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Last glacial dynamics of the Vale of York and North Sea lobes of the British and Irish Ice Sheet

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ABSTRACT

During the Last Glacial Maximum, the Vale of York and North Sea lobes of the British and Irish Ice Sheet extended to within 10 km of each other, impounding a series of pro-glacial lakes. Such an interplay of ice lobes provides a useful analogue for elsewhere in the North Sea basin. This paper focusses on reconstructing the Vale of York and North Sea Ice lobes using a regional suite of 25 luminescence ages in combination with stratigraphical and geomorphic evidence. Results extend and revise the chronology of the Dimlington LGM typesite, showing that the North Sea Ice lobe advanced between 20.9–17.1 ka and 17.1–15.1 ka before present. Initially this lobe impounded a proto Lake Humber which likely covered parts of Holderness as well as the southern part of the Vale of York. Later stages of Lake Humber within the Vale of York show continued blockage of the Humber Gap by the North Sea Ice lobe. The Vale of York Ice extended briefly at $\sim$18.7 $\pm$ 0.63 ka across Lake Humber into South Yorkshire and North Lincolnshire before retreating to and forming the Escrick and York moraines. Both glacier lobes appear to have been short-lived, comprising relatively dynamic ice, especially when moving into areas of deformable lacustrine sediments, which allowed them to rapidly advance and over-extend their margins due to low basal shear stress. Topographic control of the extent and spatial positioning of both Ice lobes also appears to have been significant.

1. Introduction

During the Late Quaternary cold stages the North Sea basin was sub-aerially exposed due to depressed eustatic sea-levels and was at times adjacent to significant ice sheets which formed over Fennoscandia and Britain. Recent research in the region has started to systematically address the pattern and chronology of ice sheet occupancy of the North Sea Basin during the Last Glacial Maximum (LGM) and Lateglacial (e.g. Nygård et al., 2004; Carr et al., 2006; Bradwell et al., 2008; Sejrup et al., 2009, 2015). These studies have proposed the likelihood of a dynamic interplay between the Fennoscandian Ice Sheet (FSIS) and the British and Irish Ice Sheet (BIIS). Each ice sheet appears to have undergone multiple advances and recession phases as well as ice flow directional switches in response to changing ice dispersal centres and internal re-organisations (Livingstone et al., 2010; Sejrup et al., 2015). Such palaeo-ice sheet dynamism is now widely accepted in palaeoglaciological reconstructions and helps explain complex glacial landform and stratigraphic assemblages (e.g. Dyke and Morris, 1988a,b; Boulton and Clark, 1990a,b; Dyke et al., 1992; Clark, 1997; Kleman et al., 1997, 2006; Salt and Evans, 2004; Stokes et al., 2006; Livingstone et al., 2008, 2012; Evans et al., 2009).

Mapping of the North Sea and adjacent areas has identified a prevalent occurrence of interlocking lobate ridges, either indicating overprinting by oscillating ice margins or more significant readvances of separate ice lobes (e.g. Fig. 5 in Bradwell et al., 2008). Despite advances in marine sub-surface mapping and high resolution seismic profiling, detailed studies have been limited due to the difficulties of sampling ocean bottom sediment as well as securing a chronology. Such constraints are less problematic for terrestrially based palaeo-ice sheet depositional records, although evidence of spatial and temporal interplay between different ice lobes appears far less common. They have been reported in Scotland (Merritt et al., 2003; Hall et al., 2011) and in the Tyne Gap

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where the BIIS North Sea Ice lobe and ice moving east from the Stainmore Gap met forming proglacial Lake Tyne (Yorke et al., 2012). Another BIIS example of glacier lobe interactions is thought to have existed within the Yorkshire/Lincolnshire region (Fig. 1). Here, a 125 km long ice lobe (Vale of York lobe) is known to have flowed from the Stainmore Gap south-eastward into the southern part of the Vale of York (Boulton et al., 1985; Clark et al., 2004). Further east, an approximately 400 km long ice lobe (North Sea lobe) advanced from southern Scotland (Catt and Penny, 1966; Boulton et al., 1985; Busfield et al., 2015) southwards down the eastern margins of the North Sea basin (Eyles et al., 1994; Clark et al., 2004; Boston et al., 2010; Evans and Thomson, 2010), as far south as north Norfolk (Pawley et al., 2006; Moorlock et al., 2008). These lobes, if they were coeval, will have moved within 10 km of each other either side of the chalk escarpment in East Yorkshire and Lincolnshire, thereby forming ice dams and a series of proglacial lakes in the lowland terrain of eastern England (e.g. Livingstone et al., 2012).

This paper seeks to reconstruct the dynamics and interactions of the Vale of York and North Sea lobes in Yorkshire and adjacent Lincolnshire using a regional suite of luminescence ages in

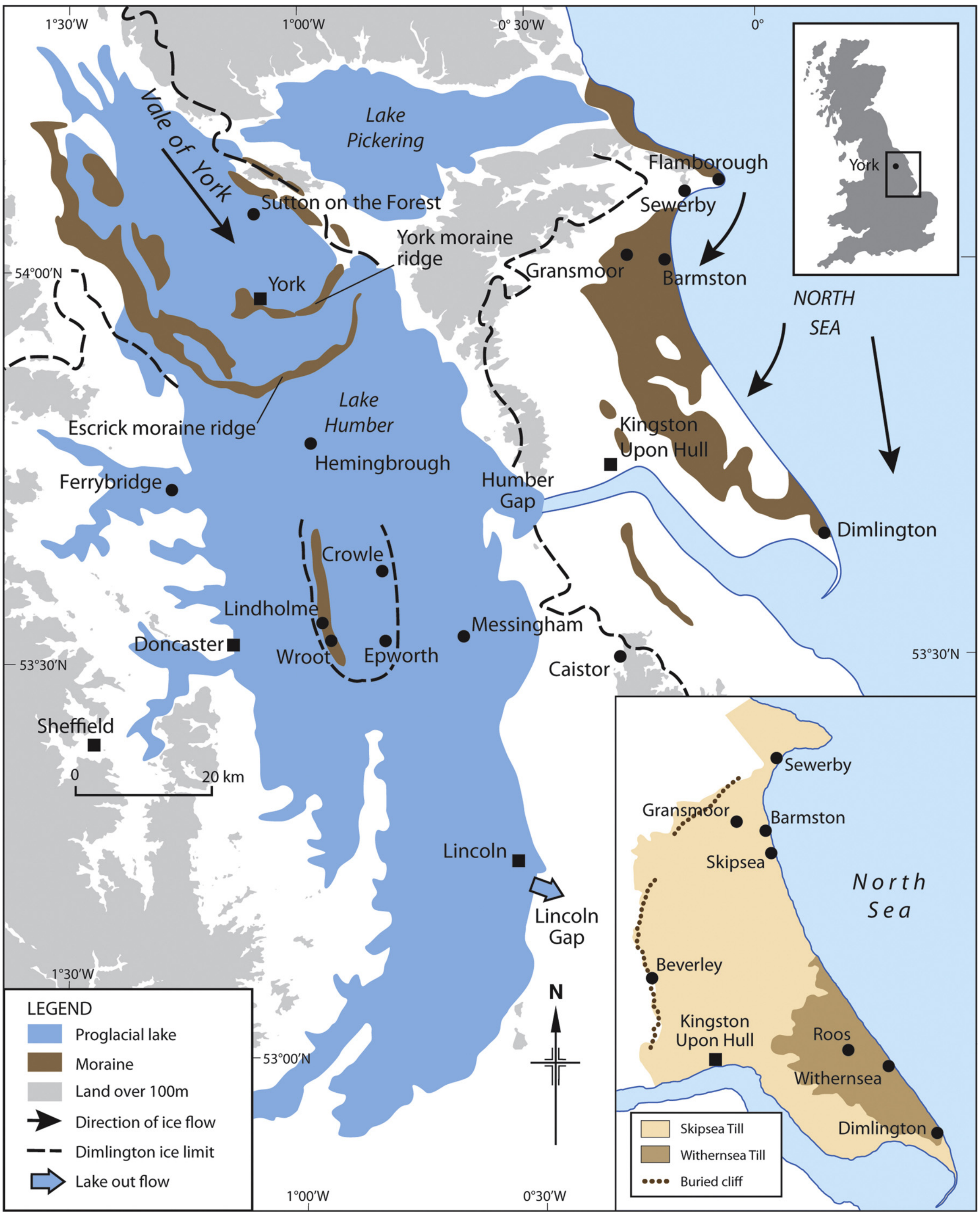

Fig. 1. Map of Yorkshire and Lincolnshire region of eastern England with principal localities, sites referred to in text and landscape features. Last Glacial Maximum ice limits after (Catt, 2007; Gaunt 1994) and ice vectors after Boston et al. (2010). Extent of glacial lakes Humber and Pickering and moraines after Clark et al. (2004). Inset shows the western limits of Skipsea and Withernsea tills (after Evans and Thomson, 2010).

combination with stratigraphical and geomorphic evidence. The resulting palaeoglaciological reconstruction facilitates a better understanding of the pattern and timing of the dynamics of the eastern sector of the BIIS more widely, addressing specifically its response to climate versus internal ice sheet (surge) drivers.

2. Previous research

Whilst the Vale of York and North Sea lobes of the BIIS hold the potential to be useful analogues for, and chronological controls on, ice lobe advances further out in the North Sea basin, the dynamic and chronological history of neither lobe are known with any certainty. Three major uncertainties exist in relation to the Vale of York lobe during the LGM and Lateglacial: (1) the maximal extent of the ice lobe; (2) its relationship to pro-glacial Lake Humber; and (3) the chronology of ice lobe-lake interactions. First, outcrops of gravels with a major component of Magnesian Limestone have been reported at various localities from Snaith, Thorne and Lindholme in South Yorkshire to Wroot and High Burnham in North Lincolnshire (Fig. 1, Gaunt, 1994, his Fig. 43). These have been interpreted as being ice marginal sediments formed by an expansion of the Vale of York lobe south into proglacial Lake Humber (Gaunt et al., 1992; Gaunt, 1994). This interpretation has proved controversial, and Straw (1979, 2002) has suggested that the gravel deposits date to an earlier glaciation. More recently, Ford et al. (2008) failed to identify any coarse clastic deposits from numerous cores within lacustrine sediments south of the Escrick moraine, concluding that the Vale of York lobe did not advance beyond the Escrick moraine (Fig. 1).

Second, Gaunt (1976) proposed two phases of Lake Humber; a high-level lake at *c.* 33 m OD followed by a low level stage at elevations between 9 m and 12 m OD. Murton et al. (2009), however, reported only evidence for a shallow Lake Humber which they dated to 22.2 $\pm$ 0.3 ka. In contrast, Bateman et al. (2008) reported a younger age of 16.6 $\pm$ 1.2 ka for High Stage Lake Humber from beach deposits found at 33 m. Recent work based on shoreline mapping has added to this controversy by proposing an 8-stage recessional model for Lake Humber from its final High Stage (Fairburn and Bateman, 2015). In summary, the interpretations of Murton et al. (2009) and Bateman et al. (2008) are apparently at odds with one another, and together with the work of Fairburn and Bateman (2015) are incompatible with the two stage model of Gaunt (1976).

Finally no direct chronology exists for the activity of the Vale of York lobe. A loess deposit located at Ferrybridge dated to 23.3 $\pm$ 1.5 ka, indicates ice-free conditions at that time (Bateman et al., 2008). As some lacustrine sediments lie beneath till, Vale of York ice must have moved into Lake Humber and therefore must post date 22.2 $\pm$ 0.3 ka (Ford et al., 2008; Murton et al., 2009). A date on organic sediments beneath coversands at Sutton on the Forest, northeast of York, of 12,879 $\pm$ 168 cal yr BP (Matthews, 1970) indicates that Vale of York ice had retreated northward by this time. Thus in summary, the Vale of York lobe advanced to a contested maximum point sometime between 22.2 and 12.9 ka and was coeval with a least one stage of Lake Humber sometime within this time window.

