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A new multi-stage recession model for Proglacial Lake Humber during the retreat of the last British–Irish Ice Sheet

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The single most prominent lake associated with the retreat phase of the last British–Irish Ice Sheet (BIIS) was Proglacial Lake Humber. The present research elucidates a revised regional history of Proglacial Lake Humber from its maximum elevation to its demise using a combination of landscape mapping and luminescence dating. The results of mapping multiple Lake Humber strandlines are now best described by an eight-stage recessional model. Erosional highstands of the lake can be shown to post-date the BIIS advance that deposited the Skipsea Till at around 17 ka whereas new OSL ages show that Lake Humber was nearing its demise by 15.5±0.8 ka, indicating a possible short-lived lake. Multiple lake level stands are attributed to the switching of lake outlets from the Lincolnshire Gap to the Humber Gap and to oscillations of the BIIS blocking the latter on more than one occasion and subsequently at a lower elevation with till. The horizontal or near-horizontal shorelines confirm that isostatic adjustment did not occur during the demise of Lake Humber, indicating that BIIS advances in the North Sea region and Vale of York were not only dynamic but of short duration.

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During the Last Glacial Maximum (LGM) in the British Isles during Marine Isotope Stage 2 (MIS 2), the British–Irish Ice Sheet (BIIS) attained its overall maximum size by 27 ka BP, although absolute maximal extents varied in time from region to region (Clark *et al.* 2012: fig. 1). During this and the BIIS's subsequent demise a number of proglacial lakes was formed as drainage lines were disrupted and blocked by ice (Clark *et al.* 2004). The single most prominent of these was Proglacial Lake Humber (Fig. 1), which formed to the south of the Vale of York BIIS ice lobe and to the west of the North Sea BIIS ice lobe. It is thought that at its maximum Lake Humber may have covered an area of ~4500 km^2 (Clark *et al.* 2004; Bateman *et al.* 2008).

The first to conceive Proglacial Lake Humber was Henry Carvill Lewis (1894: map IV and p. 62), who envisaged a great North Sea glacier blocking the mouth of the Humber where it crosses through a 4-km-wide gap between the Yorkshire and Lincolnshire Wolds. Currently about 25% of the drainage of England passes through this point (Versey 1940; Rees 2006) so it is clear that any blockage of this flow would lead to the development of an extensive lake to the west in the Humberhead Levels in the Vales of Trent and York and extending northwards to include Lake Pickering (Fig. 2).

Localized terracing, that could be interpreted as Lake Humber shorelines, has been recognized previously by Melmore (1940), de Boer *et al.* (1958) and Penny (1974) but the only formally recognized strandline is a 30.5 m (100 ft) a.s.l. terrace eroded into the Permian escarpment between Tadcaster and south of Ferrybridge (Fig. 2), which was mapped by Edwards (1937: fig. 1; see also Bateman *et al.* 2008 and Murton & Murton 2011). Since the recognition of the 100 Foot Strandline, mapping of Lake Humber, at its maximum extent, has been based on a shoreline of ~30 m (Straw 1979; Clark *et al.* 2004) with outflow through the Lincoln gap (Fig. 2) to The Wash area of eastern England.

The model proposed by Gaunt (1976), for the Late Devensian physiographical evolution of Lake Humber, is for a transient high-level lake at ~33 m a.s.l. resulting from glacial blockage of the Humber Gap – an event linked to the westernmost penetration of the BIIS up the Humber estuary (Frederick *et al.* 2001; Evans *et al.* 2005): the recorded level increasing slightly in elevation northwards in response to isostatic unloading. Subsequent regression ultimately lowered the lake to −4.0 m a.s.l. before the lake stabilized at elevations between 9.0 and 12.0 m a.s.l.; a level that rises northwards to 14.0 m a.s.l. at the Escrick Moraine (Figs 2, 3) owing to continuing isostatic rebound in that direction (Gaunt 1981). Gaunt (1976) also considered that the disappearance of Lake Humber occurred without leaving regressive shoreline deposits. This may have been a result of silting up (Gaunt 1981) or rapid emptying. Evidence for the latter jökulhlaup-style of drainage are the large-scale foresets, in gravel beds, dipping south-easterly at angles of about 45°, exposed in Prescott's pit near Elloughton and at West Woodside in North Lincolnshire (Sheppard 1897: fig. 2; de Boer *et al.* 1958;: p. 1. II; Bateman *et al.* 2001). Similar bedforms have however been described from braided river deposits (e.g. Hodgson 1978).

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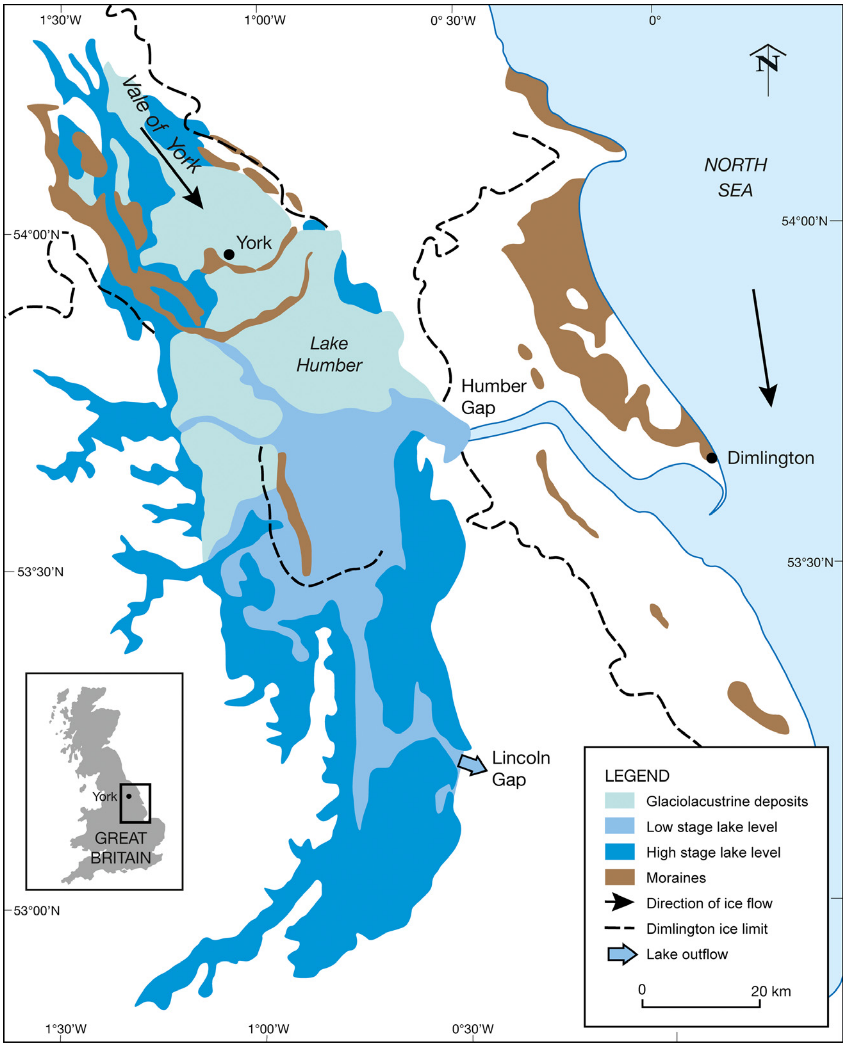


Fig. 1. The high level of Lake Humber, its low-level stand and the distribution of associated moraines and lake deposits (adapted from Clark *et al.* 2004).

In contrast to the model proposed by Gaunt (1976: fig. 1), recent landform mapping and the recognition of localized horizontal or near-horizontal terracing on the York and Escrick moraines (Figs 2, 3), between 15 and 40 m a.s.l., led to conclusions that these planar surfaces could be shorelines marking a retreat of Lake Humber punctuated by stillstands (Fairburn 2009) that gradually drop on a number of occasions.

Each model has profound implications for the size and duration of Proglacial Lake Humber and the advance/retreat dynamics of BIIS in the Vale of York and North Sea basin (Fig. 1). With Gaunt's (1976) two-stage model the North Sea BIIS ice would have had to advance to block the Humber Gap on two occasions and the Vale of York Ice would have had to extend to at least the Escrick Moraine. Additionally, to account for the recognized isostatic depression, ice of considerable volume must have persisted for a long period.

Although the two models are not necessarily mutually exclusive, this study set out to test which model is correct. The approach used was to extend the regional landform mapping from Fairburn (2009, 2011) to other locations (Fig. 2), to confirm the continuity and validity of the major horizontal terracing that is not affected by perceived differential isostatic uplift, establish a better chronology using optically stimulated luminescence (OSL) and utilize recent revisions in understanding of the region's superficial sediments (Ford *et al.* 2008). The resultant lake model, through mapping in GIS, is then discussed with regards to dynamics of the BIIS in the Vale of York and the North Sea.

Geological overview

The Vale of York evolved as a strike-controlled glacial valley eroded into soft Triassic rocks between the east-

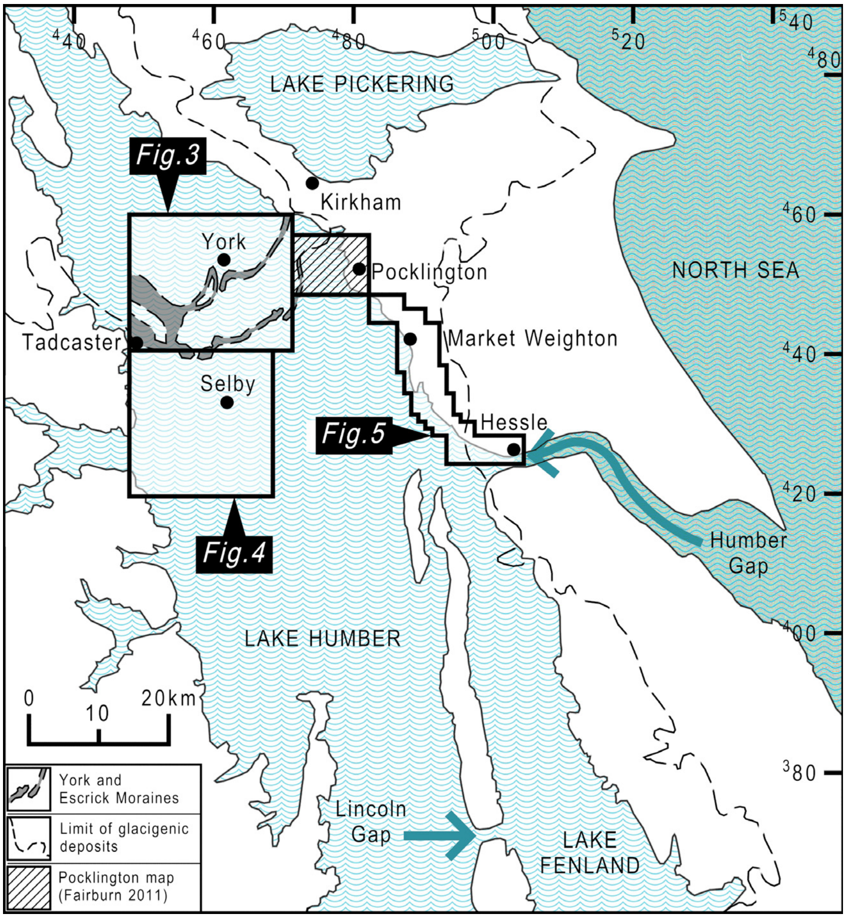


Fig. 2. Location of landform maps Figs 3–5 and the Pocklington map from Fairburn (2011: fig. 2). The mapping of the York and Escrick moraines is from Fig. 3, with part of the Escrick Moraine from Fig. 4.

