The evolution of Palaeolake Flixton and the environmental context of Star Carr, NE. Yorkshire: I) stratigraphy and sedimentology of the Last Glacial-Interglacial Transition (LGIT) lacustrine sequences.

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Abstract

The basal topography and sediments recording the Last Glacial Interglacial Transition (LGIT) from Palaeolake Flixton, North Yorkshire have been reinvestigated through a detailed, systematic auger and borehole survey. The data presented in this paper, from the area to the north of Flixton Island and the River Hertford suggests that the basal topography of Palaeolake Flixton is irregular with a series of deep and areally small basins interspersed within a gravel surface of around 21m OD. At its shallowest the gravel surface is *ca*. 2m below current land surface and the deeper, steep-sided basins are up to 9m in depth. Examination of the sediment sequences indicates the deeper basins accumulate sediments from the Dimlington Stadial (DS), Windermere Interstadial (WI), Loch Lomond Stadial (LLS) and the Holocene, whilst the shallower sequences only record the Holocene. The configuration of the deposits in the basins suggest that lake levels declined during the WI from 24 mOD to 23mOD and then fell further during the LLS to *ca*. 20.90mOD. The lake water levels then rose slowly during the Holocene to a height of between 23-24mOD. These fluctuations in lake water level at the transition from the LLS to Holocene perhaps indicate that the configuration of the water body during the resettlement of the area in the Mesolithic was radically different than previously thought, with lower water levels and therefore a greater area of land exposed for habitation. This highlights the potential for additional preservation of archaeological assemblages in the area of the former lake. Moreover the complex basal stratigraphy suggests that a systematic analyses of the Palaeolake Flixton

sedimentary archive is required as part of an ongoing strategy to resolve high-resolution palaeoclimate data from this lake sequence.

Introduction:

The British Isles and surrounding areas contain evidence for multiple glaciations within the Quaternary period (Bowen et al., 1986). These glaciations caused changes in local and regional drainage networks and hydrological systems as a result of the direct presence of the ice either acting as a barrier to natural drainage systems (Sissons, 1979; Kendall, 1902; Gaunt, 1994; Clark et al., 2004), eroding and overdeepening valleys, or by the deposition of sediment released during ice retreat (Turner, 1970; Walker and Godwin, 1954). These changes in drainage systems allowed the formation of lacustrine systems in the newly-formed basins during the transition to full interglacial conditions. The sediments that accumulated in these lake systems span the glacial to interglacial transition and are therefore important archives for two reasons: 1) they record palaeoenvironmental fluctuations, which occur during frequently unstable climate transitions; 2) the freshwater bodies were natural resources exploited by early humans as they re-colonised the British Isles after the extreme cold of the glacial episodes.

In the UK, our most detailed understanding of the timing and duration of the transition from Glacial to Interglacial conditions is recorded in high-resolution lacustrine sediments deposited between 16-8ka (Last Glacial-Interglacial Transition: LGIT). The Vale of Pickering in Yorkshire is a key locality for understanding such LGIT lake systems. Initially, during the LGM, the Vale of Pickering formed part of a large ice-dammed lake complex known as Glacial Lake Pickering (GLP; Kendall, 1902, Foster, 1985). This was succeeded by a considerably smaller and shallower water body that existed during the Lateglacial and early Holocene called Palaeolake Flixton (PF; Figure1), in the eastern end of the Vale. This smaller lake system preserves a unique combination of palaeoenvironmental archives deposited during the LGIT, and was situated in close proximity to a unique suite of Mesolithic occupation sites around the Star Carr area (Clark, 1954; Day, 1996; Conneller and Schadla-Hall, 2003; Conneller et al., 2012). This archaeology, found in PF shoreline deposits, indicates multiple periods of human occupation during the early Holocene as well as evidence for earlier human colonisation during the Windermere Interstadial (Conneller, 2007). Previous archaeological and high-resolution basin surveys have primarily focussed on mapping marginal deposits on the palaeolake shorelines, the basin fill sediments being reconstructed at much lower resolution (Figure 1; Cloutman, 1988a, b; Cloutman and Smith, 1988; Day, 1996; Dark, 1998). Consequently, we currently have a limited understanding of the bathymetry, stratigraphy and sedimentology of the basin that was a crucial resource for humans who occupied this region in the early Holocene. Moreover, only a limited palaeoenvironmental record for the PF sequence has thus far been published and this work is part of a programme of developing additional palaeoenvironmental context for this period.

In this paper we present the results of a new survey of the sediments of PF. A systematic auger survey at a higher spatial resolution has produced a bathymetric map of a restricted part of the basin between two important archaeological sites, Star Carr and Flixton Island (Figure 1). The survey reveals that the bathymetry of the basin is complex, whilst the extraction of overlapping sediment cores at a number of locations also shows that the complexity is mirrored in the sediment fill. The survey data is used to propose a model for the formation and evolution of the basin, whilst the stratigraphy of the sediments is used to infer significant lake level fluctuations during the LGIT. The paper concludes by discussing the impact of lake level changes on the morphology of PF, and highlighting the implications of these changes for the landscapes of early human occupation.

