Article:

Fairburn, W.A. orcid.org/0000-0002-9503-6238 and Bateman, M.D. orcid.org/0000-0003-1756-6046 (2021) Possible new evidence for Mid-Pleistocene glaciation in the Vale of Pickering, North Yorkshire, UK. Proceedings of the Yorkshire Geological Society, 63 (4). pygs2020-019. ISSN 0044-0604

https://doi.org/10.1144/pygs2020-019

POSSIBLE NEW EVIDENCE FOR A MID-PLEISTOCENE GLACIATION IN THE VALE OF PICKERING, NORTH YORKSHIRE, U.K.

William A. Fairburn[1*] and Mark D. Bateman[2]

[1] Apartment 101, Leetham House, Core 3 Palmer Street, York YO1 7PD, UK.

[2] Department of Geography, University of Sheffield, Winter St., Sheffield S10 2TN, UK

*corresponding author email: williamfairburn001@yahoo.com

Abstract: Whilst the Late Devensian glaciation (MIS2) of the Vale of Pickering is well-documented, earlier glaciations within it are not. A proposed limited glaciation in the Mid-Pleistocene, thought to be of Marine Isotope Stage 8 (MIS) age is not well constrained. This paper aimed to obtain preliminary ages for two of the most prominent geomorphic features in the Vale of Pickering to see if they related to pre-Devensian glaciations. New luminescence dating by infra-red stimulation of feldspars from sand accumulations near the summit of Gallows Hill, part of the Wykeham Moraine, and from a section through poorly sorted fluvial sand and gravel on the flanks of the Hutton Buscel Terrace in Yedman Dale gave ages of 176±14 ka and 156±12 ka respectively. Evidence suggests they represent a glacial incursion (MIS 6) into the Vale of Pickering blocking its eastern end and forming a pre-Devensian Glacial Lake Pickering. Whilst they could be older, this style of glaciation is very different to the limited plateau ice-field proposed for MIS 8 at the western end of the Vale of Pickering. Taken at face value, these preliminary ages suggest that the Vale of Pickering was partially glaciated in MIS 6 as part of a wider ice-sheet and contemporary with the Saalian glaciation in Europe.

Keywords: Vale of Pickering, glacial lake, luminescence, moraine, Saalian

The Vale of Pickering (VOP; Fig.1), is a flat-based wide valley which conceals at least 15 m of superficial Quaternary deposits of glacial, lacustrine and fluvial origin (e.g. Edwards 1978;). The VOP is bounded by the Chalk Group escarpment of the Yorkshire Wolds to the south, Middle and Upper Jurassic sandstones, mudstones and limestones of the Howardian Hills to the west and south, Upper Jurassic Corallian Group limestones, which form the tabular hills of the North York Moors to the north (Powell 2017, fig. 4 see Fig.2). The eastern end of the VOP is open to the North Sea currently eroding the low level glacial diamictons, some of which form part of the Flamborough Moraine (Evans *et al.* 2017).

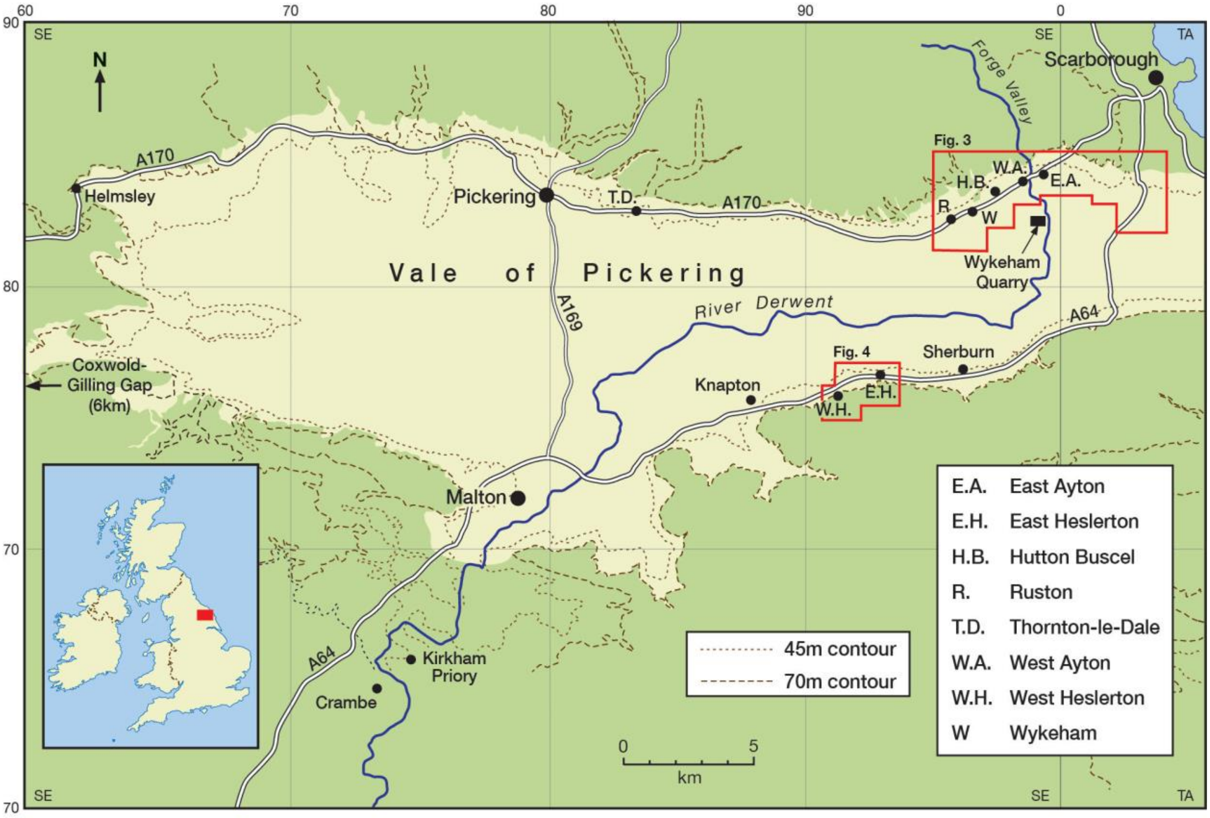

Figure 1. Locality map of the eastern end of the Vale of Pickering as per Fairburn (2019) showing the 45 m and 70 m O.D. shorelines and the location of Fig. 3 (the Hutton Buscel Terrace) and Fig.4 (the geological mapping between East and West Heslerton).

The VOP was thought to have been at least partly glaciated in Marine Isotope Stage 2 (MIS 2; *c.* 29-14 ka). At this time the North Sea Lobe of the British and Irish Ice Sheet (BIIS) advanced into the eastern end of the VOP and deposited the Flamborough and Wykeham Moraines between 21 and 18 ka (e.g. Penny and Rawson 1969; Edwards 1978; Eddey *et al.* 2017; Bateman *et al.* 2018, figs.1 and 12). In blocking the eastern end of the VOP an extensive proglacial lake (Lake Pickering) formed on at least two elevations (45 m and 30 m O.D.; e.g. Eddey *et al.* 2017; Evans *et al.* 2017).

Figure 2. View of Vale of Pickering looking north-west from Staxton Hill, on the northern edge of the Yorkshire Wolds, showing the flat nature of the Vale surrounded by the Howardian Hills to the west and North Yorkshire Moors to the north.

An assertion by Foster (1985) and Edwards (1978) that the North Sea lobe may have extended at least as far west as Thornton-le-Dale (the Pickering/Thornton-le-Dale stage) is not supported by glacial erosion west of Ruston (Fairburn 2019). As the North Sea lobe retreated it left hummocky moraine and the topographically distinctive Flamborough Moraine in the east. Ice from the Vale of York lobe did not enter the VOP but formed a moraine at Ampleforth (Powell *et al.* 2016, fig.1).

Evidence for pre-Devensian glaciations of the VOP is more tentative and is based on evidence lacking conclusive dating:

1. Outliers of pebbly clay (glacial diamicton) southwest of Pickering and on the flanks of the Tabular Hills at *c.* 120 m O.D. (Powell *et al.* 2016) first mapped by Fox-Strangways (British Geological Survey 2000). Whilst Edwards (1978) attributed the diamictons to an MIS 2 glaciation, Powell *et al.* (2016) suggested they are related to a small, warm-based

plateau ice field that flowed down from the scarp of the North York Moors and covered the western part of the VOP at some point post-Anglian (MIS 12; *c.* 478-424 ka) and pre MIS 7; possibly MIS 8 (*c.* 300-243 ka). This tentative MIS 8 date is mainly based on dating of River Trent terrace deposits and their relationship with the Wragby till and equivalent in central and eastern England (White *et al.* 2010; 2016).

