography of the Lincolnshire Wolds and Marsh with relevant glacial deposits and landforms derived from BGS mapping and with the 75 m contour highlighted as a maximum possible ice-dammed lake shoreline; c) LiDAR based topography of North Norfolk with relevant glacial deposits and landforms derived from various sources and this study. (The reader is referred to the web version of this article in order to view all the figures in colour).

has been traditionally drawn along the Stickney Moraine on the north side of The Wash (Straw, 1979; Fig. 2), but in the Cretaceous cuesta of the Lincolnshire Wolds and North Norfolk the occurrence of complex glacigenic deposits, not always associated with clear landforms, appears to demarcate multiple ice sheet margins that have been variably allocated ages from MIS 12 to 2 (e.g. Gale et al., 1988; Pawley et al., 2008). In the context of a potentially dynamic (surging) North Sea Lobe (NSL) at the southern margin of the British-Irish Ice Sheet (BIIS; cf. Eyles et al., 1994; Boston et al., 2010; Evans and Thomson, 2010; Bateman et al., 2018) that could have constructed multiple landform-sediment assemblages during MIS 2, it is critical to differentiate the ages of former moraines and associated deposits along the English east coast.

In the Cretaceous cuesta of the Lincolnshire Wolds, Straw (1979) proposed two major Devensian ice limits based upon the distribution of the Lower and Upper Marsh tills (Straw, 1957, 1958, 1961). The most extensive Lower Marsh Till is related to the Horkstow Moraine in the Humber Estuary (Bateman et al., 2018) and the Stickney

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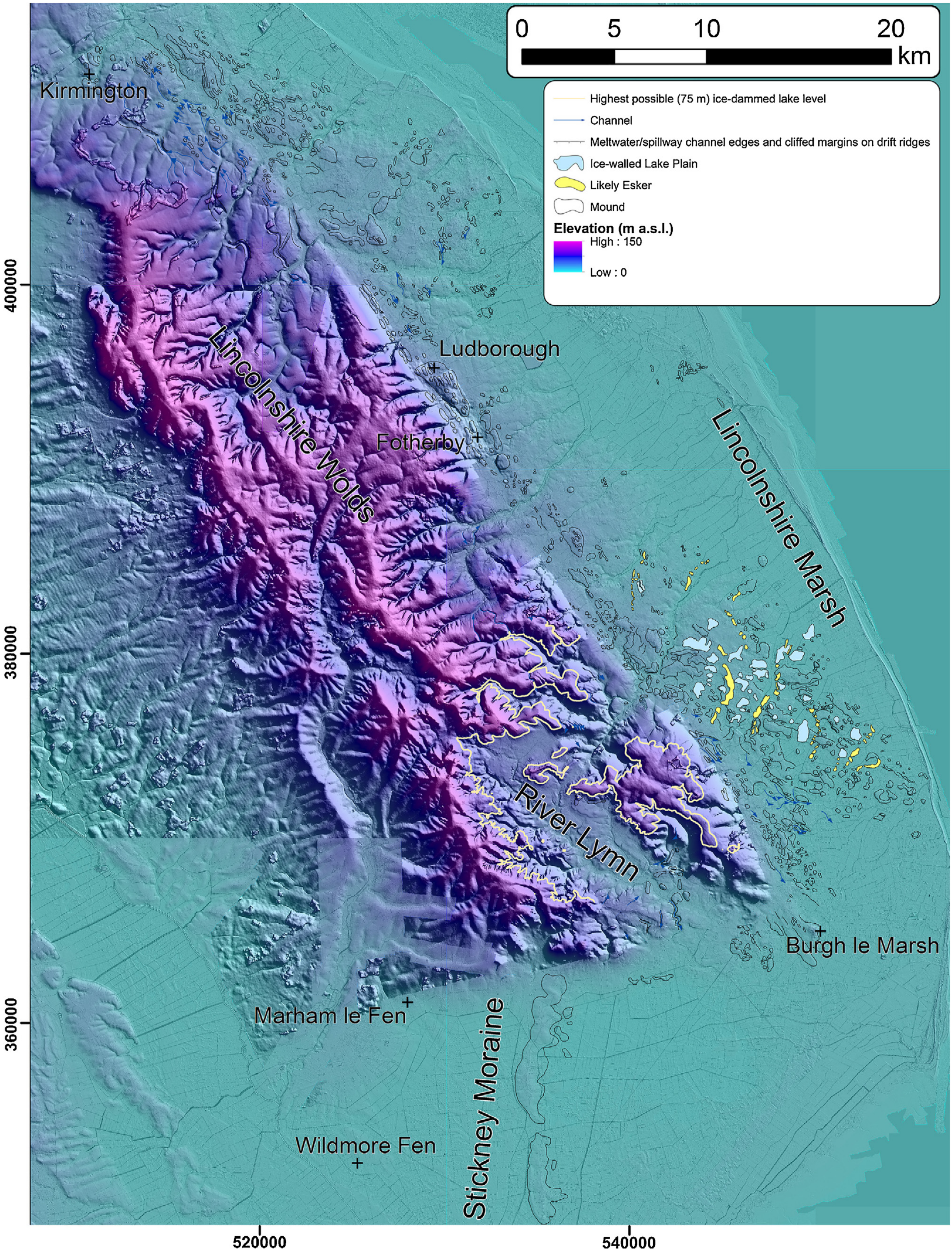

Fig. 2. Glacial geomorphology mapped onto LiDAR imagery of eastern England. Also included are the 75 m contour in the Lincolnshire Wolds.

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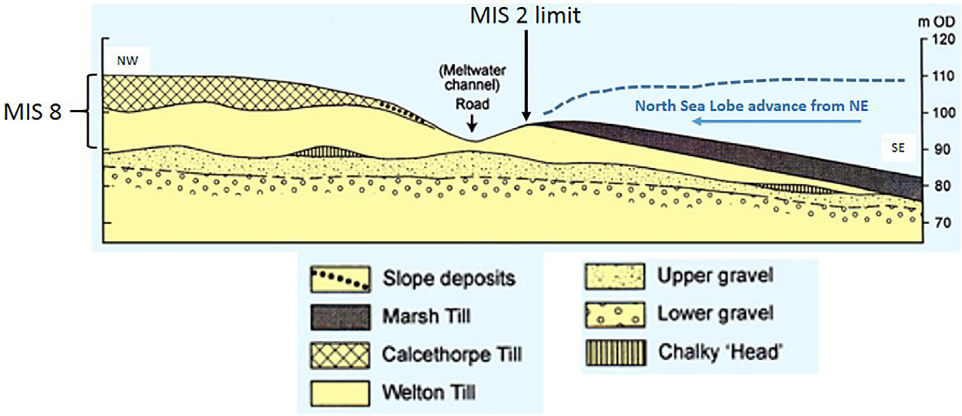

Fig. 3. Summary stratigraphic section of the sequence exposed at Welton le Wold, modified from Straw (2015).

moraine in The Wash and extends up to 114 m OD in the higher terrain of the Wolds (Figs. 1 and 2). This limit was assigned an Early Devensian age by Straw (1979) particularly because it contrasts with that marked by the Upper Marsh Till, which reaches only up to 80 m OD in the northern Lincolnshire Wolds and is associated with morainic topography on valley floors and some permanent drainage diversions (Figs. 3 and 4). The Lower and Upper Marsh Tills have never been observed together in a single exposure. Straw (1957, 1958, 1961) allocated the terms to the two "tills" separated by sands and gravels that appear on a number of borehole records from the Lincolnshire Marsh. Straw's till distribution maps do not depict the limit of the Lower Marsh Till and earlier depictions of the deposits of the last glaciation (e.g. Clayton, 1957) combine the apparent Lower and Upper Marsh Tills as the "younger boulder clay" or "younger drift". Straw (1979) correlated the Stickney Moraine with the early Devensian Lower Marsh Till. He defined the limit of the Upper Marsh Till advance at the westernmost limit of the thicker, hummocky drift along the Wolds scarp foot. Subsequent compilations of Devensian till extent in the region (e.g. British Geological Survey maps; Fig. 1b), display only the Upper Marsh Till on the Lincolnshire Wolds. On the Lincolnshire Marsh, Straw (1979) referred to the more widespread morainic topography as the Hogsthorpe-Killingholme moraine belt, which he used to propose a Late Devensian readvance after an early recession from the Upper Marsh Till limit. Somewhat problematic is the fact that the Lower and Upper tills are very similar in lithology and colour and display the same weathering characteristics. The Marsh Till is distinctly reddish brown and Madgett and Catt (1978) used its colour, particle size and petrology to confirm that it is the equivalent of the Skipsea Till further north in Holderness. The two tills have never been dated and the complete sequence has been related to the Devensian Stage based on the assumption that the underlying marine platform is of last interglacial age (Straw, 1979).

The most prominent ice-dammed lake associated with the Marsh Tills is the 30 m Lake Fenland of West (1993) and West et al. (1999), which Straw (1979) dated to early MIS 3 or MIS 4 based upon morphostratigraphic relationships between the deltaic Kirkby Moor Sands (at altitudes up to 30 m OD) and the later Tattershall fan gravels (Fig. 1a). This lake required the North Sea Lobe to block The Wash and hence the ice margin is drawn along the maximum altitude of the Holkham Till in the south and at the Stickney Moraine in the north. Straw (1957) described an extensive kame terrace deposited at around 30 m OD along the lower slopes of the Wolds and associated this with the northern end of the Stickney Moraine. However, this feature is only mapped up to 25 m OD by the BGS and moreover is depicted as extending westwards down to 10 m OD at Mareham-le-Fen before then curving southwards with elongate pockets of till to the area of Wildmore Fen (Figs. 1b and 2). This apparently demarcates a further ice limit to the west of the Stickney Moraine, beyond which glacifluvial gravels descend westwards and are eventually dissected by those of the Tattershall fan, although small pockets of the gravels are mapped at altitudes of 30–33 m OD north of Mareham-le-Fen (Fig. 2).

The till infill in the Brinkhill gap and in the upper South Ormsby valley around Tetford has been used by Straw (1957, 1961) to demarcate a lobe of ice that penetrated the headwaters of the River Great Eau, its downwasting margins being recorded by marginal meltwater channels and kame terraces down to South Thoresby in the east (Figs. 1b and 5). The mapped extent of Lower Marsh Till

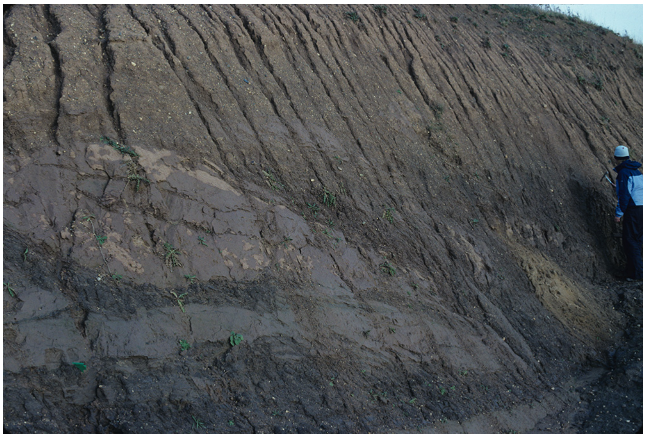

Fig. 4. Exposure through the glacitectonised rhythmites folded into the Marsh Till and sampled for OSL dating at Welton le Wold.