erly dipping Permian/Carboniferous escarpment to the west and the easterly dipping Jurassic/Cretaceous escarpment to the east; the latter characterized by dry valleys in Chalk formation (the Wolds). Two glacial episodes have been recognized in the Vale of York: a pre-MIS 5e glaciation and a Marine Isotope Stage 2 (MIS 2) glaciation. The Vale of York, a mostly flat, featureless plain, sloping gently southwards, has been partly infilled with deglacial glacifluvial and glaciolacustrine sediments. Rising above this plain are the Escrick and York Moraines as well as eroded inliers of Triassic sandstone (Figs 3, 4). The Triassic ridges, namely the Hambleton Hough/Brayton Barff ridge and the Snaith ridge extending between Kellingley and Pollington (Fig. 4), contain remnants of the pre-MIS 5e glaciation (mainly in excavations) by way of tills and glacifluvial gravels (Gaunt 1994). The oldest of the gravels, termed the 'Younger Pennine Glacial Sand and Gravel' has a distinctive erratic assemblage including Permian limestone referred to by Gaunt (1994) as the 'east Pennine Suite'. This is overlain in places on the Snaith ridge by the 'Fluvioglacial Sand and Gravel' (Gaunt 1994) containing mainly erratics of Carboniferous sandstone. The western slope of the Wolds, in the present study area, is characterized by a mantle of chalk and flint gravel forming coalescing alluvial fans that originated by erosion and fluvial transport of frost-shattered chalk locked in place by permafrost (French 2007; Hitchens 2009). These gravels, named the Pocklington Gravel Formation (Ford *et al.* 2008: pl. 3), were subdivided into two temporally distinct sets of alluvial referred to herein as the Younger and Older Alluvial fans.

Study methods

Mapping

The mapping was completed over three regions (Figs 3–5) covering an area of nearly 1200 km^2 and was undertaken through extensive field visits between 2006 and 2011. Mapping involved many hundreds of kilometres of close-spaced traversing, recording all observed topographical changes in the landscape that could be plotted on 1:25 000 base maps. These features included any level or gently inclined planar land sur-

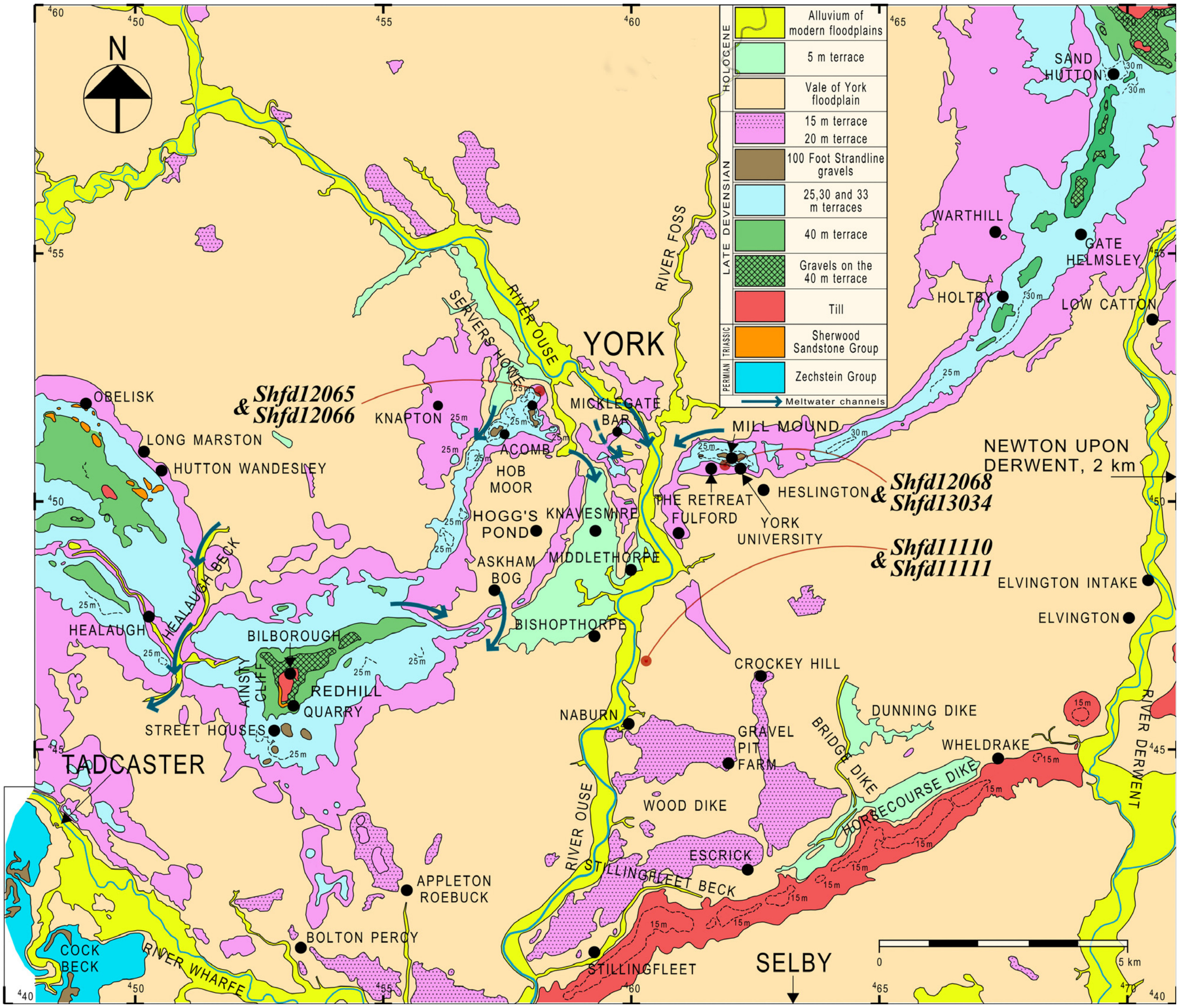


Fig. 3. Geomorphological map of the York and Escrick moraines showing landforms that developed between shorelines during the retreat of Lake Humber. Note OSL sample locations (Shfd nos). Topographical data on Figs 3–5 are 'Crown copyright Ordnance Survey'.

face that had distinct topographical boundaries resulting from erosional or depositional processes.

In contrast to the mapping of the parallel roads (shorelines) of Glen Roy (Lowe *et al.* 2008: fig. 2), planar terraces on the York and Escrick moraines do not provide conspicuous features. Because of this, mapping of the convex frontal edge of a terrace is often not precisely defined. This contrasts with the back-wall or strandline of the terrace because the point of inflection between the level terrace and the rising back-wall is a visible feature often highlighted by a bottom-slope drainage ditch or field-boundary hedgerow. Consequently as the back-wall or strandline can be plotted with a vertical accuracy of ~1.0 m in most cases (without the need for GPS), it was decided to use as the mapping unit the interval between two successive strandlines. This interval is referred to as a terrace following the definition by Jackson & Bates (1997) who described a terrace as consisting of a flat or gently sloping geomorphic feature called a tread, that is typically bounded by its ascending back-wall and the descending slope to the terrace below: the tread and the descending slope together constitute the terrace.

In addition, so as to check the validity and accuracy of the landform mapping, high-resolution LiDAR Digital Elevation Model (DEM) data with a surface spatial resolution of 50 cm was acquired over an area of 1.0 km^2 on the crestal part of the York Moraine around Mill Mound (Fig. 3). This was obtained as LiDAR has successfully been employed elsewhere to map shorelines, e.g. Yang & Teller (2012) for proglacial Lake Agassiz in North America.

On the final maps produced (Figs 3–5) it was decided not to colour code terracing on the Hambleton

