A revised terrace stratigraphy and chronology for the early Middle Pleistocene Bytham River in the Breckland of East Anglia, UK

Simon G. Lewis[1], Nick Ashton[2], Rob Davis[1,2], Marcus Hatch[1], Peter G. Hoare[1,2,✞], Pierre Voinchet[3] and Jean-Jacques Bahain[3]

[1] School of Geography, Queen Mary University of London, Mile End Road, London, E1 4NS, UK

[2] Department of Britain, Europe and Prehistory, British Museum, Franks House, 38-56 Orsman Road, London, N1 5QJ, UK

[3] UMR 7194 HNHP, MNHN-CNRS-UPVD, Département Homme et Environnement du Muséum National d'Histoire Naturelle, Institut de Paléontologie Humaine, 1 rue René Panhard, 75013 Paris, France

✞ deceased

Corresponding author: Nick Ashton nashton@britishmuseum.org

Abstract

The Bytham River was one of the major pre-Anglian (MIS 12) rivers of eastern England. Flowing from the Midlands to the East Anglian coast, it has been recognised at numerous sites by its distinctive lithological suite consisting of quartzose-rich gravels originating from central England. In the Breckland of Suffolk and Norfolk, deposits of the Bytham River can be identified at 26 sites by this distinctive clast lithological composition. These sediments, referred to as the Ingham Formation, consist of a series of sand and gravel aggradations, which due to their differences in elevation can be interpreted as at least five early Middle Pleistocene terrace remnants of the former river. This paper reports on recent fieldwork at six of these sites, which through stratigraphic and lithological analyses, together with new Electron Spin Resonance age estimates, contribute to a revised geological framework for the Bytham River as represented in the Breckland. These sites can be attributed to the four lowest fluvial aggradations, lowest and youngest of these aggradations can be shown to be early Anglian in age. The river was subsequently overrun by Anglian ice during Marine Isotope Stage 12. This revised geological and chronological interpretation provides an important framework for understanding the Lower Palaeolithic artefacts that have been found within these gravel aggradations, and contributes to the understanding of the human occupation of north-west Europe during the early Middle Pleistocene.

Keywords: Bytham River; early Middle Pleistocene; UK; ESR dating; Lower Palaeolithic

1. Introduction

The development during the Quaternary of the major rivers in the lowland regions of southern Britain is the product of the interaction of changing climate and tectonics, though glaciation has also played a major role in the formation, diversion and destruction of drainage systems during the

Pleistocene. The evolution of the River Thames has been investigated for a long period and there is a substantial body of evidence for large-scale catchment changes, the impact of glaciation and the response of the river to climate and base-level changes over glacial-interglacial timescales. Over the last thirty years models of the early Middle Pleistocene palaeogeography of southern England have incorporated the Bytham River, a now-eradicated drainage line that flowed from the English Midlands into East Anglia and thence to the southern North Sea (Rose, 1987, 1989, 1994; 2009; Lewis, 1993; Bridgland et al., 1995; Lee et al., 2004). The Bytham River drained a significant part of southern England and, along with the River Thames, formed one of the major river systems in Britain in the earlier Middle Pleistocene.

The Bytham River in East Anglia is represented by the Ingham Formation, a lithologically distinctive suite of deposits that contain a significant proportion of far-travelled rock-types that are derived from Triassic and Carboniferous bedrock sources in the English Midlands. The deposits also have a heavy mineralogical signature and a pre-Quaternary palynological component that indicate derivation from bedrock sources in midland and western Britain (Rose et al., 1992; Bateman and Rose, 1994). In addition, palaeoflow measurements indicate a generally eastwards or south-eastwards flow for the river in central East Anglia, in contrast to the westerly flow of the modern drainage. The model for the Bytham River system has been developed as new information has become available such that there is now a detailed reconstruction of the river’s catchment. The development of a terrace stratigraphy for the Bytham River has been possible for that part of the river where terraces, as opposed to stacked sequences of sediments, can be recognised, which is east of the Wash/Fen Basin. Terraces of the Bytham River can be recognised in the Breckland area, where a number of altitudinally distinct gravel aggradations can be identified (Lewis, 1993, 1999; Lewis and Bridgland, 1991).

The reconstruction of terrace long profiles is of particular importance, as terrace stratigraphy is often used to constrain regional stratigraphical models and it also provides a framework within which evidence for human presence, in the form of lithic artefacts, can be considered. In order to develop a robust stratigraphic scheme for the Bytham River it is necessary to identify bodies of sediment for which the thickness and height range can be determined at each locality, these form the basis of correlation of terrace fragments which is carried out largely on altitudinal grounds. This is particularly problematic in instances where the sediments are buried beneath younger sediments and there is therefore little or no topographic expression of the terrace surface. In addition, burial by glacigenic sediments may also have resulted in removal of part of the fluvial sequence.