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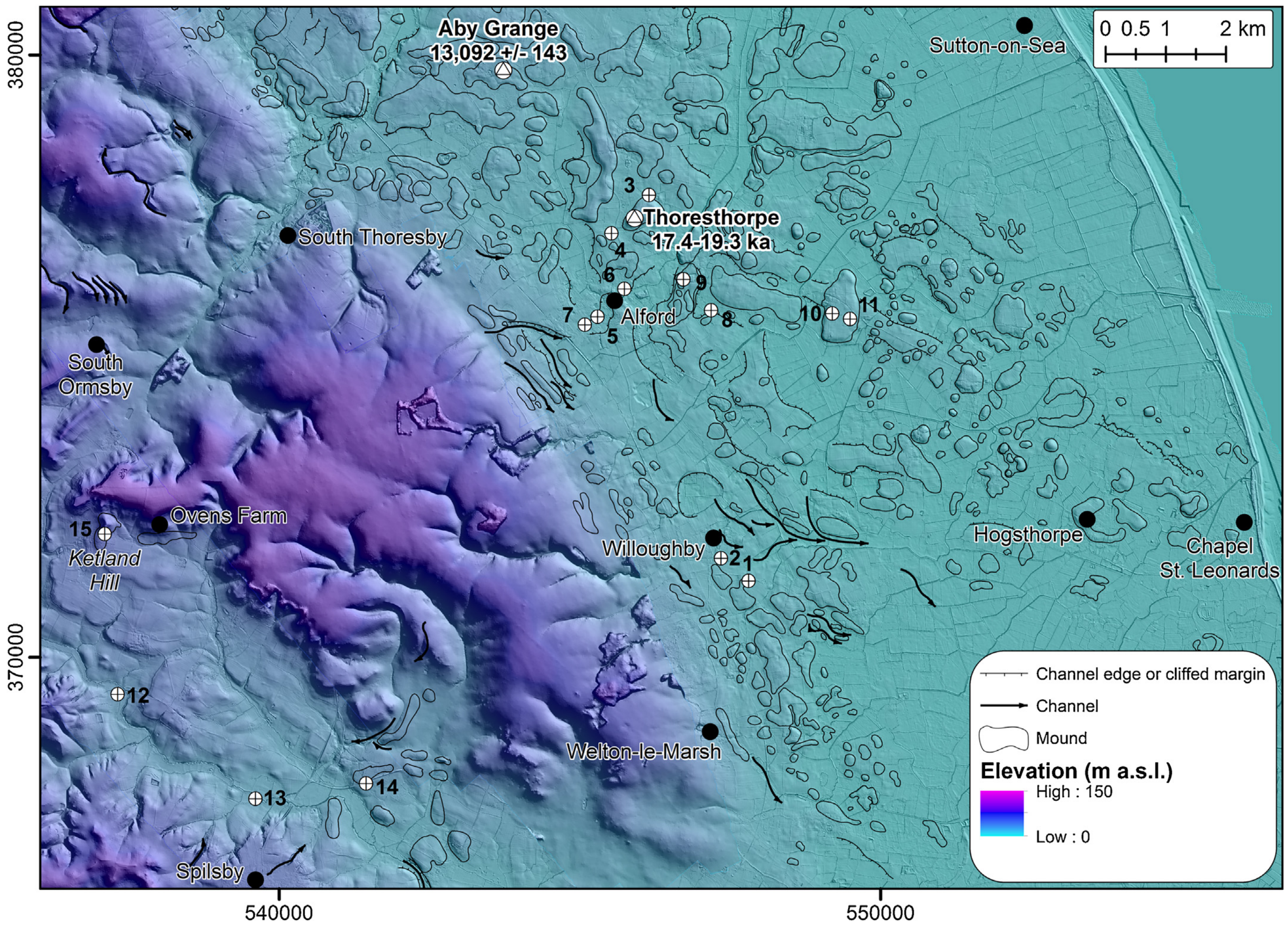

Fig. 5. Large scale geomorphology map for the area around Thoresthorpe on the Lincolnshire Marsh. Locations of selected borehole records are the numbered cross in circle symbols. Dated sites are triangle in circle symbols.

associated with the Stickney Moraine reaches altitudes of 30 m on both sides of the lower Lymn valley and indicates that the former ice margin backfilled the valley to at least as far as Partney (Fig. 1a). At its maximum extent the ice lobe was responsible for the reversal of the drainage so that it flowed westwards into the head of the River Lymn catchment over a col at 55 m OD at Tetford; Straw (1961) mapped "lacustrine gravels" up 55 m OD in this area and in the Brinkhill gap, implying that the gravels represented glacifluvial outwash grading to a lake located directly to the west. The diverted River Lymn is thought to have drained along the descending ice margin to the west to form Straw's (1957) kame terrace. Such former drainage pathways were identified by Straw (1957) as spillways to the southeast of Spilsby. Although the upper altitude of this glacial Lake Lymn was only around 30 m OD, Straw (1979) depicts "lacustrine clays and sands" around Harrington at 47 m OD, on the northeastern slopes of the Lymn Valley below the Brinkhill gap. This gap was mapped by Straw (1957,1979) as a pathway for meltwater draining across a col and into the Lymn Valley from lakes dammed by the Devensian ice margin as it moved westwards up the chalk dip slope; these lakes occupied the heads of the tributary valleys of Calceby Beck and extended up to 55 m OD (Figs. 1b, 2 & 5).

In the area of The Wash, the ice limit demarcated by the Stickney Moraine is regarded by Straw (1960, 1979) as coeval with the Hunstanton Till (Holkham Member, Lewis, 1999) in North Norfolk (Figs. 1c & 2). While occupying the Stickney Moraine, the North Sea Lobe is thought to have dammed the drainage into The Wash to create Lake Fenland, which was linked in the north via the Lincoln Gap to Lake Humber and thought to have reached up to ca. 30 m OD (cf. Lewis, 1894; Edwards, 1937; Gaunt, 1976, 1994; Gaunt et al., 1992; West, 1993; West et al., 1999), at least temporarily (Evans et al., 2018.) and draining through a spillway located in the Waveney valley (Fig. 1a). On the south side of The Wash and along a narrow strip of the North Norfolk coast, banked up to 37 m OD against the older marine cliff between the Heacham Moraine and Morston, the Lower Marsh Till equivalent and hence the Late Devensian limit was mapped by Suggate and West (1959) and Straw (1960, 1979) and classified as the Hunstanton Till. This thickens to the Heacham Moraine southwest of Hunstanton (Fig. 1c). More recently classified as the Holkham Till Member (Lewis, 1999), this till overlies a raised beach that has been assigned alternative ages of MIS 5e and the MIS 6–7 transition at Morston, which in turn overlies older till (Straw, 1960, 1979; Gallois, 1978; Gale et al., 1988; Hoare et al., 2009). Other deposits related to the Late Devensian ice margin are the ice-dammed lake sediments of Glacial Lake Stiffkey, which was dammed in the lower Stiffkey valley (Fig. 1c); the course of the River Stiffkey was later diverted eastwards along the receding ice margin along a course that it follows today (Brand et al., 2002). This newer river course was incised down through older Quaternary deposits as well as bedrock, isolating glacial landforms and sediments of various ages along both sides of the valley in the vicinity of Stiffkey

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village. To the north of the River Stiffkey, the Holkham Till and associated glacifluvial sand and gravel of the Ringstead Member demarcate the Late Devensian limit, whereas to the south of the river the landforms and sediments are older and were classified originally as "Wolstonian" by Straw (1979). Later nomenclature changes for these older deposits recognized the Britons Lane Sand and Gravel Member (Lee et al., 2004a; Pawley et al., 2005) and the Sheringham Cliffs Formation of the MIS 12 glaciation (Pawley et al., 2008) but some have proposed that glaciations dating to MIS 10, 8 or 6 (i.e. "Wolstonian") could be recorded along this coast (Hamblin et al., 2005; Rose, 2009).

In the lowland area of The Wash, Gibbard et al. (2018) have speculated that an MIS 6 ("Wolstonian") surging ice lobe penetrated westwards to produce an assemblage of ice-contact deltas and associated features called the "Skertchly Line" during the Tottenhill Glaciation (Fig. 1a). Also constructed at this time were an inset series of ice-marginal glacitectonic landforms, involving substantial disruption of bedrock strata, and ice-dammed lakes in the valleys of the Lark, Little Ouse, Nar and Wissey, with the uppermost level of Lake Paterson being at 30–32 m OD. Proposed glacitectonized ice-contact deposits and bedrock forming the Fenland "islands" and ridges are regarded by Gibbard et al. (2018) as evidence for numerous oscillations by the ice lobe as it retreated from The Wash. No such complex oscillations have been identified in the stratigraphy and geomorphology along the North Norfolk coast, but ice lobe surging driven by drawdown into the expansive lower terrain of The Wash, especially if it hosted proglacial lake waters, could explain the more complex moraine systems proposed by Gibbard et al. (2018). However, only one exposure has been reported through the substantial "ice thrust" ridges in the western areas of The Wash as depicted on Fig. 1a. Although this exposure did display a bedrock mega-raft (Skertchly, 1877), this does not necessarily confirm a glacitectonic origin for all the ridges and islands in the area. Moreover, glacitectonic thrust moraines, if this is a viable interpretation of the features, are not solely diagnostic of palaeo-surging and need to be juxtaposed with other surge-related landform-sediment associations (cf. Sharp, 1988; Evans and Rea, 1999, 2003; Evans et al., 2007; Kjær et al., 2008, Ingólfsson2016), a problem that applies also to the proposed paleao-surges of the North Sea Lobe in Holderness (cf. Eyles et al., 1994; Boston et al., 2010; Evans and Thomson, 2010).

In summary, it is unclear whether the classification of the Lincolnshire Marsh tills into two units relating to separate Devensian glaciations is appropriate and their chronology is unknown. Secondly, it is not unequivocal as to where the southern margin of the MIS 2 NSL is located or what its relationships are to deposits and landforms left by previous glaciations in the area. The landforms, sediments and optically stimulated luminescence (OSL) ages from three locations are presented in this paper. These include Welton-le-Wold, on the dip slope of the Cretaceous cuesta in north Lincolnshire, Thoresthorpe, which is located within a hummocky terrain belt on the coastal lowlands of the Lincolnshire Marsh, and Stiffkey, located within the hummocky terrain of the North Norfolk coast and previously variously associated with ice sheet marginal deposition in relation to MIS 12 through to MIS 2 (Fig. 1). Summary details of a previously reported site at Garrett Hill in North Norfolk (Roberts et al., 2018; in press) are also included as they pertain to the regional reconstruction of North Sea Lobe incursion onto the east coast. Finally, the borehole stratigraphic records from the relevant areas of the Lincolnshire Marsh and River Lymn catchment in the Cretaceous cuesta landscape are used in combination with geomorphological mapping to re-assess the extent of glaciation and potential ice-dammed lake development in South Lincolnshire.