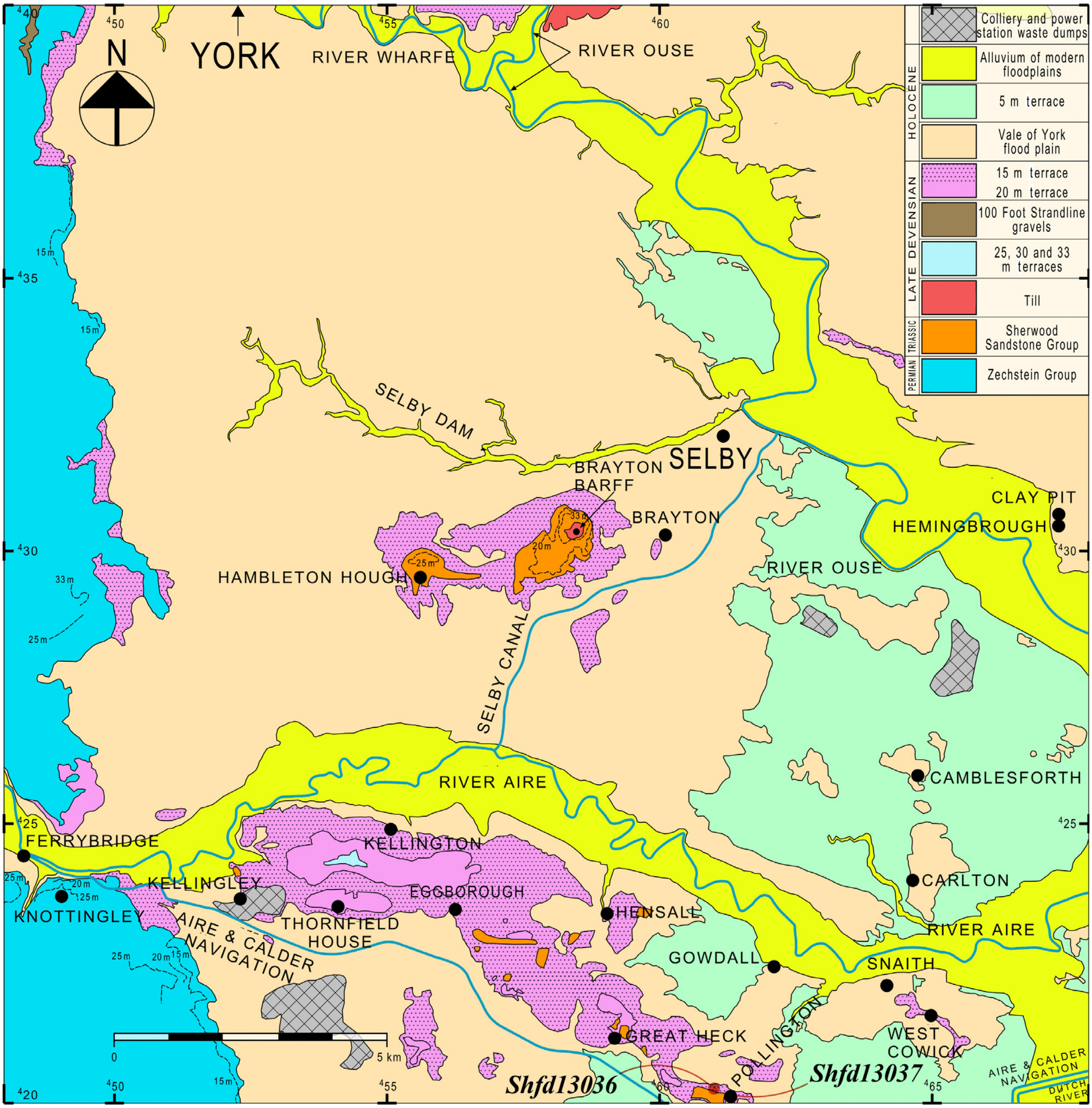


Fig. 4. Geomorphological map in the region of Selby showing Lake Humber terraces developed on the eastern side of the Pennine escarpment and on the Brayton Barff and Snaith Triassic ridges (OSL sample locations are shown).

Hough/Brayton Barff ridge and the Escrick Moraine, similarly to that on the York Moraine and the Wolds (Figs 3, 5) in order to differentiate till on the summit of Brayton Barff and equate the Escrick Moraine with mapping near Pocklington.

OSL dating

Sample preparation designed to clean and isolate quartz grains, under low-intensity red lighting, followed the procedures of Bateman & Catt (1996), took place in the Sheffield Luminescence Laboratory to separate sand in the range 90–250 μm. Sample purity after preparation was tested using infrared stimulated luminescence. OSL measurements were conducted on 9.6 mm discs with samples mounted as a monolayer. Measurements were undertaken with a TL-DA-15 RISØ automated luminescence reader with stimulation provided by blue diodes emitting at 470 nm. The OSL signal was detected through a 7.5 mm Hoya U340 filter with measurements carried out for 80 s at 125 °C.

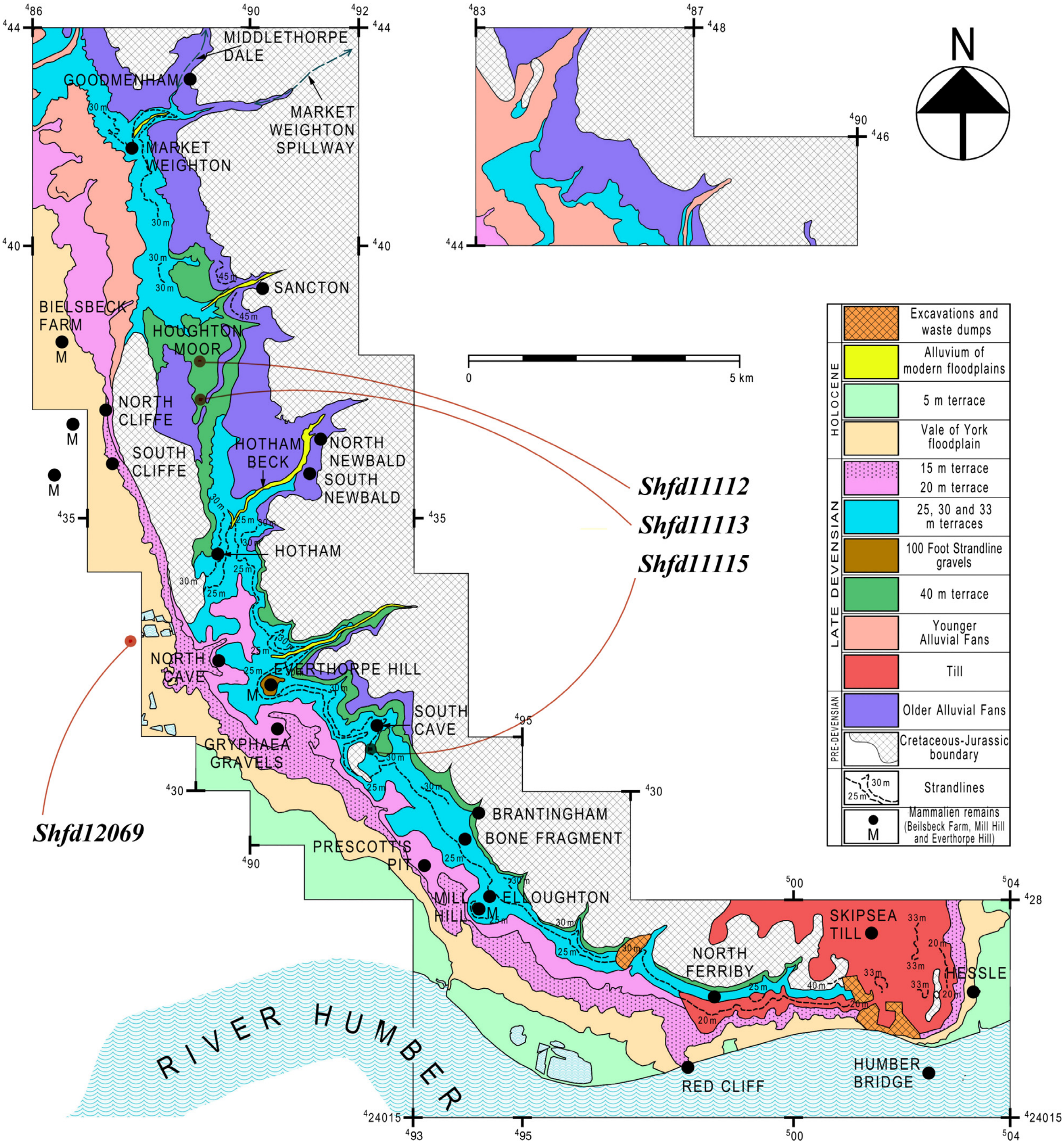


Fig. 5. Geomorphological map along the western face of the Wolds between Market Weighton and Hessle showing the imprint of Lake Humber shorelines on the Skipsea Till and the Older Alluvial Fans (OSL sample locations are shown).

Palaeodose (De) values were derived using the single aliquot regeneration (SAR) protocol (Murray & Wintle 2000) using four regeneration points and a recycling dose. The preheat temperature in the range 160–180 °C for 10 s used for the SAR protocol was determined experimentally using a dose-recovery preheat plateau test (Murray & Wintle 2003). For each aliquot OSL measurement, the first 1.6 s was used as signal and the final 12 s was averaged and subtracted as background. Multiple replicates of each sample were undertaken to give an indication of De reproducibility. All samples exhibited low thermal transfer, good recycling and OSL decay curves, indicating that the signal was dominated by the fast component and rapidly bleachable.

Dose rates were determined from *in situ* field measurements carried out with an EG&G Micronomad field gamma-spectrometer. Dose rates were appropriately attenuated for sediment size and palaeomoisture contents. The latter were based on moisture content at the time of sampling with an absolute error of 5.0% incorporated to allow for past changes. Cosmic dose rates were determined following published algorithms (Prescott & Hutton 1994).

Results

Mapping

The results of the landscape mapping can be seen on Figs 3–5. These were used as the basis for a re-interpretation of the physiographical evolution of Lake Humber since the LGM. Within this a number of terraces have been identified. As Lake Humber is known to have been in recession, with falling lake levels, it is assumed that the majority of the imprinted shorelines are regressive in nature (cf. the model for Lake Agassiz proposed by Yang & Teller (2012)), although this cannot be demonstrated from field mapping alone. By contrast, transgressive events would probably have been of short duration. These can be identified from mapping where lake levels were able to wash across the crest of a moraine to deposit sand and gravel ridges, and in places subaqueous fans or screes.

52 m terrace. – The 52 m terrace was originally recognized by de Boer *et al.* (1958) in the region of Market Weighton where it forms the boundary between the Older Alluvial Fans and the base of the Cretaceous (Fig. 5). It was later referred to as the 52 m strandline or shoreline by Penny (1974) and Thomas (1999). Mapping shows that from the north, near Market Weighton, the terrace declines southerly to about 40 m near Hessle (Fig. 5). The terrace is interpreted as a shoreline, below which the Older Alluvial Fans were deposited, that has been tilted by differential isostatic uplift. Dating of the terrace (see OSL dating results) is based on a single OSL sample taken from the Older Alluvial Fans, near South Cave (Fig. 5). It is therefore suggested that the terrace represents a mid-Pleistocene shoreline below which were deposited the Older Alluvial Fans that were terraced by Lake Humber subsequent to the MIS 2 glaciation.

42 m terrace (Stage 1). – Evidence for a 42 m terrace, marking a possible maximum elevation for Lake Humber (S1, Table 2), is based on the recognition of a cobble-strewn level erosion surface corrugated in places with discrete mounds of sand and gravel above a 40 m terrace on the York Moraine around Bilbrough (Fig. 3). That transgressive shoreline washing may have occurred is indicated by sand and boulder beds, on the southern flanks of the moraine, in a road-cut east of Bilbrough. Although not present everywhere above the 40 m terrace, it has been identified in places on the Wolds between Market Weighton and Sancton (Fig. 5), again marking the maximum elevation of Lake Humber.

40 m terrace (Stage 2). – The first distinctive terrace below the crest of the York Moraine (S2, Table 2), is recorded by the 40 m terrace that is demonstrably below the 42 m terrace around Bilbrough (Fig. 6A) and by terracing around gravel deposits near Gate Helmsley (Fig. 3). Elsewhere it is formed by till with a surface lag of boulders and cobbles overlying an erosional surface on Triassic sandstone (Fig. 7A).