2. Other evidence for possible pre-MIS 2 glaciations in the Vale of Pickering is based on an occurrence of Basement Till overlying the Speeton shell bed at the eastern end of the Vale near Reighton in Filey Bay (Catt 2017, fig.1) Catt and Penny (1966) and Catt (2007) have considered this till to be pre-Devensian in age as it is overlain by the Ipswich Stage (MIS 5e) raised beach at Sewerby (Catt 2017, fig 9) and therefore represents an MIS 6 glaciation or older. Wilson (1991), using amino acid racimisation, attributed the shell bed to MIS 7 (*c.* 191 -123 ka) while others (e.g. Edwards 1978; Thistlewood and Whyte 1993) have referred the shell bed to MIS 5e and MIS 7. Consequently the age of the till at Reighton remains uncertain (Catt 2017).

3. Fairburn (2019), based on an extensive field mapping programme suggested a glacial origin for the gravels and boulder beds mapped at the Newton Dale outlet and in gravel pits located between Forge Valley and Yedman Dale.

   In the gravel pits the deposits appear to have originated from a high-energy fluvial event as Franks (1978) has recorded metric scale cross bedding in these deposits. Remnants of the deposits display crude horizontal bedding formed by angular slabs of limestone (Fairburn 2019) suggesting only minimal transport in a high energy environment. This could be indicative of trapped meltwater in Forge Valley and Yedman Dale being released during an easterly retreat of ice from the Wykeham Moraine.

   At the Newton Dale outlet an outwash fan of gravel and boulders was described by Kendall (1902; Fairburn 2019, fig. 5). The deposit contains both sub-rounded and faceted cobbles and pebbles (Fairburn 2019, fig. 7j) as well as imbricate textures. Gravel not of local provenance, recognized by Kendall (1902), include 'moorland grit' and 'whinstone' from the Cleveland Dyke. It is thought that these boulder beds may have originated as a glaciofluvial deposit prior to Glacial Lake Pickering and therefore prior to 17.6 ka (Fairburn, 2019)

4. Kendall (1902), who examined gravel pits in Yedman Dale and Hutton Buscel recorded pebbles consisting of Jurassic sandstones and limestones but with many of Cheviot

andesites, some greywackes, jasper and a few of granite. While the sandstones and limestones are of local provenance the more exotic material could have been sourced from till on the Jurassic dip slope outside the MIS 2 glacial limit of Straw (1979). An MIS 8 age was suggested by Fairburn (2019) for this material in accordance with the proposed MIS 8 dating of diamictons near Pickering (Powell *et al*. 2016)

For a lake to form in the VOP its eastern end has to be blocked by ice. Based on observations of gravels between West Ayton and Wykeham and in Forge Valley, Straw (1979) proposed that there had been two phases of Glacial Lake Pickering: a high-level phase at 70 m O.D. and a younger low-level phase at 45 m O.D., with the lake emptying completely between the two phases. Evans *et al.* (2017) also concluded that the 70 m O.D. lake was probably much older than the 45 m O.D. lake, which they dated to around 17.6 ± 1.0 k.a. Mapping of the 45 m O.D. shoreline by Fairburn (2019) has shown that it forms the boundary between Chalk-gravel fans and the Sherburn Sands on the southern flanks of the VOP (Fig.4) and an erosional surface at the base of the Hutton Buscel terrace (Fairburn 2019, fig.7c; Fig. 4). Evidence for the 70 m O.D. lake thereby implies an earlier glaciation occurred. Critical to the case for the earlier 70 m O.D. stage of Lake Pickering has been the evidence from the Hutton Buscel Terrace. This name has been applied to a wedge of sediment between 45 and 70 m O.D. with a steep southerly facing surface that extends across the eroded edge of the rising Jurassic dip slope from Forge Valley to Ruston in the Vale of Pickering (Fairburn 2019, fig. 7c; Fig. 3). The origin of this terrace has been disputed since Fox-Strangways (1880 and 1892) suggested it had formed as a beach or shoreline terrace while Kendall (1902) proposed that the landform was a ‘deformed delta’ marginal to a glacier. Straw (1979) and subsequent authors have referred to this feature as a kame terrace (e.g. Eddey *et al.* 2017).

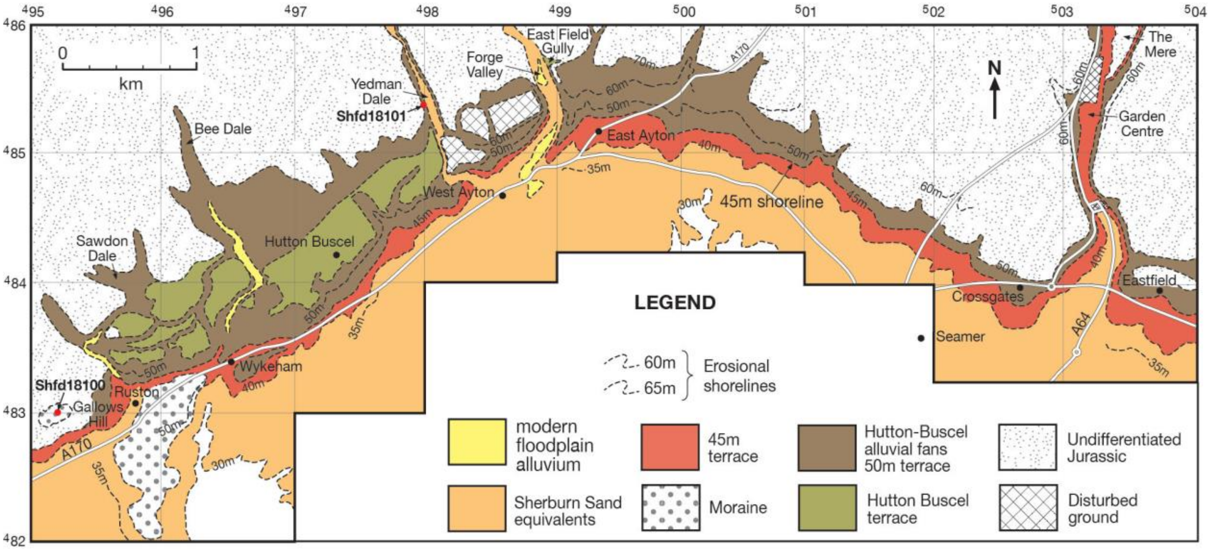

Figure 3. Landform map of the Hutton Buscel Terrace between Ruston and Forge Valley showing the northern edge of the 70 m O.D. glacial lake bounding the Hutton Buscel alluvial fans with shorelines imprinted at lower levels between 45 m and 65 m O.D (as per Fairburn 2019). The site of the two IRSL samples are indicated.

This northern 70 m O.D. shoreline, along the northern edge of the Hutton Buscel Terrace (Fig.3), can be readily mapped as it forms a marked slope break as well as a distinct lithological and crop usage boundary between the Corallian Group limestones and the terraced sands and gravels resting upon them (Fig.5a). To the south of the VOP, mapping by Fairburn (2019), around the area of East and West Heslerton, also discerned a 70 m O.D. shoreline forming a boundary between the Chalk Group and Chalk-gravel alluvial fans. In places remnants of a shoreline terrace has been preserved (Fairburn 2019, fig.7a)

A 70 m shoreline marker has also been recognised near Crambe (Fig.1) where it forms a 'washing line' of silt winnowed from till deposits resting on Jurassic bedrock (Fig.5b; see Saarnisto 1970). Black laminated clays were exposed in an excavation nearby at 65 m O.D. (Fairburn, 2019, fig 7l).

In conclusion, the work of Fairburn (2019) confirms the existence of two temporarily distinct proglacial lakes.

This paper aims to obtain preliminary ages for two of the most prominent geomorphological features in the Vale of Pickering, the Wykeham Moraine and Hutton Buscel Terrace, to see if they relate to pre-Devensian glaciations.