2. Methods

2.1. Geomorphology and surficial geology mapping

Previously reported glacial landforms (cf.cf., Clayton, 1957; Straw, 1957, 1958, 1960, 1961, 1969, 1979; Pawley et al., 2006) were combined with new mapping from LiDAR imagery in order to reconstruct the limits and recession pattern of the North Sea Lobe of the BIIS along the Lincolnshire coast, The Wash and North Norfolk. The surficial geology, compiled largely from the work of Straw (1957, 1960, 1961, 1969, 1979) by the British Geological Survey and made available through Digimap, was used to identify the extent of glacigenic deposits, especially till, of Devensian age, although Upper and Lower Marsh Tills are not differentiated. This information was draped over the LiDAR imagery in order to reconcile the extent of surficial materials with glacigenic landforms (Fig. 1b). The LiDAR imagery has a resolution of 2 m in the x–y direction, with a vertical error (RMSE) of 0.2 m.

2.2. Stratigraphy and sedimentology

Sediments and stratigraphy were analysed either on natural or artificially excavated exposures and recorded on scaled photomontages and vertical profile logs. These include information on primary sedimentary structures, bed contacts, sediment body geometry, sorting and texture and secondary structures, as well as data on clast form and lithology and palaeocurrents where appropriate. These data were then used to characterize lithofacies types and to allocate facies codes following the procedures of Evans and Benn (2004). Clast lithological analysis was undertaken on samples of 50 clasts. At Welton-le-Wold, where the former quarry has been largely reclaimed, the previously reported stratigraphic and sedimentological information of Alabaster and Straw (1976) and Straw (2005, 2015) was utilized.

Selected borehole logs archived by the BGS reveal the stratigraphy of the areas of the Lincolnshire Marsh and Wolds. The proposed stratigraphic interpretations are the likely genetic origins of the sediments based upon the drillers' descriptions, in addition to any interpretive notes provided by them at the time of logging. A glacilacustrine origin is inferred wherever fine-grained interbeds are noted from boreholes through areas of relative high topography (i.e. hummocks) but an alluvial or glacilacustrine origin is assumed in the lower topography or depressions. As sea level has not been higher than present in the area since deglaciation the fine-grained sediments cannot be marine if they overlie till or glacifluvial deposits. However, marine sediments are identified or assumed where gravels and sands lie at the base of borehole logs and/or overlie the interglacial marine platform. A glacifluvial origin is assumed for gravel where it overlies till and/or occurs in a hummock.

2.3. Geophysics

Geophysical surveys were undertaken at Thoresthorpe and Ovens Farm in order to determine the nature of the substrate in areas that were devoid of natural or artificial exposures. Ground penetrating radar (GPR) data were collected at 200 MHz using the University of Liverpool GSSI sir3000 system. Data were collected with the antennas orientated perpendicular broadside relative to the survey line (i.e. antenna long axes were orientated ninety degrees relative to the survey direction) reducing reflections from offline sources. It was not possible to collect common mid-point (CMP) surveys used to calculate radar wave velocity, but instead velocities used for data migration and depth correction were estimated based on the range expected for the stratigraphy and optimised for the best migration at each site. Survey lines were mapped using a Trimble differential global positioning system (dGPS). Three crossing GPR lines were

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collected over the landform at Thoresthorpe, and GPR penetration was poor (<2.5 m). Two GPR lines were collected over mound-like landforms (M1 and M2) at Ovens Farm and the GPR penetration was again poor (≤ 2 m). The data were processed in ReflexW (version 7.5.5). This included application of a band pass filter to remove high frequency noise, background removal to filter out low frequency and repetitive horizontal background reflections. Each data set was processed with and without a migration algorithm, which collapses hyperbolic reflections (diffractions created by strong point source reflectors located offline from the antenna position) back to their point source (e.g. coarse gravels or boulders). The data without migration, although noisier, allow identification of the coarsest units. Signal amplitude, which reduces with depth, was enhanced by a gain function that results in an equal data amplification regardless of depth. Topographic correction of the GPR data (the raw data are shown as if the ground surface was flat) were applied using elevation data collected with a dGPS and the data were truncated at a specified depth to remove that beyond the maximum GPR penetration. A high pass filter was applied to the data, as low frequency noise (below 50 MHz) was filtered out during data collection and so no low frequency noise is present in the data.

2.4. Dating

In addition to one legacy radiocarbon date from Aby Grange (Suggate and West, 1959), samples for OSL were collected at Welton-le-Wold and Stiffkey in light-tight PVC tubes from recently cleaned exposures. At Thoresthorpe, duplicate cores in opaque liners were collected in parallel to cores collected for sedimentological purposes. The latter were used to target sandy facies and then OSL samples were cut from the former under controlled dark-room conditions. Quartz grains of size 180–250 μm were extracted and cleaned from each sample under controlled light conditions as per Bateman and Catt (1996). Equivalent doses (De) were estimated based on the optically stimulated luminescence (OSL) signal of small multigrain aliquots (containing $\sim$20 quartz grains each), which has been shown to be appropriate to measure samples potentially affected by incomplete bleaching as it provides similar resolution to single grain measurement (Evans et al., 2017). Results for Shfd15155 from the Thoresthorpe site were also checked using single grain OSL SAR measurements and the resultant age was <2% different (Table 1).

All luminescence measurements were carried out using an automated Risø TL/OSL DA-15 luminescence reader (Bøtter-Jensen et al., 2010) and the SAR protocol of Murray and Wintle (2003), with an additional second recycling stage with IR stimulation prior to OSL measurement, in order to detect any feldspar contamination. Within the SAR protocol, a preheat based on a dose recovery temperature test was performed on one sample from each site. Based on these tests, preheats of 200 °C for 10 s were used for Stiffkey, 220 °C for 10 s for Welton-le-Wold and 240 °C for 10 s for Thoresthorpe.

Up to 95 small multigrain aliquots were measured for each sample in order to have a representative dose distribution. Equivalent dose (D_e) estimates were accepted only if the relative uncertainty on the natural test-dose response was less than 20%, the recycling and the IR depletion ratio including uncertainties were within 20% of unity and the recuperation was less than 5%. These criteria lead to dose distributions containing 40–60 independent dose values.

Samples from Welton-le-Wold, Stiffkey and Thoresthorpe all had scattered D_e distributions and high overdispersion (OD) values, suggesting incomplete bleaching. As a result, ages are based on D_e values derived from a minimum age approach using the Internal External Uncertainty model. Such an approach has been shown to be appropriate to estimate accurate ages for incompletely bleached glacial sediments (Bateman et al., 2018).

For all samples, in situ field gamma spectroscopy measurements were undertaken using an EG&G micronomad. This was used for the gamma dose rate. Beta dose rates were calculated from elemental concentrations of potassium, uranium and thorium as determined by inductively coupled plasma mass spectroscopy. The total dose rates were calculated according to attenuation caused by moisture and grain size. Palaeowater contents were determined using site information. For Stiffkey, located in a topographic high with free-draining sands and graves a value of 10% was assumed. For Welton-le-Wold, despite also being on a topographical high and underlain by Cretaceous chalk the sample collected was in a sand between tills and so was assumed to be in an aquaclude. As such a palaeomoisture value of 23% was assumed. Finally, at Thoresthorpe water rapidly infilled the boreholes, indicating a perched high level water table, so a saturated value of 27% was assumed. An uncertainty of 5% was used on all water contents to account for variability from the adopted values. The contribution of cosmic radiation to samples was calaulated according to position and burial depth based on the work of Prescott and Hutton (1994). Sampling depths, assumed water contents, beta, gamma and cosmic dose rates and derived total dose rates to an infinite matrix are summarized in Table 1.

3. Landforms, sediments and chronological control

3.1. Regional geomorphology and surficial geology

The geomorphology map (Fig. 2) reveals important new local details in terms of landform morphology and patterns, especially

Table 1
Summary of OSL estimated ages and associate information for all sites examined. Depth, water content and the calculated contribution to the total dose rates are summarized. Table also includes information on the total number of aliquots measured with OSL and in parenthesis those which passed the acceptance criteria, palaeodose and overdispersion (OD) of the D_e replicates.

Site	Lab code	Depth (m)	w %	β dose rate (Gy/ka)	γ dose rate (Gy/ka)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	Aliquots accepted (measured)	OD (%)	Palaeodose $(D_e)_{-}$ (Gy)	Age (ka)
Welton-le-Wold	Shfd13074	3.5	23	1.06 ± 0.09	0.72 ± 0.05	0.13 ± 0.01	1.95 ± 0.097	93 (65)	66	37.4 ± 4.7	19.5 ± 2.6
Thoresthorpe	Shfd15154	2.2	27	0.93 ± 0.08	0.59 ± 0.04	0.16 ± 0.01	1.70 ± 0.086	(49)	27	29.6 ± 1.1	17.4 ± 1.1
	Shfd15155	2.4	27	0.87 ± 0.07	0.55 ± 0.04	0.15 ± 0.08	1.598 ± 0.080	(60)	28	30.4 ± 3.2	19.3 ± 2.2
	Shfd15155 (single grain)	2.4	27	0.87 ± 0.07	0.55 ± 0.04	0.15 ± 0.08	1.598 ± 0.080	2200 (58)		30.8 ± 1.5	19.3 ± 1.4
Stiffkey	Shfd15030	1.4	10	0.22 ± 0.02	0.28 ± 0.02	0.17 ± 0.01	0.74 ± 0.038	60 (50)	52	96.4 ± 5.4	141 ± 9.4
	Shfd15032	1.8	10	0.29 ± 0.02	0.26 ± 0.01	0.17 ± 0.01	0.68 ± 0.025	65 (46)	54	121 ± 6.8	165 ± 11
Garret Hill	Shfd15033	1.1	10	0.90 ± 0.07	0.65 ± 0.03	0.18 ± 0.01	1.74 ± 0.078	80 (41)	41	32.1 ± 1.4	21.5 ± 1.3
(Roberts et al., 2018; in press)	Shfd15034	1.5	10	0.68 ± 0.05	0.51 ± 0.03	0.17 ± 0.01	1.37 ± 0.058	70 (47)	55	32.3 ± 1.8	22.8 ± 1.8

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as they pertain to the last (MIS 2) glaciation on the Lincolnshire Marsh, and a newly defined MIS 6 glacial limit as determined by our new chronology reported below and summarized in Table 1. The most prominent landforms are the moraines of the Lincolnshire Marsh and northern lowlands of The Wash. These assemblages have been previously identified as the Hogsthorpe-Killingholme Moraine and Stickney Moraine respectively (Straw, 1979 and references therein) and together they demarcate the western edge of the North Sea Lobe.