Quaternary Landscape Evolution in the Vale of Pickering:

The Vale of Pickering trends east-west and is bounded to the north by the North York Moors, which are composed of limestone, and the Yorkshire Wolds to the south, which are composed of chalk. The area occupied by PF (TA 035 813) is situated at the eastern end of the Vale of Pickering in the base of a broad valley bottom (4km wide) at an altitude of between 23-27mOD.

The Vale of Pickering formed an extensive basin during the deglaciation of the area at the end of the Dimlington Stadial, which saw the evolution of two major lake systems. The first ice-contact, glaciolacustrine system was the most extensive and occurred when ice blocked drainage at the eastern and western end of the Vale of Pickering, allowing an ice-dammed lake to form with water levels rising to the level of 65m OD (Kendall, 1902: Figure 1A) before draining through a col at Kirkham Gorge. The exact position of the ice dam at the eastern end is debated; Foster (1985) suggests that ice extended into the Vale as far as Pickering, whereas Penny and Rawson (1969) favour an eastern limit in the area of Wykeham. Clark et al (2004) use the limit suggested by Foster (1985). Nonetheless it remains unclear what the exact configuration of the lake was during the final decay of ice that blocked the eastern part of the system. The second stage, occurring after deglaciation, was characterised by a shallower and more spatially restricted lake basin which existed during the Lateglacial and early Holocene and is referred to as Palaeolake Flixton (PF). It is likely that the lake levels of PF were maintained at *ca*. 25 m OD (Cloutman, 1988a), a height controlled by the influence of the local water table and drainage to the west by the PalaeoHertford river.

Our current understanding of the form, sedimentology and evolution of PF is derived from the survey of Cloutman (1988a, b) around the former lake margins and auger transects through the western area of deeper sediments (Figure 1B, 1C). Augering was aligned on 6 transects: Transects D, E, M and U to the north of Flixton Island and the current course of the River Hertford; and Transects ME and A to the south of the Hertford. The base of the sequence was characterised by either gravels or diamicton, although the base was not always reached. The maximum depth recorded was *ca*.19 m OD (transect M; southern sector), and, in the northern part of the basin, Cloutman (1988a, b) was able to identify gravel highs in Transects E and M. The maximum thickness of sediment infilling the basins is 5.5m. The stratigraphy varies within different parts of the basin but is usually characterised as sand and gravel at the base overlain by clays, which are succeeded by calcareous muds containing shells and in certain locations thin beds of sand and silt. A fine detritus mud is sometimes found to overlie the calcareous muds, and is then succeeded by peat containing Phragmites and wood remains.

The Cloutman (1988a) survey demonstrated that the lake margins had relatively shallow gradients, small embayments and islands exposed within the lake and a gently undulating lake bed. Cloutman (1988b) also established the relationships between the archaeological remains and lake-marginal deposits, by using the altitude and dating of the nearshore deposits. He concluded that lake water level was between 23-25mOD during the period of Mesolithic activity and, prior to this, the Lateglacial water levels were *ca*. 23mOD (Cloutman, 1988 b).

Day (1996) and Dark (1998), building on the work of Walker and Godwin (1954) and Cloutman (1988 a,b), were able to constrain the timing of sediment infilling by extracting a long sediment core recovered between Star Carr and Flixton Island (Figure 1C; Core A). This lake-centre core was 6.77m long with gravel at the base and overlain by a 0.28 m thick sequence of gravel, sand, silt and clay. A 1.43m unit of silty clay marl succeeded this unit, which was then overlain by 1m of grey silty clay and clay with pebbles and then 1.63m of marl containing plant and mollusc remains. The final unit in the succession was a 0.45m thick black detrital mud. Their detailed palynological and lithological analysis of the core indicate deposition throughout the Windermere Interstadial (silty clay marl), Loch Lomond Stadial (grey silty clay and clay with pebbles) and early Holocene (marl), with radiocarbon determinations indicating sedimentation prior to 8220-8600 cal BP (OXA-4042: 7640±85 ^{14}C BP). Cloutman (1988a), Day (1996) and Dark (1998) indicate the basal topography is relatively flat but the data from the Star Carr core demonstrate that, in certain sectors of PF, depressions up to 6.77m in depth exist. The previous survey data also indicate the presence of gravel highs (Flixton Island; No Name Hill) within the basin, thus hinting that the subsurface topography is not as uniform as suggested.

Methods:

The data were collected during a series of field visits from 2009 to 2012 and the basal topography was surveyed using a combination of Dutch gouge (2.5cm diameter), Russian coring (5cm diameter; 0.5m and 1m long) and Eijkelkamp Stitz coring equipment. Dutch gouge material was used to obtain preliminary sediment descriptions and to record the maximum depth of post-Dimlington Stadial sediments at each location. Ten transects were constructed in the area to the north of Flixton Island and to the west of No Name Hill. The west-to-east dimensions of the survey area was 1200m from the area to the north east of the original Star Carr excavations to No Name Hill; the north-to-south dimensions of the survey area extended for 300m to the north of Flixton Island and the River Hertford (Figure 2). A total of 110 locations were examined during this investigation. A maximum interval between core locations of 50m was used to produce a high density bathymetry of the basin, with coring suspended when reaching gravels. Russian coring and Eijkelkamp Stitz coring were used for sample recovery at selected locations (see below) identified from the bathymetric survey. The altitude of each coring point was surveyed using a Total Station and linked directly to archaeological investigations at Flixton Island (Figure 2).