The North Sea lobe is also poorly constrained temporally and its southern limit and possible surge activity (e.g. Eyles et al., 1994; Boulton and Hagdorn, 2006; Boston et al., 2010) is not fully understood. Whilst multiple tills and flow directions have been recognised from the sedimentary record (e.g. Boston et al., 2010) this dynamism is not reflected in the current chronology. No flowsets exist for the North Sea lobe, thereby precluding Hughes et al. (2014) from placing it within a relative chronology for the BIIS. Hughes et al. (2011) in compiling all previously published ages applicable to the BIIS commented on the lack of information for the marine sectors of the ice sheet in the North Sea. The current understanding is based on Clark et al. (2012), who modelled the advance and retreat of the BIIS, suggesting the North Sea lobe advanced into the Yorkshire region about 23 ka, reaching its maximum southerly extent between 19–17 ka. The collapse of all BIIS marine sectors was thought to have occurred by 17 ka (Clark et al., 2012). However, this chronology was largely based on three ages; an early thermoluminescence age from beneath weathered Skipsea till at Eppleworth of 17.5 $\pm$ 1.5 ka (Wintle and Catt, 1985), a radiocarbon date from silts beneath till from the UK LGM typesite at Dimlington of $\sim$21.7 cal ka (Catt and Penny, 1966), which possibly has a hard water effect problem, and a luminescence age of $\sim$17 ka dating Lake Humber (Bateman et al., 2008), which had to have been impounded by the North Sea lobe. Bateman et al. (2011) refined this with new luminescence ages, indicating ice advances at the Dimlington typesite within the periods 21.7–16.2 ka and 16.2–15.5 ka. Thus Livingstone et al. (2012) when producing a six-stage model of the central sector of the BIIS based on geomorphic mapping and stratigraphy showed ice persisting through to 16 ka, with oscillations occurring from their "stage III" (20 ka) onwards.

The ice source for the North Sea lobe, as proposed by Busfield et al. (2015) based on erratic lithologies, was the Midland Valley in Scotland. Ice flowing eastward from the upland dispersal centres of northern Britain appears to have been deflected southward and this may have been due to the presence of ice in the central and northern North Sea. Part of the BIIS has been shown to have advanced southeast in the Witch Ground Basin around 17.5 cal ka BP (Fladen 1; Sejrup et al., 2015). However the extent of this advance remains largely unknown and it would have had to have extended much further south to affect ice from the Midland Valley. Merritt et al. (2003) postulated a deflecting dome in the northern North Sea. One of the scenarios proposed by Clark et al. (2012) was that an ice dome in the central North Sea caused the North Sea ice lobe to be deflected southwards, but evidence of this has yet to be found. Both Bateman et al. (2011) and Busfield et al. (2015) observed that the flow occurred in a topographical low where soft sediment and the Jurassic mudstone substrate probably enhanced basal sliding (presumably also deformation) between the north-south striking outcrop of Cretaceous Chalk along the western North Sea margins and the southwest-northeast trending topographic high of Dogger Bank. The topography of the latter may have been enhanced by the FSIS forebulge which uplifted the centre of the North Sea basin by 10–20 m (Busschers et al., 2007). Whilst this would explain the southerly flow direction of the ice lobe it does little to explain the mechanism for the westerly ice oscillations reported on the County Durham and Yorkshire coastlines (e.g. Davies et al., 2009; Evans and Thomson, 2010).

3. Materials and methods

This paper presents results from the sedimentological investigation and stratigraphic logging, together with a suite of twenty five optically stimulated luminescence (OSL) ages from six sites critical to the palaeoglaciological reconstruction of the eastern sector of the BIIS (Fig. 2).

3.1. Field logging and sampling

Although Yorkshire has some of the most rapidly eroding coastline in Europe, with the potential for many kilometres of cliff exposure through the Quaternary stratigraphy, continual slumping results in only occasional good exposures for examination and sampling of sedimentary sequences. In contrast the low lying and subdued landscape of the southern end of the Vale of York precludes natural sediment exposures, although aggregate and clay extraction by open pit excavation does sporadically take place. As such the sites presented here are the result of opportunistic sampling and logging over the period between 2005 and 2014. Sites have been chosen based on their association with the glacio-lacustrine and other glacigenic deposits encompassing the area of the Vale of York and the Holderness coastline thought to have been partially occupied by the Vale of York and North Sea lobes of the BIIS.

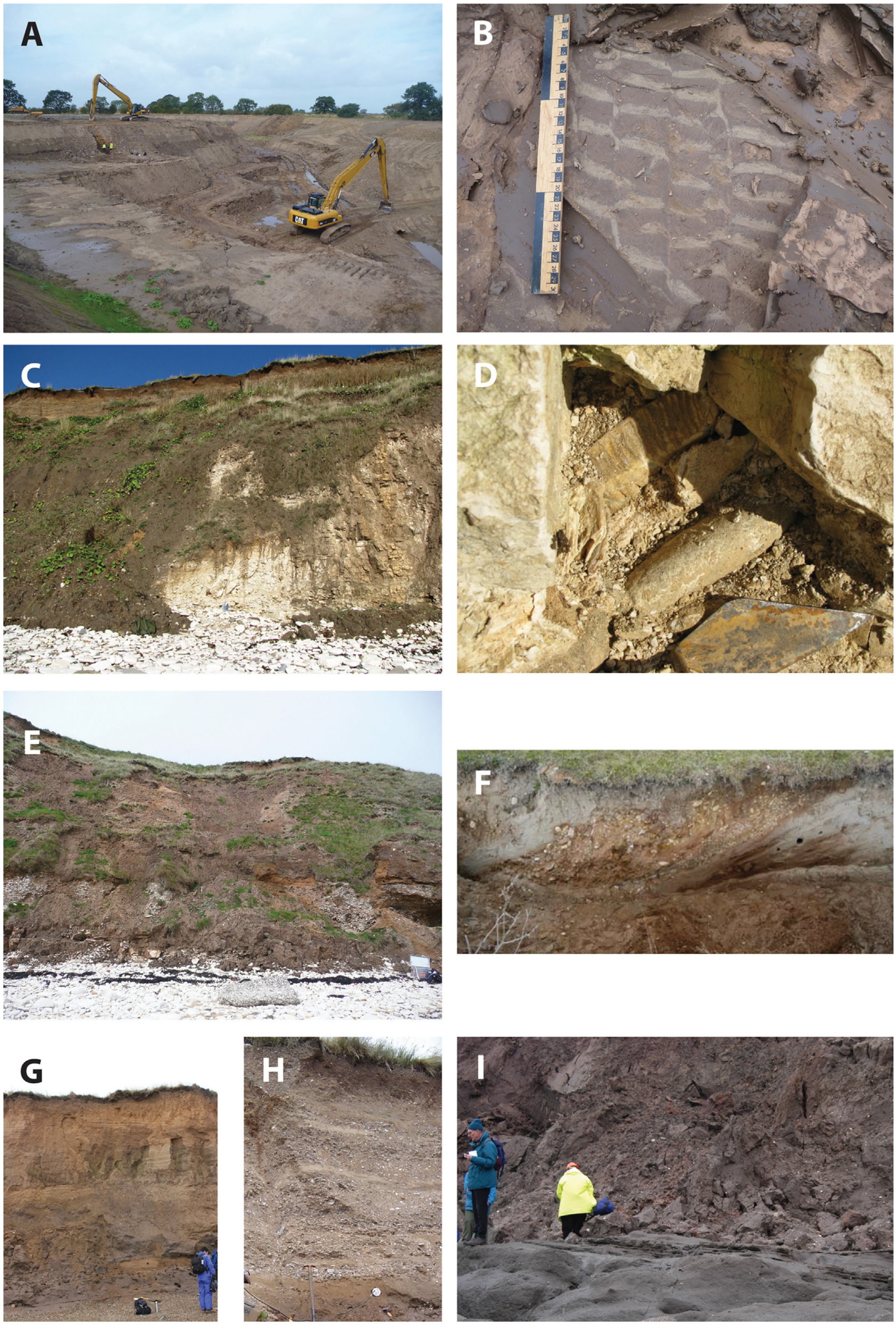

Fig. 2. Photographs of sampled sites. (a) Hemingbrough pit showing in vertical section two distinct units of laminated clays (lower) and sandy-clay laminations (upper–above people) Excavator is ~5 m in height for scale. (b) Plan view of sand ripples within lower laminated clays at Hemingborough. (c) Sewerby vertical section showing extensive diamict on left banked against chalky solifluctate, cliff fall and raised beached units on right all overlain by sand and gravel unit. Spade is ~0.75 m for scale (d) tooth of an adolescent elephant found by MDB within cliff fall unit at Sewerby. 12 cm trowel for scale (e) Flamborough site showing vertical section of sampled sand units below Skipsea till and overlying chalk rich gravels. Metal box ~75 cm for scale (f) Vertical section (2.6 m high) at Lindholme site showing repeating packages of sands and sands and gravels dipping at high angles from north to south. (g) Vertical section at Barmston showing sampled sand lens from within Skipsea Till overlain by cross-bedded sands and gravels, laminated silts and sands and planar sands and gravels. Person is ~1.5 m for scale (h) Vertical section showing Sewerby sands and gravels overlying Skipsea Till with OSL sample position. Note also periglacial ice wedge pseudomorphs on left. Spade handle is ~0.5 m for scale (i) Dimlington silts exposed underneath Skipsea Till at the LGM typesite at Dimlington. Person is ~1.5 m for scale.

At each of the six sites presented here, vertical exposures were cleaned for logging (Fig. 2). Where this was not possible, composite logs were compiled using either multiple small cleaned exposures through the stratigraphy or through repeat visits to rapidly slumping and eroding sites. For each exposure all lithofacies characteristics, including boundaries, sediment textures, colours, structures and bedding features, were recorded following the procedures set out in Evans and Benn (2004). Sediment properties and structures were further classified according to the scheme set out in Evans and Thomson (2010, Tables 1 and 2), including a lithofacies association (LFA) classification coding in order to aid regional correlation. Clast macrofabrics were collected on diamictons at a variety of sites using samples of 50 clasts, processed in Rockworks stereonet software and depicted using Schmidt equal-area lower hemisphere projections based on spherical Gaussian distributions.

To enable lithological analysis at Lindholme a large sample of gravel was collected from which 100 clasts (>5 cm) were randomly selected once back in the laboratory. These were identified with the help of a geological reference collection housed at the University of Sheffield. At Flamborough two large volume (874 and 454 clasts) samples were examined for lithological comparison to other units of differing genesis at nearby sites. Samples for OSL dating were collected in opaque PVC tubes from freshly cleaned sandy units, immediately sealed and wrapped in opaque black plastic for transportation to the luminescence laboratory.

Additionally, we have employed localised field terrace mapping as per Fairburn and Bateman (2015) to try and identify evidence that Lake Humber extended into the hummocky terrain containing the ice-contact subaqueous depo-centres reported previously by Evans and Thomson (2010). This mapping was undertaken around Beverley and Brandesburton.

3.2. OSL dating

All samples underwent OSL dating at the Sheffield Luminescence Laboratory. They were prepared to extract and clean quartz under low-intensity red lighting following the procedure laid out in Bateman and Catt (1996). Infrared stimulated luminescence was used to check for feldspar contamination of which none was observed. Multiple replicates of all samples were undertaken with the aliquot size varied as appropriate for a given site and depositional setting. Standard aliquot OSL measurements were conducted with samples mounted as a monolayer on 9.6 mm diameter aliquots. For small-aliquots, samples were mounted as a 2-mm-diameter monolayer in the middle of 9.6 mm diameter discs. Single grain measurements were conducted with aliquots with 100 μm $\times$ 300 μm diameter pits into each of which a grain could be placed. All measurements were undertaken with Risø automated luminescence readers with stimulation provided by blue diodes emitting at 470 nm or in the case of single grain measurements by a Nd:YVO4 laser. OSL signal was detected through Hoya U340 filters. Irrespective of the aliquot size, sample palaeodoses (D_e) were measured using the single aliquot regeneration (SAR) protocol with a cut heat of 160 °C (Murray and Wintle, 2000, 2003). Preheats within this protocol were derived experimentally for each site using a dose-recovery preheat plateau test (Murray and Wintle, 2003). Overall, samples measured with the SAR protocol showed rapid OSL decay curves, good recycling and low thermal transfer although it was noted at the single grain level that the number of grains producing measurable OSL and meeting quality assurance criteria was low as the grains were mostly dim.

Where possible, dose rates were determined from *in situ* field measurements made with an EG&G Micronomad field gamma-spectrometer. Where this was not possible, dose-rates are based on concentrations of potassium, uranium and thorium as determined by ICP-MS and ICP-OES. All dose rates were appropriately attenuated for sediment size and included a contribution from cosmic sources as determined following published algorithms of Prescott and Hutton (1994). Dose rates were also attenuated for the average palaeo-moisture. Given many samples were from quarry faces or eroded cliff sequences present-day values were thought to under-estimate true palaeodose values. For samples where saturation or near saturation was likely a value of 20 $\pm$ 5% was used. For samples which were likely to have been wet but not saturated a value of 10 $\pm$ 5% was used. For consistency of approach the dose rates from Dimlington reported by Bateman et al. (2011) were adjusted, resulting in revised ages for this site (Table 1).

Multiple replicates of each sample were undertaken to give an indication of D_e reproducibility. Where overdispersion (OD) was high and the D_e replicate distribution either multi-modal or skewed, final D_e values for age calculation purposes were derived using the Finite Mixture Model (Roberts et al., 2000;Table 1). Where D_e distributions were normally distributed and OD low, the final derived D_e is based on the Central Age Model (Galbraith and Green, 1990;Table 1). Where aliquot and single grain data were measured for the same sample, both are reported (Table 1) but ages based on the single grain results, which for partially bleached sediments are less prone to problematic D_e averaging affects, are used for discussion purposes.