Whereas the Stickney Moraine appears on LiDAR imagery (Fig. 2) as a simple arcuate ridge of significant width (1.5 km) and length (14 km) but modest amplitude (6 m), the Hogsthorpe-Killingholme Moraine appears to be more complex than the NW-SE trending hummocky mound assemblage originally depicted by Straw (1958, 1969). In detail there appear to be two sets of NW-SE trending ridges, one comprising narrow, closely-spaced ridges with associated hummocks that lie along the full length (70 kms) of the Wolds foot slope and the other set being less extensive and more subtle, wider ridges best exemplified between Hogsthorpe to Alford but also appearing as an arcuate assemblage to the west of Grimsby. The more subtle, wider ridges are overprinted, especially south of Grimsby, by N–S and NE-SW trending ridges and hummock chains, characterised by weakly sinuous and occasionally bifurcating patterns and including conspicuous flat-topped, rectangular to near-circular hills. These N–S and NE-SW trending ridges occur throughout the Lincolnshire Marsh and terminate at the western edge of the narrow NW-SE trending ridges and associated chaotic hummocks near the Wolds foot slope. Closer to the Wolds foot slope in the north, the sinuous ridges are aligned exclusively N–S and clearly run through flat-topped hills, the best example being north and south of the flat-topped hill at Brackenborough Hall.

Only towards the northern half of the Lincolnshire Marsh do the narrow ridges extend eastwards beyond the Wolds foot slope, where they gradually turn to trend northwards to form the Killingholme Moraine. The lower eastern slopes of the Wolds are also adorned with these small linear ridges, especially towards the north between Bielsby and Kirmington, where they are associated with numerous inset meltwater channels demarcating the receding North Sea Lobe margin. In places the narrow linear ridges comprise the multi-crested summits of extensive hummocky terrain, best exemplified by the area between Ludborough and Fotherby at the base of the Wolds foot slope. These assemblages represent either closely spaced or composite minor push moraines (Krüger, 1993, 1995, 1996; Evans and Twigg, 2002; Evans and Hiemstra, 2005; Chandler et al., 2016) or composite thrust ridges, similar to those identified on the North American prairies (Kupsch, 1962; Bluemle and Clayton, 1984; Aber et al., 1989; Evans et al., 2008, 2014).

The southernmost extension of the linear ridge belt from the Wolds foot slope into the lowlands north of The Wash is represented by a curvilinear assemblage of up to three wide, low amplitude ridges, the highest point being on the easternmost ridge and the location of the town of Burgh le Marsh. This high point is mapped by the BGS as glacifluvial sands and gravels, unlike the remainder of the ridged area which is mapped as till (cf. Clayton, 1957). This area of ridges (hereby named the Burgh le Marsh Moraine) was used by Straw (1969) to demarcate an ice margin of younger age to the Stickney Moraine (hence potentially the Upper Marsh Till limit?), and indeed our mapping indicates a clear distinction between the two moraines, with the Stickney Moraine linking to morainic mounds plugging the valley of the River Lymn. Between the two moraines, in the area around Bratoft, further till cored, and occasionally glacifluvially cored, short ridges and mounds appear to be confluent with the Burgh le Marsh Moraine. All of these landforms between and including the Stickney and Burgh le Marsh moraines represent the marginal deposits demarcating the limit of the North Sea Lobe when it occupied the base of the Wolds foot slope and wrapped around the southern corner of the Wolds to form a lobe occupying the outer part of The Wash. This is the limit most often used in reconstructions of the last glacial maximum for the BIIS in this region (e.g. Suggate & West, 1957; Brand et al., 2002; Pawley et al., 2006) but such reconstructions clearly blend Straw's (1969) dual ice advances. Detailed interpretations of the origins of many of these landforms are presented below in relation to specific study sites.

3.2. Welton-le-Wold

The former quarry at Welton-le-Wold, located ~5 km west of Louth, has been the location of significant stratigraphic, palaeoecological and archaeological study for more than a century (Jukes-Browne, 1885; Alabaster and Straw, 1976; Wymer and Straw, 1977; Straw, 2005, 2015). It has served as a classic site for the support of a Wolstonian glaciation (*sensu* Mitchell et al., 1973) in eastern England based upon evidence of faunal remains and human artefacts in gravels underlying at least two tills. A simplified stratigraphy at the site is presented in Fig. 3 and reveals that the upper diamictons (Calcethorpe and Marsh Tills) do not occur in stratigraphic sequence but both lie in erosional contact with the underlying, older Welton Till. The Welton and Calcethorpe tills) are now thought by Straw (2015), based on glacial reconstructions in the adjacent Trent Basin by White et al. (2007) and Bridgland et al. (2014) to be MIS 8 in age (Wragby Glaciation). It is thought the Devensian North Sea ice, in advancing up to 100 m up the Wolds dip slope, eroded away all of the Calcethorpe Till and much of the older Welton Till. Boston et al. (2010), using geochemistry, confirmed that the Marsh Till at this site is a lateral equivalent of the Late Devensian Skipsea Till found on Holderness. Attempts to date the stratigraphy at Welton-le-Wold using OSL were reported by Schwenninger et al. (2007; supplement to Aram et al., 2004; 2007) and included preliminary maximum ages of 96 ± 10 ka (X1785) and 166 ± 22 ka (X1786) from a sand lens within the base of the Marsh Till.

Sampling for OSL dating at Welton-le-Wold targeted the "sand lens" previously used by Schwenninger et al. (2007). This unit comprises heavily contorted fine sand, silt and clay rhythmites that display complex overfolds and reverse faults indicative of intense glacitectonic deformation, imparted during the emplacement of the overlying Marsh Till (Fig. 4). The sand lens is 1.75 m thick at its maximum where it has been stacked by thrust overfolds, but its upper contact is interdigitated with the 3–4 m thick Marsh Till, where it has been cannibalised and partially ingested to form boudins and attenuated pods. One age was secured for these deposits and dated 19.5 ± 2.6 ka (Shfd13074; Table 1), which is interpreted here as an immediate maximum age for the emplacement of the Marsh Till at this site and hence onshore flow by the North Sea Lobe during MIS 2.

3.3. Thoresthorpe

Thoresthorpe (also known as high Bibers) is a 10 m high, near circular mound located 1.4 km northeast of Alford, within low amplitude hummocky terrain previously named the Killingholme-Hogsthorpe Moraine (Straw, 1961, 1969, 1979). Straw's (1979) Late Devensian ice limit occurs some 4 km further inland and up to ca. 80 m OD on the Lincolnshire Wolds dip slope (see Welton-le-Wold). Importantly, the hummocky terrain in the area around Thoresthorpe was regarded by Straw (1961, 1969, 1979) as a Late Devensian readvance. In order for this to represent a readvance, the landform assemblage should constitute a push moraine and/or glacitectonic complex with strong ice-marginal parallel ridges (cf. Krüger, 1993, 1995, 1996; Evans and Twigg, 2002; Evans and Hiemstra, 2005; Chandler et al., 2016).

Mapping from LiDAR imagery of the hummocky terrain in the Thoresthorpe area (Figs. 2 & 5) reveals a series of weakly sinuous and occasionally bifurcating ridges and linear chains of short ridges and flat-topped, rectangular to near-circular hills, the latter including the hill locally named Thoresthorpe. Together these landforms constitute an assemblage of discontinuous ridges of varying width and orientated NE-SW, with the longest single ridge complex being named Snape Hill. They terminate at a line of NW-SE trending ridges and more chaotic hummocks located at the break in slope that marks the boundary between the coastal lowland and the rising dip slope of the chalk cuesta, in places also marked by the relict cliff line thought to represent the last interglacial sea level maximum (Linton, 1954; Straw, 1957, 1958, 1961). These ridges are distinctly different to the broader NW-SE orientated ridges upon which they are clearly superimposed (Fig. 5).

Selected BGS borehole records are located on Fig. 5 as numbers 1–9 and detailed in Table 2. Boreholes from within the chaotic hummocks near Willoughby (boreholes 1 & 2) record 7.6 m of lacustrine clay overlying 13 m of sand and gravel and 5.5 m of sand and gravel respectively. Both sequences cap 6.7–12.2 m of diamicton/till respectively. These two boreholes indicate that the hummocks are cored by glacifluvial deposits overlying till with lake sediments on the higher relief areas amongst the hummocks. Nearby in the linear hummocks at Thoresthorpe (boreholes 6 and 9), borehole 6 contains a tripartite sequence of glacilacustrine sediments between two glacifluvial units, whereas borehole 9 displays thick units of possible marine sediment overlain by till and capped by glacilacustrine deposits. Between these linear hummocks, boreholes 3, 4 and 8 reveal sediments likely to be alluvial and/or glacilacustrine in origin overlying till. Together the selected boreholes from the Thoresthorpe area show that the linear hummocks and ridges contain cores of glacifluvial and glacilacustrine sediment overlying till, or in the case of borehole 9 are capped by fine-grained, glacilacustrine sediments. These contrast with the borehole stratigraphies from the NW-SE trending ridges located closer to the Wolds footslope (e.g. boreholes 5 and 7 at Alford). These contain complex sequences including interbedded multiple tills and glacifluvial sediments overlying large chalk rafts, till and glacitectonite overlying apparent marine beach deposits.

Boreholes 10 and 11 are from the largest flat-topped hill in the area at Thurlby. Its summit lies up to 8 m above the surrounding topography which itself lies only 2–5 m above sea level. The boreholes reveal 6.1–11.6 m of fine-grained stratified sediments of predominantly clay, thereby indicating that the whole landform is composed of glacilacustrine deposits. Finally, a borehole record located 11.5 km north of the Thoresthorpe area, at Brackenborough Hall, is critical to further discussions on glacial landform genesis in the present context, because it was collected from the most impressive circular-shaped flat-topped hill in the region. The hill summit is up to 15 m higher than the surrounding terrain and measures 550 x 600 m across. It is cored by 12.2 m of glacifluvial gravel overlying almost 18.5 m of predominantly clays that contain a 1.8 m thick gravel bed; a basal 1.8 m thick chalk gravel bed is likely marine as it lies at the altitude of the marine platform. The occurrence of gravel and clay in this isolated hill can be explained only by former ice-contact sedimentation.

The borehole data presented above strongly suggest that the NE-SW trending ridges and elongate hummocks are fragmented eskers. For example, the linear ridge of borehole 9 appears to represent an esker tunnel fill that opened up to the ice surface to form an ice-walled lake plain towards the end of its development. The flat-topped hills (exemplified by Thurlby and Brackenborough Hall) and related features are most likely to be ice-walled lake plains (Johnson and Clayton, 2003; Clayton et al., 2008), created wherever ice-walled tunnels collapsed or enlarged to form glacier karst ponds (Clayton, 1964). The Thurlby and Brackenborough Hall flat-topped hills appear identical to ice-walled lake plains found in their type area on the North American prairies (Gravenor and Kupsch, 1959; Johnson and Clayton, 2003; Clayton et al., 2008). If this interpretation is correct then they are the first to be identified around the southern margins of the former BIIS (cf.cf., Livingstone et al., 2010).