Consequently seven continuous cores were extracted from the survey (Core's B, C, D, E, F, G and H; Figure 2). These were considered important localities for understanding stratigraphic complexities where inferences on lake level changes could be made. Magnetic susceptibility measurements of cleaned sediment cores were made using a Bartington MS2C core loop sensor at 3 cm intervals (Walden, 1999; Dearing, 1999). Measurements were made at 1.0 $\times 10^{-5}$ SI units resolution. Calcium carbonate ($CaCO_3$) determinations were made using an Eijkelkamp Calcimeter following the Bascomb calculation (Avery and Bascomb, 1982), with a minimum sampling interval of 4cm. Repeat measurements for magnetic susceptibility and $CaCO_3$ were made on 10% of the total sample size.

Although this was primarily a stratigraphic and sedimentological study, in order to place the sequence in a chronostratigraphic context, three of the core sequences (B, C & E) were also examined for the presence of microscopic volcanic ash (cryptotephra). The tephra shard extraction process followed the recommendations of Blockley et al. (2005) and the subsequently identified tephra shards were mounted in resin, sectioned and polished. These were chemically analysed using a JEOL Wavelength Dispersive Electron Microprobe (WDS-EPMA) based at Oxford. The microprobe conditions utilised an accerating voltage of 10KeV, beam current of 6na and beam diameter of 10µm. To check for machine precision and accuracy a series of primary calibration and secondary glass standards (MPI-DING) were used (Jochum et al., 2006).

Results:

Auger Survey.

The depths to the upper surface of the Dimlington Stadial gravels, as indicated by the auger survey, are presented in Figure 2. The survey area to the north and north-west of Flixton Island is characterised by a variable underlying topography with three major basins developed below the 21m OD contour. The first, which is centred near Core F (Figure 2), is immediately to the north of Flixton Island (300m x 200m) with the majority of the basin no deeper than 18m OD but reaching a minimum altitude of 15.97m OD. This basin has relatively shallow sides on the northern, eastern and western flanks but steeper relief on the southern side. The second basin, which in the vicinity of Core E (Figure 2), is situated to the NNW of Flixton Island and is more irregularly shaped (300m x 200m), with the majority of the basin surface above 19m OD but reaching a minimum altitude of between 14.83m and 16m OD in two isolated deeper basins. The basin as a whole is relatively low relief but, in the vicinity of the two deeper parts of the basin, the western and northwestern flanks are significantly steeper. The third basin, situated around Core C (Figure 2), is identified at the western end of the survey area. It is smaller (150m x 150m) again with the majority of the basin above the 18m contour, but with a single deeper point reaching 16.54m OD. The basal topography of this basin is relatively shallow. It should also be noted that in the area to the north of the current survey a larger more extensive basin probably exists to the north of the current survey site, but this was not studied.

Between these relatively deep basins the underlying gravel surface forms a series of topographic highs. The most clearly defined of these are Flixton Island and No Name Hill which exceed 24m OD. However, a large proportion of the survey area lies between 21 and 24m OD. This "intermediate" gravel surface forms a series of relatively extensive shallow, shelf-like areas. These include the area between Flixton Island and No Name Hill and a large promontory (200 m x 200m) to the north and north-west of Flixton Island which separates two of the basins described above. The southern area of the survey to the west of Flixton Island is also fringed by this shelf-like feature.

Description of Sediment sequences:

Figure 3 summarises the sediment successions of core sequences B, C, D, E, F, G and H. These cores were extracted to characterise the sediment succession at selected localities. All altitudes are m OD and the magnetic susceptibility (MS) values are volume specific susceptibilities at x 10^{-5} SI units.

Core B is 3.95 m in length between 20.08-24.48m, and is divided into 3 units. At the base are dark grey silts and clays (20.08-20.28m) with between 15-25% $CaCO_3$ and MS values between 5 and 30. This is overlain by marl (20.28-23.13m) with abundant shells and visible plant remains above 20.40 m. In this unit, $CaCO_3$ content is generally maintained near 80% except for a sharp decrease to *ca*. 55% at 20.85m; MS values are zero. Between 23.13-24.48m is a peat with zero MS and $CaCO_3$ values.

Core C is 7.35m in length between 16.54 and 23.89m OD, and is divided into 4 units. The lowermost is a brown, massive and weakly laminated silty clay (16.54-16.69m) with relatively high MS values (>25) and low $CaCO_3$ values (<15%). This is overlain by a short sequence of massive and weakly laminated marl deposits between 16.69-18.20m OD with high $CaCO_3$, ranging between 25-80%, and low MS (*ca*. 2-10). In this unit the $CaCO_3$ values decline upwards through the sequence and there is a subtle increase in the MS values, both of which correspond to increasing input of sand. This is succeeded by grey silty clay with occasional sand beds and laminae between 18.20-20.53m OD. $CaCO_3$ is present but less than 25% in the lower parts, but above 20.17m OD the $CaCO_3$ values increase to range between 20-70%. MS values vary from 5 to 15. This is succeeded by a marl unit between 20.53-21.05m OD, which is laminated in parts and contains shells; $CaCO_3$ values range between 60 to 85%, and MS decreases to zero. Between 21.05 to 23.89 m OD is a peat.