4. Results

Sites at Dimlington, Sewerby, Hemingbrough and Barmston have been previously reported and therefore only summary descriptions of newly revealed exposures at these sites are reported before results given. Sites at Lindholme and Flamborough are previously unreported and hence full details are provided as well as new lithological and luminescence results. Unless otherwise stated, attribution to Formations, Members and Beds are based on those of Lewis (1999) and Thomas (1999).

4.1. Hemingbrough (Lat 53°46′36″ N, Long 0°58′38″ E)

This site is located just north of Hemingbrough, near Selby, in the Vale of York and is 10 km south of the Escrick moraine (Fig. 1). Due to rapid aggregate extraction extensive sections were available to view in 2011 (Fig. 2a). A tripartite sequence of sediments was logged, all of which can be attributed to the Hemingbrough Glaciolacustrine Formation (Figs. 1 and 3; Ford et al., 2008). At the base, at least 10 m in thickness, is a dark greyish brown (10YR 4/2) thinly laminated clay and silt unit (Fm, Fl; Fig. 3) with the silt layers containing increasing quantities of fine sand towards the top. Laminations are parallel or wavy, 1–2 cm in thickness and when parted revealed extensive, regular wave and current ripples (Fig. 2b). This unit is thought to be characteristic of the rhythmic settling of fine material found in benthic deposits of proglacial lakes (Reineck and Singh, 1975; Ashley, 2002). This unit is ascribed to the Park Farm Clay Member (Ford et al., 2008). Above this, and separated by a sharp erosive boundary, is >1 m of thicker (up to 5 cm) wavy, non-parallel and convoluted laminations of yellow brown sand (10YR 5/6) and silty clay (Fl, Sh; Fig. 3). The contortion (interpreted as open folding due to sediment loading) and coarsening up of laminations of this unit is interpreted as indicating repeated pulses of higher energy from water flowing in (Ashley, 2002) and either turbidity currents (Davies, 1965) or shallow water wave conditions (Allen, 1985). This unit is ascribed to the distal part of the Lawns House Farm Sand Member, representing outwash deposited when Vale of York Ice was positioned at approximately the Escrick moraine (Ford et al., 2008). The final unit is 1.8 m thick and consists of a poorly sorted dark

Table 1
OSL summary data and ages.

	Site and lab. code	Stratigraphic information	Depth (m)	Water content (%)	Total dose rate (Gy/ka)	N[a]	D_e (Gy)	OD (%)	Age (ka)
Hemingborough	Shfd11087	Thorganby Clay Member, Lake Humber	1.9	20 ± 5	2.226 ± 0.056	24 (22)	37.33 ± 0.72[f]	14	16.77 ± 0.53
	Shfd11088	Thorganby Clay Member, Lake Humber	2.6	20 ± 5	2.260 ± 0.066	24 (23)	35.06 ± 0.60[f]	8	15.51 ± 0.53
	Shfd11093	Park House Clay Member, Lake Humber	14.1	25 ± 5	1.041 ± 0.019	24 (21)	22.77 ± 0.52[f]	13	20.46 ± 0.59
Sewerby	Shfd05250	Sewerby Gravels above Skipsea Till (LFA3)	3.75	20 ± 5	1.035 ± 0.053	2900 (39)	18.54 ± 1.69[c,d]	88	17.9 ± 1.9
	Shfd05251	Sewerby Gravels above Skipsea Till (LFA3	3.75	20 ± 5	1.068 ± 0.054	36 (26)	25.65 ± 1.95[b,d]	46	<24.0 ± 2.2
	Shfd07184	Loess within soliflluct under Skipsea Till	12.0	20 ± 5	0.857 ± 0.071	24 (24)	51.17 ± 1.18[f]	14	59.7 ± 5.1
	Shfd05247	Dune under Skipsea Till	19.0	10 ± 5	0.684 ± 0.041	24 (21)	69.78 ± 1.95[f]	18	102 ± 7.1
	Shfd05248	Dune under Skipsea Till	19.0	10 ± 5	0.552 ± 0.033	24 (20)	49.13 ± 1.28[f]	16	89 ± 5.8
	Shfd05249	Dune under Skipsea Till	19.6	10 ± 5	0.617 ± 0.035	24 (17)	62.75 ± 2.27[f]	20	102 ± 7.0
Dimlington	Shfd07115	Sand between Withernsea and Skipsea Tills (LFA2a)	18.7	10 ± 5[e]	0.985 ± 0.054	2400 (47)	15.5 ± 0.24[c,d]	36	15.8 ± 0.9
	Shfd07116	Sand between Withernsea and Skipsea Tills (LFA2a)	20.0	10 ± 5[e]	0.977 ± 0.053	2700 (41)	17.4 ± 0.28[c,d]	43	17.8 ± 1.0
	Shfd07114	Sand between Withernsea and Skipsea Tills (LFA2a)	20.8	10 ± 5[e]	1.039 ± 0.054	3100 (43)	18.7 ± 0.28[c,d]	53	18.0 ± 1.0
	Shfd07113	Sand between Withernsea and Skipsea Tills (LFA2a)	21.6	10 ± 5[e]	1.133 ± 0.063	2300 (40)	19.2 ± 0.36[c,d]	37	16.8 ± 1.0
	Shfd09062	Dimlington Silts beneath Skipsea Till	26.0	20 ± 5	1.517 ± 0.088	24 (21)	32.13 ± 1.18[f]	27	21.2 ± 1.5
	Shfd09063	Dimlington Silts beneath Skipsea Till	26.0	20 ± 5	1.813 ± 0.100	24 (21)	37.22 ± 0.91[f]	18	20.5 ± 1.2
Flamborough	Shfd10084	Sand beneath Skipsea Till	18.4	20 ± 5	0.942 ± 0.048	24 (18)	18.85 ± 0.88[b]	31	20.0 ± 1.4
	Shfd10085	Sand beneath Skipsea Till	6.7	20 ± 5	0.949 ± 0.047	24 (20)	19.25 ± 0.94[b]	33	20.3 ± 1.3
	Shfd14052	Sand and gravel beneath Skipsea Till	20.9	20 ± 5	0.950 ± 0.049	27 (23)	34.67 ± 1.65[b,d]	37	36.5 ± 2.6
Lindholme	Shfd10071	High angled sands and gravels (LFA3)	0.95	20 ± 5	1.675 ± 0.095	3900 (36)	32.06 ± 4.06[c,d]	74	19.1 ± 2.7
	Shfd10072	High angled sands and gravels (LFA3)	1.2	20 ± 5	1.727 ± 0.098	3600 (34)	31.38 ± 3.07[c,d]	84	18.2 ± 2.1
Barmston	Shfd10213	Cross bedded silts and sands (LFA2a)	4.65	10 ± 5	1.639 ± 0.082	28 (26)	18.45 ± 0.62[b,d]	26	11.26 ± 0.68
	Shfd10216	Silts and sands below lake (LFA2a)	4.68	10 ± 5	0.872 ± 0.028	29 (26)	10.22 ± 0.43[b]	30	12.17 ± 0.59
	Shfd10214	Sands and gravels above Skipsea Till (LFA3)	2.05	10 ± 5	1.323 ± 0.062	24 (20)	20.35 ± 0.87[b]	41	15.0 ± 1.0
						5700 (41)	19.86 ± 1.31[c,d]	75	15.0 ± 1.2
	Shfd11007	Sands and gravels above Skipsea Till (LFA3)	1.65	10 ± 5	1.389 ± 0.067	26 (24)	22.75 ± 0.94[b,d]	44	16.4 ± 1.0
						4500 (50)	20.79 ± 1.28[c,d]	44	15.0 ± 1.2
	Shfd10215	Sand lens within Skipsea Till (LFA1)	7.54	20 ± 5	1.048 ± 0.064	27 (25)	19.52 ± 0.98[b]	31	18.6 ± 1.5
						5800 (42)	22.54 ± 1.11[c]	36	21.5 ± 1.1

[a] Number of measurements made with number of accepted aliquots/grains used for age calculation in parenthesis.
[b] D_e based on quartz SAR OSL measurements at the small aliquot (5 mm diameter) level.
[c] D_e based on quartz SAR OSL measurements at the single grain level.
[d] Reported D_e based on Finite Mixture modelling.
[e] Single grain ages first published in Bateman et al. (2011) but shown here with revised moisture content of 10% to better reflect long term average moisture content during since deposition.
[f] D_e based on quartz SAR OSL measurements at the standard aliquot (9.6 mm diameter) level.

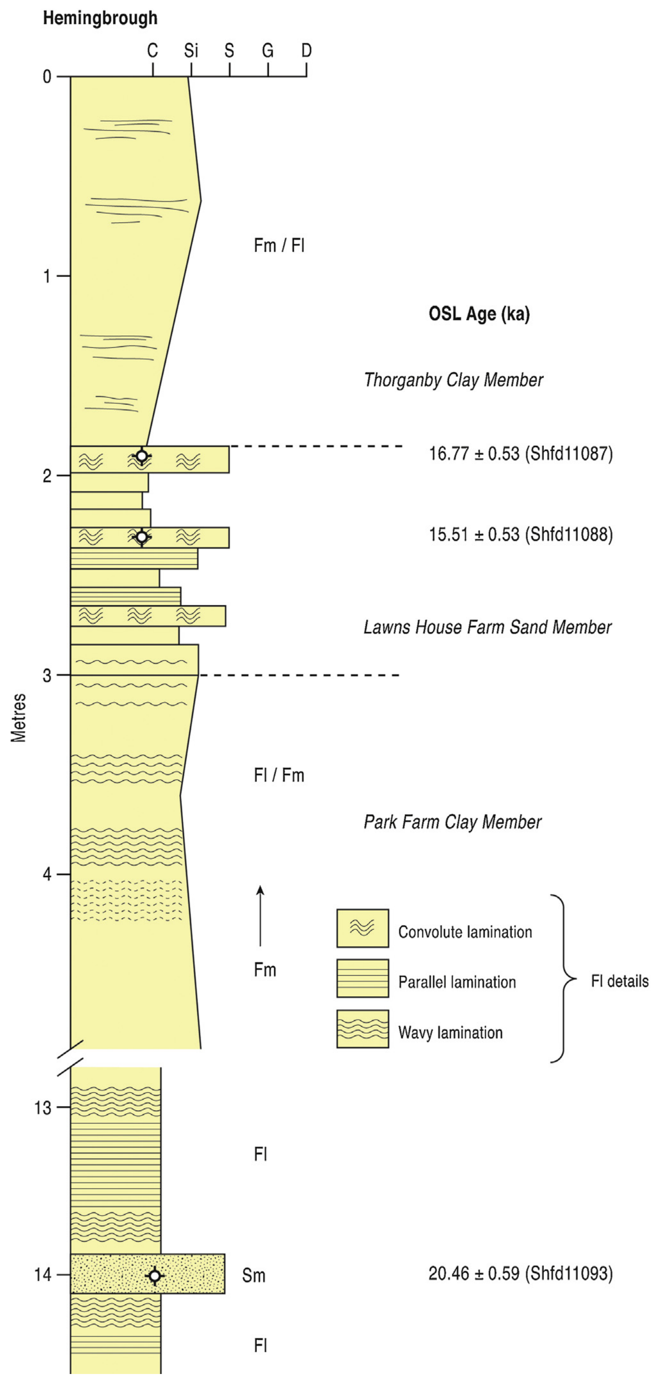

Fig. 3. Vertical profile log for the Hemingbrough site based upon observations in this study with OSL sample locations and ages of this study.

greyish brown (10YR 3/2) massive, silty clay (Fm, Fl; Fig. 3) coarsening upwards into a silty sand. Although lacking the laminations of lower units and those found elsewhere, this is ascribed to proglacial Lake Humber and forms part of the Thorganby Clay Member (Ford et al., 2008).