In contrast, the borehole records from the NW-SE aligned ridges reveal stratigraphies consistent with those reported by Straw (1961). Specifically this includes not only multiple tills and glacifluvial sediments but also large chalk rafts and bedrock glacitectonite, the latter being particularly diagnostic of proglacial thrust stacking of local bedrock and thereby explaining the NW-SE alignment of the ridges as constructional moraine ridges. The wider ridges that are superimposed by the eskers and ice-walled lake plains (Fig. 5) likely also relate to ice-marginal construction and later overriding by the North Sea Lobe, which then downwasted to produce glacier karst features on top of overridden moraines.

Because the eskers and ice-walled lake plains record the advanced stages of ice sheet marginal downwasting, securing an age on the deglaciation of this part of Lincolnshire is possible through the sampling of sands within one of these prominent landforms for OSL dating. Hence the Thoresthorpe flat-topped hill was selected for geophysical analysis and shallow borehole drilling. The GPR penetration was only 2–2.5 m, likely due to the fine-grained nature of the sediments and an apparent high ground saturation. Nevertheless, once a migration was applied to the data a mostly flat-lying stratigraphy was apparent, with some very shallow dipping beds being visible at the northern end of the landform and a number of superimposed shallow basin infills otherwise dominating the architecture (Fig. 6). A number of short (3–4 m) cores collected from the centre of the landforms by surface drilling (Fig. 6) yielded a consistent stratigraphy of rhythmically bedded sands, silts, silty sands and minor clay laminae (Table 3). Both the GPR data and core samples are entirely consistent with an ice-walled lake plain interpretation for the flat-topped hill at Thoresthorpe.

Two samples were collected from the more sandy areas of the rhythmically bedded sediments at depths of 2.2 and 2.4 m and yielded ages of 17.4 ± 1.1 ka (Shfd15154) and 19.3 ka (± 2.2 single aliquot, ± 1.4 single grain, Shfd15155; Table 1) respectively, providing an early deglaciation age range. A previously reported radiocarbon date from the area, at Aby Grange, yielded a minimum deglaciation date of 13,092 ± 143 CAL years (12,870 ± 180 of Suggate and West, 1959).

3.4. Ovens farm

The identification by Straw (1979) of “lacustrine clays and sands” at the western end of the Brinkhill gap (47 m OD), are significant in terms of the demarcation of a potential ice-dammed lake in the River Lymn catchment and hence the drift ridges and a prominent 75 m OD bench located immediately below the Chalk escarpment around Harrington Hill and Ovens Farm, directly south of Brinkhill gap, were identified for possible OSL sampling (Fig. 7a). A GPR survey revealed shallow cross-bedded sediments and pockets of clinoforms (Fig. 7b), which were cored down to 4 m and revealed sand, silt, clay & minor gravel interbeds (Table 2). These observations indicate nearshore lake sedimentation, consistent with the production of a wide bench at this location and potential evidence in support of Straw's (1979) Glacial Lake Lymn. An altitude of 75 m OD is therefore a maximum for this glacial lake (see 75 m contour on Fig. 1b), dammed by the ice lobe that constructed the Stickney Moraine to the south and backfilled the lower Lymn catchment as far north as Partney (Fig. 1b). Water depths would have been 50 m maximum but more consistently only 30–40 m over most of the catchment. Unfortunately the sediments did not include enough sand to secure an OSL date.

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Table 2
BGS borehole details.

Number on Figure 5	BGS ID	National Grid ref	Altitude borehole surface (m OD)	Depth of Quaternary deposits (incl. soil)	Stratigraphic interpretation (m thickness)	Landform context
1	506496	547760, 371340	9	27.3m	7.6 glacilacustrine 13 glacifluvial 6.7 till	Chaotic hummocks
2	506463	547321, 371866	7.6	17.7m	5.5 glacifluvial 12.2 till	Between chaotic hummocks
3	506347	546030, 377710	7.11	20.5m	1 glacilacustrine/ alluvium 14.5 till 4 solifluctate	Between linear hummocks
4	506328	545600, 376980	7.6	18.3m	13.7 alluvium 4.6 glacilacustrine/ alluvium	Between linear hummocks
5	506354	545280, 375890	8.5	24m	2.5 glacifluvial 6.3 till 3 glacifluvial 8.2 chalk raft 3 till 1 marine?	Linear (NW-SE trending) ridges
6	506323	545390, 375980	10	15m	5.2 glacifluvial 3.7 glacilacustrine 6.1 glacifluvial	Linear hummock
7	506439	544830, 375660	9	24.3m	9.1 till? 3.1 glacifluvial 0.6 till 1.8 glacifluvial 1.8 till 3.1 chalk raft 1.5 glacifluvial 3.3 glacitectonite	Linear (NW-SE trending) ridges
8	506289	547170, 375670	4.4	15m	3 glacilacustrine/ alluvium 11.5 till	Lowland between hummocks
9	506238	546877, 376257	9	21.4m	4.6 glacilacustrine 12.2 till 4.6 marine?	Linear hummock
10	506282	549154, 375697	10	13.1m	0.6 glacilacustrine 0.3 glacifluvial 10.7 glacilacustrine 1.5 marine?	Flat-topped hill
11	506369	549510, 375640	10	21.1m	6.1 glacilacustrine 15 till	Flat-topped hill
12	504532	537410, 369460	26	8.3m	6.5 sand, silt, clay interbeds (alluvium/ glacilacustrine?) 0.1 fluvial? 1.2 glacilacustrine	River Lymn valley
13	504514	539656, 367599	18	7.45m	4.25 alluvium 2.1 fluvial 3 glacilacustrine?	River Lymn valley
14	506133	541410, 368020	24	6m	5.5 glacilacustrine?	River Lymn valley (lower stretch/ hummocky terrain)
15	Ovens Farm (BRITICE-CHRONO)	537031, 372560	75	4m	3 sand, silt, clay & minor gravel interbeds (near shore glacilacustrine)	River Lymn valley (north rim)
Brackenborough Hall	505675	532980, 390640	33	32.4m	12.2 glacifluvial 7 glacilacustrine 1.8 glacifluvial 9.6 glacilacustrine 1.8 chalk gravel (marine?)	Flat-topped hill

3.5. *Stiffkey*

Sand and gravel ridges lying immediately south of the River Stiffkey valley and mapped as outcrops of Britons Lane Sand and Gravel Member (Pawley et al., 2005) were identified as targets for OSL dating in order to differentiate previously identified glacial limits, especially in comparison to Garrett Hill to the east (Pawley et al., 2006; Figs. 1c & 8 ; see below) and in the context of proposals for the existence of MIS 10, 8 or 6 (i.e. “Wolstonian”) glacial limits along this coast (cf. Lee et al., 2004b). The site sampled at Stiffkey is locally named Home Hill and constitutes a west-east orientated ridge rising abruptly 25 m above the River Stiffkey but forming an extension or promontory from the 40 m high upland to the south, which is topped by the Sheringham Cliffs Formation and the

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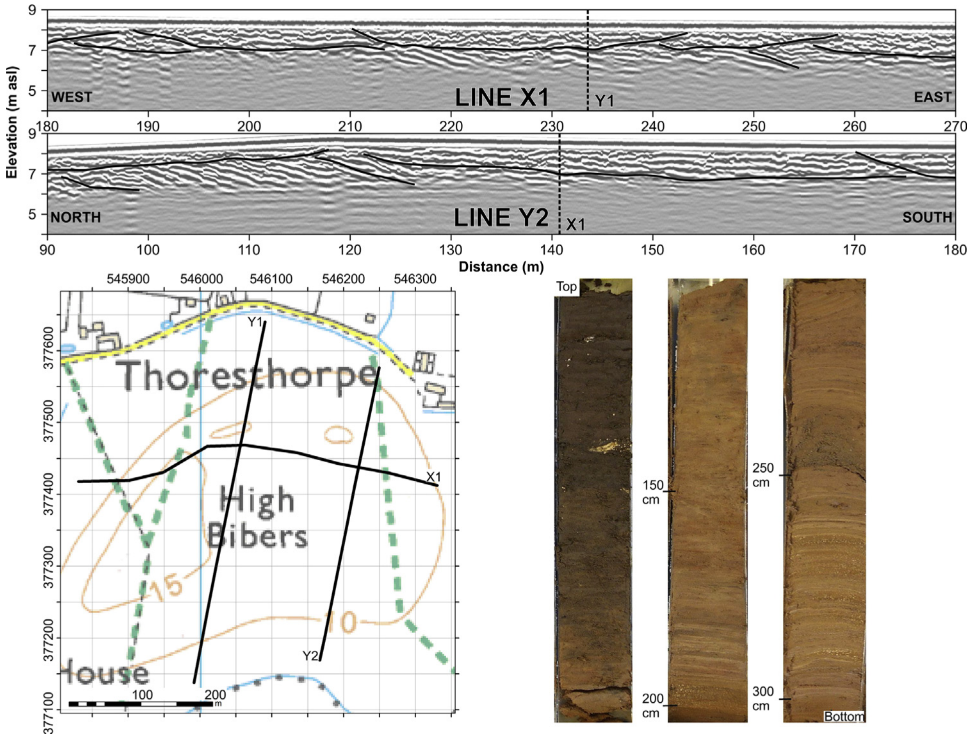

Fig. 6. Results of GPR surveys across Thoresthorpe (High Bibers), with migrated results for three transects and interpretive stratigraphic boundaries annotated on the print-outs, and details of the borehole that was recovered and sampled for OSL dating.

Britons Lane Sand and Gravel Member (Figs. 1c & 8). The outcrops of the latter comprise an arcuate assemblage that lies just beyond but also parallels the arcuate assemblages of the Ringstead Sand and Gravel Member, which demarcate the limit of the last (MIS 2) glaciation in the Stiffkey valley near Warham.

Two excavations were undertaken on the Home Hill ridge, one near the summit (Stiffkey 1) and another (Stiffkey 2) on the lower slopes (Fig. 9). Stiffkey 1 displayed a coarsening upwards sequence comprising three lithofacies. The lowest lithofacies was characterized by planar cross-bedded sands with either planar bedded granule gravels and gravel lags or climbing ripples and gravel lags. Palaeocurrents were towards the east-northeast or east. This was overlain by a lithofacies characterized by matrix-supported gravels arranged in alternating cobble and pebble clinoforms, providing a distinct palaeocurrent direction towards the south. Finally, the top of the sequence comprised crudely stratified tabular units of matrix-supported, horizontally bedded and massive gravels. A clast lithological sample from the uppermost lithofacies revealed 90% flint of local derivation together with small amounts of sandstone, quartzite and chert as well as further travelled dolerite of a likely northern provenance. Stiffkey 2 displayed a similar sequence of matrix-supported and crudely stratified pebble to cobble gravels, overlying planar cross-bedded sands with gravel lenses. Distinctly different to Stiffkey 1, however, was the erosional cut and fill nature of the lithofacies and more importantly a capping unit of reddish-brown diamicton comprising a silty, sandy matrix and rare scattered pebbles derived from the underlying gravels. The structure of the diamicton also changed vertically from crudely laminated or banded to massive and had been pedogenically altered with a darker humified upper zone, and contained infilled animal burrows.