Core D is 6.27 m in length between 17.81-24.08m OD, and is divided into 5 units. The lowermost unit between 17.81-18.13m OD is brown, massive silty clay with occasional weakly developed laminations, low $CaCO_3$ (0-5%) and high MS values (5-30). This is overlain by laminated marl deposits (18.13-20.78m OD), with high $CaCO_3$ (25-85%) and low MS (<2). This is succeeded by a very thin grey silty clay and sand between 20.78-20.83m OD, where $CaCO_3$ values drop sharply (<15%) and MS values increase to a small peak (5). The subsequent massive marl unit, between 20.83-21.88m OD, shows a rapid upward increase in $CaCO_3$ (60-80%) and low MS values (<2). This is overlain by a humified peat deposit between 21.88-24.08m OD with zero $CaCO_3$ and MS values.

Core E is 9.26m in length between 14.83 and 24.09m, and is divided into 5 units. The lowermost unit between 14.83-15.18m is a massive brown clay or silty clay with high MS values (10-100) and initially low $CaCO_3$ values (5%) rising to 55% in the silty clay at the top of the unit. This is overlain by a sequence of massive or weakly laminated marl deposits (15.18-18.62m OD) with initially very high $CaCO_3$ (60 - 80%) and low MS (<5). The $CaCO_3$ values begin to decline *ca*. 16.00m OD to values between 40-60% and then decline further to values <40% above 17.59m OD, where there is a slight increase in MS (5-10). This is succeeded, between 18.62-20.44m OD by silty clay with isolated pebbles and sand, both increasing towards the top of the unit. The $CaCO_3$ values are low (0-20%) and MS values around 5-10. A massive marl overlying this unit between 20.44-21.17m OD shows a rapid increase in $CaCO_3$ to >80% and a drop in MS to 0. The final unit is a humified peat from 21.17-24.09m OD with no $CaCO_3$ and very low MS values.

Core F is 8m in length between 15.98-23.97m OD, and is divided into 5 units. Between 15.97-16.18m OD is a massive brown silty clay which becomes siltier toward the top of the unit and is characterised by high MS values (5-44) and low $CaCO_3$ (<5%). This is succeeded by a unit of laminated marl (16.18-19.11m OD), which has alternations of marl and silt or clay. This unit has MS values between 0-4 and $CaCO_3$ predominantly between 60-75% but there are zones, particularly towards the top of the unit, where values fall to *ca*. 45%. The third unit between 19.11-20.11m OD comprises predominantly laminated silts and clays, with occasional thick sand laminations. Isolated single pebbles are distributed thoughout this unit. The sand laminations become more common toward the top. The $CaCO_3$ content ranges between 0-20% and MS values between 4.5 and 6. This is overlain by the fourth unit between 20.11- 20.47m OD, which is massive marl with occasional shell fragments, $CaCO_3$ contents between 60-70%, and MS values between 0-4. The fifth unit is a well-humified peat which extends from 20.47- 23.97m OD.

Core G is 1.40m long between 22.69-24.09m OD. It is composed of massive marl between 22.62-23.12m OD with occasional shell fragments and a $CaCO_3$ content of 60-85% and MS values *ca*. 0. This is overlain by peat between 23.12- 24.09m OD.

Core H is 1.66m long between 21.96- 23.62m OD. There is massive marl between 21.96-22.46m OD with $CaCO_3$ content of *ca*.80% and MS values of *ca*. O. The $CaCO_3$ content falls sharply at 22.38m OD at the transition to overlying peat between 22.46-23.62m OD.

Cryptotephra Analysis:

Tephra shards were identified in core C at a depth of 18.66m OD, but were absent from cores B and E. They form a peak in concentration of 1565 shards g^{-1} of dry sediment at 18.66m OD with several subsidiary peaks occurring up to 20.54m OD. In order to test whether this distribution represented a single or multiple eruptive event/s, three locations were sampled for chemical characterisation: these were at 18.66m OD, 19.09m OD and 19.86m OD. Each level analysed returned a consistent chemical composition (Figure 4), which is interpreted as the Vedde Ash that occurs, in the Greenland ice cores, at 12,171 +/- 141 yrs b2k, in the middle of GS-1 (equivalent to the LLS).

Interpretation:

The formation of the basins

The topography on the upper surface of the Dimlington Stadial gravels is undulating and with basins of varying depths and shapes. The random arrangement of basins is similar to that in recently deglaciated terrains due to the melting of dead-ice blocks, which develop kettle holes in glaciofluvial outwash plains (Clayton, 1964; Brodzikowski and van Loon, 1991). In this instance, the landforms were likely formed during the eastward retreat of the LGM ice lobe, as glacigenic debris was laid down on the valley floor. Large debris-covered ice blocks that became detached potentially survived for long periods after ice retreat. The accumulation of outwash sediments around them and their subsequent melting left large depressions, acting as lacustrine sedimentary basins that became infilled during the LGIT.