Evidence for a 40 m strandline was noted from Market Weighton to Everthorpe (Figs 5, 6B) where older alluvial fans are terraced at 40 m. Localized terracing at 40 m a.s.l. was also observed on Hambleton Hough and Brayton Barff (Fig. 4).

33 m terrace (Stage 3). – The 33 m terrace (S3, Table 2) is the most conspicuous terrace of Lake Humber as it has produced a well-marked shoreline eroded into the Magnesian Limestone along the western margin of the Lake, mapped by Edwards (1937) as the 100 Foot Strandline, as well as a conspicuous scarp eroded into Triassic sandstone south of Bilbrough (Fig. 6C), indicating emergence of much of the York Moraine from Lake Humber. On the crest of the York moraine (Fig. 3), where the elevation of the moraine was close to the 33 m lake level, a distinctive transgressive beach was formed by shoreline washing across the moraine. The beach, with a strandline on Mill Mound (Fig. 6D), is largely formed of sand and gravel reworked from the underlying till that contains Carboniferous sandstone and limestone erratics. The most distinctive feature produced by the shoreline washing has been the segregation of the till into boulder lag deposits and banks of sand and gravel. In addition, a sandy mantle, or sand scree, at least 2.0 m thick, covers the southern slopes of the York moraine (Fig. 7B). The origin of the sand, with an accompanying spoon-shaped slump scar (Fig. 8A, B), has been likened to the formation of steep-face coarse-grained deltas (Nemec 1990a,b), but without appreciable ravinement owing to similar water levels on both sides of the moraine. Although the southerly flow of meltwater in Lake Humber was partially impeded by the York Moraine causing spillage across the moraine, there is evidence along Healaugh Beck, west of Bilbrough (Fig. 3), by way of erosion channels along the back-wall of the 33 m terrace (Fig. 3), that there was discharge of meltwater through this valley, referred to as the Healaugh Gap.

This terrace, recognized on Brayton Barff (Fig. 4), is also a well-defined feature (Fig. 6B) on the Wolds that can be followed from Market Weighton to Hessle where it can be traced across the Skipsea Till (Fig. 5).

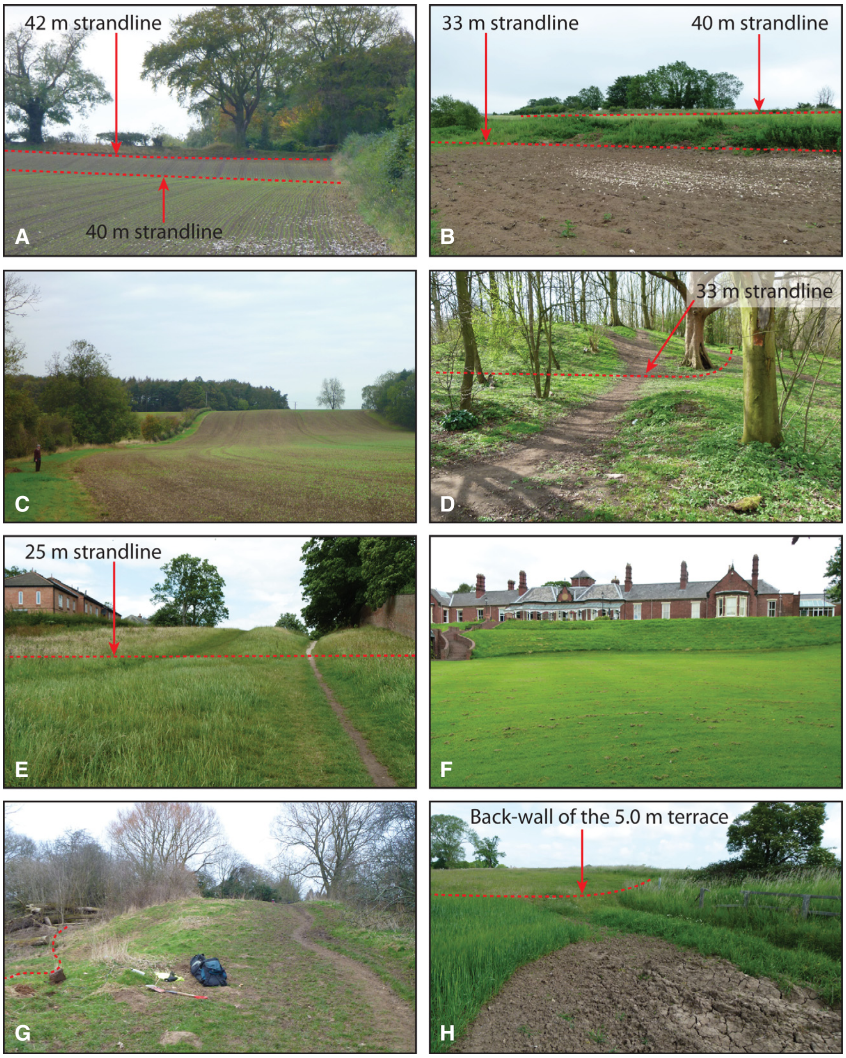


Fig. 6. Terracing and strandlines mapped in the Vale of York. A. The 42 and 40 m terraces north of Bilbrough (Fig. 3). B. The 33 and 40 m terraces in the Hotham valley (Fig. 5). C. The back-wall of the 33 m terrace south of Bilbrough (Fig. 3). D. The 33 m strandline around Siwards How near York University (Fig. 3). E. The 25 m terrace west of The Retreat (Fig. 3). F. The 20 m terrace below The Retreat (Fig. 3). G. The back-wall of the 20 m terrace rising to the 25 m terrace below Mill Mound (Fig. 3). H. The 5 m terrace south of Snaith (Fig. 4).

Gravel deposits on the terrace at Everthorpe (Dakyns *et al.* 1886; de Boer *et al.* 1958; Gaunt 1976) and Mill Hill at Elloughton (Lamplugh 1887; Sheppard 1897; de Boer *et al.* 1958) are thought to be equivalent to the 100 Foot Strandline gravels of Edwards (1937) and have been mapped as such along with coeval gravels at Mill Mound and Street Houses south of Bilbrough (Fig. 3).

30 m terrace. – Recognizable as a minor terrace on the crest of the York Moraine on Mill Mound (Fig. 8A, B), and in places below the crest of the moraine between Mill Mound and Sand Hutton (Fig. 3), this terrace lacks distinct lateral continuity. Although also recognizable on Hambleton Hough (Fig. 4) and in places along the Wolds (Fig. 5), mapping has not confirmed this feature as marking a major stage in the demise of Lake Humber as it could also mark a change of lithology in the superficial deposits. It has therefore been incorporated within the unit comprising the 33 m terrace.

25 m terrace (Stage 4). – This terrace is a distinctive feature on the York Moraine near Severs Howe (Fig. 3; S4, Table 2) and at the eastern end of Mill Mound where the terrace has a steep back-wall rising to the 33 m terrace (Fig. 9A). At both these locations the terrace has been modified by channel-confined flow through the moraine. The 25 m terrace has also been mapped on Mill Mound (Figs 3, 6E, G) and on the northern end the Escrick Moraine. The 25 m terrace is also conspicuous on Hambleton Hough and along the face of the Wolds, particularly northwest of Hessle (Fig. 5).

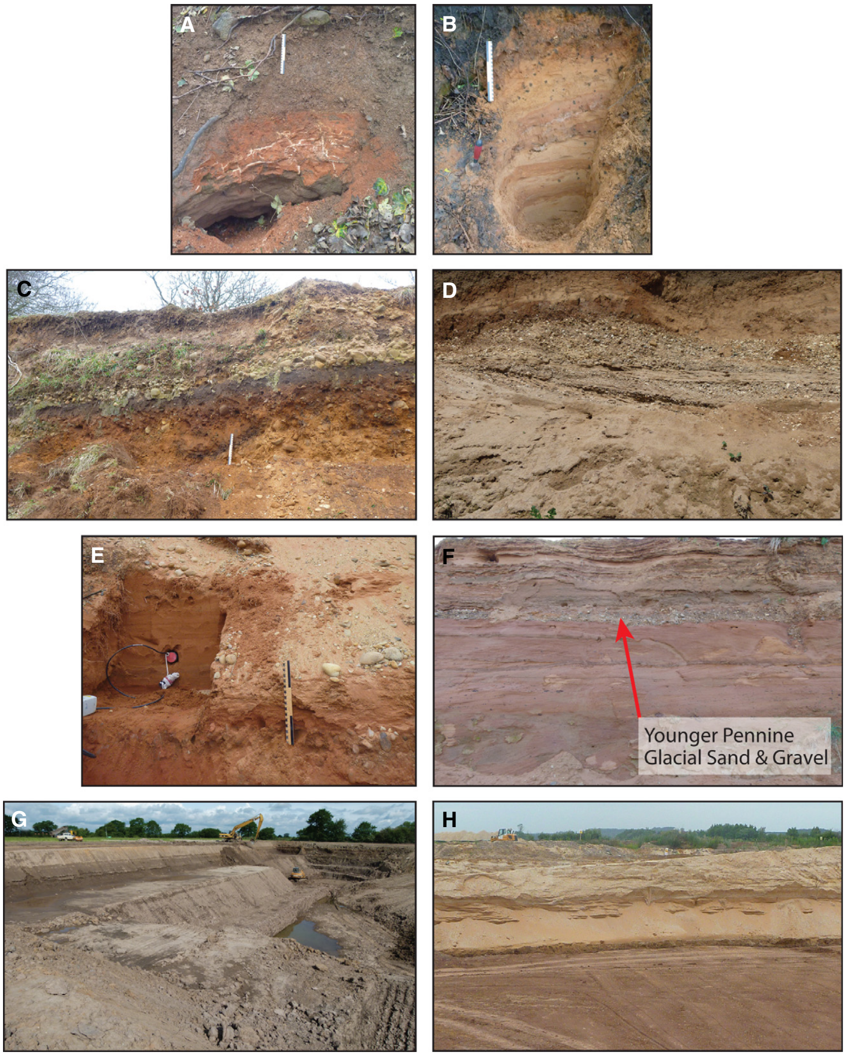


Fig. 7. Sections exposed in quarry and pit excavations. A. Till overlying Triassic red sandstone south of Bilbrough (Fig. 3). B. OSL sample point below Severs Howe (Fig. 3). C. Gravels below the 15 m terrace in a sand pit near Pollington (Fig. 4). D. Gravels below the 15 m terrace at Red Cliff (Fig. 5). E. 'Younger Pennine Glacial Sand and Gravel' exposed at an OSL sample point in a sand pit near Pollington (Fig. 4). F. 'Younger Pennine Glacial Sand and Gravel' exposed above red Triassic sandstone in a sand pit near Hensall (Fig. 4). G. The Hemingbrough clay pit (Fig. 4). H. Interbedded sand and flint gravel in the North Cave Wetlands (Fig. 5).