The generally poorly sorted, coarse-grained and crudely bedded to clinoform bedded nature of the gravels, especially as they are located on a ridge located above the present River Stiffkey, is indicative of a former ice-proximal depositional environment, an interpretation consistent with the designation of these deposits as part of the Britons Lane Sand and Gravel Member (Pawley et al., 2006). Importantly in this respect, the palaeocurrents of the upper gravels are strongly directed southwards, especially in the clinoforms, whose architecture is indicative of sedimentation on a minor fan surface dipping at 18°. This direction of progradation

Table 3
Thoresthorpe borehole log lithofacies.

Depth (cm)	Lithofacies
0-45	Top soil
45-78	Dark brown/light brown mottled sandy silt
78-163	Ochre/red mottled silty sand becoming laminated towards base and gradational lower contact.
163-215	Laminated ochre/red silts and sands. Laminae range from 2-4 mm (silts) to 4-10 mm (silts & sands). Sharp lower contact.
215-223	Dark red/brown silty, medium to coarse sand with some crude stratification and gradational lower contact.
223-233	Laminated ochre/red silts and sands. Laminae range from 2-4 mm (silts) to 4-10 mm (silts & sands). Sharp lower contact.
233-246	Dark red/brown silty and massive coarse sand. Sharp lower contact.
246-300	Laminated ochre/red silts and sands with distinct rhythmicity, including interlaminated silts and well sorted medium to fine sands. Laminae ranging from 2-4 mm (silts) to 4-10 mm (silts & sands). Possible couplets recognizable towards base with distinct sandy laminae ranging from 5-15 mm.

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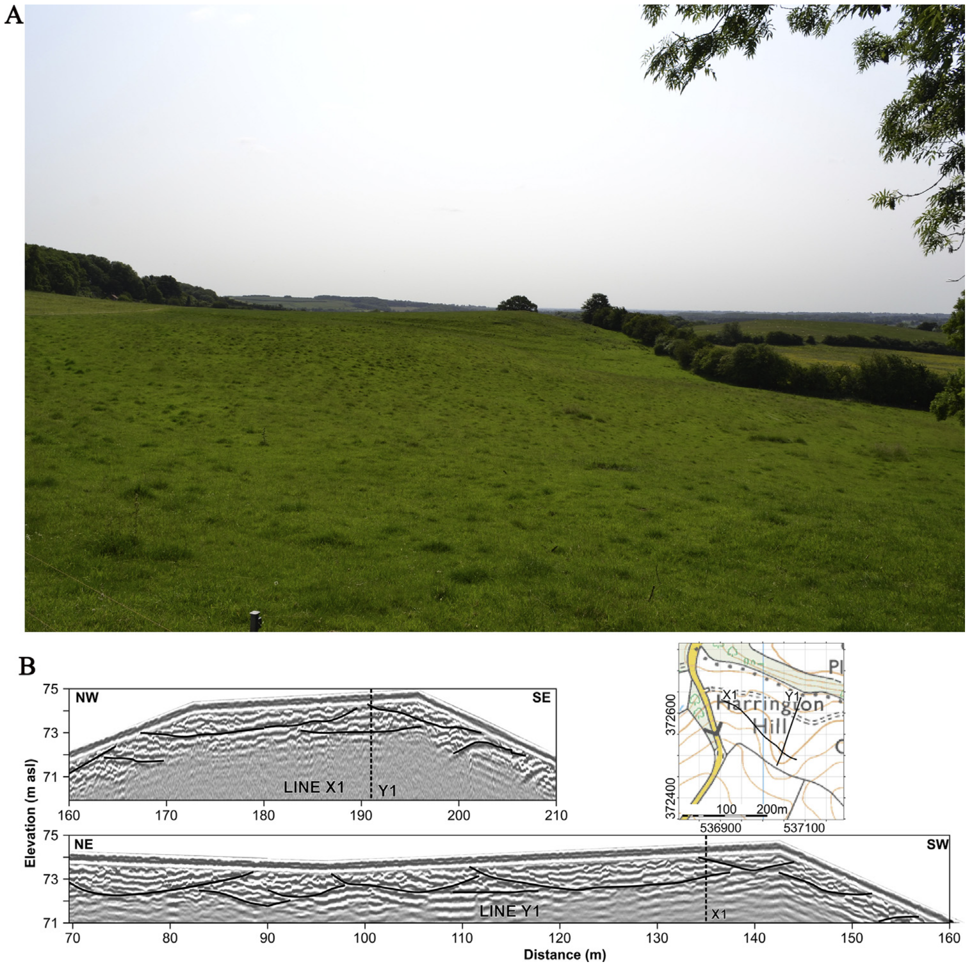

Fig. 7. Ground photograph (a) and GPR survey results (b) of the drift bench at 75 m OD at Ovens Farm/Harrington Hill. The GPR print-outs show migrated results for two transects and annotated interpretive stratigraphic boundaries.

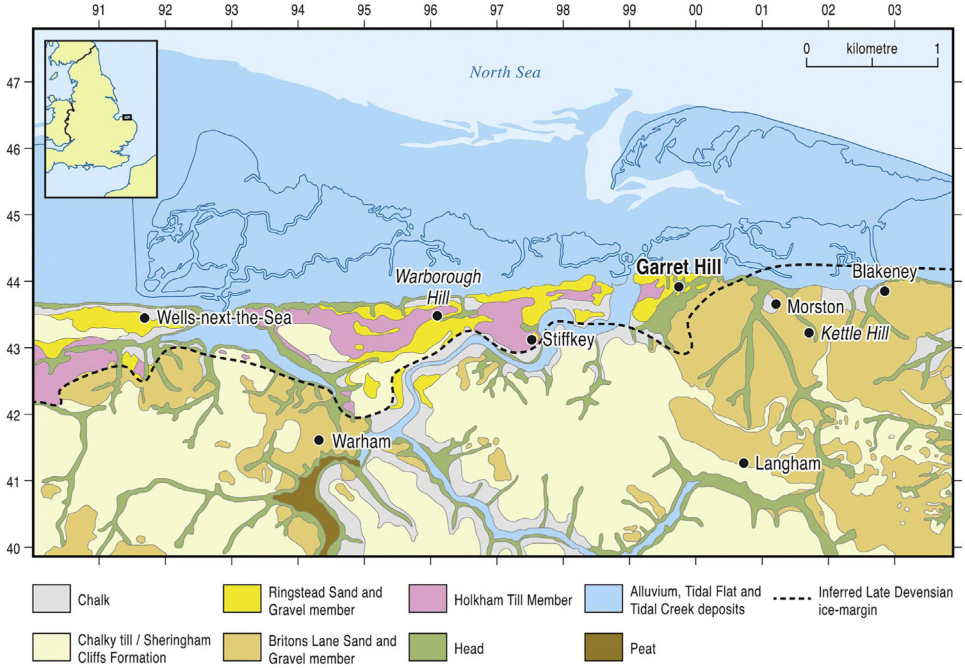

Fig. 8. Quaternary geology map for North Norfolk, showing also the locations of Garrett Hill and Stiffkey and the MIS 2 (Late Devensian) ice limit.

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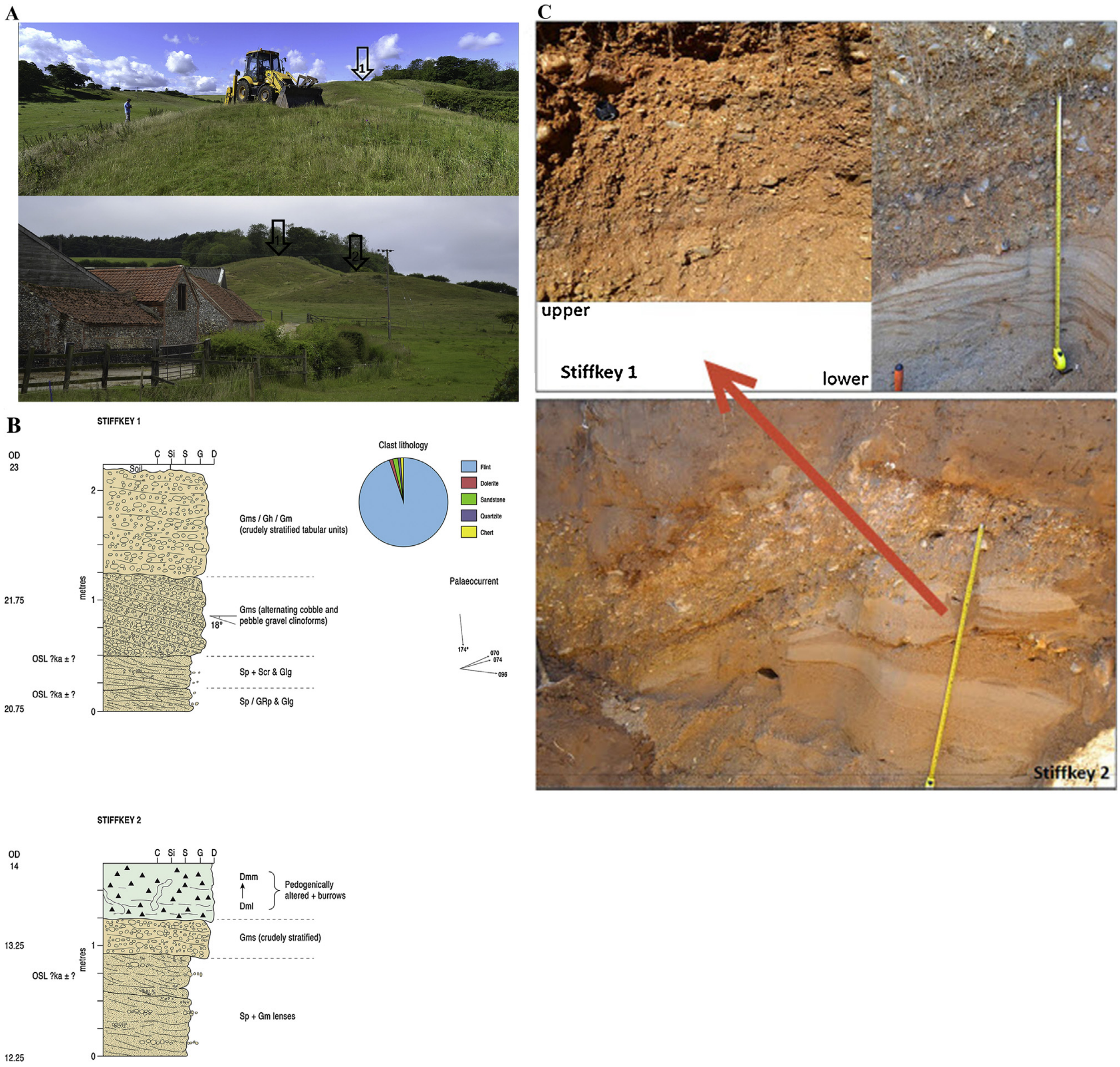

Fig. 9. Stiffkey landforms and sediments: a) ground photographs of Home Hill and the location of excavations 1 and 2; b) vertical profile logs for excavations 1 and 2; c) details of main lithofacies.

replaced an easterly directed palaeocurrent that was responsible for the earlier deposition of underlying cross-bedded sands and minor gravels. A shallowing of the bedding and coarsening of the depositional environment was then recorded by the emplacement of matrix-supported gravels. Because these coarser gravels are capped by diamicton (presumably a till) in Stiffkey 2, they indicate the encroachment of the glacier margin. The occurrence of the gravels and the diamicton in a ridge connected to a chalk bedrock upland to the south, strongly suggests that they comprise a partially glacially overridden ice-contact fan; the lowermost and more subdued part of the ridge, with its till carapace, constitutes the glacially modified segment and hence the ridge as a whole is an ice-marginal feature, possibly a thrust block sequence.. Prior to ice encroachment, the proto-River Stiffkey is recorded by the lower cross-bedded sands, which record an easterly flow because the river was likely ice-marginally directed and hence flowing parallel to the chalk cliffline, just as the postglacial river was much latter forced to do by the receding MIS 2 ice margin (Brand et al., 2002).