Based on their position in the valley and morphology, the gravel highs of Flixton Island, No Name Hill and the peninsula around the Star Carr archaeological site are probably kame deposits, as they show a long axis trend from north to south and there are intermediate gravel surfaces between 19 to 24m OD also aligned north to south. It is possible that these represent ice-contact slopes associated with the retreat of an active ice margin. This N-S alignment might correspond to Penny and Rawson's (1969) ice-front position that deposited the Flamborough Moraine (Figure 1A: iii), which was the second stage of ice retreat from the area. However, the survey area is too small extensive to support this interpretation confidently. Irrespective of this, the survey clearly demonstrates that between Star Carr archaeological site, Flixton Island and No Name Hill the upper gravel surface is more uneven than previously envisaged (Cloutman, 1988a, b) with basins of different dimensions and depths.

The lithostratigraphy of the deeper basins:

The sequences can be divided into four lithofacies: lithofacies 1, 2 and 3 are considered to represent lacustrine deposits (marls and clays) and lithofacies 4 reflects the final infilling of the basin with peat. Lithofacies 1 is the massive or weakly laminated brown clay or silty clay which is found at the base of Cores C, D, E and F (Figure 3). The sediment is fine-grained minerogenic material indicating that there was little organic productivity in the lake waters or in the immediate catchment. The accumulation of thick units of clay or silty clay with little evidence of variation in sediment supply suggests a stable low energy lacustrine environment with the majority of sedimentation occurring from suspension settling occurring by settling from suspension in the water column (Ashley, 1975). This suggests that the lake waters were, for substantial periods, unaffected by the development of currents that would re-suspend this grade of material, perhaps because freezing of the lake surface was a common occurrence. The source of the sediment was either directly from the glacier or through reworking of tills deposited near the small lake basins.

Lithofacies 2 are marl deposits with $CaCO_3$ values between 25-60%, which occur both above and below lithofacies 3. The marl below lithofacies 3 tends to display laminations with increased detrital silt and clay content that alternate with marl-rich layers (Figure 3; observed only in Cores C, D, E, and F: lithofacies 2a), whereas the marl above lithofacies 3 is generally massive, contains a greater concentration of shells and is observed in all of the cores (Figure 3; Cores C, D, E, F, G and H; lithofacies 2b,). In both cases the lake hydrology has switched to a system allowing marl deposits to form by a reduction in minerogenic sediment supply, and/or an increase in the rates of authigenic carbonate production. Increased marl production is likely to reflect increased organic productivity, which through photosynthesis removed CO_2 from the lake waters, increased this pH and permitted precipitation of $CaCO_3$ (Kelts and Hsu, 1978). Such deposits are more likely to be formed in warmer environments, where greater organic productivity is favoured. However, in lithofacies 2a, the lower marl deposit, there is an upward decline in $CaCO_3$ values, which coincides with the more laminated appearance of the sediments and more frequent silt and sand beds. This suggests that this period was initially stable with little minerogenic inwash into the basin allowing uninterrupted marl formation, but was succeeded by periods of greater instability in the catchment indicated by increased minerogenic inwash to the basin. The reduction of $CaCO_3$ content may reflect progressive climate deterioration. This is in contrast to lithofacies 2b, which is a massive marl, with a consistently high $CaCO_3$%, and appears to have formed under more stable conditions (Kelts and Hsu, 1978, Glenn and Kelts, 1991).

Lithofacies 3 is composed of dark grey silty clay, silts and occasional sand beds or laminations. This is present in all cores, forming the base of the sequence in Core B and dividing lithofacies 2 into the upper and lower marls in cores C, D, E and F (Figure 3). This unit reflects an increase in fine-grained, minerogenic sedimentation indicating low organic productivity and sediment deposited from suspension during periods of limited turbulence in the water column. Initially, the lake waters were relatively stable with clay and silty clay being deposited in the deeper parts of the basin. However in the basin immediately to the north of Flixton Island, where Cores F and D (Figure 3) were extracted, there are subtle differences in the sedimentology of lithofacies 3 indicative of higher energy processes supplying sediment to the basin. In the longer core F, clays with rare pebbles are present to an altitude of 19.83m OD and the overlying sediment is sandier. In core D this unit consists of a thin (0.05m) sandy pebbly silt at an altitude of 20.78-20.83m OD. In Core C the base of lithofacies 3 is at 18.20m OD and it becomes increasingly sandy above 18.64m OD. The increased sand component indicates an increase in allochthonous material reaching the basin, suggesting an increase in physical erosion of the gravel shorelines or sediment flow down gravel slopes from higher areas. This coarsening could have resulted from increased wave erosion at the lake margins, or an increase in periglacial activity at the site. Both might cause local instability at the shorelines of the lake and deposition of coarse sediment in the sub-littoral zone. The upper altitudinal limit of this coarser minerogenic facies is in Core D at 20.83m OD (Figure 3), which indicates the minimum height of the water level. This evidence allows us to revise the interpretation by Cloutman (1988a, b) and Day (1996) because it suggests a series of constrained basins with restricted sediment catchments rather than a single large basin that received all sediment. As such it is most likely that lithofacies 3 is a product of local processes rather than an extensive basin wide feature. There is no clear evidence that this deposit was formed by periglacial processes; it may just reflect local instability at the lake margins, which is supported by the location of core D at the edge of a deeper basin.