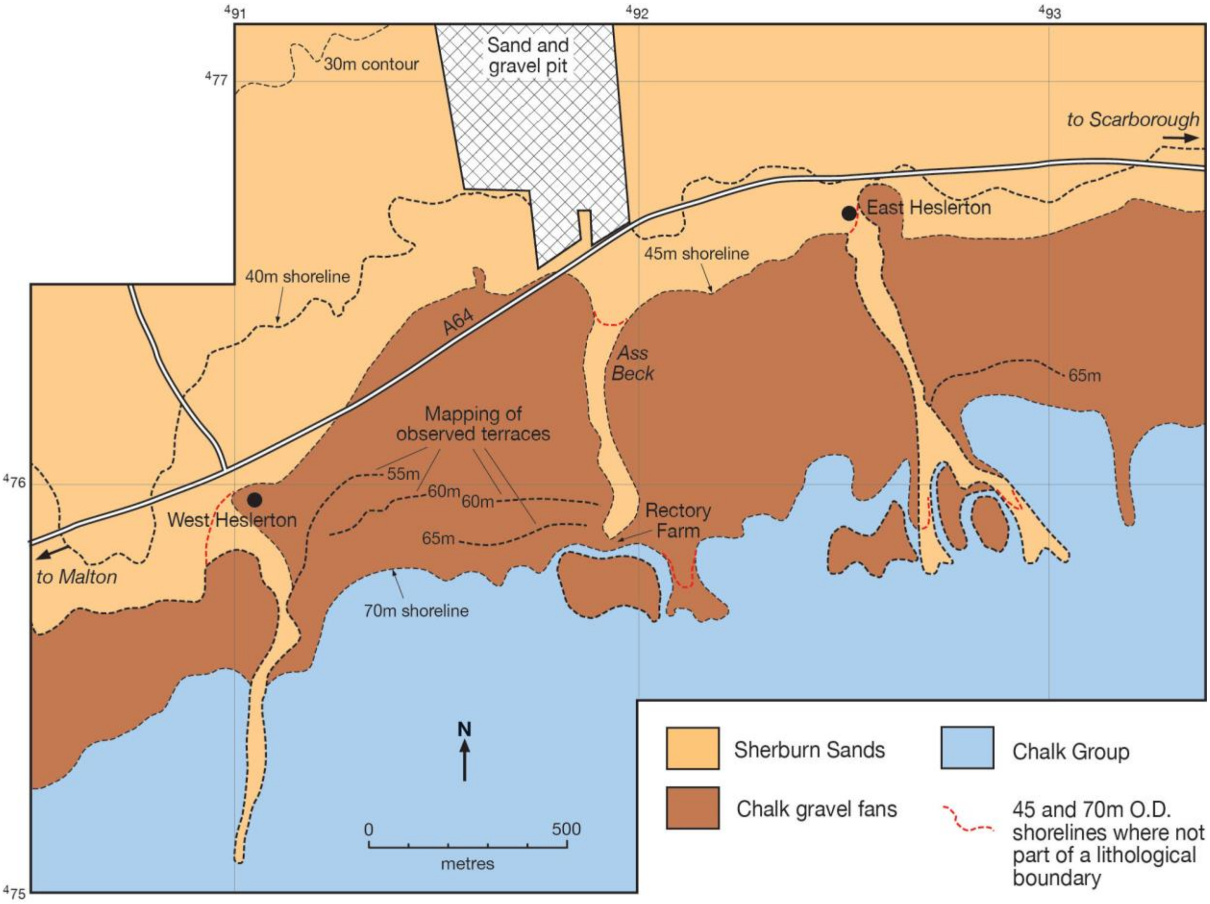

Figure 4. Geological map between East and West Heslerton showing the Chalk Group escarpment, the hummocky chalk-gravel alluvial fans mainly constrained between 70 and 45 m O.D., with the Sherburn Sands, apart from feeder valleys, restricted below 45 m O.D. Note the 65 m, 55 m, 40 m and 30 m O.D. shorelines. From Fairburn (2019).

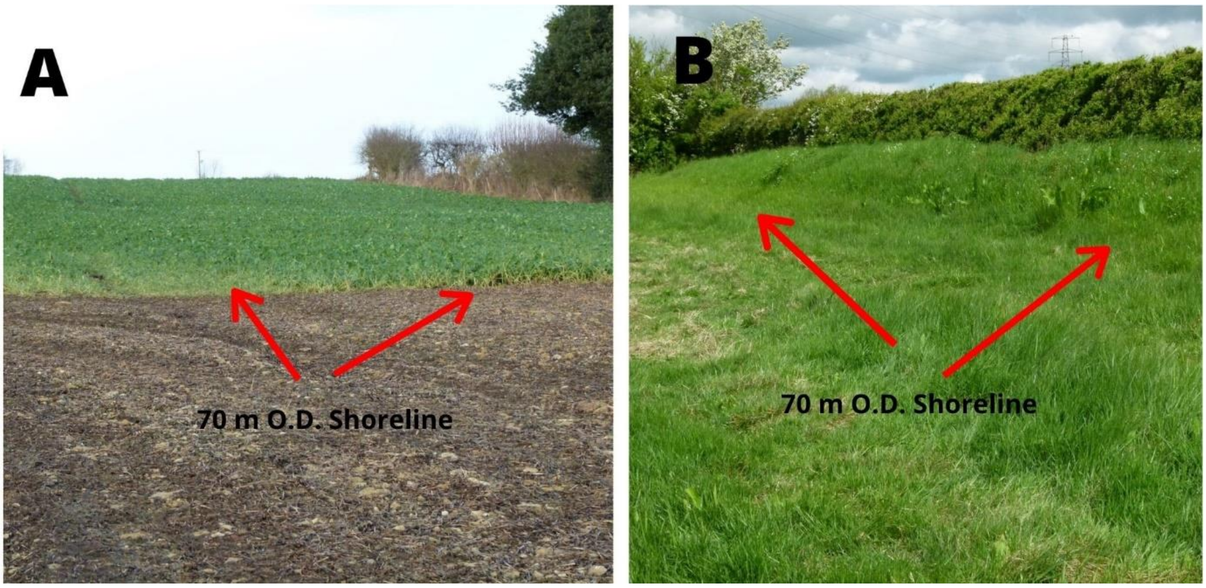

Figure 5. Shorelines at 70m O.D. (A) In Yedman Dale [SE 982 853], north of West Ayton, where the north east trending shoreline marks a distinct crop usage boundary between grass-covered shallow sub-cropping Corallian

Group limestone bounding well-ploughed sand and gravel along an erosional contact that extends for over 20 m. (B) near Crambe [SE 726 645] where the back-wall of the 70m O.D. terrace forms a 'washing line' between glacial till above from Jurassic bedrock below. The NE-SW trending back-wall is formed by silts separating Jurassic bedrock in the foreground from upslope tills above the hedgerow. The contact here extends for about 100 m.

Study sites.

Two sites were selected: one near the summit of Gallows Hill [TA 952 859] 600 m southwest of Ruston and the other from Yedman Dale [TA 980 853] 900 m northwest of West Ayton (Fig. 3).

Gallows Hill was chosen as it is a northerly eroded remnant of the Wykeham Moraine, which marks the maximum advance of a lobe of North Sea ice-sheet into the Vale of Pickering (Powell *et al*. 2017), a view confirmed by Fairburn (2019). The deposits forming the moraine consist mainly of glaciofluvial sand and gravel probably deposited at the frontal lobe of an ice-sheet (Penny and Rawson 1969). Gallows Hill has a planar summit at the 60 m O.D. thought to have been eroded by the 70 m O.D glacial Lake Pickering (Fairburn 2019). This level was also recorded on the summit of the Wykeham Moraine south of Ruston and on the face of the Hutton Buscel Terrace between Yedman Dale and Forge Valley (Fairburn 2019, fig. 7b). By trying to derive an age for Gallows Hill, it was hoped to provide a minimum age for the Wykeham Moraine. The auger drilling was undertaken to confirm the uppermost lithology of the moraine on Gallows Hill, as it is devoid of natural outcrops and therefore the moraines internal structure is unknown. Auger drilling on the summit of Gallows Hill revealed a cap of lag gravel and no sediment suitable for luminescence dating. However, approximately 5 m downslope from the summit, below and to the left of the person, sand was visible (Fig. 6A). A small section dug at this site, below the soil horizon revealed, sand with no visible bedforms (Fig. 6B) that could be near-surface slope wash

Particle size analysis of this sample showed it to be bimodal with a dominant component (90%) comprising a well-sorted sand (mean of 200 µm) and a minor (10%) clay component (mean of 8 µm; Fig. 7). A luminescence sample was collected from undisturbed sediment at a depth of 0.9 m.

The Yedman Dale site (Fig. 3) lies in a cutting along a farm track on the eastern side of Yedman Dale just below the 70 m O.D. shoreline mapped by Fairburn (2019). The site is marginal to the rudaceous deposits of the Forge Valley-Yedman Dale embayment, now largely removed by quarrying, that pass laterally to the arenaceous sediments that form the Hutton Buscel Terrace between Yedman Dale and Ruston (Fig.3). While these arenaceous sediments do contain pebbles of Jurassic sandstones and limestone and some larger fragments of limestone of presumed local provenance, the bulk of the landform is composed of siliceous sand and grit from an unknown copious source. This conclusion, coupled with the identification of more exotic material by Kendall (1902), has resulted in the suggestion that the Hutton Buscel terrace originated from sub-aqueous fans built by fluvio-glacial sediments, supplied by feeder channels, eroding pre-Devensian till on the Jurassic dip-slope.

At this site location, the cleaned section revealed poorly sorted rounded quartz gravel with a sand matrix (Fig, 6D). In places the section contained lenses of free sand, one of which was sampled (Fig, 6C).