Two samples were collected for OSL dating, one from the lowermost cross-bedded sands at Stiffkey 1 and another from the cross-bedded sands with gravel lenses in Stiffkey 2 (Table 1). The sample from Stiffkey 1 yielded an age of 141 ± 9.4 ka (Shfd 15030), whereas the sample from Stiffkey 2 provided an older age of 164.6 ± 11.1 ka (Shfd 15032). Given the lower altitude of the older age sample at Stiffkey 2 (13 m OD) it most likely dates the relatively early ice-directed channel deposits, whereas the younger age from 21 m OD relates to the later stages of sedimentation immediately prior to coarser-grained fan progradation towards the south. Hence both dates relate to the modification of local drainage initiated by the southerly advance

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of glacier ice that was responsible for the emplacement of the capping diamicton (till). This indicates an MIS 6 age for the emplacement of the sediments in the ridge.

3.6. Garret hill

The MIS 2 glacial limit at Garret Hill has been previously defined by Pawley et al. (2006) based upon the stratigraphic relationships of sediment within a NE-SW trending sand and gravel ridge near the lower Stiffkey valley (Fig. 1c). This is one of a number of prominent gravel cored hummocks at the margin of the Holkham Till. Pawley et al. (2006) report that the till has been emplaced on the north side of the main ridge and the ridge is cored by the Britons Lane Sand and Gravel Member, which in turn lies over the local Weybourne Town Till (Sheringham Cliffs Formation) of MIS 12 age (Fig. 8). Our re-investigations of the Garret Hill site have been reported by Roberts et al. (2018, in press), who provide new geochronological control for this ice limit, but we review the findings of that work again here in order to provide consistency with, and context for, the other sites in this study. Five exposures were created by mechanical digger in the Garret Hill ridge and the sediments that were revealed are classified as lithofacies associations (LFAs) GA1 – GA3 by Roberts et al., 2018a; in press; Fig. 10).

At the base of the sequence and exposed only in the lowest elevation excavation, LFA GA1 is a massive, matrix-supported diamicton with abundant chalk and flint clasts and is recognized as Pawley et als. (2006) Weybourne Town Till. This is overlain by a variably stratified sand and gravel deposit (LFA GA2) that appears to form the core of the ridge and comprises sub-horizontally stratified sands with gravelly lags and lenses as well as coarser matrix-supported, tabular gravel units that are massive to weakly stratified. The sediments appear to be deformed in the northernmost exposures, located at the base of the ridge. Palaeo-current directions taken from undeformed fluvial bedforms near the ridge crest indicate flow towards the west or northwest. This is interpreted as a glacifluvial outwash deposit that has been locally glacitectonically deformed. Two samples from the sands of LFA GA 2 returned OSL ages of 21.5 ± 1.3 (Shfd15033) and 22.8 ± 1.8 ka (Shfd15034) at 9.0 m and 8.6 m OD respectively (Fig. 10; Table 1). This age range indicates that this outwash deposit cannot be Britons Lane Formation as proposed by Pawley et al. (2008) but instead represents a proglacial fluvial system relating to the arrival of an ice sheet on the Norfolk coast shortly after 22.8- 21.5 ka with the meltwater drainage following the local topography towards the west/northwest, the location of Brand et als. (2002) Glacial Lake Stiffkey. The sequence is capped by LFA GA3, which is a brown, massive, poorly consolidated, silty/sandy diamict, pedogenically altered in its upper 0.20-0.30 m. A range of local and far travelled erratics were reported from this diamicton by Pawley et al. (2006), including low-grade schist, basaltic/andesitic porphyries, dolerites, Devonian Old Red Sandstone, granite, acid porphyry, Carboniferous Millstone grit, crystalline limestone, coal, Triassic red/green mudstones, Jurassic sandstones and Lower Cretaceous glauconitic

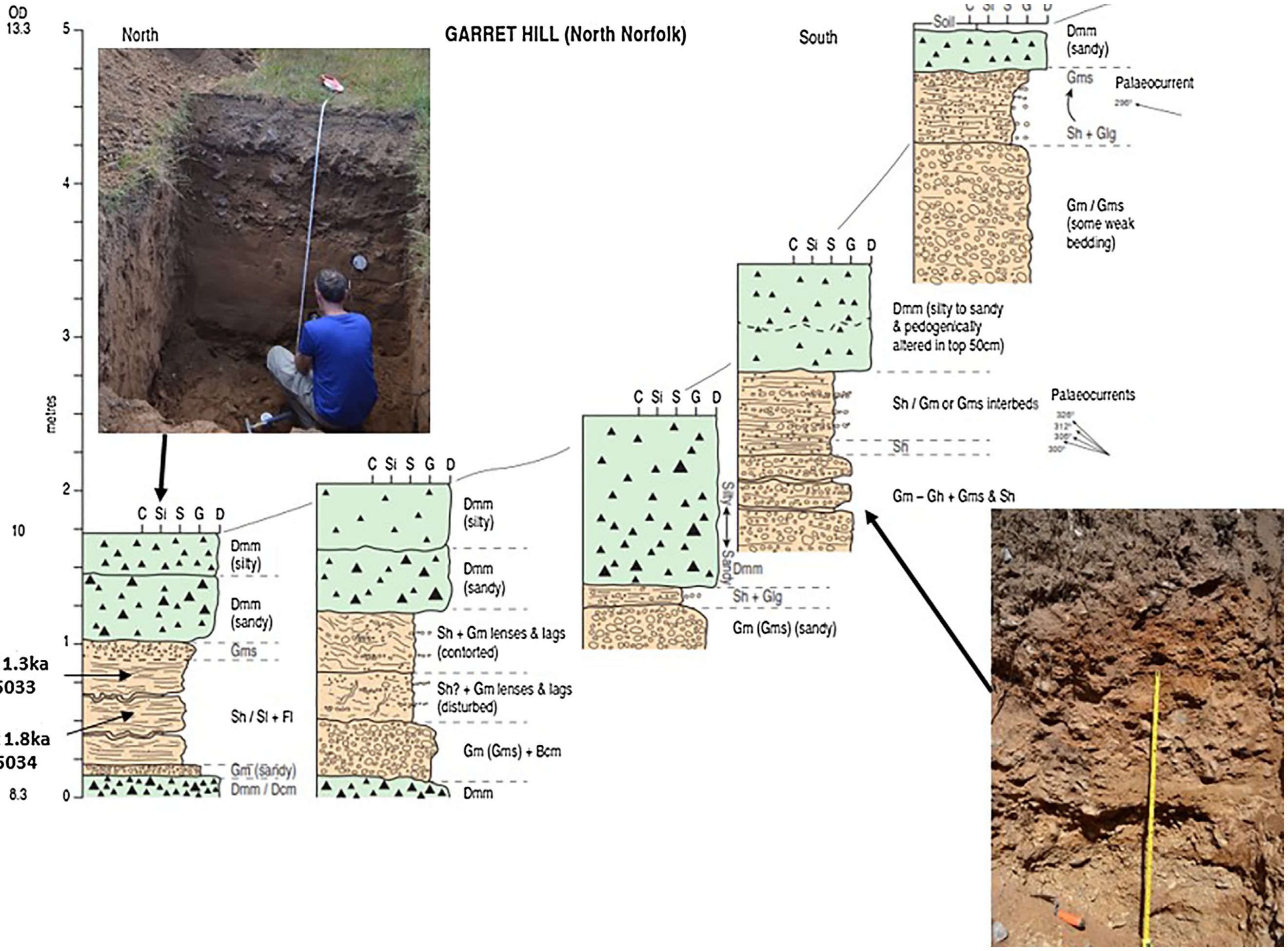

Fig. 10. Stratigraphy and OSL dates of the northwest side of the Garret Hill moraine ridge (after Roberts et al., 2018; in press).

sandstone and Carstone. These characteristics are consistent with the local MIS 2 Holkham Till (Straw, 1960; Pawley et al., 2006) emplaced by the North Sea Lobe at around the same time as the Skipsea Till in Yorkshire (Bateman et al., 2011, 2015, 2018).

4. Discussion

Beyond the MIS 2 limit in both the lowland area of The Wash/Fenland and the North Norfolk coast, the existence of MIS 10, 8 or 6 (i.e.i.e., "Wolstonian") glacial limits is a subject of considerable and protracted debate. A chronostratigraphic framework in the Fenland area has facilitated Gibbard et als. (2018) proposal for an MIS 6 surging ice lobe during the Tottenhill Glaciation (Fig. 1a). Although an inset series of ice-marginal glacitectonic landforms and ice-dammed lakes appear to record oscillations of this North Sea Lobe over the Fenland/Wash basin, the apparent close juxtaposition of Middle Pleistocene (possible post MIS 12) glacial features in North Norfolk (cf. Straw, 1979; Hart, 1990; Lee et al., 2013, 2017; Pawley et al., 2005, 2008) makes it difficult to decipher whether or not any similarly substantial MIS 6 glaciation signatures exist in that area. Rose (2009) has entertained the notion of MIS 6 glacial deposits in North Norfolk and tentatively equated the Cromer Ridge glacitectonic moraine and its associated outwash fans and esker with the Saalian Glaciation in mainland Europe, but acknowledges the lack of chronological constraints on this correlation. Our sampling and dating of sediment-landform assemblages located south of the River Stiffkey, previously classified as "Wolstonian" by Straw (1979) and entertained as potentially of MIS 10, 8 or 6 age by Hamblin et al. (2005) and Rose (2009), indicate that they are indeed likely of MIS 6 age and record the modification of local drainage by advancing glacier ice during the Tottenhill Glaciation. The juxtaposition of the MIS 2 and MIS 6 ice limits along this coast, in contrast to their greater separation over the Fenland/Wash basin gives some credence to Gibbard et als. (2018) notion of topographically-induced lobe surging in the region. The continuation of the MIS 6 limit northwards into Lincolnshire remains unknown but could be demarcated by the arcuate assemblage of glacifluvial deposits and till mapped by the BGS between Mareham-le-Fen and Wildmore Fen, to the west of the Stickney Moraine. Importantly in this respect, the Kirkby Moor Sands are dated to MIS 6 and reach altitudes of ca. 30 m, the highest level of proglacial lakes proposed for the Fenland area during both MIS 6 and 2 due to the spillway control altitude of the River Waveney valley.