Three samples were collected from this site (Fig. 3), one from low within the Park Farm Clay Member (14.1 m from the surface) and a further two from the sandy facies within the Lawns House Farm Sand Member. As shown in Fig. 3, the Park Farm Clay Member yielded an OSL age of 20.46 ± 0.59 ka (Shfd11093) and the Lawns House Farm Sand Member was dated to between 15.51 ± 0.53 (Shfd11088) and 16.77 ± 0.53 (Shfd11087). The former are similar to the OSL results of Murton et al. (2009; 21.0 ± 1.9 ka and 24.1 ± 2.2 ka) and the latter comparable to the Lake Humber beach age at Ferrybridge of 16.8 ± 1.2 ka reported by Bateman et al. (2008). However, a stratigraphic inconsistency remains. Murton et al. (2009) ascribed all sediments to the Park Farm Clay Member, but sampled sandy facies (Murton et al., 2009, Fig. 3) which appear equivalent to what is ascribed above as the distal facies of the Lawns House Sand Member. That the ages do not agree between their study and this one can be reconciled only if quarrying, in stripping back ~200 m of sediment, has now revealed the Lawns House Farm Sand Member and overlying Thorganby Clay Member. Making this assumption, all ages ascribed to the Park Farm Clay Member imply fairly rapid sedimentation of a low level proto Lake Humber over a relatively short period of time at 21.9 ± 1.6 ka. Using ages from the Lawns House Sand Member and that from Ferrybridge give an average age of 16.4 ± 0.75 ka for the final high stage of Lake Humber and the timing of Vale of York ice near the Escrick moraine (Ford et al., 2008).

4.2. Sewerby (Lat 54°06′54″ N, Long 0°10′07″ E)

The cliff site at Sewerby, approximately 3 km north of Bridlington (Fig. 2c), has a long history of investigation, being first described by Lamplugh (1888) and by many others subsequently (e.g. Boylan, 1967; Bateman and Catt, 1996; Evans and Thomson, 2010). The sediments exposed at the site all form part of the Holderness Formation. Lying on top of a chalk wave-cut platform, the basal unit comprises a rounded chalk cobble raised beach ~2 m OD (Gm; Fig. 4). These raised beach deposits are exposed where the modern cliff line intersects a buried cliff and are thought to be of MIS 5e age (Bateman and Catt, 1996). Overlying this, and interdigitated with it in places, is a marly clay, sand and small-large chalk clast unit (Dmm) interpreted as cliff fall material. A gradational boundary separates this from up to 4 m of well sorted sand (Sc) thought to represent a dune banked up against the cliff line. All these lower units have yielded mammalian fauna (Boylan, 1967), including elephant (Fig. 2d) and significantly *Hippopotamus amphibius*. Near the cliff face the dune unit is overlain with a brecciated chalk unit (Dcm, solifluctate; Fig. 4) which grades laterally into a discontinuous well-sorted sand and laminated silt (LFA 2b; Sr (s), Sl, Fl, Fm) probably partially loessic in origin. The upper part of this unit has been deformed and partially cannibalised by the emplacement of the overlying unit. The raised beach, dune sand and brecciated chalk units form the Sewerby Member. Above this, LFA 1 is a massive matrix supported clay-rich diamicton (Dmm) around 6 m in thickness, which has occasional intraclasts near the base (Fig. 4). This is of glacial origin and known as the Skipsea Till or the Skipsea Member. The uppermost unit at this site (LFA 3; Figs. 2h and 4) is referred to as the Sewerby sands and gravels of the Flamborough Member and are thought to be of glaciofluvial origin deposited during deglaciation of the area. This unit comprises a sequence of fining up, massive to normally graded medium to coarse gravels (Gp, Gm, Gfu) which are imbricated NNE-SSW in places. Within the deposit are horizontal, trough and planar cross-bedded medium to fine sands, interbedded with asymmetrical ripples of coarse massive silt (Sh, St, Sp, and Frg). Epigenetic ice wedge pseudomorphs can be observed penetrating through this gravel unit from close to the modern ground surface.

A total of five samples were collected for OSL from this site (Fig. 4); three from the dune unit, one from the loess of LFA 2b and two from sand within LFA 3 (Fig. 2 h). Results show that the age of the dune sand ranges from 89 ± 5.8 ka (Shfd05248) to 102 ± 7.1 ka (Shfd05247; Table 1; Fig. 4). These are a little younger than the ages of ~121 ± 12 ka previously reported by Bateman and Catt (1996). However, as the latter were based largely on harder to reset thermoluminescence signals and only on a single D_e assessment using the multi-aliquot approach, the new ages are thought to be more accurate burial ages. The solifluctate/loess of LFA2b returned an age of 59.7 ± 5.1 ka

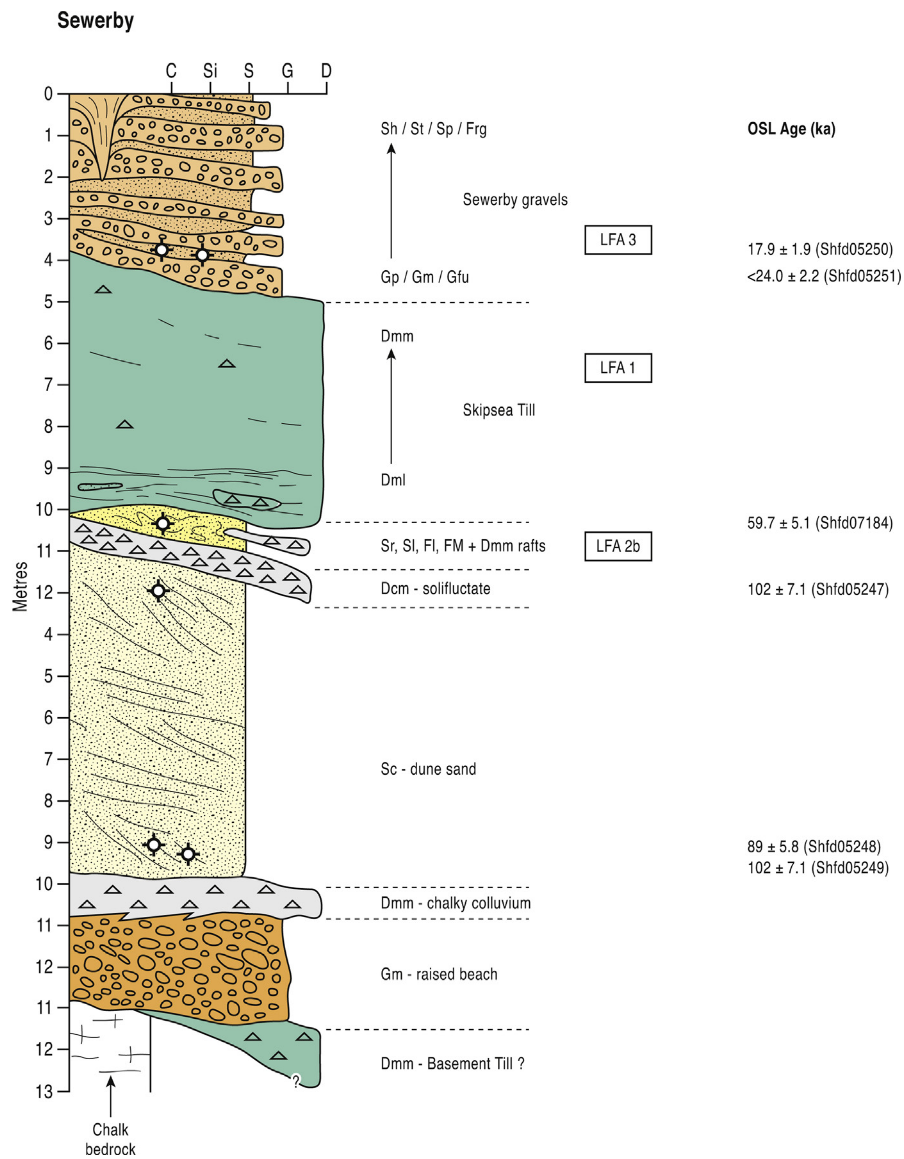

Fig. 4. Vertical profile log for the Sewerby site modified from Evans and Thomson (2010) with OSL sample locations for this study shown in appropriate stratigraphic position.

(Shfd07184), indicating a significant lapse of time both between dune formation and the solifluctate, but also between the solifluctate and the overlying diamicton. The Sewerby sands and gravels of LFA 3 dated to $<24 \pm 2.2$ ka (Shfd050251) and 17.9 ± 1.9 ka (Shfd050250) with the former date being an over-estimation due to partial bleaching. Based on these new OSL ages, the diamicton of LFA1 (Skipsea Till) was emplaced at Sewerby sometime between ~60 and 18 ka.

4.3. Dimlington (Lat 53°40′23″ N, Long 0°6′14″ E)

The Dimlington site is the type site for the LGM in the British Isles (Rose, 1985) containing many of the Members of the Holderness Formation. Storms between 2007 and 2009 and in 2011 caused rapid cliff erosion north of Dimlington, exposing new sections for chronostratigraphic analysis. Detailed descriptions of the stratigraphy of this site have been given elsewhere (e.g. Evans and Thomson, 2010; Bateman et al., 2011; Fig. 5) so herein follows only a brief summary. At the base, with sporadic outcropping, occurs the Basement Till or Bridlington Member, of glacial origin and characterised by matrix supported over-consolidated clay. The age of this unit is contested. Whilst most report it as a pre-Devensian (i.e. pre-MIS4; e.g. Catt, 2007) deposit, Eyles et al. (1994), using amino acid ratios on shells, suggested it was of LGM age, and the absence of deep weathering in the few exposures available might support this interpretation. Lying on top of this in places are thinly bedded and laminated silty lacustrine deposits referred to as the Dimlington silts or the Dimlington Bed (Fig. 2i). Above this, the cliff at Dimlington is composed of up to 12 m of LFA 1 massive glacial diamicton (Dml, Dmm), referred to as the Skipsea Till or Skipsea Member (Catt, 2007). Chalk and gravel stringers show clear evidence of deformation into open and overturned folds. Overlying LFA1 in places are clast-supported cross-bedded gravels (Gh, Gm; LFA 3), rich in chalk fragments. These are waterlain and derive from reworking of underlying Skipsea Till material. The overlying silts with mud drapes (Fl, Sh; LFA 2b) are 0.5–2 m thick and finely laminated on a millimetre scale. Occasional dropstones have been reported. Ichnofauna and delicately preserved adult and larval Diptera were found in the unit and used to show that LFA2b formed in a sub-aerially exposed glaciolacustrine environment (Bateman et al., 2011). These grade upwards into 1–2 m of laminated sand (Fl, Sh) before they are truncated by a massive, matrix-supported diamicton (Dmm/Dml) up to 10 m thick (LFA 4). This is the most recent of the Dimlington Stadial glacigenic deposits and is

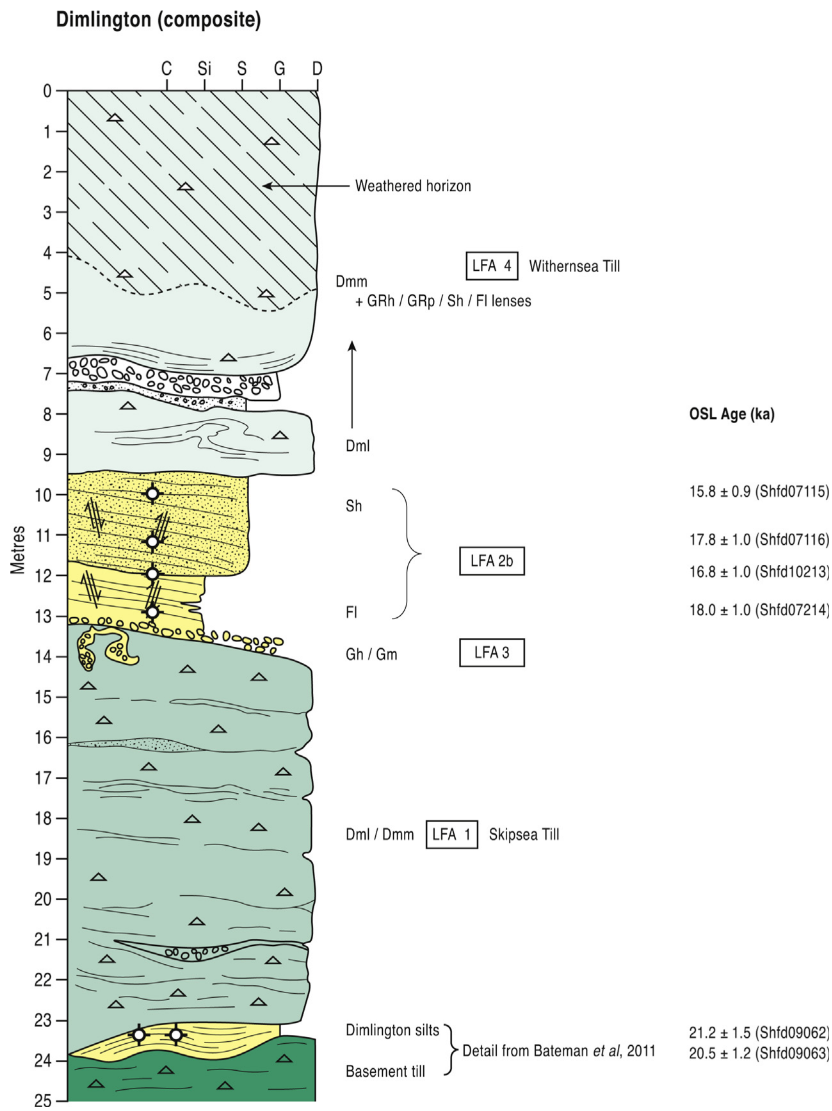

Fig. 5. Composite vertical profile log for the LGM typesite at Dimlington modified from Evans and Thomson (2010) with detail of Dimlington silts and Basement Till taken from Bateman et al. (2011). OSL sample locations and ages of this study shown in appropriate stratigraphic position.

traditionally referred to as the Withernsea Till or Withernsea Member (Catt, 2007).