Lithofacies 4 is a humified peat developed during hydroseral succession and forming a fen and carr woodland (Cloutman 1988a, b; Cloutman and Smith, 1988).

Comparison of sequences to the chronostratigraphic sequence of Day (1996)

On the basis of the lithological evidence present in the cores recovered in this survey, there are clear similarities to the sediment succession presented in Core A (Day, 1996). It is proposed that the brown clay (LFA 1) represents the initial infilling of the basins immediately after the area became deglaciated during the later part of the Dimlington Stadial (DS). The lower marl unit (LFA 2a) was deposited during the climatic amelioration of the Windermere Interstadial (WI), the warmer climates and increased landscape stability of which promoted the formation of the marl. Through this unit, there was a decrease in $CaCO_3$ production with increasing minerogenic supply to the basin, producing a banded or laminated marl deposit resulting from progressive climatic deterioration. Eventually the allochthonous input to the basin dominated the sediment, and this we suggest coincided with the climatic deterioration of the Loch Lomond Stadial (LLS), which is represented by deposition of the grey silty clay with pebbles (LFA 3). Climatic amelioration is then recorded with the formation of marl sediments (LFA 2b) during the early Holocene, with complete infilling of the basin being represented by the transition to carr peat as a part of a hydroseral succession (LFA 4).

This interpretation is consistent with the chronostratigraphic framework of Day (1996) for sedimentation during the LGIT, a correlation that is confirmed, in this study, by the presence of the Vedde Ash in deposits proposed to be of LLS age in Core C at 18.66m OD. This ash is detected in the overlying sediments to 20.54m OD. The input of tephra over this relatively long stratigraphic interval suggests significant reworking of the ash from the immediate catchment and, when combined with the coarser sediment grade observed in the later part of the sequence, indicates higher sedimentation rates in the later part of the LLS. Both the survey data and lithological information indicate that formation of kame and kettle landscape took place during deglaciation of the LGM ice sheet during the DS preceding the onset of the

WI. These records indicate a relatively stable period of minerogenic clay sedimentation at the end of the DS.

The basins were smaller in area than that originally conceived by Cloutman (1988a,b). Sedimentation during the Lateglacial period was restricted to the deeper basins but there are clear contrasts in the style and rate of sedimentation, which was probably controlled by the shape and gradient of the gravel surface in the immediate vicinity (Figure 5). Table 1 illustrates the range of sediment thicknesses present during the LGIT record in PF. The late DS sediments of LFA 1 are consistently thin and only observed in the deeper basins. The WI deposits range in thickness from 1.55 to 3.44m; the LLS sediments from 2.32 to 0.05m; and the Holocene marl sediments between 0.35 and 2.85m. There is also a wide variance in the thickness of these units in comparison with Core A of Day (1996). As such the infilling of PF was not uniform across the whole area and a single core does not provide a 'type' sequence for PF. More specifically, it would appear that the deeper basins were all infilled by the end of the LLS to a maximum height of 20.83m OD and the whole basin was then capped by the early Holocene marl (lower contact is between 19.20-20.83m OD) deposited uniformly across the basin, as reported by Cloutman (1988a), and by the upper peat deposit, the lower contact of which is between 20.47-23.13m OD.

Evidence for lake level change in Palaeolake Flixton during LGIT:

As detailed in the previous section, the irregular topography of the gravel base imposed local controls on the style and preservation of the sedimentary sequence. It is also possible to use the vertical and horizontal variability of the lithological units within these separate basins to propose a model for changes in the lake water levels during the LGIT (Figure 5A-D). This schematic diagram utilises the heights of the upper surfaces of the different facies present as an indication of the minimum water level required to account for the accumulation of the units. This is outlined below:

1] The later part of the Dimlington Stadial is represented by clay and silty clay, which accumulated at the base of the deeper basins in the former glacigenic sediments (Figure 5a). Water levels were probably >21m OD, and the primary mode of sediment delivery was transportation of silt and clay by currents in an open water body. This could only occur if the water level submerged all gravel highs, so it was probably controlled by a glacial ice dam. The lack of similar deposits at the base of Core B (Figure 3; Table 1) suggests that the minimum lake level for this deposit is represented in Core D at an altitude of *ca.*18.20m OD.

If lake waters were only 1-2m higher than this, only fine-grained, colluvial sediments would be supplied to the basin from the unvegetated slopes exposed above the lake water level after deglaciation. However, this survey demonstrates that large quantities of coarse grained sediment that could have been paraglacially reworked, existed above the lake waters at 21m OD or lower. As such the sediments accumulating in the deepest part of the basin would have been coarse grained, which is not the case.

2] Sediments of the WI are present in Cores C, D, E and F and equivalent to the marl facies described by Day (1996). The maximum altitude for the top of these deposits occurs in Core D at 20.78m OD (Figure 5b). Since biogenic marl formation is favoured in water depths between 1.5-2m (Murphy and Wilkinson, 1980), the maximum water level at this time would have been *ca*.23m OD. The lack of evidence for WI deposits above 20.78m OD could also result from subaerial erosion during the LLS, when lake levels were lower (discussed below).