20 m terrace (Stage 5). – The 20 m terrace is the most widespread terrace fringing the York Moraine, as it has been mapped extensively on both its northern and southern flanks (Figs 3, 6F; S5, Table 2). It has also been mapped on Brayton Barff, Hambleton Hough, on the crestal parts of the Snaith ridge (Fig. 4), on the face of the Wolds south of North Cave and across the Skipsea Till near North Ferriby (Fig. 5). Emergence of parts of the crest of the Escrick Moraine must also have occurred at this stage. Further evidence of the littoral origin of the 20 m terrace is provided near South Cave where a gravel deposit at Ellerker containing horizontally bedded gravels, over an erosional surface on steeply dipping fluvial gravel, are thought to be back-beach deposits (Sheppard 1897; de Boer *et al.* 1958: fig. 5).

The 20 m terrace is especially significant as its wide distribution particularly to the north of the York Moraine indicates appreciable shrinkage of Lake Humber (Fig. 3). The elevation of the 20 m terrace also meant that the moraine became an effective dam across the Vale of York, and flow became restricted to drainage through the Healaugh and York gaps. Erosion in the latter formed a multi-channel system over 2.0 km wide east of Severs Howe and an alluvial coarse-grained fan delta (as defined by Nemec 1990a) extended from Fulford towards Crockey Hill and Gravel Pit Farm (Fig. 3). Evidence for flow across the crest of the moraine was observed east of Mill Mound (Fig. 3). Only remnants of the original 20 m terrace through the York Gap now remain.

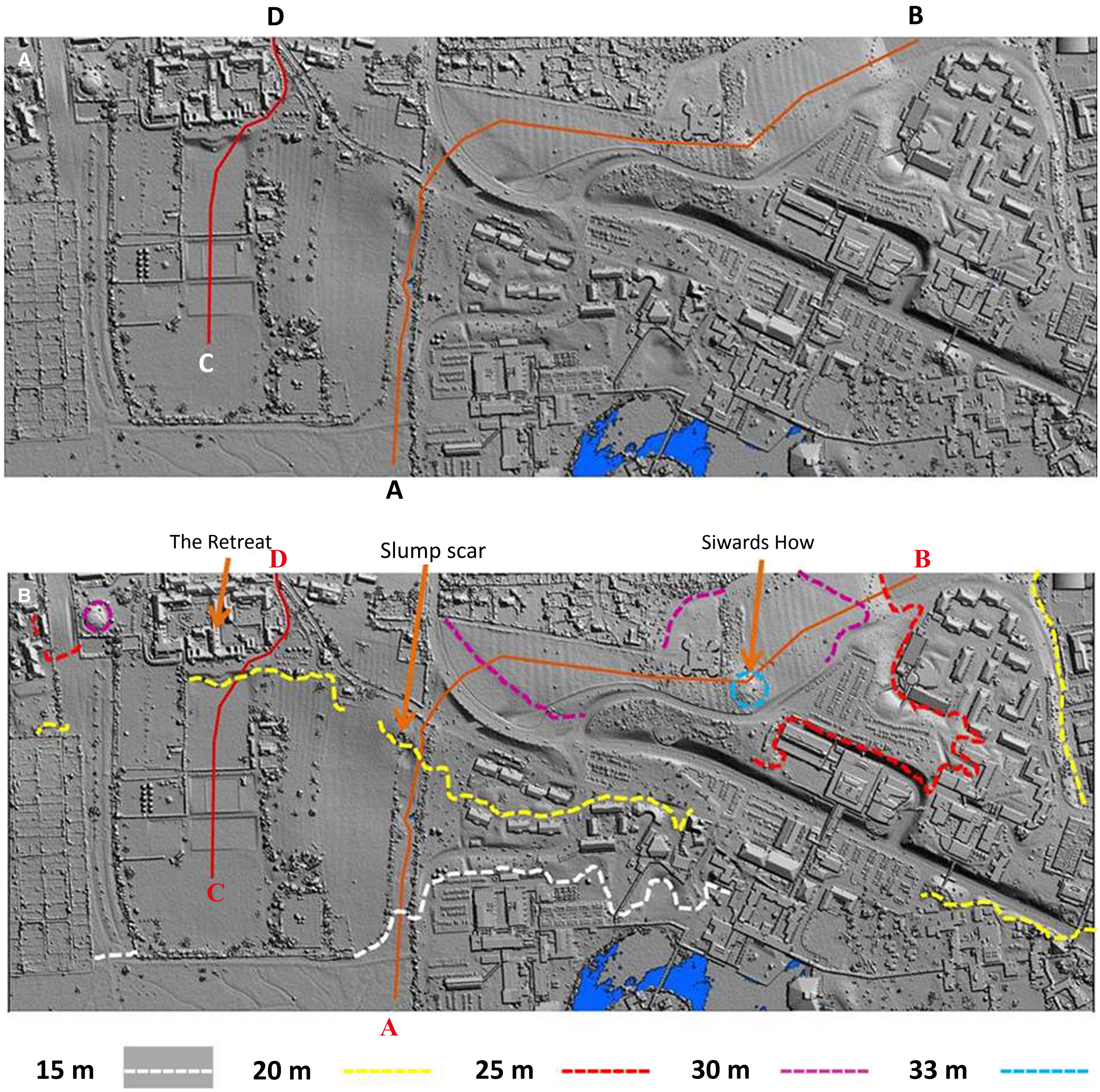


Fig. 8. A. LiDAR hillshade map of the York Moraine below Siwards How on Mill Mound. A–B and C–D are the section lines of the profiles shown on Fig. 9A, B. Scale: 0.5×1.24 km. LiDAR data on Figs 8A, B, 9A, B are '© Environmental Agency 2014'. B. LiDAR hillshade map as in (A). The back-wall of the terracing, where recognized, has been colour coded. Note the slump scar.

The only evidence provided by the detailed mapping, where the Lake Humber terraces are not horizontal and may show convergence, occurs near the drainage outlets through the York Moraine where the 20 m terrace has been modified by later flow during lake drainage.

15 m terrace (Stage 6). – At the 15 m a.s.l. lake level, this shoreline of Lake Humber forms a distinct terrace extending from Bolton Percy to Crockey Hill and then eastwards to the edge of the Wolds south of North Cliffe (Figs 3, 5; S6, Table 2), indicating a southerly retreat of the lake. As a consequence of this, a lower erosion level was imposed on the southern part of the Crockey Hill fan delta between Crockey Hill and Gravel Pit Farm (Fig. 3). The 15 m shoreline is less distinct on the York Moraine below the 20 m terrace, indicating that, although the 15 m a.s.l. lake did extend as far north as the moraine, either the terrace has not been well preserved or this event was transitory. Emergence of the Escrick Moraine must have produced a short-lived period when water washed across the crest of the moraine but there is no recognizable evidence for a coarse-grained sandy delta deposit or sand scree,

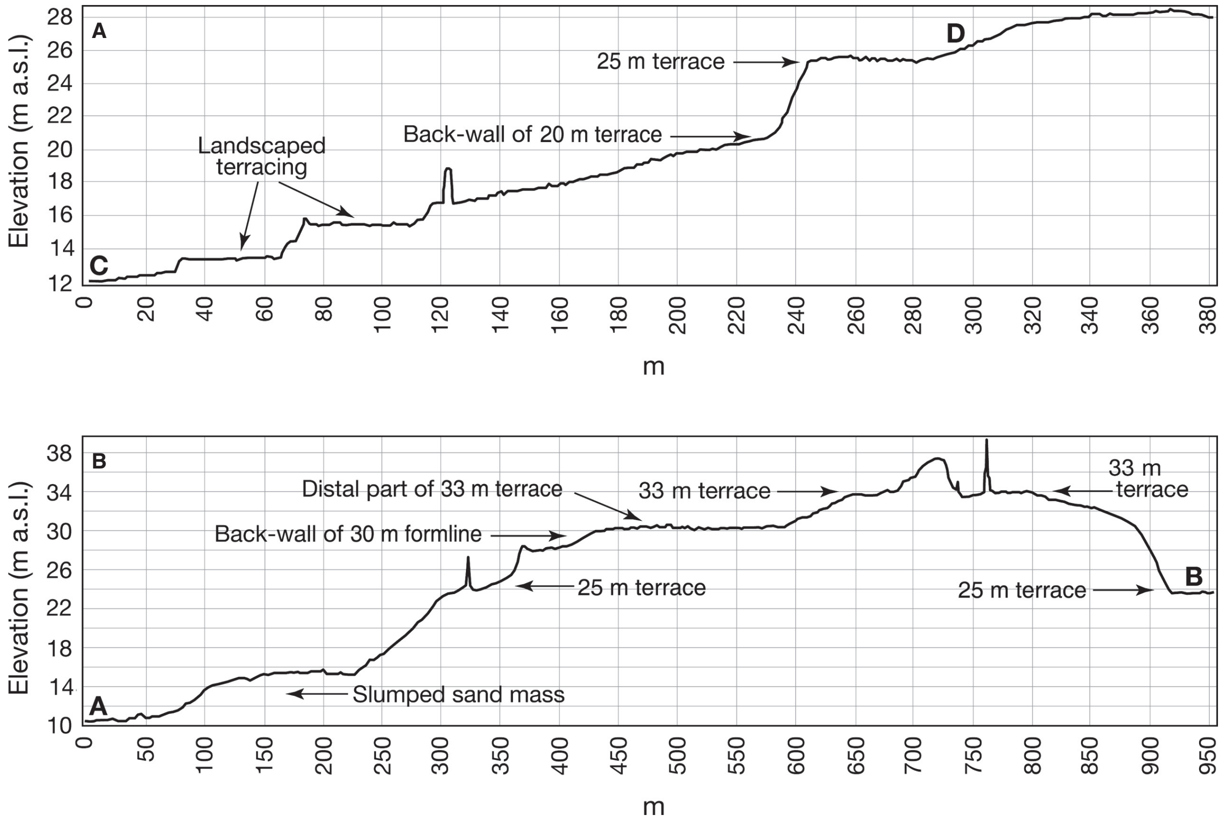


Fig. 9. A. LiDAR DEM profile A–B on the York Moraine (see Fig. 8B) showing planar terracing at ~25, ~30 and ~33 m. Note the apparent absence of the 20 m terrace and the presumed slumped mass at the base of the section. B. LiDAR DEM profile C–D below 'The Retreat' (see Fig. 8B). Note the steep back-wall of the 20 m terrace – the indistinct terrace below, at this point, is a result of landscape modification (cut and fill). The 25 m terrace is more conspicuous.

as found on the York Moraine, when it emerged from the lake. Any redeposited sand would therefore have to have been incorporated into sediments bordering the southern flanks of the moraine.