Two sets of samples for chronological purposes were collected (Fig. 5). Firstly, two samples were collected from the Dimlington Silts, which gave OSL ages of 21.2 ± 1.5 ka (Shfd09062) and 20.5 ± 1.2 ka (Shfd09063). These coincide well with each other and corroborate radiocarbon dates from moss remains in this unit, which were originally dated to 20.8–23.0 cal ^{14}C ka BP (18.25 ± 0.25 ka BP) and 20.9–22.3 cal ^{14}C ka BP (18.0 ± 0.4 ka BP) (Penny et al., 1969). Dating the silts to an average of 20.9 ± 1.4 ka provides a maximum age for when the North Sea lobe deposited the Skipsea Till (LFA 1) and overran the site. Secondly, four samples were collected from the laminated sands of LFA2b. The revised OSL ages for these samples (Table 1; Fig. 5) are 15.8 ± 0.9 ka, 17.8 ± 1.0 ka, 18.0 ± 1.0 ka and 16.9 ± 1.0 ka (Shfd07115, Shfd07116, Shfd07114 and Shfd07113). This provides an average age of 17.1 ± 1.0 ka, by which time the North Sea ice responsible for the Skipsea Till must have retreated. It also provides a maximum age for the North Sea ice responsible for the emplacement of the Withernsea Till (LFA 4). Based on these new OSL ages, the chronology of the LGM typesite is extended and revised. The diamicton of LFA1 (Skipsea Till) was emplaced at Dimlington sometime between 20.9 and 17.1 ka and the diamicton of LFA4 (Withernsea Till) after 17.1 ka before present.

4.4. Flamborough (Lat 53°06′15″ N, Long 0°7′10″ E)

The exposures for this site are located at South Landing on Flamborough Head, about 6 km north-east of Bridlington. Whilst originally mapped by Lamplugh (1891), no published research has since been carried out at this locality. Due to the active slumping of the sediments in the upper part of the cliff (Fig. 2e), exposures were viewed on a number of occasions between 2009 and 2014, from which a composite log was obtained (Figs. 2e and 6).

Sediments at the site fill a north-south aligned palaeovalley, cut down to +2.5 m OD into bedrock of the Upper Cretaceous Flamborough Chalk Formation (Whitham, 1993). The basal part of the sequence comprises ~4.3 m of well-imbricated gravels and planar and cross-bedded sands (Gfu, Gm, Sm, Sh, Sp, LFA3, Fig. 6). The gravels are rich (26–43%) in northern British erratics and palaeocurrent measurements indicate flow from the north. This unit is therefore interpreted as glaciofluvial outwash emplaced by meltwater flowing from the north. Within the uppermost part of this unit is a 0.5 m thick cryoturbated layer, indicating the establishment of a periglacial landsurface for a time before glaciofluvial outwash sedimentation resumed. LFA2b overlies the gravels and sands, is up to 4.6 m thick, and comprises laminated silts and clays (Fl, Fl(w), Sm). This unit is interpreted as

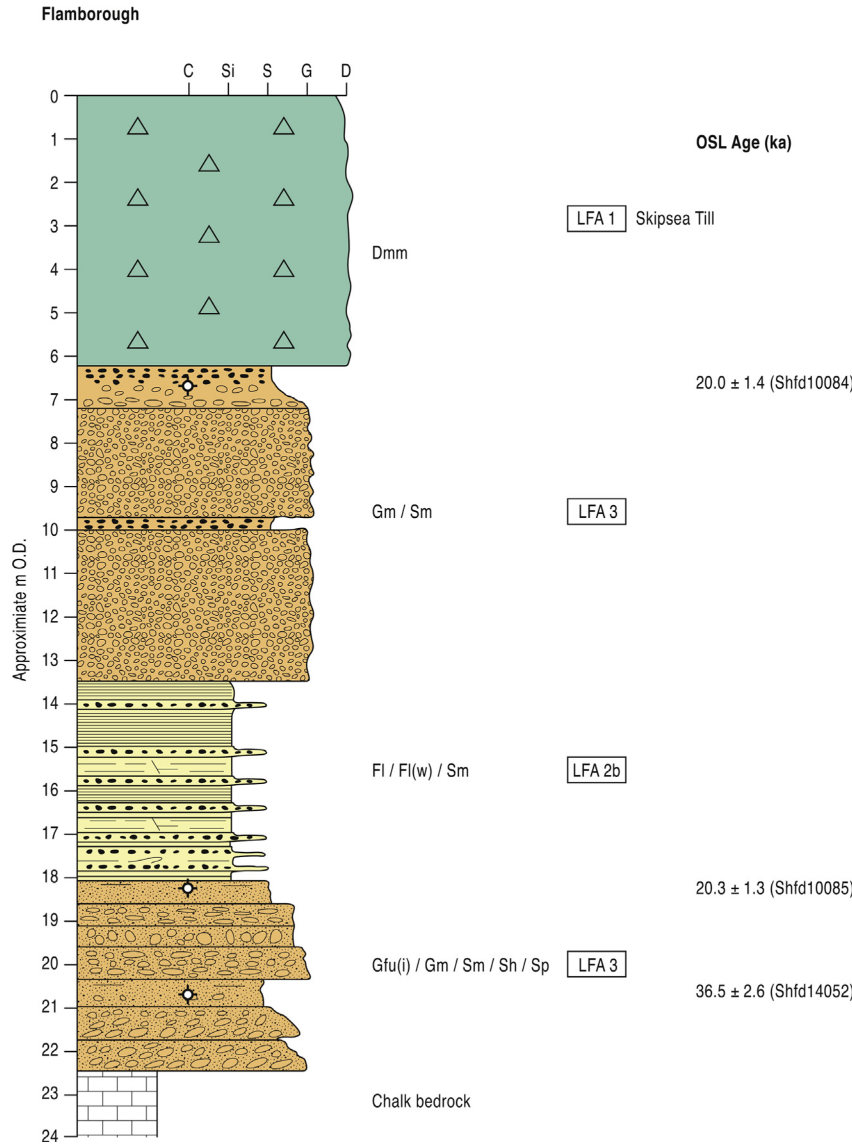

Fig. 6. Composite vertical profile log for the Flamborough (South Landing) site based upon observations in this study with OSL sample locations for this study shown.

the product of glaciolacustrine ponding when the drainage southward in the palaeovalley was disrupted. LFA2b is overlain abruptly by ~7.3 m of erratic-rich gravels with minor sand beds (Gm, Sm, LFA3, Fig. 6), interpreted as the products of the re-establishment of glaciofluvial outwash from the north. A massive diamicton (Dmm, LFA1), ~6.3 m thick and dark greyish brown to dark brown in colour (10YR 3/2–10YR 3/3) overlies the upper gravels and sands. This is interpreted as a subglacial traction till equivalent to the Skipsea Till or Skipsea Member of the Holderness Formation (LFA 1) of Holderness (Catt, 2007; Evans and Thomson, 2010). Clast fabric measurements within this unit by Penny and Catt (1967) indicate former ice flow from the ENE.

A total of three samples were collected for luminescence dating from this site. Two samples were collected from sand and gravel (LFA 3) near the base of the sequence and one from a sandy facies within LFA 3 directly beneath the Skipsea Till (Fig. 6). The basal samples returned an OSL age of 36.5 ± 2.6 ka (Shfd14052) indicating that these gravels pre-date significantly the LGM glaciation of this site (Table 1; Fig. 6). The overlying two sand units, bracketing the glaciolacustrine and glaciofluvial units (LFA2b and LFA3) are apparently much younger at 20.0 ± 1.4 ka (Shfd10084) and 20.3 ± 1.3 ka (Shfd10085). That their ages are similar indicates rapid sedimentation. Using an average, this puts a maximum age on the North Sea ice responsible for depositing the Skipsea Till (LFA1) at ~20.2 ka before present. The glaciolacustrine unit at +6.5 to +11.5 m OD (LFA 2b) between these two ages suggest ice had advanced into what is now Bridlington Bay sufficient to pond water in the palaeovalley prior to advancing across Flamborough Head and depositing the till of LFA 1.

4.5. Lindholme (Lat 53°32′45″ N, Long 0°55′50″ E)

The Lindholme site is located ~13 km east-northeast of Doncaster. Here a 1.5 km long, low (5.6 m OD) island of sand and gravel, orientated NNW-SSE occurs in the middle of the cutover peatlands of Hatfield Moors. This forms part of a much longer feature forming a discontinuous ridge of higher ground (Fig. 1). At Lindholme, gravel extraction pits, originally dug in 2004, were cleared for geological recording in 2009, of which one is reported here. This ~2.6 m deep exposure was orientated north–south and had an 8 m long face which revealed stratified sediments (Fig. 2f). The stratigraphy displays a series of repeated, stacked 'packages' which wedge out as they onlap onto the higher ground of Lindholme Island (Figs. 2f and 7). Within each 'package' four units are recognised. First, is a basal ~1.4 m thick unit of thin planar laminated sands (Sh; moderate brown 5YR 4/4; Fig. 7) with scattered sub-angular and frost shattered pebbles which locally form coarse gravel cross-bedding. The dip of the bedding planes is 18° and the unit interpreted as of fluvial origin. The upper irregular surface of this unit shows evidence of disturbance where pebbles from the overlying unit have penetrated downwards into the bedded sands. Second is a ~0.6 m thick faintly bedded, clast-supported coarse gravel with a fine, poorly sorted and fining-upward sand matrix (Gm, Gh; Fig. 7). Where bedding is evident, it occasionally drapes clasts, and flow and dewatering 'flame' structures are evident. Third is a unit comprising ~1.0 m of massive gravel (Gm, Fig. 7). This contains unsorted, unbedded sand and gravel with sub-angular to sub rounded clasts, mostly of sandstone and heavily weathered (in situ?) Permian Lower Magnesian Limestone in a medium sand matrix. The boundary between units 2 and 3 is irregular but gradational. Clast fabric analysis revealed a mean clast dip of 38° towards the south (mean = 178°; Fig. 7). Further mapping showed the gravels to be restricted to the crest of Lindholme in a NNW-SSE orientated spread of up to 3 m thick. Clast lithological analysis of units 2 and 3 indicates that the gravel comprises sub-rounded to sub angular clasts of Lower Magnesian and Lower Carboniferous limestones (the former dominating), Carboniferous and Triassic (Sherwood) sandstones and ganister (Fig. 8). Fragments of Carboniferous chert with diagnostic 'Derbyshire Screw' crinoids, wind polished flint and rare greenish Tuff, possibly from the Borrowdale Series of the Lake District, are also present. The gravel is therefore distinct from local Older River Gravels as reported by Gaunt (1976, 1994) and indicates a north-western source. The fourth unit is a thin (~0.2 m) bed of heavily cryoturbated, poorly sorted sand (Sm) and silt with pebbles, largely of Carboniferous sandstone lithology (Fig. 7). Taken as a whole the units cannot be attributed to solifluction due to a lack of proximal high ground, whilst the angularity and softness of many of the gravel clasts, combined with a distinct erratic lithology compared with adjacent fluvial gravels (Older River Gravels), rules out fluvial transportation. The '*en echelon*' arrangement of the sedimentary 'packages' (representing crude clinoforms), combined with the southerly palaeo-flow direction of the gravel units are all taken to indicate glaciofluvial deposition in a very ice proximal setting. Ice flowing over the Stainmore gap and then southward into the Vale of York accounts for the long distance erratic transport of Lake District and dominant Carboniferous rocks, with Permian limestone coming from the western margins of the vales of York and Mowbray. The unit is therefore thought to be a correlative of the Escrick Formation.

Two chronological samples were collected from unit 1. These returned OSL ages of 19.1 ± 2.7 ka (Shfd10071) and 18.2 ± 2.1 ka (Shfd10072; Table 1; Fig. 7) which when combined give an average of 18.7 ± 0.63 ka. In doing so they provide an age for when Lindholme became proximal to a Vale of York ice lobe.