3] Sediments of the LLS are recorded in Cores B, C, D, E and F (Figure 5b). The thickest are in Core C and E (2.33m and 1.82m respectively), with the maximum altitude of the deposits occurring in Core D at *ca*. 20.83m OD. In Core B the minerogenic sedimentation ceases at 20.28m OD but in Core C the presence of the mineral sediments up to 20.53m OD suggests that water levels were at least this high during the LLS. The LLS is represented by a 0.05m thick predominantly sand unit in Core D, which is interpreted either as solifluction material deposited subaqueously or on the subaerial margins of the lake. It suggests that the water level during the later part of the LLS was at 20.90m OD but was probably lower than this during the earlier part of the LLS due to the lack of silty clay in Core D. Irrespective of this, lake water levels had dropped from WI levels (Figure 5b).

4] The onset of marl sedimentation reflects the return to more stable conditions at the start of the Holocene (Figure 5c). Cores B, G and H show the water levels probably rose gradually during the Early Holocene, eventually reaching a height of *ca*. 22m OD. The final stages of infilling is represented by the peat which reaches a height of *ca*. 24m OD (Figure 5d).

Therefore the depth of the Lake Flixton water body fluctuated during the LGIT. Initially water levels stood at 23-24m OD but then fall to a minimum of *ca*. 20.90m at some time during the WI and the LLS. These changes in lake water level probably reflect groundwater control on the lake water levels with decreased precipitation during the LLS lowering the local water table. The drop in water level to *ca*. 20.90m would have exposed many of the gravel surfaces and decreased the surface area of the lakes, although the lakes still appear to be interconnected (Figure 5c). During the early Holocene, the lake level was higher but was subsequently infilled with peat to an altitude of *ca*. 24m; this occurred between *ca*. 10.5-11.1ka BP (Taylor, 2011).

Wider significance

Clearly these changes in water level through the LGIT would have changed the palaeogeography of the area substantially between the WI and the early Holocene. From the evidence, the palaeogeography of PF was potentially characterised by a number of different islands, peninsulas and extended shorelines existing during this period of rapid climate change. As such the landscape during the migration of late Palaeolithic and early Mesolithic people to the area could have been substantially different to that previously envisaged from the earlier excavations at Star Carr and Seamer Carr. For example, in the area to the north west of Flixton Island, which lies above 21m OD, may have been exploited by the earliest migrants to the area (Figure 5). This research has demonstrated the importance ofconducting detailed basin surveys in order to fully access the pa;aeogeography of the landscape for both palaeoenivronmental reconstructions but also to identify previously unrecognised sites of archaeological potential and targeted for future research.

In addition, the sequences identified within the different basins contain sediments that span the LGIT at different resolutions with the potential to generate new palaeoclimatic proxy data, such a Chironomid –inferred temperature reconstructions and stable isotope analysis (see Candy et al, submitted), which were previously unavailable prior to Day (1996). This will also provide critical understanding of the palaeoenvironmental context for the periods of occupation and settlement of the PF shorelines by early humans.

Conclusions:

In conclusion this study has demonstrated that:

- The bathymetry of a restricted but archaeologically important part of Palaeolake Flixton is complex comprising deep but highly localised basins separated by shelf-like topographic highs.
- This topography is consistent with a classic kame and kettle topography reflecting dead ice features and in glacio-fluvial deposits during deglaciation.
- The stratigraphy of the sediments in this survey is consistent with this, where the longest sediment sequences record a typical ‘tripartite’ LGIT sequence.

- The shallower parts of the basin only record Holocene sediments suggesting that water level fluctuated significantly.
- The distribution of stratigraphic units recovered in this coring survey suggests water level fluctuations during the LGIT of around 3m with the main drop in lake levels occurring during the LLS. The lake water levels recovered during the early Holocene to allow the formation of a marl deposit succeeded by gradual infilling by peat.
- Given the complex nature of the bathymetry of Palaeolake Flixton these changes in water level have major implications for the landscape and human occupation during this time period, with the possibility of archaeological remains being preserved on gravel surfaces extending further into Palaeolake Flixton.

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Terminology:

When discussing chronostratigraphic relationships, the convention of using british terminology has been followed. Here the Dimlington Stadial (DS) refers to the cold stage immediately prior to the Windermere Interstadial broadly equivalent to GS-2; the Windermere Interstadial (WI) is broadly equivalent to the Bolling-Allerod of northern Europe and GI-1 from Greenland; Loch Lomond Stadial is broadly equivalent to the Younger Dryas in Europe (Nahanagan Stadial in Ireland) and GS-1 from Greenland and the Holocene for the period post 11,753 years b2k.