Along the northern edge of the Escrick Moraine the 15 m terrace, underlain by till, has been detached from the moraine by an erosion channel extending from the River Derwent to the River Ouse. This channel east of Escrick has been deepened possibly in the Holocene to form a 5 m terrace in the region of Bridge Dike and Horsecourse Dike (Fig. 3). Such a feature must have resulted from the entire length of the Escrick Moraine emerging as a barrier across the Vale of York and diverting meltwater towards the Derwent and Ouse river outlets causing steepening of the north face of the moraine (Melmore 1935: fig. 7). A trench section, extending from Elvington to the south of the moraine (Gaunt 1970: fig. 1), clearly shows this erosional episode with an initial gravel-filled channel later excavated and refilled with cross-bedded and parallel-bedded sands below the 10 m terrace (Gaunt 1970: fig. 2).

Both Brayton Barff and Hambleton Hough are surrounded by the 15 m terrace, which has a back-wall eroded into the Triassic sandstone of both hills. The terrace is underlain by cross-bedded red sand (observed in excavations), with some surface erratics of Carboniferous sandstone.

On the central part of the Snaith ridge (Fig. 4) the 15 m terrace has been eroded into the pre-MIS 5e 'Fluvioglacial Sand and Gravel' of Gaunt (1994) but towards the eastern end of the ridge as at Pollington (Fig. 7C) and Hensall it is formed by littoral deposits over an eroded surface (possibly cryoturbated) of Triassic sandstone.

South of North Cliffe to beyond Hessle (Fig. 5), the 15 m terrace has been imprinted into the Skipsea Till thus again confirming that the till must pre-date Lake Humber and did not form a barrier across the Humber gap at this time. At Redcliffe (Fig. 5) a section through the 15 m terrace (Fig. 7D) displays easterly dipping bedforms of sand and gravel overlying an erosional surface on the Skipsea Till, indicating drainage towards a Humber mouth exit.

Vale of York flooding surface (Stage 7, ~10 m). – A widespread phase of lacustrine, fluvial and shoreline deposition in the Vale of York is represented by the Vale of York flooding surface that extends in places from the Permian escarpment in the west to the foothills of the Wolds in the east and is underlain by lami-

Table 1. OSL data for sample sites in the Vale of York.

Site	Sample no.	Alt. (m a.s.l.)	Depth (m)	Moisture (%)	Size (µm)	K (%)	U (ppm)	Th (ppm)	Dose rate (μGY ka^{-1})	±	Cosmic (μGY ka^{-1})	±	De (Gy)	±	Age (ka)	±
Naburn sewer 1	Shfd11110	10.0	1.0	14.16	125–180	1.2	1.33	4.6	1739	87	184	9	7.51	0.32	4.32	0.28
Naburn sewer 2	Shfd11111	10.0	1.0	14.81	125–180	1.4	1.38	5.0	1925	98	184	9	17.58	0.76	9.13	0.61
Houghton Moor 1	Shfd11112	38.8	0.75	15.58	125–180	0.8	0.89	2.3	1166	56	191	10	8.75	0.21	7.51	0.40
Houghton Moor 2	Shfd11113	38.5	1.30	18.27	125–180	0.7	0.60	1.5	936	46	178	9	7.71	0.27	8.24	0.49
South Cave 1	Shfd11115	35.0	0.85	16.05	125–180	1.3	1.63	4.4	1829	92	189	9	370.8	10.6	202.7	11.7
Severs Howe 1	Shfd12065	20.0	0.60	5.70	125–180	1.43	1.39	4.79	2162	112	195	10	112.4	3.8	52.0	3.2
Severs Howe 2	Shfd12066	20.0	0.95	4.60	125–180	1.29	1.23	3.81	1952	101	186	9	123.1	3.9	63.1	3.8
Mill Mound 2	Shfd12068	22.0	0.86	16.10	125–180	1.55	1.55	6.62	2139	109	188	9	33.95	0.73	15.9	0.9
North Cave 1	Shfd12069	6.0	4.00	9.10	125–180	1.11	0.83	3.75	1535	82	124	6	89.62	1.77	58.4	3.3
Mill Mound 3	Shfd13034	22.0	1.76	10.85	125–180	1.06	1.09	4.33	1596	68	166	8	24.27	0.33	15.21	0.68
Pollington 1	Shfd13036	11.0	0.55	3.85	125–180	0.83	1.26	4.76	1545	77	127	6	23.95	0.27	15.5	0.8
Pollington 2	Shfd13037	6.2	3.20	4.58	125–180	1.65	0.89	4.44	2174	126	116	6	103.6	2.6	47.6	3.0

nated clay and fluvial sands. Much of this surface is represented by the eroded remnants of an original 10 m terrace (S7, Table 2).

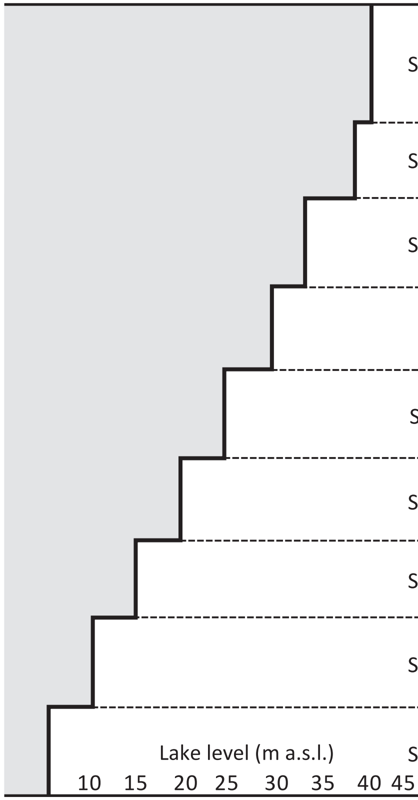
Laminated Clays, originally included as part of the '25 Foot Drifts' by Edwards (1937), have since been redefined and subdivided into three temporally related but geographically distinct members, one of which (Thorganby Clay Member) is considered to form the upper part of the Hemingbrough Glaciolacustrine Formation (Ford *et al.* 2008: fig. 6). The most informative data on the nature of the laminated clays have been provided by clay pits and excavations that are now infilled or inaccessible. These include the Wheldrake section (Gaunt 1970: fig. 3) and its extension southwest of Brayton Barff (Gaunt 1976), a drainage ditch along the disused Selby railway line (Dakyns *et al.* 1886: fig. 3) and former clay pits at Hog's Pond (Kendall & Wroot 1924: fig. 3) and Newton on Derwent (Ford *et al.* 2008).

Where the laminated clays are absent, for example to the east of Brayton Barff and at the eastern end of the Snaith ridge (Fig. 4), the flooding surface is commonly underlain by a thin sequence of fluvial cross-bedded red sand on gravels of the 'east Pennine Suite' over Triassic sandstone as at Pollington (Fig. 7E), Hensall (Fig. 7F) and Great Heck (Parsons 1887). Elsewhere, such as at Bielsbeck Farm (Schreve 1999 from Harcourt 1829) and quarries west of North Cave (Figs 5, 7H), the flooding surface is underlain by chalk and flint gravels comparable to those on the terraced slopes of the Wolds.

Breighton Sand Formation, the sequence of fluvial sands (Ford *et al.* 2008: fig. 7), is widespread in the Vale of York, but because of its erosional contact, through incision, into the laminated clays below, such as the Thorganby Clay Member, it was not recognized as a discrete unit and mapped incorrectly as 'Sand of the 25–Foot Drift of the Vale of York' (Edwards *et al.* 1950; British Geological Survey 1971). The formation is therefore younger than the final stage of lacustrine sedimentation but older than a late phase of the 5 m terrace that forms an erosional surface across it north-northwest of Selby (Fig. 4). The erosional contact with the underlying laminated clays was illustrated by Gaunt (1970: fig. 2). To the east of the River Derwent, the sand can be mapped in a shallow, southeasterly trending valley with the basal contact of the sand inclined southwards at 0.62 m km^{-1}, comparable to modern drainage.

The age of the sand (Table 1) is early Holocene based on OSL dating of samples from near Naburn (Shfd1 1110, Shfd11111) and Houghton Moor (Shfd11112, Shfd11113). Based on the above dating and the erosional incision of the Breighton Sand Formation into the laminated clays it would appear that much of the southerly slope on the plain of the Vale of York is the result of Holocene erosional flooding.

Table 2. Chronology of the multi-stage demise of high-level Lake Humber from Stage 1 to Stage 8 (S1–S8).



Lake levels		Time (ka)	Depositional event	BIIS/Vale of York glacier
Pre-cursor Low-level Lake Humber		<23.3±1.5	Loess under till Ferrybridge (Bateman *et al.* 2008)	Advance of Vale of York glacier
		<22.2±0.5	Park Farm Clay Member – lacustrine sediments (Murton *et al.* 2009)	Deposition of Vale of York till
		c. 22.2±0.5	Lawns House Farm Sand Member – lacustrine sediments (Murton *et al.* 2009)	Emplacement of Escrick Moraine
	S1	<17.5±1.7 17.01±1.33	42 m terrace Loess below Skipsea Till (Wintle & Catt 1985) Sediments in Skipsea Till (Hartmann 2011)	BIIS advance Humber Gap blocked
		>16.6±1.2	High-level Lake Humber (Bateman *et al.* 2008)	
	S2	>16.6±1.2	40 m terrace at Bilbrough, Brayton Barff and the Yorkshire Wolds (this study)	
	S3	16.6±1.2	33 m terrace at Ferrybridge (Bateman *et al.* 2008) Deposition of sand scree on Mill Mound (this study)	Skipsea Till terraced at Hessle, 33 m a.s.l.
		16.2±0.4	Sands below Withernsea Till (Bateman *et al.* 2011)	Skipsea ice retreat before 16.2 ka Advance Withernsea ice after 16.2 ka Humber Gap blockage stabilized
	S4	15.9±0.9 (Shfd12068) 15.2±0.68 (Shfd13034)	Reworked sand scree between 20–25 m below Mill Mound (this study)	
			Termination for some Younger Alluvial Fans	
	S5	15.38±0.92 cal. BP	Roos Bog (Bateman *et al.* 2011) develops over Withernsea Till	Retreat of Withernsea ice before 15.38 ka
			Most Younger Alluvial Fans terminate	
	S6	15.5±0.8 (Shfd13036)	Sand below 15 m terrace at Pollington (this study)	
	S7	<15.5±0.8	10 m terrace Southerly dipping bedforms of sand and gravel below 10 m terrace at Pollington (this study)	
	S8	<15.5±0.8	Lowest level of Lake Humber (this study)	

5 m terrace (Stage 8). – The ultimate stage in the regression of Lake Humber is recorded by a shallow lake with a 5 m shoreline in an area still subject to present-day flooding (S8, Table 2). It is developed to the east and northeast of the Snaith Ridge where it extends down the west bank of the River Ouse from Wistow towards the River Aire (Fig. 4). Its back-wall is generally a distinct boundary that can be seen south of Snaith (Fig. 6H) and around 'islands' within the terrace occupied by the villages of Camblesforth and Carlton (Fig. 4).