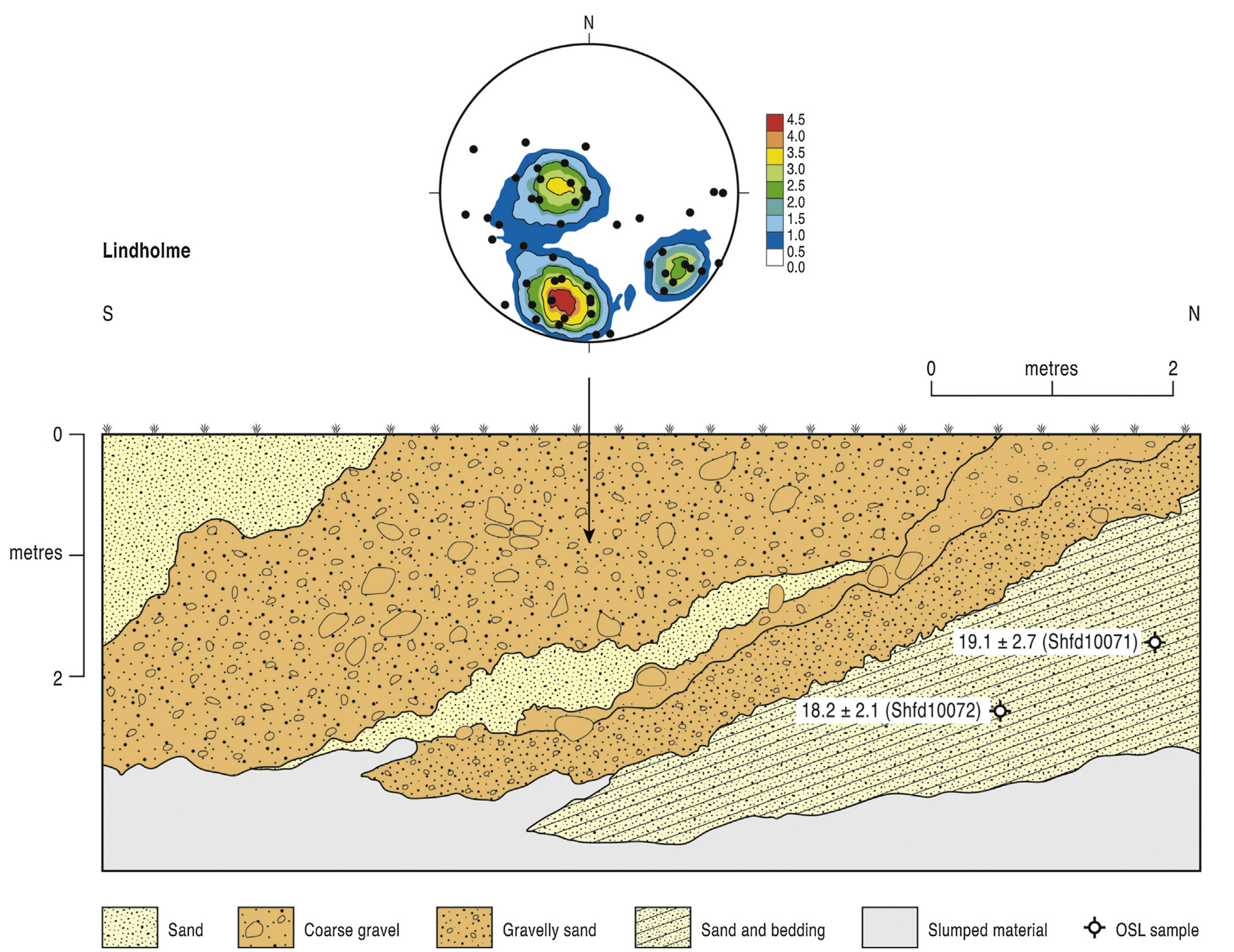

Fig. 7. Section log of exposure at Lindholme (shown in Fig. 2e) based upon observations in this study with OSL sample locations and ages of this study. Above Schmidt equal-area lower hemisphere projections of macrofabric from upper gravel unit.

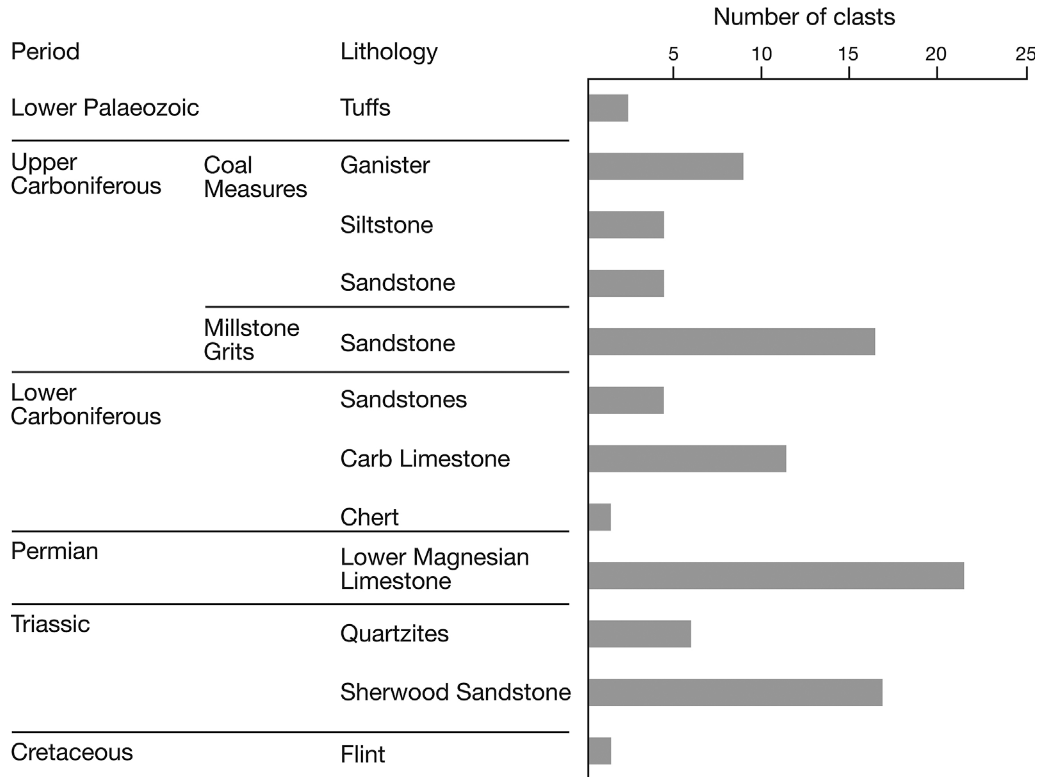

Fig. 8. Lithological analysis of Units 2 and 3 from Lindholme based on 100 clasts.

4.6. Barmston (Lat 54°01′1″ N, Long 0°12′54″ E)

The Barmston site lies on the present day Holderness coastline around 8 km south southwest of Bridlington. Ongoing coastal erosion provides extensive cliff sequences through parts of the Holderness Formation (Fig. 2g) from which Evans and Thomson (2010) produced a composite log (Fig. 9). The basal unit at Barmston is a matrix supported diamicton interpreted as of glacial derivation and attributed to being the Skipsea Till or Skipsea Member (Dmm, Dml + Dms; LFA 1). This can be up to 8.5 m thick with localised stratification and deformation largely in the form of folding and rare thrust faults. Deformed intrabeds, including sands are complexly folded and fragmented within the surrounding diamicton and are thought to relate to subglacial to sub-marginal stream deposits (Evans and Thomson, 2010). A number of apparently undeformed sand/sand and gravel units, up to ~2 m in thickness are also known from the site. Lying unconformably on the irregular upper surface of LFA 1 are localised pockets of cross-bedded, poorly sorted

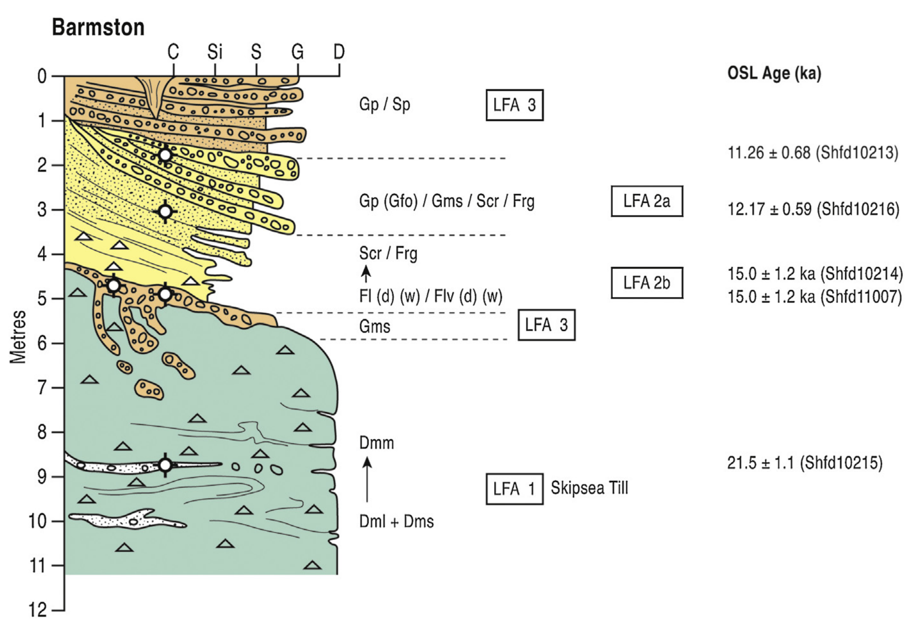

Fig. 9. Vertical profile log for the Barmston site modified from Evans and Thomson (2010) with OSL sample locations and ages of this study shown in appropriate stratigraphic position.

and matrix-supported gravels (LFA 3) which commonly display loaded contacts with LFA 1. These are interpreted as glaciofluvial deposited once ice had withdrawn from the area and therefore assigned to the Flamborough Member. The surface of LFA 1 (Skipsea Till) varies in elevation by 8 m, with the lowest outcrops giving rise to infilled stratified basins (LFA 2a). The basin infills are ~3.5 m thick and comprise thick sequences of rhythmically bedded laminated clays and rippled silty sands with dropstones (Fl (d) (w), Flv (d) (w); LFA 2a)). These coarsen upwards into climbing rippled sands with clay drapes (Scr, Frg) and eventually into cross-bedded, poorly sorted and matrix-supported gravels with rippled sands and silts (Gp, Gfo, Gms, Scr, and Frg; LFA 2b). These have previously been interpreted as rhythmic glacio-lacustrine and proglacial glaciofluvial sediments (Evans et al., 1995). The rhythmites within the basin at Barmston could be varves, in which case they represent more than 350 years of sedimentation into a glacial lake (Rushworth, 1998). Capping the sequence at Barmston is a more extensive and thicker unit of LFA 3, which comprises coarsening upwards, planar cross-bedded sands and gravels (Gp, Sp). This thicker unit of LFA 3 is found lying either directly above LFA 1 or conformably infilling the basins above LFA 2a. Prominent within LFA 3 and upper LFA 2 are ~1.2 m deep ice wedge pseudomorphs. LFA 3 therefore is interpreted as of fluvial origin whilst the area was subjected to periglacial conditions.

Five samples were collected for luminescence dating. These included a sand intrabed from within LFA1 as well as samples further up the profile in LFA 2a and 3 (Fig. 9). The OSL result from the sample from LFA 1 (Shfd10215) returned an age of 21.5 ± 1.1 ka (Table 1) which based on D_e replicability is not the result of partial bleaching. This is the first direct age for the Skipsea Till. Samples from LFA 3 (Shfd10214 and Shfd11007) both returned identical OSL ages of 15.0 ± 1.2 providing a *terminus ante quem* for North Sea lobe retreat after the final episode of Skipsea Till (LFA 1) deposition. This is supported by a radiocarbon date from basal peat in the Barmston Drain above the Till which dated to 14.2 ± 1.0 cal ka BP (12,100 ± 355, GK-5635; Allen, 1980). Samples Shfd10216 and Shfd10213 provided ages of 12.17 ± 0.59 ka and 11.26 ± 0.68 ka indicating the age of sedimentation of LFA 3, with ice wedge development at this site, took place during the Loch Lomond Stadial (Younger Dryas equivalent).

5. Discussion

The new dates presented above, in combination with previously published chronological control for the region, allows for a more tightly constrained reconstruction of the advance and retreat patterns for both the Vale of York and North Sea ice lobes from the LGM and through the Lateglacial period (Tables 2 and 3). Site-specific stratigraphic information on the presence and/or absence of ice and associated dammed lake waters, together with the improved chronological control on such events facilitates the palaeogeographic reconstruction depicted in Fig. 10.

5.1. Vale of York

Based on existing and the new evidence presented in Section 4, post LGM events in the Vale of York can be placed into six stages.

Stage I (24–21 ka): At this stage there is no evidence for glacier ice in the region. Livingstone et al. (2012) suggested that Vale of

Table 2
Summary events and chronology for the Vale of York Ice lobe based on new and previously published ages. (1) This paper, (2) Bateman et al. (2008), (3) Murton et al. (2009), (4) Fairburn and Bateman (2015), (5) Bateman et al. (2001).