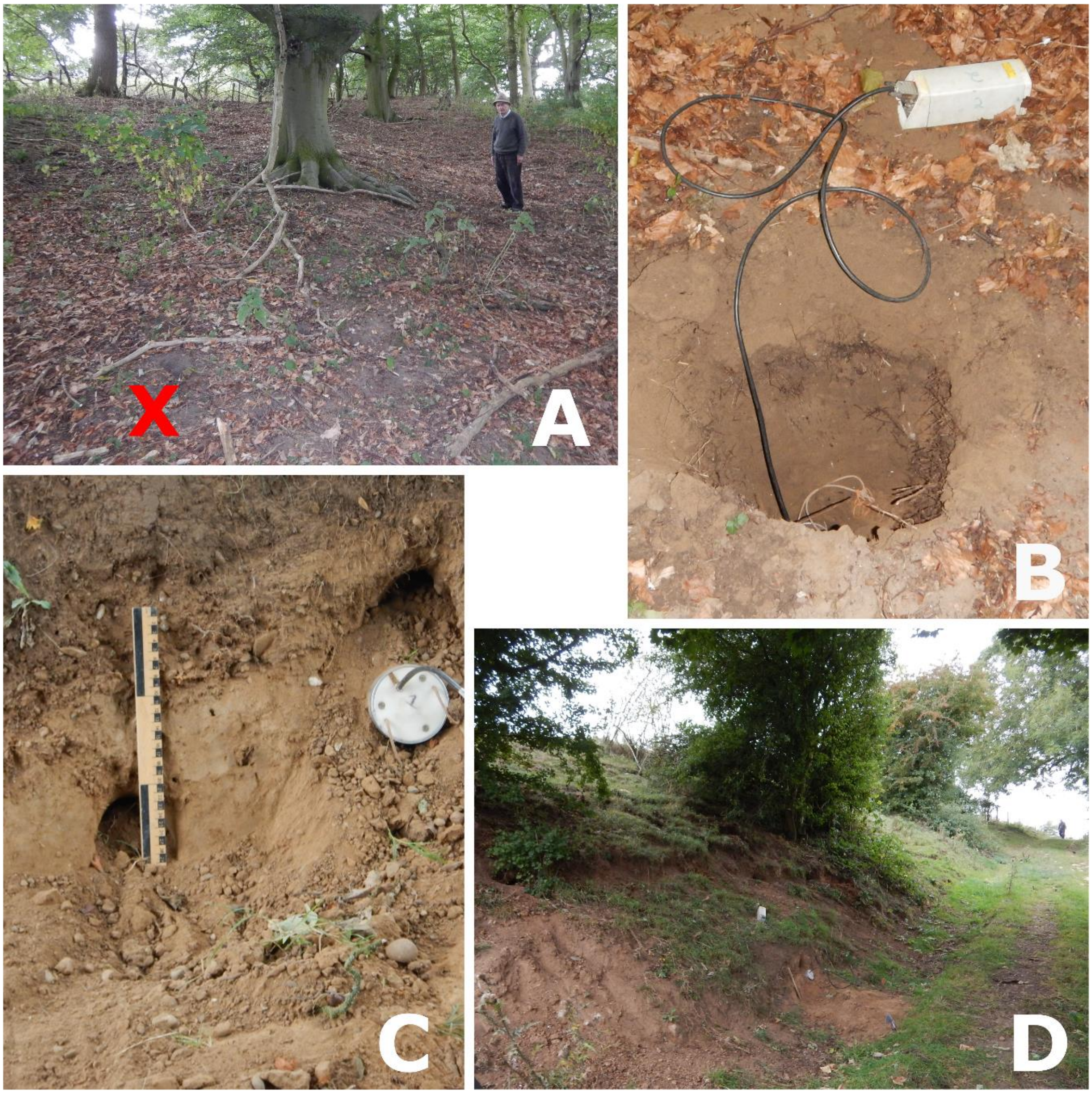

Figure 6. Sites in the Vale of Pickering sampled for luminescence dating. (A) The slope below the flat top of Gallows Hill upon which a gravel lag was found. Note, X indicates the locality where the pit shown in Fig 6B was dug (B) The sandy unit just below the summit on Gallows Hill sampled for luminescence dating. Gamma spectrometer 20 cm in length for scale; (C) gravelly fine sand sampled for luminescence dating at Yedman Dale (D) Yedman Dale section along a farm track with a person standing on the 70 m O.D. shoreline mapped by Fairburn (2019).

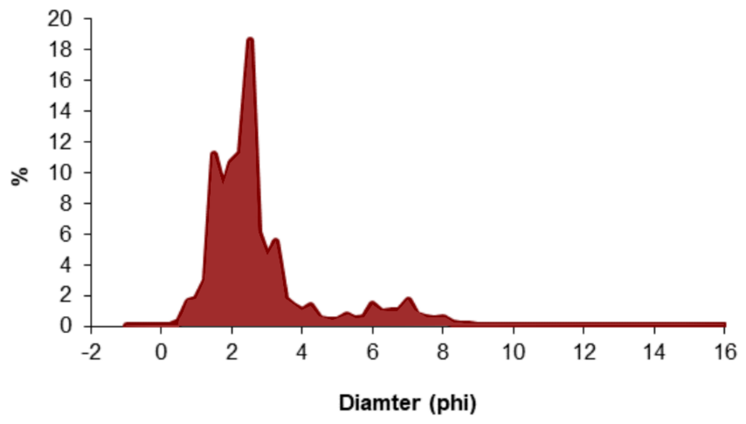

Figure 7. Particle size distribution of the sand sample collected from Gallows Hill and measured using a Horiba Laser diffraction system. The fine clay component is interpreted as being derived by elluviation from the overlying soil. The dominant well-sorted fine sand is interpreted as being deposited in a low-energy fluvial environment.

Methods employed

For both sites, a single sample of sand was obtained by driving an opaque PCV tube into the sections and wrapping it in opaque plastic bags once extracted. *In situ* dose rate measurements were also undertaken for both sample sites using an EG and G micronomad.

Whilst quartz OSL has been successfully applied to sediments back to MIS 8 (e.g. Pawley *et al.* 2008), this is only where background dose rates are extremely low. More commonly, average background dose-rates as found in the VOP, lead to the saturation limit of quartz being exceeded by around 150,000 years of burial or younger. The higher saturation dose limit of feldspar, when measured using infra-red stimulated luminescence (IRSL), means that an upper dating limit of 200,000–300,000 years or even more is possible (Mahan and DeWitt 2019). As such, given the potential antiquity of the samples for this study, the dosimeter used for dating was feldspar. Unfortunately, the IRSL signal of feldspars when measured at 50˚C has been shown to suffer from anomalous fading problems, which have led to age under-estimations (Mahan and DeWitt 2019). However, it has been found that making additional IRSL measurements at elevated temperatures (e.g. 225˚C) significantly reduced or eliminated fading (e.g. Buylaert *et al.* 2009; Buylaert *et al.* 2012). Referred to as the post-IR IRSL technique this measurement approach was adopted for these samples. The final challenge for IRSL dating to obtain a sediment burial age is the need for all IRSL signals at burial to have been removed by exposure to sunlight. Given the fluvial origin of the samples in this study, this full resetting prior to burial could not be guaranteed. To help exclude not fully reset material two approaches were taken. In the absence of the possibility of single grain measurements, firstly measurements were made using a monolayer of sample 5 mm in diameter containing approximately 500 grains rather than the more standard 2500 grains. In a sample with heterogeneous bleaching this reduces the averaging affects. Secondly, both samples had 24 replicates measured. With this combined approach it was hoped that if incomplete bleaching had occurred in either sample this would be discernible.

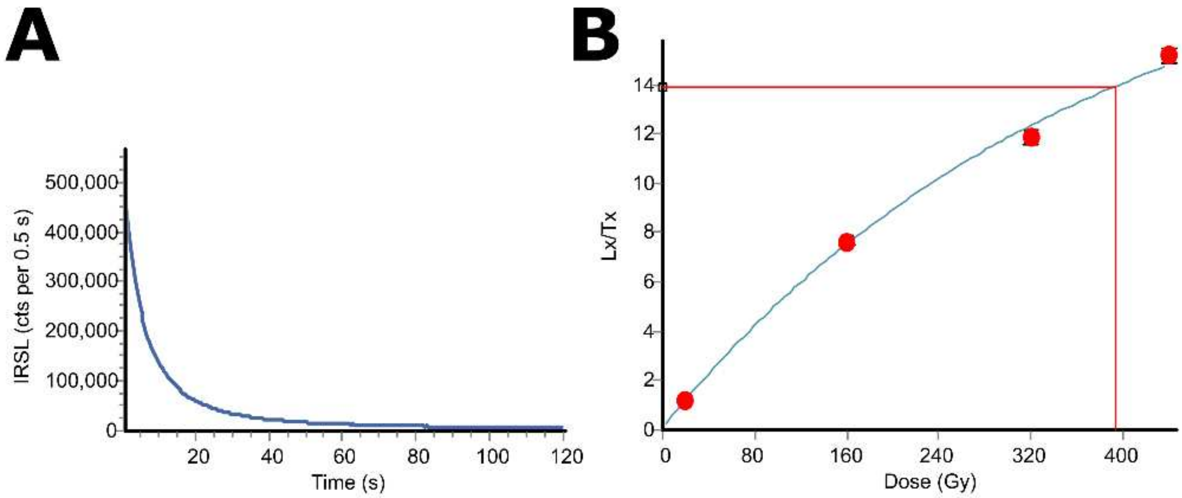

Figure 8. Example of a post-IR IRSL SAR data. (A) A shine down curve showing rapid trap emptying with IR stimulation. (B) A growth curve measured at 225ºC showing data well fitted by a single saturating exponential curve and that the sample is not at saturation.