In North Norfolk, the former MIS 2 maximum limit as demarcated by the Hunstanton Till (Holkham Member) and the Garret Hill moraine in North Norfolk (Pawley et al., 2006) has been dated by Roberts et al. (2018, in press); using OSL on glacitectonized glacifluvial outwash overlying MIS 12 till (Fig. 11). The two ages recovered from LFA GA 2 indicate that proglacial fluvial sedimentation associated with the approach of the North Sea Lobe in this area began some time just prior to 22.8 ka. The North Sea Lobe margin then overran the deposits shortly after 21.5 ka, emplacing the Holkham Member till. The geochemical characteristics of the Holkham Member, Marsh Till and Skipsea Till indicate that they are likely laterally equivalent lithostratigraphically (Boston et al., 2010), but the lithological signatures of all of the Devensian and Middle Pleistocene tills are dominated by Jurassic and Cretaceous materials and hence variability in lithological content is subtle (cf. Scheib et al., 2011). The apparent glacial onset occurs at similar times at Welton-le-Wold in Lincolnshire (Lower Marsh Till at <19.5 ka) and Garett Hill in Norfolk (Holkham Member/Hunstanton Till <21.5 ka).

In Lincolnshire the former MIS 2 maximum limit is demarcated by the Marsh Tills. Whereas Straw's (1979) proposal that the Hogsthorpe-Killingholme Moraine belt represents a significant glacial depositional event (possibly of readvance status) after early recession from the Upper Marsh Till limit is an entirely logical one, its position inside of the maximum extent of the Marsh Tills is also entirely compatible with the regional architecture of the Skipsea Till in East Yorkshire. This comprises an outer till veneer representing the MIS 2 maximum limit and an inner hummocky drift belt with multiple till layers and ice-contact outwash/subaqueous fans related to ice-marginal oscillation during overall recession (Catt, 2007; Evans and Thomson, 2010). The lack of any stratigraphic exposures displaying the two proposed Marsh Tills overlying one another, or of any isochronous surfaces and dated material from between the two "tills" recorded in borehole archives, prompts a further direct comparison with the Holderness depositional record. Hence we see no reason at present to regard the Marsh Till limits as anything other than former margins of the MIS 2 North Sea Lobe (Fig. 11).

Localized thickening of the outer MIS 2 till limit in such a scenario is based on the occurrence of the Stickney and Horkstow Moraines, which can be explained by the availability of larger volumes of glacially deformable sediment in both lowland settings. The attainment of the MIS 2 glacial limit as defined here is constrained by our date of ~19.5 ka from beneath the undifferentiated Marsh Till at Welton le Wold. Deglaciation of the Lincolnshire Marsh is clearly recorded geomorphologically by the superimposition of glacier karst features (eskers and ice-walled lake plains) on overridden moraine ridges and glacitectonized bedrock rafts, collectively known as the Hogsthorpe-Killingholme Moraine. This phase of extensive ice sheet marginal downwasting is dated by our OSL dates from the ice-walled lake plain at Thoresthorpe, which represent an average age of 18.4 ka (Fig. 11). The radiocarbon age of 12.9 ka from Aby Grange (Suggate and West, 1959) records the later and more advanced stages of landscape stabilization and vegetation succession. Our 18.4 ka age for initial deglaciation indicates rapid downwasting of the North Sea Lobe after its advance over lake sediments at Welton le Wold immediately after 19.5 ka.

As the North Sea Lobe dammed proglacial lakes Stiffkey (Brand et al., 2002) in Norfolk and Lake Fenland in The Wash (West, 1993; West et al., 1999), as well as Lake Lymn in the Wolds, these sub-till dates also provide a maximum age for a coherent phase of regional ice-dammed lake development. The occupation of the Stickney Moraine by the North Sea Lobe resulted in the damming of the River Lymn catchment within the Wolds as far north as Partney, creating an ice-dammed lake (Fig. 11). The upper level of this Glacial Lake Lymn was certainly higher than the "lacustrine clays and sands" reported by Straw (1979) from around Harrington at 47 m OD and potentially as high as the 75 m OD bench and nearshore lake sediments we report from the same area. If such a lake, fed by glacifluvial outwash through the Brinkhill gap, did fill the River Lymn catchment up to 75 m OD, then the only outlet would have been through the col immediately east of the village of Old Bolingbroke, which today lies below 60 m OD (see 75 m contour on Fig. 1b). If this was the outlet, for however long, some evidence of spillway sedimentation should be apparent to the southwest of Old Bolingbroke (Fig. 11). The large expanse of undated glacifluvial material that comprises Straw's (1957) "kame terrace" at 30 m OD to the west of the Stickney Moraine (mapped up to 25 m and descending westwards to 10 m OD by the BGS) is a contender for such a spillway outlet fan, an hypothesis that requires further testing. The MIS 2 glacial limit was reached immediately after 19.5 ka based on the Welton le Wold OSL age, which places a maximum age on the sedimentation of ice-dammed lake sediments deposited in the Wolds valleys and then glacitectonized by the onshore flowing North Sea Lobe.

These ice-dammed lakes fit within a larger context of the North Sea Lobe damming lakes as it advanced upslope out of the North Sea Basin. Lake Wear formed ~ 18.7-17.1 ka by the separation of Tyne Gap and North Sea ice (Livingstone et al., 2015). A Glacial Lake Tees is also known to have existed sometime within 21 – 16 ka (Davies et al., 2012). Lake Pickering formed when North Sea ice

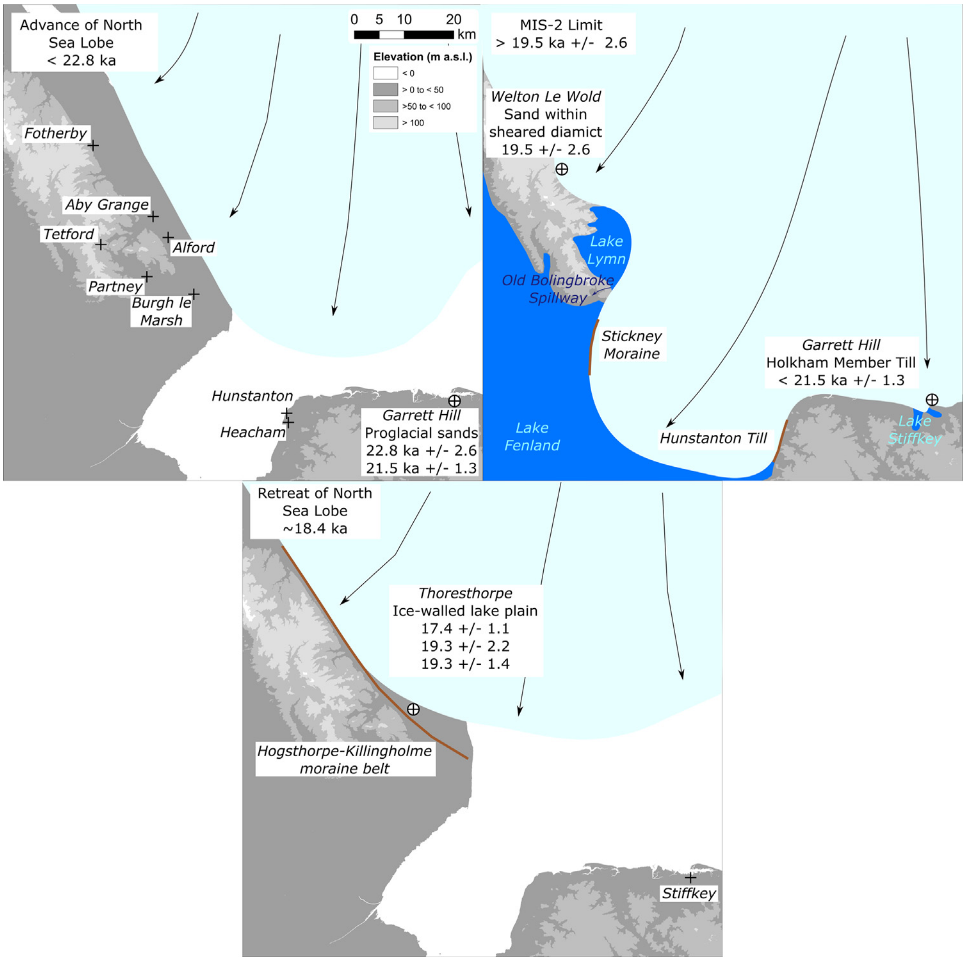

Fig. 11. Palaeogeographic reconstruction of North Sea Lobe advance and recession in Lincolnshire, The Wash and North Norfolk during MIS 2 with key locations and the OSL chronological control. The extent of Lake Fenland is approximate but would have been no higher than the spillway at the Waveney Valley (Fig. 1a) at ~30 m OD.

blocked the eastern end of the Vale and persisted until ~17.5 ka (Evans et al., 2017). Lake Humber is thought to have formed at least by 22-21ka with its final demise occurring around 16 ka (Bateman et al., 2018; Fairburn and Bateman, 2016). The ice-draw down and highly deformable and saturated marginal deposits associated with these ice-dammed lakes are thought to have been an important contributory factor in the rapidity of the North Sea Lobe advance as well as the initial oscillatory nature of its retreat (Bateman et al., 2018; Roberts et al., in press).

5. Conclusion

The spatial architecture of the Marsh Tills and the Hogsthorpe-Killingholme Moraine belt is compatible with that of the Skipsea Till in East Yorkshire. Hence we propose that the limit of the outer Marsh/Skipsea till veneer and the Stickney and Horkstow Moraines represent the MIS 2 maximum margin of the NSL and the younger hummocky drift belt, comprising ice-contact outwash/subaqueous fans and ice stagnation topography, demarcates a significant ice-marginal oscillation of more restricted extent during overall recession. The MIS 2 glacial limit was attained at ~19.5 ka and was followed rapidly by ice sheet marginal stagnation at ~18.4 ka. Hence we identify only one, rather than two, Devensian glacial advances in Lincolnshire. The NSL advanced onshore in North Norfolk slightly earlier at ~21.5ka, compatible with the age of damming glacial Lake Humber to the north. In addition to the large ice-dammed lakes in the Humber and Wash lowlands, we propose that an extensive Glacial Lake Lymn was dammed in the southern Lincolnshire Wolds by NSL ice when it occupied the Stickney Moraine. The extent of NSL advance in Norfolk was at least partially constrained by a pre-existing MIS 6 Stiffkey moraine which we have identified as further evidence for a major MIS 6 ("Wolstonian") glaciation in the Wash region.

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