Event	Sites	Ages (ka)	Average ages (ka)	Notes
Pre Glacial advance	Ferrybridge	23.3 ± 1.5 (2)	22.3 ± 1.5	No ice in southern part of Vale of York
Early low level Lake Humber	Hemingbrough	20.5 ± 0.6 (1)	21.9 ± 1.6	Rapid sedimentation of shallow lake
		21.0 ± 1.9 (3)		
		21.9 ± 2.0 (3)		
		24.1 ± 2.2 (3)		
Max Ice advance into North Lincolnshire	Lindholme	18.2 ± 2.1 (1)	18.7 ± 0.63	Input of north-western derivation lithologies
		19.1 ± 2.7 (1)		
Main phase Lake Humber and Ice retreat to around Escrick moraine	Hemingbrough	15.5 ± 0.5 (1)	16.4 ± 0.75	Lake Level at 33 m
		16.8 ± 0.5 (1)		
	Ferrybridge	16.6 ± 1.2 (2)		
Regression of Lake Humber	York Moraine	15.9 ± 0.9 (5)	15.6 ± 0.49	Lake level dropping to 25–20 and to 15 m.
		15.2 ± 0.7 (5)		
Demise of Lake Humber	Messingham	13.7 ± 0.4 (9)	13.7 ± 0.4	Minimum age of Lake drying up.

Table 3
Summary events and chronology for the North Sea Ice lobe based on new and previously published ages. (1) This paper, (2) Allen (1985), (3) Beckett (1981), (4) Straw (1979).

Event	Site	Ages (ka)	Average ages (ka)	Notes
Pre Glacial advance	Flamborough	20.0 ± 1.4 (1)	20.5 ± 0.51	Sample from directly below till
		20.3 ± 1.3 (1)		
	Dimlington	21.2 ± 1.5 (1)		
		20.5 ± 1.2 (1)		
Skipsea Till Ice advance	Barmston	21.5 ± 1.1 (1)	21.5 ± 1.1	Sand incorporated into till
Skipsea Till Ice retreat	Sewerby	17.9 ± 1.9 (1)	17.3 ± 0.95	Sub-aerial deposited sediments directly above till
	Dimlington	18.0 ± 1.0 (1)		
		17.8 ± 1.0 (1)		
		16.8 ± 1.0 (1)		
		15.8 ± 0.9 (1)		
Withernsea Till Ice advance	Dimlington		?	Till present at site but no direct age obtained
Withernsea Till Ice retreat	Barmston	15.0 ± 1.2 (1)	14.9 ± 0.44	Minimum age for ice retreat
		15.0 ± 1.2 (1)		
	Roos	14.2 ± 1.0 (6)		
		15.6 ± 0.9 (6)		
		13.2 ± 0.5 (10)		

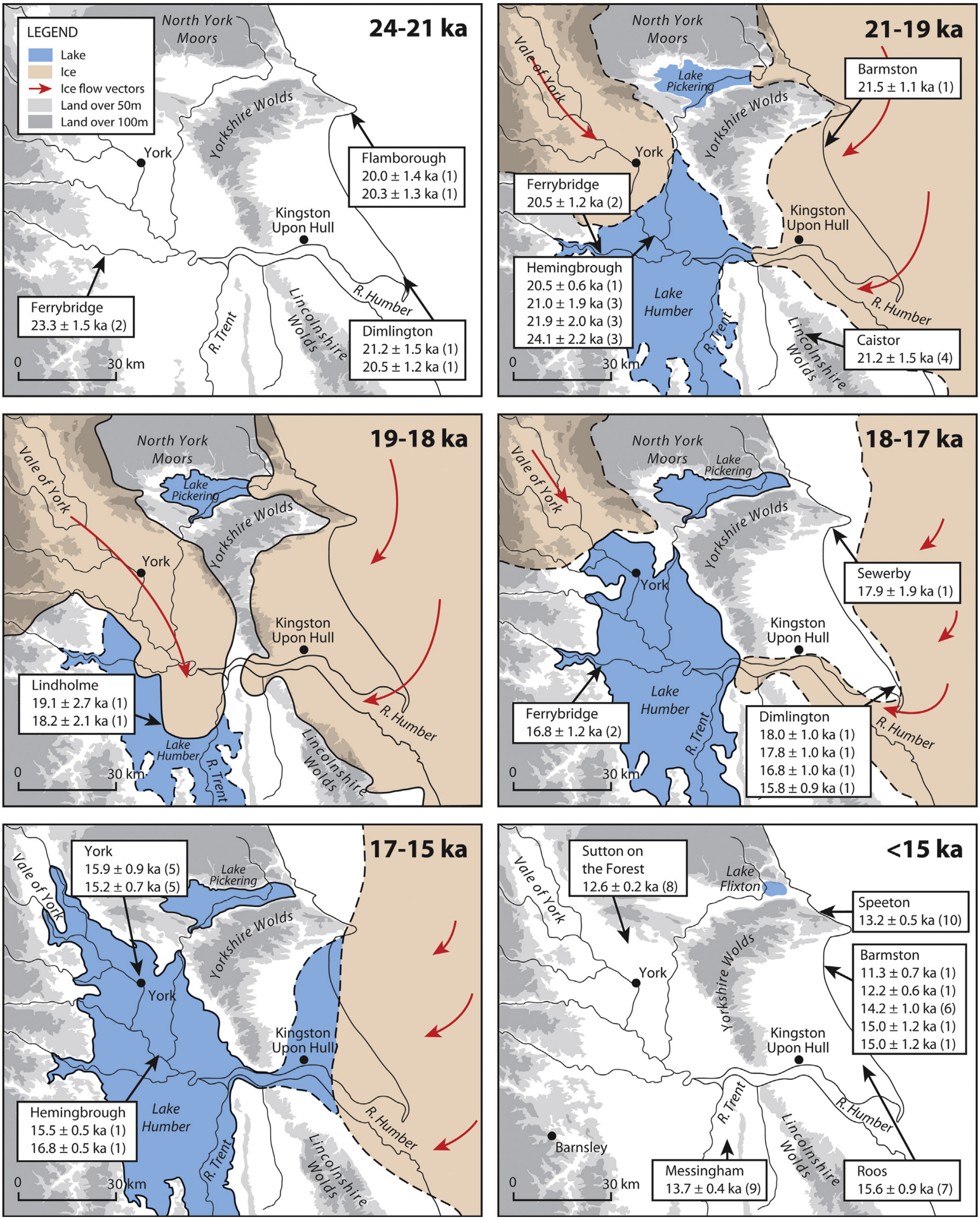

Fig. 10. Schematic reconstruction through time of the relative ice movements of the Vale of York and North Sea lobes of the BIIS. Ice margins are illustrative only and are based, where available, on dated stratigraphic and geomorphic evidence indicating either ice free or ice inundated conditions. Within time slices ice margins may have moved significantly from that shown. Lake Humber margins where appropriate are based on those of Fairburn and Bateman (2015) and for simplicity do not show emergent high ground within them. Lake Pickering extent is based on Clark et al., 2004 with the vestige (Lake Flixton) based on Palmer et al. (2015). Ages from the following sources; (1) This paper, (2) Bateman et al. (2008), (3) Murton et al. (2009), (4) Bateman et al. (2000), (5) Fairburn and Bateman (2015), (6) Allen (1980), (7) Beckett (1981), (8) Matthews (1970), (9) Bateman et al. (2001), (10) Straw (1979).

York ice moved through the Stainmore Gap and southward into the Vale of York between 25 and 21 ka. Existing data from the Vale of York and North Lincolnshire shows that the areas around Ferrybridge and Caistor were ice and lake free at 23.3 ± 1.5 ka (Bateman et al., 2000, 2008; Fig. 10). Therefore an ice advance down the Vale of York must have been fairly late within the time window suggested by Livingstone et al. (2012).

Stage II (21–19 ka): At this stage our evidence indicates that proto Lake Humber developed, specifically at sometime around 21.9 ± 1.6 ka, based on the ages of Murton et al. (2009) and the older age from Hemingbrough outlined above (24.1 ka BP). The existence of sand ripples within the laminated silty clays suggests this lake was relatively shallow at times. The exact elevation or extent of the Lake is not known other than it did not extend as far as Ferrybridge, which remained both sub-aerially exposed and ice free (Fig. 10). For impoundment of this Lake to have occurred, damming of the drainage through the Humber Gap must have taken place, although this has never previously been reported for this time. If credence is given to the disputed LGM age proposed by Eyles et al. (1994) for the Basement Till, then ice associated with the Basement Till could have blocked the Humber Gap. However, it is perhaps significant that this proto Lake Humber is coeval with the deposition of the Dimlington Silts on the Holderness coast which have now, on the basis of OSL, been found to date to ~20.9 ± 0.5 ka. The Dimlington silts are thought to have formed subaqueously although the spatial extent of the associated water body is poorly known. Coleopteran evidence from the Dimlington silts at Dimlington is terrestrial rather than aquatic, with the exception of the eurytopic water beetle *Agabus bipustulatus*, and is a less cold assemblage than that from the stratigraphically higher lacustrine sequence (Bateman et al., 2011). Together with the aquatic mosses, this indicates that the Dimlington Silts at Dimlington were deposited in a small localised basin such as a pond. However, Boston et al. (2010, Fig. 17) associated the Dimlington silts with the impoundment of water within the Holderness embayment as the North Sea Ice lobe advanced westward. This is referred to by Evans and Thomson (2010, p. 186) as "*a northern arm of Glacial Lake Humber*" associated with their LFA 2. Between the two basal ages from Ferrybridge, Bateman et al. (2008) noted a diamicton which was ascribed to the "Early Main Dales glaciation", implying that glacial advances were impacting on the area. It is assumed that the Vale of York lobe was advancing southward perhaps to a position at or near the Escrick moraine (Murton et al., 2009, p. 12).

Stage III (19–18 ka): During this stage, at around 18.7 ± 0.63 ka, the Vale of York lobe reached its maximum southerly extent, moving into and across the proto Lake Humber (Fig. 10). This is based on the deposition of north-westerly derived gravels at Lindholme. This advance coincides with the GS-2b episode of the GRIP ice core (19.5–16.9 GRIP ka BP; Björck et al., 1998). In association with the ice margin defined by the Lindholme deposits, Gaunt (1994) noted glacial sands and gravels at High Burnham, north of Epworth and Crowle. If these sediment assemblages are of the same ice-marginal origin, the ice lobe that deposited them by penetrating this far into North Lincolnshire was only in the order of 8 km wide.

Stage IV (18–17 ka): At this stage the Vale of York lobe had retreated northwards, allowing the development of High Stage Lake Humber (Fig. 10). The ice margin is presumed to have been at the Escrick and York moraines in order for these extensive features to form. The main phase of Lake Humber, based on ages from both Ferrybridge and Hemingbrough, was slightly later at around 16.4 ± 0.75 ka, at which time the Lake was 33 m OD and spatially extensive (Fig. 10). Given shorelines have been mapped on the south side of the York Moraine that date to this time, Vale of York ice must have retreated to north of the York moraine (Fairburn and Bateman, 2015). Retreat of the Vale of York lobe is corroborated by ice loss reported from the adjacent Yorkshire Dales (Telfer et al., 2009). The westerly extent of the North Sea lobe is unknown but was likely not far offshore.

Stage V (17–15 ka): During this stage Lake Humber continued to exist at least until 15.6 ± 0.49 ka, based on dated shorelines on the York Moraine, although regressive shorelines at 25 m, 20 m and 15 m have been reported, showing lake levels were dropping and size diminishing (Fairburn and Bateman, 2015; Fig. 10). New mapping found similar shorelines at 10 m 15 m 20 m and 25 m across the Holderness lowlands, where they trim the morainic topography reported by Evans and Thomson (2010). Continuance yet dropping of lake levels across the region indicates the presence of ice and moraines damming the drainage through the Humber Gap and north Holderness. Lacustrine sequences overlying till north of the York moraine indicate that continued recession of the Vale of York lobe northwards led to these areas being flooded.

Stage VI (<15 ka): By 13.7 ± 0.4 ka at the latest there is no evidence for the presence of glacier ice or Lake Humber in the Vale of York (Fig. 10). Based on the mapping of Gaunt et al. (1992), Lake Humber was eventually reduced in altitude to between 9–12 m OD and may have either emptied rapidly by breaching the moraines in the Humber Gap or silted up (Gaunt, 1981).

5.2. North Sea Ice lobe

Based on existing and the new evidence presented in Section 4, post LGM events for the North Sea Ice lobe in the Yorkshire region can be placed into five stages.