Samples for post IR-IRSL dating were prepared to clean and extract feldspars under subdued red lighting following the procedure outlined in Bateman and Catt (1996). Feldspar grains in the medium sand size range were mounted as a ~5 mm diameter monolayer on 9.6 mm diameter stainless steel using silkospray. All measurements were undertaken following a preheat of 260˚C for 300 seconds in a Riso DA18 luminescence reader using an array of IR LEDs to provide stimulation. Sample palaeodoses (D_e) were analysed using the single aliquot regenerative (SAR) approach of Murray and Wintle (2003) with five regeneration points14 including a repeat one to assess sensitivity correction. As per Buyleart *et al.* (2012) following IRSL measurement at 50˚C the IRSL signal was measured a second time with the sample held to 225˚C. External dose rates for the samples were based on the field gamma spectrometry measurements for the gamma dose. External beta dose rates were based on ICP-OES and

ICP-MS elemental measurements converted dose rates using data from Guerin *et al.* (2011). Both were attenuated for grain size, density and a palaeomoisture value based on present-day moisture levels with a ± 5 % error to incorporate fluctuations through time (Table 1). An internal dose-rate was based on an assumed internal potassium content of 12%.

Table 1. Luminescence related data for sampled sites.

Sample Site	Sample code	Depth from surface (m)	Water content (%)	K (%)	U (ppm)	Th (ppm)	Cosmic dose rate (μGy a^{-1})	Beta dose rate (μGy a^{-1})	Gamma dose rate (μGy a^{-1})	Total dose rate (μGy a^{-1})
Gallows Hill										
	Shfd18100	0.9	3.1	0.7	1.14	4.5	188 ± 9	1366 ± 67	481 ± 24	2064 ± 72
Yedman Dale										
	Shfd18101	1.6	5.2	1.0	1.77	6.7	171 ± 9	1682 ± 89	743 ± 38	2633 ± 97

Sample Site	Sample code	n	$IRSL_{50}$ D_e (Gy)	$IRSL_{50}$ OD (%)*	$IRSL_{225}$ D_e (Gy)	$IRSL_{225}$ OD (%)*	$IRSL_{50}$ Age (ka)	$IRSL_{225}$ Age (ka)
Gallows Hill								
	Shfd18100	24	348 ± 11	16(14)	364 ± 25**	19(17)	169 ± 8	176 ± 14
Yedman Dale								
	Shfd18101	21	336 ± 9	14(12)	412 ± 26**	16(14)	127 ± 6	156 ± 12

* Overdispersion (OD) as calculated using the central age model of Galbraith and Green (1990) with values in parenthesis showing OD once outliers had been removed.

** De based as calculated using Minimum Age Model (MAM) of Galbraith and Green (1990) with a Sigma-b value of 0.1.

Post IR-IRSL measurements showed a strong rapidly decreasing signal and growth curves which grew well with laboratory doses (Fig. 8). Importantly growth curves showed no signs of saturation. Of the 24 replicates per sample only three aliquots in Sample Shfd18101 from Yedman Dale when measured at 225°C failed the recycling test and had to be discarded. D_e replicates showed that for all samples low overdispersion values of < 20% with a broadly normal distribution for the IR_{50} data (Fig. 9). For the IR_{50} data the final D_e values for age calculation purposes, as shown in Table 1, were derived using the Central Age Model (CAM) of Galbraith and Green (1990). The IR_{225} data shows a slight skewing indicative of some incomplete bleaching of this harder to reset signal. To mitigate the effects of this for the IR_{225}

data the final D_e values for age calculation purposes, as shown in Table 1, were derived using the Minimum Age Model (MAM) of Galbraith and Green (1990). D_e values for measurements at IR_{225} also include a subtraction of a residual of 10.73 Gy as determined by prolonged daylight bleaching in Sheffield University followed by measurement as above.

Ages are shown in ka with one sigma confidence levels. Given the above approach, the ages for the samples are considered to reflect true sediment burial ages.

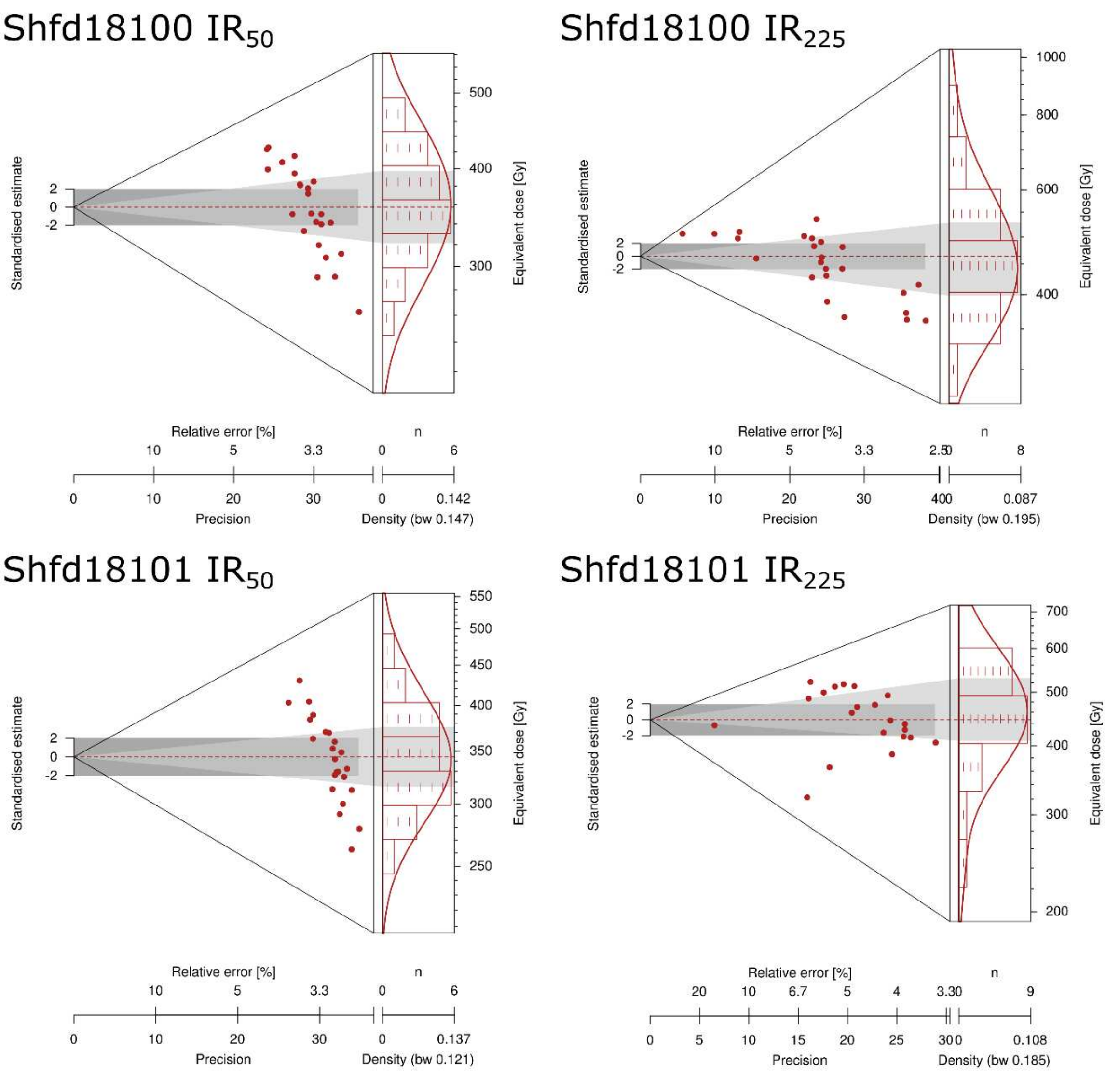

Figure 9. Replicate palaeodose (D_e) data for the two samples measured at both IR_{50} and IR_{225}. Sample Shfd18100 was from Gallows Hill on the Wykeham Moraine and sample Shfd18101 was from Yedman Dale.

As can be seen in Table 1, whilst the IR_{50} D_e measurements are consistent with each other they are much smaller than the equivalent IR_{225} D_e values. As a consequence the ages derived from the IR_{50} data are much younger at 169 ± 8 ka and 127 ± 6 ka for samples Shfd18100 and Shfd18101 respectively. Given both the IR_{50} and IR_{225} D_e distributions are broadly similar in shape (Fig. 9) it is thought less likely that the younger IR_{50} ages represent better resetting prior to burial. Instead it is thought the lower ages represent the impacts of anomalous fading. On this basis the IR_{225} ages are preferred and used in the discussion that follows.