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Figure 1: Location of the study sites within a regional and local context. Figure 1A illustrates the regional context of Glacial Lake Pickering in relation to Glacial Lake Humber, including the models of the ice sheet extent in the Vale of York and extending along the east coast of Yorkshire and Lincolnshire. The maximum extent of the ice dam in the eastern end of the Vale is still debated and two maximum positions are shown. The first has the maximum of ice forming the Wykeham Moraine at Position ii; the second, proposed by Foster (1985; Position i), suggests the maximum position to the west of the Wykeham Moraine. Clark et al (2004) favour this latter position. Penny and Rawson (1969) suggest that the ice sheet retreated eastwards from Wykeham and stabilised to form the Flamborough Moraine at Position iii. Figure 1B provides the extent of Palaeolake Flixton as reconstructed by Cloutman (1988a) and includes the location of significant evidence of Mesolithic activity. Figure 1C illustrates the detail of the shoreline contours associated with the archaeological sites at the western end of Palaeolake Flixton. The figure includes the four auger transects reported by Cloutman (1988a) who reconstructed both the deeper parts of the basin as a wide, shallow basin and an older palaeochannel of the Hertford river. The location and areal extent of the detailed and systematic survey in this study is shown in the area to the north of Flixton Island and the current course of the River Hertford. The location of the original deep core study of Day (1996) and Dark (1998) is located to the south of the survey area (Core A). Figure 1B and 1C are adapted from Cloutman (1988a)

Figure 2: Contour map of the upper surface of the gravels identified in the study area. The red crosses indicate the position of the auger points and the location of the deeper cores with more detailed sediment descriptions are indicated. The denser network of levelling points is derived from surveying of archaeological sites on Flixton Island.

Figure 3: Summary description of the cores extracted in this study, which includes lithofacies description, $CaCO_3$ determinations and magnetic susceptibility. The cores have been aligned west to east and to reflect the height above sea-level (mOD). Note that the $CaCO_3$ scale is shortened on Core G. Refer to text for descriptions of LFA1-4.

Figure 4: Geochemistry of the tephra shards identified in Core C and comparison with the Vedde Ash at key sites in Europe. A) total alkalis vs silica plot using subdivisions of Le Bas (1986); B) CaO v $FeO^{(total)}$ plot of the same data and describing the overlap between the Star Carr Core C dataset and typical chemistry for the Vedde Ash.

Figure 5: Schematic representation of the sub-surface topography with sequential infilling of the basin identified by the formation of the different lithofacies (see Figure 3 for key). Proposed lake level at the time of deposition is provided with the dashed line in the schematic cross-sections, allied to a plan view of the lake extent with water at this level (blue infill). The gravel surface utilises the heights of the gravel surface along transect a-a' (the position of this is indicated in the top right plan view reconstruction). The deeper basins located for Core B, D and F have been represented within this diagram at the point in which basins are identified normal to this transect. A represents the transition from the deposition of the DS brown clay and the formation of the WI marl (light brown). B illustrates infilling of the basin during LLS with the proposed drop in lake levels from 23m to 21m. C shows the sediment infill of the Early Holocene marl associated with an increase in the lake water levels. D represents the final infilling with the carr fen peat to *ca*. 24mOD.

Table 1: Comparison table for the altitude (mOD) and thickness (m) of lithofacies in Core's B-H in mOD. Core A (italicised) refers to the thickness of units quoted directly from Day (1996). No altitude is given for Core A from the Day (1996) study and therefore the maximum elevation of units is unknownand the interpretation of the units relate to climatostratigraphic zones made by comparison to Day (1996) lithostratigraphic and palynological evidence. The distinction between marl (LFA2a) and silty clay facies (LFA3) is made on a decrease in $CaCO_3$ percentages to below 25%, an increase in MS values to above 5 (SI units) and a consistent change in the style of sedimentation from clay to marl or marl to clay. The 'distance along transect' column is used to form the schematic in Figure 5. All of the cores do not lie on this transect and therefore the schematic is a representation of the subsurface topography assuming that all of the deeper basins were orientated along this axis. Their position is interpolated measuring the point at which the core position intersects when normal to the transect A-A'.

Table 1:

Core	*A*	B	C	D	E	F	G	H	Chronostratigraphic zone and water level
Length of Core (m)	*6.77*	4.40	7.35	6.27	9.26	8	1.4	1.66	
Max. Altitude of LF4 *Thickness of LF4*	- *0.45*	24.48 1.35	23.89 2.79	24.08 2.20	24.09 2.92	23.97 2.50	24.09 0.97	23.62 1.16	Hol. Peat
Max. Altitude of LF2b *Thickness of LF2b*	- *1.63*	23.13 2.85	21.05 0.52	21.88 1.05	21.17 0.73	20.47 0.36	23.12 0.50	22.46 0.50	Hol. Marl Lake High lake water levels
Max. Altitude of LF3 *Thickness of LF3*	- *0.99*	20.28 0.20	20.53 VA 18.66 2.33	20.83 0.05	20.44 1.82	20.11 1.00	- -	- -	LLS Lake Low water levels
Max. Altitude of LF2a *Thickness of LF2a*	- *1.51*	- -	18.20 1.51	20.78 2.65	18.62 3.44	19.11 2.93	- -	- -	WI Lake High water levels
Max. Altitude of LF1 *Thickness of LF1*	- *0.19*	- -	16.69 0.15	18.13 0.32	15.18 0.35	16.18 0.21	- -	- -	DS Lake Unknown water levels
Base of Core	-	20.08	16.54	17.81	14.83	15.97	22.62	21.96	
Distance along transect A-A’		1000	950	225	850	235	350	350	

Core A’s (italicised) data is presented from Day (1996)