Stage I (24–21 ka): Evidence from Flamborough and Dimlington indicates that ice was close but did not reach this part of the Yorkshire coast until after ~20.5 ± 0.51 ka. The age at Barmston of 21.5 ± 1.1 ka either indicates that glaciation was rapid around this time or that it is in fact a pre-glacial age from sediment in which the OSL signal had not been reset and which was cannibalised and transported a short distance by the advancing North Sea lobe in association with the deposition of the Skipsea Till.

Stage II (21–18 ka): Between 20.5 ± 0.51 ka (possibly 21.1 ± 1.1 ka) and 17.3 ± 0.95 ka the North Sea lobe extended southward to Yorkshire and moved on-shore. This is later than the 25–22 ka proposed by Livingstone et al. (2012) and coincides with slight warming associated with the GS-2b episode of the GRIP ice core (19.5–16.9 GRIP ka BP; Björck et al., 1998). In the context of the rapid demise of the Irish Sea ice lobe of the BIIS it is thought that the ice which penetrated into the Cheshire Basin only did so after 21 ka (Clark et al., 2012). This glacial advance also coincides with FSIS advances reported for the eastern side of the North Sea. The Tampen advance, dated to 22–19 ka, was characterised by significant ice advancement westwards into the North Sea basin from Sweden (Sejrup et al., 2009), and the Fladen 1 advance south eastwards into the Witch Ground Basin of the North Sea has been dated to *c.* 17.5 cal ka BP (Sejrup et al., 2015).

Stages III and IV (18–17 ka): In order for Dimlington to be the location of a sub-aerially exposed lake and for the Sewerby sands and gravels to have been deposited, the Skipsea Till-depositing North Sea lobe must have receded eastward into the current off-shore area ~17.3 ± 0.95 ka (Fig. 10). Lake Humber could not have existed at 33 m OD if the Humber Gap was blocked by moraines alone. Evidence of moraines within the Humber Gap is compelling, with a moraine mapped at North Ferriby (Bisat, 1932) and Horkstow (Frederick et al., 2001), but neither reach close to the 33 m OD lake level in terms of elevation. Evidence for ice impounding water in Holderness as well as Lake Humber is absent at this stage. Therefore, the presence of Lake Humber implicates the presence of a glacier ice plug in the form of an onshore flowing lobe on the Humber estuary, potentially the precursor to the slightly later Withernsea Till advance immediately to the north (Fig. 10). Whilst a westerly extension of the North Sea lobe at this time looks glaciologically odd, the Humber channel is deeply incised into the underlying chalk bedrock so ice would have been thicker here and may have stagnated in situ during ice retreat elsewhere. Within the Humber channel the rock head occurs up to 50–80 m below OD within the Humber gap (e.g. Sunk Island borehole TA21NW/14, Berridge and Pattison, 1994) and outer estuarine channel (Straw, 1979; Fig. 4.2). Evidence for thick till and laminated sediment sequences have been recorded from within the channel (Berridge and Pattison, 1994).

Stage V (17–15 ka): The North Sea lobe readvance which deposited the Withernsea Till still remains undated although the time window for this event is refined. The Withernsea Till readvance occurred after 17.3 ± 0.95 ka and had retreated by 14.9 ± 0.44 ka coinciding with the cold GRIP ice-core GS-2a episode (16.9–14.7 GRIP ka BP; Björck et al., 1998). During this time a discrete area is known to have been covered in Withernsea Till (inset of Fig. 1) although the newly mapped occurrence of shorelines trimming the morainic topography across Holderness at altitudes similar to those in Lake Humber indicates that the Withernsea Till readvance lobe must have been larger impinging on northern Holderness, thereby preventing lake drainage in that direction. Moreover, glacitectonic structures in the glacigenic sediments of north Holderness have been related to continued onshore ice flow after the deposition of the Skipsea Till. As with Stage III, the persistence of Lake Humber, albeit at a lower level of 25–20 m, suggests that ice remained in the Humber Gap perhaps only as far as Hull, based on the St Andrew's Dock recessional moraine reported by Rees et al. (2000). The exact elevation or extent of the lake across Holderness is not known and an alternative to that shown in Fig. 10 may have been that it formed as a series of smaller ice impounded Lakes. Whilst modelling suggests that BIIS deglaciation was well advanced by this time (Boulton and Hagdorn, 2006), re-advances have been reported for other parts of BIIS. Most notably the Killard Point re-advance of the Irish Sea ice lobe has been dated, based on radiocarbon, to $<16.9 \pm 0.2$ ka reaching a maximum extent around 16.5 ka (McCabe et al., 2007). This has been supported by OSL dates from a sandur deposit on the Isle of Man which indicated ages of between 16.4 ± 1.5 ka to 14.1 ± 1.2 ka (Thrasher et al., 2009). On the western side of the North Sea, the BIIS re-advanced to the south east during the Fladen 2 event (16.2 cal ka BP) re-occupying the Witch Ground Basin in the northern sector of the North Sea (Lekens et al., 2005; Sejrup et al., 2015). European deglaciation is also thought to have slowed or been interrupted between 17 and 15.5 cal ka (Toucanne et al., 2008).

Stage VI (<15 ka): Around 14.9 ± 0.44 ka ice made its final retreat from the Holderness coastline based on the OSL dating of sand and gravel units at Barmston and peats from the Barmston Drain 14.3 ± 1.0 cal ka BP ($12{,}100 \pm 355$ ^{14}C BP, Allen, 1980) and the kettlehole deposit at Roos 15.6 ± 0.9 cal ka BP ($13{,}045 \pm 270$ ^{14}C BP, Beckett, 1981). Ice appears to have been north of Speeton before 13.2 ± 0.5 cal ka BP ($11{,}380 \pm 260$ ^{14}C BP, Straw, 1979; Table 3.1).

5.3. Implications for the BIIS

From the above it is clear that fluctuations of the North Sea lobe impacted on the Vale of York ice directly by impounding Lake Humber. The new evidence shows the Vale of York lobe did move into proglacial Lake Humber and advanced ~40 km south of the Escrick moraine to the Lindholme and Wroot area. It is possible to reconcile this southerly maximal position of the Vale of York lobe with that of Ford et al. (2008). This ice advance was dynamic with the advance to Lindholme and Wroot occurring at ~18.7 ka and ice back north of the York Moraine by ~16.6 ka. When entering the relatively shallow Lake Humber south of the Escrick Moraine it could have decoupled from its bed or accelerated due to soft-sediment basal sliding on the pre-existing laminated clays at its bed. Without ice-bed coupling, preserved evidence of what would have been a thin zone of glacitectonism has yet to be observed between the Escrick Moraine and where the ice halted at Lindholme-Wroot. It also means that the impressive moraines at Escrick and York are recessional features. The two clusters of lake ages reported for Hemingbrough and the erosive boundary at the top of the Park Farm Clay Member reflect this interruption of the lake by a short-lived ice advance. Gaunt's (1976) original two stage lake model is perhaps over simplistic and fails to account for an earlier proto Lake Humber stage. The timings of the North Sea lobe advances also make it improbable that Lake Humber ceased to exist after ~21.9 ka, as suggested by Murton et al. (2009). It would appear plausible that ice and/or moraines during the different oscillations of the North Sea lobe dammed the Humber Gap to different levels and with different efficiencies allowing for the multiple Lake Humber stages as presented by Fairburn and Bateman (2015). In summary, the presence of the North Sea lobe in the Humber Gap, thereby creating Lake Humber, appears to have directly affected the timing and extent of the most southerly extent of the Vale of York lobe as well as the extent and levels of Lake Humber itself.

Our new reconstruction also highlights a number of important aspects of the North Sea lobe that resonate with previous proposals that it was a surging system (cf. Lamplugh 1911; Eyles et al., 1994; Boston et al., 2010). Firstly it was very dynamic within a relatively short period of operation and secondly, it was surprisingly sensitive to topographic control. It would appear that ice was in the Yorkshire region only for a maximum of 6 ka (probably less), quite late in the deglaciation of BIIS. Within this timeframe a number of advances, oscillations and re-advances took place as is also reflected in the till geochemistry (Boston et al., 2010). Given this dynamism, which is inevitably linked to highly mobile ice dispersal centres in the BIIS (Livingstone et al., 2008, 2010, 2012; Evans et al., 2009) and that not all events coincide with climatic cooling, it would appear likely that some ice oscillations are in large part due to internal ice sheet reorganisations, which likely triggered increased ice volumes being diverted to the North Sea Basin. The extension of the Vale of York lobe south of the Escrick Moraine due to the enhanced sliding and/or deformation over a lacustrine sediment substrate provides an analogue for the dynamism of the North Sea lobe. The North Sea lobe also appears to have been sensitive to topographic control on at least two counts. Its deflection from an easterly flow out of Southern Scotland to a southward route down the western margin of the North Sea basin, in the absence of FSIS blocking, was explained by Busfield et al. (2015) as due to topography. This topographic relief on the eastern side of the ice lobe was provided by Dogger Bank (Busfield et al., 2015), but this could only have been in the order of ~40 m higher even if a FSIS forebulge was taken into account. The western margins of the ice lobe were constrained by the North York Moors and Yorkshire Wolds (Fig. 10; Busfield et al., 2015), but there is no evidence that the Vale of York and North Sea Ice lobes coalesced over these hills or that ice overtopped the Lincolnshire Wolds further south. As both the Yorkshire and Lincolnshire Wolds are mostly <150 m OD, it follows that the North Sea lobe, at least near its margins, was not thick. This also may be a consequence of ice marginal profile lowering due to enhanced basal sliding over Jurassic mudstones/pre-existing deformable Quaternary sediments and concomitant low basal shear stress. Localised diversion of ice-flow on the western margin of the North Sea lobe towards the west may be due to slowing of ice on this margin as ice-bed traction increased with elevated topography and better drainage over the Chalk/limestone substrate. The current study also shows that to maintain Lake Humber, North Sea ice must have persisted within the topographic low of the Humber estuary even when ice had retreated back eastward from Holderness only a maximum of ~50 m higher. This perhaps reflects a relatively low ice velocity flowing westward when the main ice flow direction of the North Sea Ice lobe was southerly.

6. Conclusions

A regional suite of 25 new and previously reported OSL ages on stratified glacigenic and glacial lake deposits has facilitated a more tightly constrained reconstruction of the ice-marginal dynamics of the Vale of York and North Sea ice lobes from the LGM through to the Lateglacial. Six stages of ice sheet marginal and proglacial lake development are recognised:

- Stage I (24–21 ka) pre-dates glacier ice advance in the region.
- Stage II (21–19 ka) was the period when proto Lake Humber developed due to damming of the Humber Gap by the North Sea lobe of the BIIS and was coeval with the deposition of the Dimlington Silts. It coincides with the slight warming associated with GS-2b and the Tampen advance of 22–19 ka BP.
- Stage III (19–18 ka) was the period when the Vale of York lobe moved across proto Lake Humber and reached its maximum southerly extent, coinciding with GS-2b. This confirms previous notions that the Vale of York lobe did extend ~40 km south of the Escrick moraine to the Lindholme and Wroot area, with the corollary that York and Escrick moraines are recessional features. The North Sea lobe must have receded off-shore, but Lake Humber could not have existed at 33 m OD if the Humber Gap was blocked by moraines alone and hence an onshore flowing ice lobe was present on the Humber estuary.
- Stage IV (18–17 ka) was marked by northwards recession of the Vale of York lobe to the York and Escrick moraines, allowing the development of High Stage Lake Humber (33 m OD). The westerly extent of the North Sea lobe was likely not far offshore but the absence of shorelines above 25 m indicates that any proglacially dammed lake waters on Holderness were not directly linked to Lake Humber.
- Stage V (17–15 ka) was a period when Lake Humber levels were dropping to 25, 20 and 15 m and the lake waters may have been continuous with those on Holderness, indicative of the presence of ice and moraines damming the drainage through the Humber Gap and north Holderness. The North Sea lobe readvanced to deposit the Withernsea Till but likely also impinged on northern Holderness to explain the prevention of lake drainage in that direction. The readvance occurred between 17.3 and 14.9 ka BP, coinciding with GS-2a and events like the Killard Point re-advance of the Irish Sea ice lobe and the Fladen 2 event in the North Sea.
- Stage VI (<15 ka) is marked by no evidence for glacier ice or Lake Humber in the Vale of York, and the North Sea lobe had receded from the Holderness coastline.

The palaeoglaciological reconstructions reported here support previous notions that the North Sea lobe was highly dynamic and possibly a surging system, being in eastern England for only 6 ka or less and late on in the deglaciation of the BIIS. This dynamism was likely driven by internal ice sheet reorganisations, and moreover, ice-marginal advances need not have coincided with hemispheric climate cooling. Additionally, the damming of the Humber Gap by the North Sea lobe to create Lake Humber appears to have directly affected the timing and extent of the most southerly extent of the Vale of York lobe as well as the Lake Humber water levels.

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