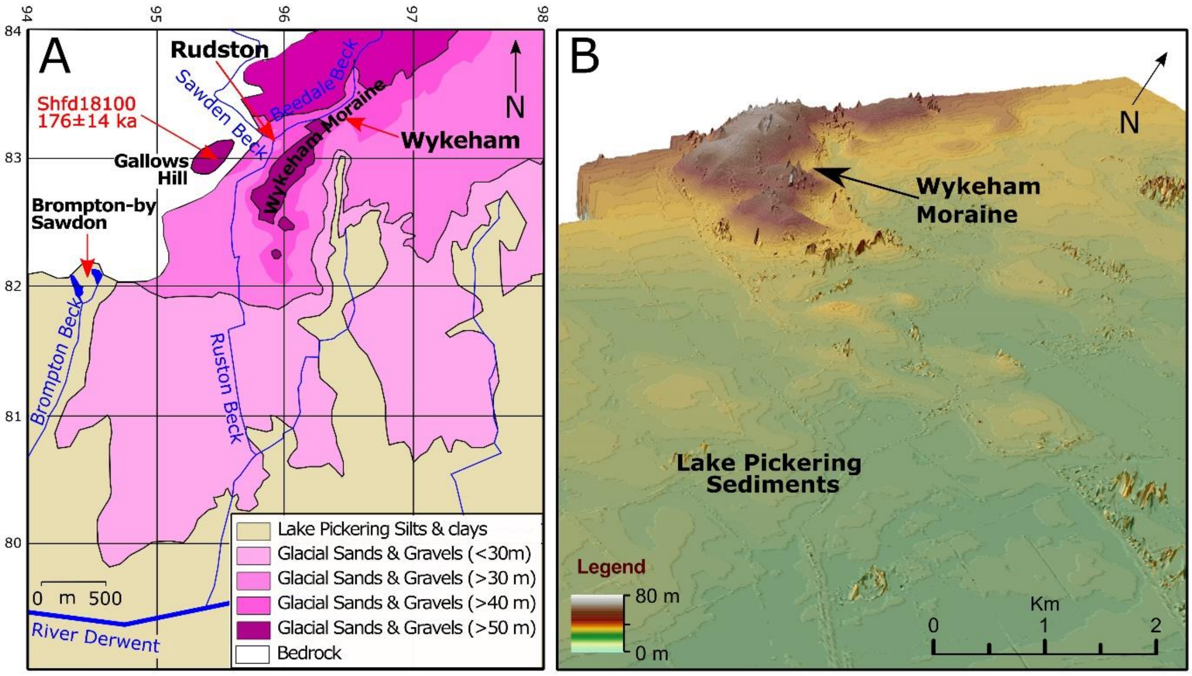

Figure 10. A) The Wykeham Moraine and Gallows Hill with associated erosional terraces of high-level and low-level Lake Pickering: 50 m - this terrace has produced a planar surface near the crest of the Wykeham Moraine and isolated Gallows Hill; 40 m - this has eroded the margins of the Wykeham Moraine to its present form; 30 m - this terrace was not mapped but was identified near Brompton-by-Sawdon; boundary of Lake Pickering silts and clays at c.25 m from British Geological Survey 2000. Adapted from Eddey et al. 2017. B) LiDAR image (2 m definition) looking north towards the Wykeham Moraine that is bounded by the 40 m O.D. shoreline of low-level Lake Pickering. Residuals of the moraine can be seen trending southwards, as remnants of the landform, following erosion of the moraine during drainage of the lake below 30 m O.D. towards the preferred or sole exit of the Derwent Valley rather than the Mere Valley (Fairburn 2019). The LiDAR also confirms an extension of the 30 m terrace recognised at Brompton-by-Sawdon. LiDAR data from Open Survey online store (data.gov.uk) provided by the Environmental Agency.

Results

The sample from Gallows Hill gave an age of 176 ± 14 ka. If the minor clay component of this sample is interpreted as post-depositional elluviation of weathered material, then the well sorted and fine-grained nature of this sample would imply sediment deposition in a low – moderate energy regime. As the sample site is elevated on the south side of Gallows Hill (*c.* 55 m O.D.) above a drainage valley through the Wykeham Moraine southwest of Ruston (Fig.10), it can be accepted that the sample is representative of the fluvial deposits that formed Gallows Hill, probably from supra-glacial streams. Consequently the date provides a minimum age for the Wykeham Moraine.

The sample from Yedman Dale gave an age of 156 ± 12 ka indicating fluvial deposition of the sand and gravels found there within MIS 6 (Fig. 11). Fairburn (2019) proposed that the Hutton Buscel Terrace originated as a Lake Pickering shoreline at *c.* 70 m O.D. with sediment supplied by feeder channels draining the Jurassic slope from a periglacial environment comparable to deposition of the Chalk-gravel alluvial fans on the south side of VOP, or the Pocklington Gravel Formation in the Vale of York (Fairburn 2014). This was later modified by lower, erosional, recessional shorelines during shrinkage of Lake Pickering. If this interpretation is accepted then the luminescence age from Yedman Dale dates from when sediment was supplied as Lake Pickering was establishing itself, providing for the first time a minimum age for the 70 m O.D. Lake Pickering.

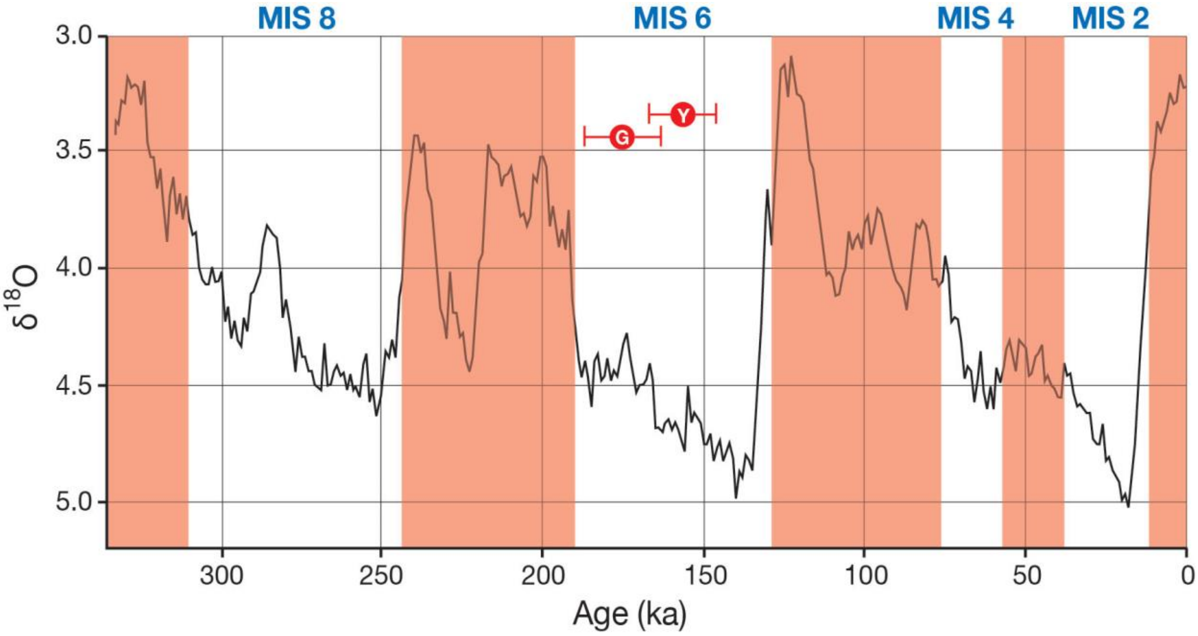

Figure 11. The first direct dates for high-level Lake Pickering placed into the Marine Isotope Stage (MIS) context with cold glacial periods labelled and warm periods shown in red. G=Gallows Hill. Y=Yedman Dale. Adapted from data from Lisiecki and Rayne 2005

Discussion

The new luminescence ages tentatively show that both Wykeham Moraine and Hutton Buscel Terrace are considerably older than MIS 2. Whilst only two in number, they provide a preliminary important minimum age for a glacial incursion into the VOP and formation of a Lake Pickering in MIS 6 or earlier. That the Wykeham Moraine might be a composite from multiple time periods (both earlier and later) should not be overlooked, as, for example, the British and Irish Ice Sheet (BIIS) reaching the Stiffkey Moraine (Norfolk) in MIS 6 and again in MIS 2 (Evans *et al* 2019). Whilst not at an ice-sheet maximal limit like in Norfolk, as the VOP runs east-west and BIIS advances in the North-Sea tend to flow south, ice incursions into the VOP would have been tangential to the main flow and on rising ground . Ice velocity would have rapidly declined the further westward it penetrated into the VOP making it possible ice could have terminated as similar points in the landscape on more than one occasion.