Drainage into the 5 m lake is also represented by terraces bordering the Ouse and Derwent rivers (Fig. 3) referred to by Melmore (1940) as the 10 ft terrace (i.e. above modern river alluvium) and by a depositional surface in the erosional channel north of the Escrick Moraine (Fig. 3).

OSL dating

The results for the samples taken are shown in Table 1. These are used to provide a chronological framework for the physiographical evolution of the Vale of York. Three distinct groups of ages were recorded.

Pre-lake Humber events. – At South Cave, a sample from the landscaped back-wall of the 33 m terrace cut into the Older Alluvial Fans gave an age of 202.7±11.7 ka (Shfd11115). This indicates that the Older Alluvial Fans just post-date the MIS 7 interglacial and the age post-dates the 52 m terrace and pre-dates the 33 m terrace. The sample from North Cave (Shfd12069, Fig. 7H), which underlies the 5 m terrace, returned an age of 58.4±3.3 ka and therefore must pre-date this terrace. As the De values of this sample (Table 1) are normally distributed, age over-estimation due to incomplete bleaching would appear unlikely. Given its proximal position from the Older Alluvial Fans, sediment at this site is attributed to fluvial reworking of older sediment during the late MIS 2 periglacial period. From the Pollington 2 site (Shfd13037, Fig. 7E), a sand sample associated with the 'east Pennine suite' of gravels gave an age of 47.6±3.0 ka. However, based on the wide scatter of De values (Table 1) indicating incomplete bleaching, this is probably a maximum age for final burial. Both samples from Severs Howe came from the back-wall of the 20 m terrace on the York Moraine (Shfd12065, Shfd12066, Fig. 7B). Both show a strong, almost bi-modal De tail (Table 1), reflecting partial bleaching from source sediment within the moraine that was redeposited in a sub-aqueous, coarse-grained delta by transgressive shoreline erosion across the moraine. Ages of 52.0±3.3 ka (age based on minimum De = 39.1±3.0 ka) and 63.1±3.8 ka (age based on minimum De = 39.6±3.6 ka) must over-estimate the burial date of the sandy delta deposit and the 20 m terrace, and hence the age of the moraine.

Lake Humber terraces. – Both Mill Mound (Shfd 12068, Shfd13034, Fig. 6G) samples came from roughly the same site on the 25 m terrace but at different depths (S4, Table 2). Ages of 15.9±0.9 and 15.2±0.7 ka, respectively, are similar with De values that suggest good bleaching of sand re-worked from the mapped terraces. Sample Shfd13036 from below the 15 m terrace at the Pollington 1 site (Fig. 7C; S6, Table 2) gave an age of 15.5±0.8 ka, comparable to the Mill Mound samples.

Holocene. – From below the Vale of York flooding surface, which post-dates the 10 m terrace (S7, Table 2), both samples (Shfd11110, Shfd11111) from the Naburn Sand Member of the Breighton Sand Formation show an almost bi-modal distribution of De values indicative of their mixed fluvial/aeolian origin. Ages of 4.3±0.3 and 9.1±0.61 ka support Holocene incision into the Vale of York laminated clays (Elvington Glaciolacustrine Formation, British Geological Survey 2008). The two samples from Houghton Moor (Shfd11112, Shfd11113) show a uni-modal distribution of De values that give ages of 7.51±0.04 and 8.24±0.49 ka, respectively, confirming a Holocene age.

LiDAR analyses

The acquired LiDAR data around Mill Mound were used to prepare a Digital Surface Model (DSM) hillshade map of the area (Holden *et al.* 2002) and profile graphs on the slope of the moraine. As can be seen on Fig. 8A, B, LiDAR shows good duplication of the field mapping. Back-wall mapping of the hillshade landforms shows distinct terracing (although not continuous) on the imaginary. occurring at approximately 15, 20, 25, 30 and 33 m. a.s.l. The LiDAR mapped terraces are most pronounced where there are indentations or recesses in the back-wall of the terrace, e.g. the 15 and 20 m terraces (Fig. 8B). Similar replication of the field mapping by LiDAR was also recognized by the authors in the region of Everthorpe. The DEM profile graphs on the slope of Mill Mound (Fig. 9A, B) also closely conform with the landform mapping. Profile A–B (Figs 8A, 9A) shows planar terracing at 25, 30 and 33 m a.s.l. in good agreement with the hillshade landforms mapped on Fig. 8B. Profile C–D (Figs 8A, 9B) better illustrates the back-wall of the distinct 20 m a.s.l. terrace and the 25 m a.s.l. terrace. In summary, LiDAR was able to verify the accuracy of the landform mapping (Figs 3–5) although the patchiness of data precluded it from being adopted more widely for this regional study.

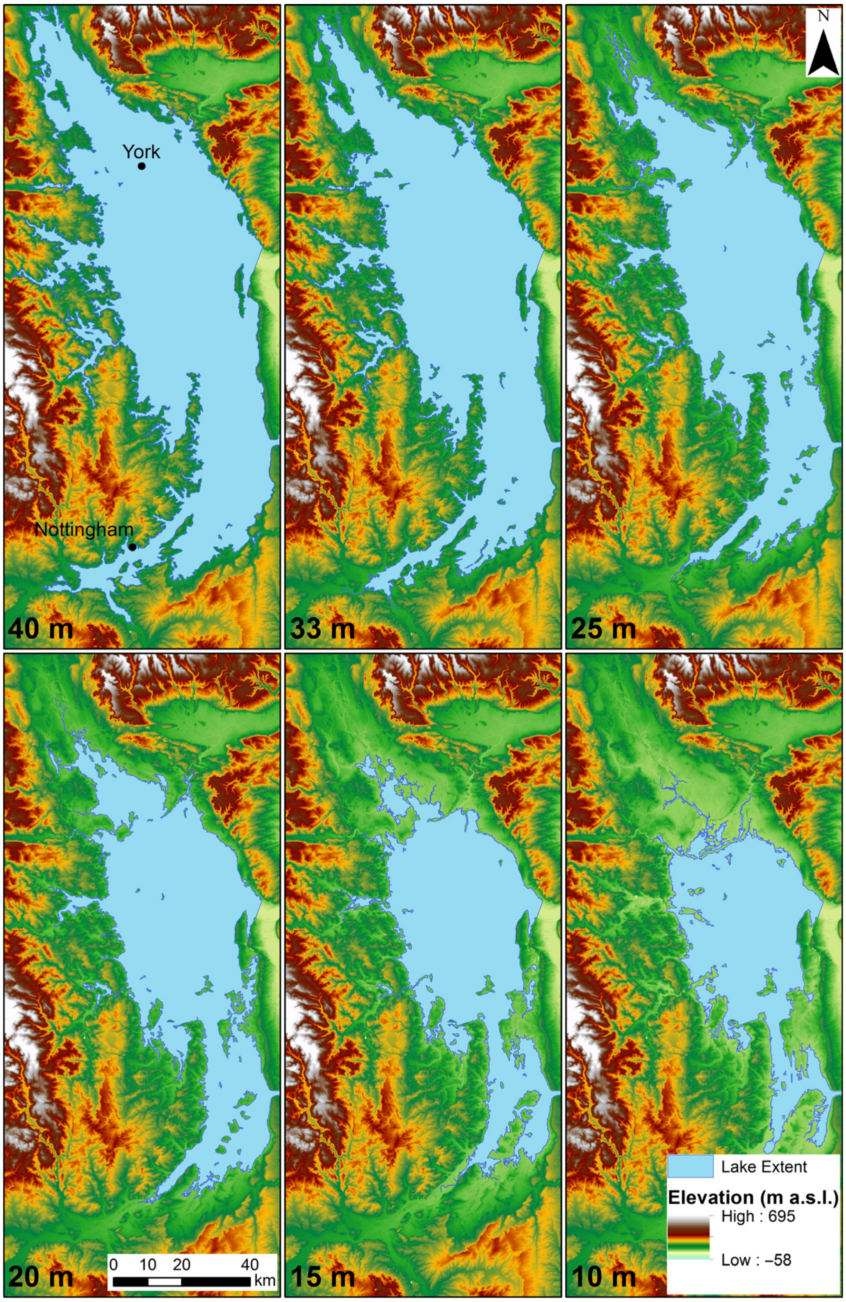


Fig. 10. NEXTMap digital elevation model (based on modern elevations) flooded to predict levels of Lake Humber from 40 m a.s.l. (Stage 2) to 10 m a.s.l. (Stage 7). Note that the true lake extent for the 10 m (Stage 7) and 15 m (Stage 6) levels may have been affected by early Holocene erosion and fluvial deposition. No correction for isostasy has been made.

Discussion

Based on the new evidence a revised model for the impounding and demise of Lake Humber is proposed. This portrays Lake Humber rising to a maximum elevation of at least 42 m a.s.l. before gradually receding to 5.0 m a.s.l., in eight stages (Table 2) without jökulhlaup lake drainage having been identified. Six of these stages, between 40 and 10 m, are shown by a NEXTMap DEM model in Fig. 10. Both regressive and transgressive shorelines are recognized during this eight-stage decline. For the highest levels of Lake Humber (Stages 1 and 2, Table 2) ice must have been present in the Humber Gap, damming the Lake, as till has been terraced by at least the 33 m a.s.l. lake level at Hessle. Filling of Lake Humber in Stages 1 and 2 would have caused outflow via the Lincoln Gap and possibly through the River Waveney (Straw 1979; Clark *et al.* 2004) or The Wash. At lower lake levels drainage could also have been controlled by oscillations of the BIIS in the Humber Gap resulting in partial emptying and re-filling of Lake Humber. Although there is no evidence for Withernsea Till south of Easington in Holderness (Catt 2007: fig. 3), Withernsea ice could have advanced into the topographical low of the Humber Gap and helped to stabilize lake levels at 25 and 20 m a.s.l. (Stages 4 and 5, Table 2). The lowest level of the lake at 5 m a.s.l. (Stage 8, Table 2) could have been maintained by tills in the Humber Gap and associated moraine ridges at Red Cliff (Bisat 1932).