The question remains whether the VOP was partially glaciated forming an earlier phase of Lake Pickering in MIS 6 or, as the new luminescence ages only give a minimum age whether this occurred in MIS 8. Evidence for a widespread MIS 8 glaciation is suggested by White *et al.* (2010) from the middle and lower Trent system in Lincolnshire where Thrussington, Oadby and Wragby tills have been correlated and named the Wragby Glaciation

(Bridgland *et al.* 2015). Eastern and Western ice sheets are envisaged for this MIS 8 glaciation with the former shown as extending as far west as the Vale of York and as far south as Peterborough and The Wash area (Bridgland *et al.*, 2015, fig 6). If the extent of the Wragby glaciation is correct it would seem unlikely that VOP would have remained ice free. Indeed, Powell *et al.* (2016) proposed an MIS 8 age for the tills they mapped and drilled near Pickering. As proposed by them, the tills, based on geomorphological orientation and preponderance of Upper Jurassic erratics, represents a more localised plateau icefield than that shown for the Wragby glaciation. The two, however, may not be mutually exclusive if the eastern ice lobe of the Wragby ice blocked the eastern end of the VOP allowing the formation of a lake restricting glaciation of the slightly higher western end of VOP to local ice. Certainly during MIS 2 the VOP and the North York Moors to the north is thought to have stayed ice-free with BIIS ice lobes passing down the North Sea and Vale of York.

Whilst the new luminescence dates could support a MIS 8 glaciation, as the Wykeham Moraine and Hutton Buscel Terrace were firmly emplaced by MIS 6, then for shorelines to have been eroded into them, a lake must have existed in MIS 6. For such a lake to have existed, by implication ice must have also been present to form the required ice dams. Some evidence is emerging for a Wolstonain (MIS 6) glaciation in the Norfolk Wash area of the UK (Gibbard *et al.* 2018). Whilst this awaits substantive confirmation with a chronology, for ice to reach the Wash, it would appear unlikely that VOP would not, at the very least have been blocked at its eastern end even if ice did not advance into the valley itself.

The events associated with the Wykeham Moraine and Hutton Buscel Terrace suggest a highly dynamic environment including the build-up of ice in the VOP, erosion of the Hutton Buscel scarp, creation of the Wykeham Moraine, build-up of Lake Pickering and release of fluvial deposits from Yedman Dale. Whilst evidence for MIS 6 glaciation in the UK is limited (and contested), a correlative can be found in the Saalian glaciation, the MIS 6 European equivalent to the Wolstonian. The Saalian glaciation is thought to have had multiple ice advances often referred to as the Drenthe and Warthe (Lang *et al.* 2018). New work has shown one such ice advance, which has been dated with post IR-IRSL$_{290}$, to have occurred between 175 ± 10 to 156 ± 24 ka and a later one to between 155 ± 21 to 130 ± 17 ka (Lang *et al.* 2018). If climatic forcing caused two ice advances in Scandinavia and the surrounding environs of continental Europe it is possible that a BIIS icesheet in this period may also have had two phases allowing for the dynamism shown in the geomorphology in the VOP at this time.

Whilst evidence for at least one MIS 6 or MIS 8 glaciation in an early phase of glacial Lake Pickering is increasing some issues remain unresolved. First amongst these is how lake levels above 45 m O.D. were maintained. Currently the Derwent Gorge with a river level below 20 m O.D., means that lake levels at 70 m O.D. could not be sustained. It is unlikely that this gorge could have been cut to its present levels post MIS 6 as the river flowing through it does not have this capacity. It is possible that a lake could only have existed when extensive ice dams to > 70 m O.D. were emplaced at both the eastern and western ends of the VOP but this would require synchronicity for ice lobes in the Vale of York and North Sea basin. Alternatively, if ice only extended from the eastern end isostatic tilting may have allowed apparently high lake levels around the eastern end of the VOP and a more restricted lake. Evidence of post-MIS 7 isostatic rebound, described for the Easington raised beach by Davies *et al.* (2009), has also been reported in the Vale of York based on the rising surface of the 52 m strandline (Penny 1974) of a pre-Devensian Lake Humber (Fairburn and Bateman 2016). Progressive uplift and rejuvenation could have led to contemporaneous erosion of gorge-like valleys such as Derwent Valley near Kirkham Priory and the Mere Valley leading into Scarborough. Finally, as the Chalk-gravel fans and the Hutton Buscel Terrace, mapped by Fairburn (2019,) appear intact down to 45 m O.D., apart from lacustrine shoreline erosion, there appears little scope for a later MIS 6 advance or even the MIS 2 ice extending into the VOP beyond the Flamborough Moraine.

Conclusions

New IR-IRSL ages from Yedman Dale and Gallows hill of 156 ± 12 ka and 176 ± 14 ka provide minimum ages for the Hutton Buscel Terrace and the Wykeham Moraine. This preliminary new work raises the possibility that, in addition to the well documented MIS 2 advance of the North Sea ice of the BIIS into the VOP impounding Lake Pickering, there is evidence for an older ice advance. The older glacial event formed Wykeham Moraine and blocked the VOP and in doing this it produced an early stage of Lake Pickering with a shoreline of *c.* 70 m O.D.. Whilst this earlier glaciation of the VOP could be MIS 8, evidence at present suggests it should be tentatively assigned to MIS 6 coinciding with the early phase of the European Saalian glaciation; the Drenthe stage of Lang *et al.* (2018). Further work is required to test the validity of this.

Acknowledgements

The authors would like to thank Rob Ashurst for help collecting and preparing the sand samples for luminescence dating at the Sheffield University Luminescence Laboratory and for his work on the particle size distribution of sand from Gallows Hill. Paul Coles is thanked for his cartographic expertise and Samantha Lyth for typing many changes to the text.

References

Bateman, M.D. and Catt, J.A. 1996. An absolute chronology for the raised beach and associated deposits at Sewerby, East Yorkshire, England. *Journal of Quaternary Science.,* **11,** 389–395.

Bateman, M.D., Evans, D.J.A. and Roberts, D.H. *et al.* 2018. The timing and consequences of the blockage of the Humber Gap by the last British-Irish Ice Sheet. *Boreas,* **47**, 41-61.

British Geological Survey 2000. *Pickering. England and Wales sheet 53. Solid and Drift Geology. 1:50 000 Provisional Series*. British Geological Survey. Keyworth, Nottingham.

Bridgland, D.R., Howard, A.J., White, M.J., White, J.S. and Westaway, R. 2015. New insight to the Quarternary evolution of the River Trent, UK. *Proceedings of the Geologists' Association,* **126**, 466-479.

Buylaert, J.P., Murray, A.S., Thomsen, K.J., and Jain, M. 2009. Testing the potential of an elevated temperature IRSL signal from K-feldspar. *Radiation Measurements,* **44**, 560-565.

Buylaert, J. P., Jain, M., Murray, A.S., Thomsen, K. J., Thiel, C. and Sohbati, R. 2012. A robust feldspar luminescence dating method for Middle and Late Pleistocene sediments. *Boreas,* **41**, 435–451.

Catt, J.A. 2007. The Pleistocene glaciations of eastern Yorkshire a review. *Proceedings of the Yorkshire Geological Society,* **56,** 177-207.

Catt, J.A. and Penny, L.F. 1966. The Pleistocene deposits of Holderness East Yorkshire. *Proceedings of the Yorkshire Geological Society,* **49,** 325-334.

Davies, B.J., Bridgland, D.R. and Roberts, D.H. *et al.* 2009. The age and stratigraphic context of the Easington Raised Beach, County Durham, U.K. *Proceedings of the Geologists' Association,* **120**, 183-198.

Eddey, L.J., Lincoln, P.C., Palmer, A.P. and Bateman, M.D. 2017. The Late Quaternary Glaciation of the Vale of Pickering. In: Lincoln, P.C., Eddey, L.J., Matthews, I.P., Palmer, A.P. and Bateman, M.D. (eds). *The Quaternary of the Vale of Pickering: Field Guide.* Quaternary Research Association, London.

Edwards, C.A. 1978. *The Quaternary history and stratigraphy of north-east Yorkshire.* Unpublished PhD Thesis. University of Hull.

Evans, D.J.A. and Bateman M.D. *et al.* 2017. Glacial Lake Pickering: stratigraphy and chronology of a proglacial lake dammed by the North Sea Lobe of the British-Irish Ice Sheet. *Journal of Quaternary Science,* **32***, 295-310.*

Evans, D.J.A., Roberts, D.H., Bateman, M.D., Ely, J., Medialdea, A., Burke, M.J., Chiverall, R.C., Clark, C.D. and Fabel, D. 2019. A chronology for North Sea Lobe advance and recession on the Lincolnshire and Norfolk Coasts during MIS 2 and 6. *Proceedings of the Geologists' Association,* **130**, 523-540.

Fairburn, W.A. 2014. *A re-interpretation of the physiographic evolution of the southern end of the Vale of York from the mid-Pleistocene to the Early Holocene.* Unpublished PhD Thesis, University of Sheffield.

Fairburn, W.A. 2019. Glacial lake terraces at the eastern end of the Vale of Pickering, North Yorkshire, UK. *Proceedings of the Yorkshire Geological Society,* **62**, 260-272.

Fairburn, W.A. and Bateman, M.D. 2016. A new multi-stage recession model for proglacial Lake Humber during the retreat of the last British-Irish Ice Sheet. *Boreas,* **45**, 135-151.

Foster, S.W. 1985. *The late glacial and early post-glacial history of the Vale of Pickering and northern Yorkshire Wolds.* Unpublished PhD Thesis, University of Hull.

Fox-Strangways, C. 1880. The geology of the Oolitic and Cretaceous rocks of Scarborough. *Mem. Geol. Surv. of Great Britain, England and Wales.* HMSO, London.

Fox-Strangways, C. 1892 Jurassic Rocks Britain, Vol.1. *Mem. Geol. Surv. of Great Britain, England and Wales,* HMSO, London.

Franks, A.C. 1978. A Re-evaluation of Late Quaternary events in the eastern half of the Vale of Pickering. Unpublished Ph.D thesis. The Open University.

Galbraith, R.F. and Green, P.F. 1990. Estimating the Component Ages in a Finite Mixture. *Nuclear Tracks and Radiation Measurements,* **17**, 197-206.

Gibbard, P.L., West, R.G. and Hughes, P.D. 2018. Pleistocene glaciation of Fenland, England, and its implications for evolution of the region. *Royal Society Open Science*, **5**, 1-52.

Guerin, G., Mercier, N. and Adamiec, G. 2011. Dose-rate conversion factors: update. *Ancient TL*, **29**, 5-8.

Kendall, P.F. 1902. A system of glacier-lakes in the Cleveland Hills. *Quarterly Journal of the Geological Society,* **58**, 471-571.

Lang, J., Lauer, T. and Winsemann, J. 2018. New age constraints for the Saalian glaciation in northern central Europe: Implications for the extent of ice sheets and related proglacial lake systems. *Quaternary Science Review*, **180**, 240-259.

Lisiecki, L.E. and Rayne, M.E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. *Paleoceanography,* **20,** 1-17

Mahan, S. and DeWitt, R. 2019. Principles and History of Luminescence Dating. In Bateman, M.D. (Ed) *The Handbook of Luminescence Dating.* Whittles Publishing, p 416.

Murray, A.S. and Wintle, A.G. 2003. Luminescence dating of quartz using an improved regenerative-dose protocol. *Radiation Measurements,* **32,** 57 – 73.

Pawley, S.M., Bailey, R.M., Rose, J., Moorlock, B.S.P., Hamblin, R.J.O., Booth, S.J., and Lee, J.R. 2008. Age limits on Middle Pleistocene glacial sediments from OSL north Norfolk, UK. *Quaternary Science Review,* **27**, 1363-1377.

Penny, L.F. 1974. Quaternary. In: Raynor, D.H. and Hemingway, J.E. (eds). *The geology and mineral resources of Yorkshire.* Yorkshire Geological Society. *Occasional Publication,* **2**, 245-264.

Penny, L.F. and Rawson, P.F. 1969. Field meeting in East Yorkshire and North Lincolnshire. *Proceedings of the Geologists' Association,* **80**, 193-216.

Powell, J.H., Ford, J.R. and Ridings, J.B. 2016. Diamicton from the Vale of Pickering and Tabular Hills, north-east Yorkshire: evidence for a Middle Pleistocene (MIS 8) glaciation. *Proceedings of the Geologists' Association,* **127**, 575-594.

Powell, J.H. 2017. Pre-Quaternary Geology of the Vale of Pickering. In: Lincoln, P.C., Eddey, L.J., Matthews, I.P Palmer, A.P. and Bateman, M.D. (eds). *The Quaternary of the Vale of Pickering: Field Guide.* Quaternary Research Association, London.

Saarnisto, M. 1970. The Late Weichselian and Flandrian history of the Saimaa Lake Complex. *Societas Scientarium Fennica, Commentationes Physico-Mathematicae,* Vol. **37.**

Straw, A. 1979. The Devensian glaciation. *In*: Straw, A. and Clayton, K.M. (eds). *The Geomorphology of the British Isles: Eastern and Central England.* Methuen, London, 21-45.

Thistlewood, L. and Whyte, M.A. 1993. A palaeomagnetic and mineral magnetic study of Speeton Shell Bed, North Yorkshire. *Proceedings of the Yorkshire Geological Society,* **49,** 325-334.

White, T.S., Bridgland, D.R., Westaway, R., Howard, A.J. and White, M.J. 2010. Evidence from the Trent terrace archive, Lincolnshire, for lowland glaciation of Britain during the Middle and Late Pleistocene, *Proceedings of the Geologists' Association,* **121**, 141-153.

White, T.S., Bridgland, D.R.,Westaway, R. and Straw, A. 2016. Evidence for late Middle Pleistocene glaciation of the British margin of the Southern North Sea. *Journal of Quaternary Science,* **32,** 261-275.

Wilson, S. 1991. The correlation of the Speeton Shell Bed, Filey Bay Yorkshire to an oxygen isotope stage. *Proceedings of the Yorkshire Geological Society,* **48,** 223-226.

William A. Fairburn

List of Figures

Figure 1. Locality map of the eastern end of the Vale of Pickering as per Fairburn (2019) showing the 45 m and 70 m O.D. shorelines and the location of Fig. 3 (the Hutton Buscel Terrace) and Fig.4 (the geological mapping between East and West Heslerton).

Figure 2. View of Vale of Pickering looking north-west from Staxton Hill, on the northern edge of the Yorkshire Wolds, showing the flat nature of the Vale surrounded by the Howardian Hills to the west and North Yorkshire Moors to the north.

Figure 3. Landform map of the Hutton Buscel Terrace between Ruston and Forge Valley showing the northern edge of the 70 m O.D. glacial lake bounding the Hutton Buscel alluvial fans with shorelines imprinted at lower levels between 45 m and 65 m O.D (as per Fairburn 2019). The site of the two IRSL samples are indicated. From Fairburn 2019.

Figure 4. Geological map between East and West Heslerton showing the Chalk Group escarpment, the hummocky chalk-gravel alluvial fans mainly constrained between 70 and 45 m O.D., with the Sherburn Sands, apart from feeder valleys, restricted below 45 m O.D. Note the 65 m, 55 m, 40 m and 30 m O.D. shorelines. From Fairburn 2019.

Figure 5. Shorelines at 70m O.D. (a) In Yedman Dale [SE 982 853], north of West Ayton, where the north east trending shoreline marks a distinct land usage boundary between grass-covered shallow sub-cropping Corallian Group limestone bounding well-ploughed sand and gravel along an erosional contact that extends for over 20 m. (b) near Crambe [SE 726 645] where the back-wall of the 70m O.D. terrace forms a 'washing line' between glacial till above from Jurassic bedrock below. The NE-SW trending back-wall is formed by silts separating Jurassic bedrock in the foreground from upslope tills above the hedgerow. The contact here extends for about 100 m.

Figure 6. Sites in the Vale of Pickering sampled for luminescence dating. (A) The slope below the flat top of Gallows Hill upon which a gravel lag was found. Note, X indicates the locality where the pit shown in Fig 6B was dug (B) The sandy unit just below the summit on Gallows Hill sampled for luminescence dating. Gamma spectrometer 20 cm in length for scale; (C) gravelly fine sand sampled for luminescence dating at Yedman Dale (D) Yedman Dale section along a farm track with a person standing on the 70 m O.D. shoreline mapped by Fairburn (2019).

Figure 7. Particle Size distribution of the sand sample collected from Gallows Hill and measured using a Horiba Laser diffraction system. The fine clay component is interpreted as being derived by elluviation from the overlying soil. The dominant well-sorted fine sand is interpreted as being deposited in a low-energy fluvial environment.

Figure 8. Example of a post-IR IRSL SAR data. (A) A shine down curve showing rapid trap emptying with IR stimulation. (B) A growth curve measured at 225^{o}C showing data well fitted by a single saturating exponential curve and that the sample is not at saturation.

Figure 9. Replicate palaeodose (D_e) data for the two samples measured at both IR_{50} and IR_{225}. Sample Shfd18100 was from Gallows Hill on the Wykeham Moraine and sample Shfd18101 was from Yedman Dale.

Figure 10. A) The Wykeham Moraine and Gallows Hill with associated erosional terraces of high-level and low-level Lake Pickering: 50 m - this terrace has produced a planar surface near the crest of the Wykeham Moraine and isolated Gallows Hill; 40 m - this has eroded the margins of the Wykeham Moraine to its present form; 30 m - this terrace was not mapped but was identified near Brompton-by-Sawdon; boundary of Lake Pickering silts and clays at c.25 m from British Geological Survey 2000. Adapted from Eddey et al. 2017. B) LiDAR image (2 m definition) looking north towards the Wykeham Moraine that is bounded by the 40 m O.D. shoreline of low-level Lake Pickering. Residuals of the moraine can be seen trending southwards, as remnants of the landform,

following erosion of the moraine during drainage of the lake below 30 m O.D. towards the preferred or sole exit of the Derwent Valley rather than the Mere Valley (Fairburn 2019). The LiDAR also confirms an extension of the 30 m terrace recognised at Brompton-by-Sawdon. LiDAR data from Open Survey online store (data.gov.uk) provided by the Environmental Agency.

Figure 11. The first direct dates for high-level Lake Pickering placed into the Marine Isotope Stage (MIS) context with cold glacial periods labelled and warm periods shown in red. G = Gallows Hill, Y = Yedman Dale. From Lisiecki and Rayne 2005.