The time frame for this new multi-stage recessional model of Lake Humber requires the westward advance of the North Sea lobe of the BIIS into the Humber Gap impounding Lake Humber either with an ice or till dam associated with the emplacement of the Skipsea Till. Impoundment occurred after 17.5±1.6 ka (Wintle & Catt 1985) and before 16.6±1.2 ka (Bateman *et al.* 2008). Although ice retreated eastwards of Dimlington by 16.2±0.4 ka (Bateman *et al.* 2011), a subsequent BIIS re-advance, depositing the Withernsea Till, occurred within the period 16.3–14.46 ka (Bateman *et al.* 2011).

Lake Humber would appear to have existed for a maximum of 3.5 ka between *c.* 17–14.5 ka but probably much less. Within this time period the 33 m terrace level has been dated to 16.6±1.2 ka at Ferrybridge (Bateman *et al.* 2008). As Skipsea Till near Hessle has been terraced at 33, 20 and 15 m a.s.l. by Lake Humber, Skipsea ice had retreated back from this locality prior to the 33 m a.s.l. stage (16.6±1.2 ka). Subsequent revisiting of the 33 m a.s.l. lake level is indicated at Street Houses (Fig. 3), where an erosional surface on till below the 33 m terrace is overlain by sand and laminated clay, indicating a post-erosional rise in lake level (Edwards *et al.* 1950: fig. 14); such fluctuations may reflect adjustments in the ability of ice in the Humber Gap to impound water. New OSL ages from this study show that the lake level dropped rapidly to 25, 20 and finally 15 m a.s.l. within the period between 15.9±0.9 and 15.2±0.7 ka (Table 2). OSL ages from Naburn confirm that it had completely drained by 9.1±0.6 ka (Table 2).

Although of significant size (~4500 km^2 at its maximum; Clark *et al.* 2004), Lake Humber was not the only proglacial lake formed during the deglaciation of the BIIS. It would appear that North Sea ice of the BIIS flowing westward onto higher ground provided conducive conditions for a number of proglacial lakes. As per Livingstone *et al.* (2012) all deglacial stages from Stage I (25–22 ka) to Stage VI (17–16 ka) were partly characterized on the North Sea margins by proglacial lakes. These included the large proglacial Lake Tees, Lake Wear and Lake Pickering, of which the latter is thought to have cascaded into Lake Humber. As ice retreated both eastward and northward more lakes, currently submerged under the North Sea, probably existed. In the Holderness coast context smaller lakes have also been reported. The earliest, occupying a small valley within chalk, comes from Barmston (Hartmann 2011) and another dating to 16.2±0.4 ka was reported by Bateman *et al.* (2011) at Dimlington. Murton *et al.* (2009) also reported a shallow, perhaps precursor, proglacial lake within the Lake Humber limits. This was based on wave-rippled laminated silts and clays found at Hemingbrough, which were attributed to the Park Farm Clay Member of the Hemingbrough Formation overlain by sandy beds that gave an average age of 22.2±0.3 ka (Murton *et al.* 2009). As these laminated clays underlie Vale of York till this lake must pre-date the Lake Humber for which strandlines are reported in this study.

Implications for the last British–Irish Ice Sheet

Through the simple expedient that Lake Humber was formed at least in part through ice impoundment from the east, the presence and fluctuations in the level of Lake Humber must represent a proxy for oscillations or advances of the North Sea ice lobe of the BIIS. The geometry and chronology of lake terraces also has implications for the duration and thickness of ice present in the Vale of York and at the western margins of the North Sea ice lobe of the BIIS.

In terms of the Vale of York part of the BIIS, this is thought to have advanced down the Vale of York after ~23 ka (Bateman *et al.* 2008; Clark *et al.* 2012; Livingstone *et al.* 2012). This age is supported by the erosional contact of the Vale of York till with the underlying Park Farm Clay Member (British Geological Survey 2008: Section 1), the latter of which was dated to 22.2±0.3 ka by Murton *et al.* (2009). As presented above, the presence of 33 m a.s.l. Lake Humber shorelines on the York moraine dated to 16.6±1.2 ka (Bateman *et al.* 2008) shows that the York moraine must have been ice free by this time. As the ice must have reached at least as far south as the Escrick moraine (Fig. 2), retreat of the Vale of York ice from its maximal position must pre-date this time. This timing is consistent with the loss of ice from an upland site in the Yorkshire Dales before 16.5±1.7 ka (Telfer *et al.* 2009).

Gaunt (1981) suggested that the Vale of York had undergone glacio-isostasy based on the northerly increase in elevation of the '100 Foot Strandline' deposits of Edwards (1937) and the northerly increase in elevation of the laminated clays and sand (the '25 Foot Drifts', Edwards 1937) underlying the Vale of York from 10 to 14 m a.s.l. (Gaunt 1974). Recently however, Murton & Murton (2011: fig. 15B) showed that the '100 Foot Strandline' deposits lie on or about the 30 m contour as far north as Tadcaster; a level comparable with the gravel deposits at Everthorpe, and Mill Hill at Elloughton much further to the south (Fig. 5). Furthermore, new mapping of the Breighton

Sand Formation has shown that the sand component of the '25-Foot Drifts' is a widespread, flood-related deposit (British Geological Survey 2008; Ford *et al.* 2008) and not an isostatically tilted lacustrine surface. The new mapping presented above also questions the presence of isostatic rebound. The shorelines mapped in the Pocklington area and between Market Weighton and Hessle (Fig. 5) run broadly north–south yet are not tilted and there appears to be no convergence towards the Humber outlet (cf. Lake Agassiz, Teller 2001). Thus, if isostatic changes have occurred, they must have been minor (<1 m) over the study region and therefore not detectable by detailed field mapping. The only evidence found for isostatic adjustment is provided by the 52 m terrace above the Older Alluvial Fans on the Wolds south of Market Weighton (described above) for which an OSL age of 202.7±11.7 ka (South Cave, Table 1) was obtained. This dates these fans to a periglacial event either coinciding with the end of or post-dating MIS7. These same fans have been horizontally terraced by Lake Humber, indicating that the rebound occurred before the latter was established.

The lack of evidence for glacio-isostatic rebound combined with a short time window for glaciation in the southern end of the Vale of York implies that the Vale of York ice lobe of the BIIS probably was short-lived and not of significant thickness.

The North Sea

Gaunt's (1976) two-stage Lake Humber level model fitted well with the 'two tier' glaciation of the North Sea Lobe of the BIIS, which initially deposited the Skipsea Till followed by more localized deposition of the Withernsea Till (e.g. Madgett & Catt 1978). This was all associated with a single advance and retreat. However, recently a more dynamic western margin to the North Sea lobe of the BIIS with an oscillating ice front has been proposed based on numerous small and indistinct sinuous and crenulate ridges across the Holderness region (Evans & Thomson 2010: fig. 5). Re-examination of the Last Glacial Maximum type-site at Dimlington by Bateman *et al.* (2011) showed that not only were at least two of these oscillations sufficient for the formation of sub-aerial lakes with biota between them but also that glaciation was occurring as late as 16.2–15.5 ka. The new multi-stage Lake Humber model lends support to a more dynamic and oscillating western margin of the North Sea ice lobe. To account for the different lake levels the Humber Gap must have been blocked with different thicknesses of ice and till on multiple occasions. Such a conclusion is supported by Boston *et al.* (2010), who thought that a number of advances, oscillations and re-advances took place based on the till geochemistry. The highest lake levels at 42 and 40 m a.s.l. must correspond with the highest ice dam competency and thickness of ice within the Humber Gap, implying that the age of the 33 m lake level of 16.6±1.2 ka (Bateman *et al.* 2008) marks a later stage for the North Sea ice lobe of the BIIS in the Humber Gap. At this time, the Vale of York ice lobe of the BIIS had already retreated northward showing that even within the Yorkshire region ice lobes were asynchronous. Although there is no terrestrial evidence for Withernsea Till south of Easington in Holderness (Catt 2007: fig. 3), Withernsea ice could have advanced into the topographical low of the Humber Gap and helped to stabilize lake levels at 25 and 20 m a.s.l. (Stages 4 and 5, Table 2). The new ages from these strandlines, also by inference, date the Withernsea re-advance to around *c.* 15.5±0.8 ka (based on average of Shfd12068, Shfd13034, Shfd13036, see Table 1). Such a re-advance falls within the GS-2c cold episode (16.9–14.7 GRIP ka BP) recorded in the GRIP ice-core (Björck *et al.* 1998) and agrees with the time window put forward by Bateman *et al.* (2011). It also supports the notion of asynchroneity with other parts of the BIIS such as the Irish Sea lobe (e.g. Hughes *et al.* 2014). Although such a glacial advance and retreat pattern of the North Sea sector of the BIIS is contrary to current modelling of the BIIS (e.g. Boulton & Hagdorn 2006; Hubbard *et al.* 2009), uncertainties remain as to how and when Fenno-Scandinavian ice and the BIIS interacted in the North Sea basin (e.g. Carr *et al.* 2006; Clark *et al.* 2012). Sejrup *et al.* (2014) noted a widespread and similarly timed two-stage Fenno-Scandinavian ice re-advance into the North Sea basin at 17.5 and 16.2 cal. ka BP.

Conclusions

Results from landform mapping of terracing in the Vale of York and the revised chronology provide compelling evidence for a re-interpretation of the genesis and decline of Lake Humber. The main phase of Lake Humber, impounded by an advance of the Skipsea ice in the Humber Gap, declined from a maximum level of 42 m a.s.l. in a sequence of eight terraces (Table 2). For this to happen the Vale of York glacier, part of the BIIS, must have retreated to the north of the York Moraine prior to imprinting of shorelines on the moraine formed by the falling levels of Lake Humber. The Vale of York glacier apparently had only a minimal impact on the landscape by way of isostatic depression, indicating that it was thin and/or its advance was short-lived. Its advance and retreat would also appear to be asynchronous with the adjacent North Sea lobe of the BIIS. The multiple recessional stages of Lake Humber are also a likely proxy for stillstands and possible oscillations of the BIIS in the North Sea during its retreat, which would appear to have been relatively late within the last glacial period (i.e. MIS 2).

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