This paper reports the results of recent reinvestigation of six sites as part of the Breckland Palaeolithic Project. The aims were to test existing terrace models against new data, to sample for ESR dating on the different aggradations and to investigate the presence and stratigraphic context of Lower Palaeolithic artefacts at the sites (Davis et al., 2017, submitted). The sites are Warren Hill (Mildenhall), Maidscross Hill (Lakenheath), Brandon Fields (also known as Gravel Hill, Brandon), Rampart Field (Icklingham), Sapiston and Fakenham Magna, all in the county of Suffolk (Figure 1, Table 1). The results from this work, together with data from other sites, including the important Lower Palaeolithic site at High Lodge (Mildenhall), have produced a revised stratigraphic framework for the Bytham River in the Breckland area, which provides a framework for understanding the age of the archaeological assemblages and human presence in Britain during the early Middle Pleistocene.

2. Material and methods

Research at a number of the sites discussed in this paper was undertaken as part of the Breckland Palaeolithic Project (BPP) between 2016 and 2019. Prior to this, research had been undertaken (at Warren Hill, Maidscross Hill and Brandon Fields) under the auspices of the Ancient Human Occupation of Britain (AHOB) and the Pathways to Ancient Britain (PAB) projects. At four of the sites (Warren Hill, Maidscross Hill, Brandon Fields, Rampart Field) small-scale, hand-dug gravel workings were active during the mid-late 19th century, but are long-since abandoned. Larger, commercial scale gravel quarries at Maidscross Hill, Sapiston and Fakenham Magna were active during the mid-20th century.

In addition, data from research undertaken during the 1980s and 1990s on several sites of particular importance to the reconstruction of the Bytham River are also included, as are a number of borehole records originating from the work of the Minerals Assessment Unit in the 1970s and 1980s and now available from the BGS borehole database (Table 1).

A major objective of the BPP was to utilise Electron Spin Resonance (ESR) dating of quartz grains to develop a geochronology for the Bytham River deposits in the Breckland. Initial results, obtained during an earlier study, indicated that ESR dating could potentially provide satisfactory age estimates in situations where Optically Stimulated Luminescence (OSL) and Amino Acid Geochronology (AAR) techniques were not applicable (Voinchet et al., 2015). During the present investigation a further eleven samples were taken from Warren Hill, five from the succession in the former gravel pit and six from test pit sections, together with samples from Rampart Field, Sapiston and Fakenham Magna.

2.1 Stratigraphic and sedimentological investigations

Sections and test pits were excavated either using a mechanical excavator or by hand digging. Boreholes were sunk using cable-percussion drilling, cobra-driven percussion or continuous-flight rotary auger drilling methods. All sections were recorded, photographed and located in relation to the OSGB grid and Ordnance Datum using optical or total station surveying or differential GNSS equipment.

Bulk samples taken from sections and boreholes for clast lithological analysis were washed and sieved and the 11.2-16.0 mm fraction, and in the case of the Warren Hill borehole samples, the 8.0-11.2 mm fraction, retained for clast lithological analysis. Samples taken for particle-size analysis were sieved using standard laboratory procedures (Gale and Hoare, 2011) and, where necessary, the <63 micron fraction was analysed using a Beckman Coulter Laser Diffraction Particle Size Analyzer.

2.2 Electron spin resonance (ESR) dating of quartz grains

ESR dating is a palaeodosimetric method (i.e. the sample is used as a dosimeter for dating) that records the total radiation dose received since the event of interest, namely the time of sediment deposition, through the quantification of electrons trapped in mineral defects within quartz grains in relation to the irradiation (Grün, 1989; Ikeya, 1993). In this case, the dated event is the last sunlight exposure of the quartz grains during its transportation by water or wind before its deposition and geological burial. This light exposure leads to the release of trapped electrons and a zeroing of the ESR signal (optical bleaching). The age calculation relies on the determination of two main parameters: the total dose (D_T), also referred to as the palaeodose or equivalent dose (D_e), and the dose rate (D_a), which is an estimation of the mean dose annually absorbed by the sample.

The equivalent dose is proportional to the concentration of trapped electrons in the sample and so to the ESR signal intensity. The D_e is determined using an additive protocol, which was first described by Yokoyama et al. (1985) and modified first by Laurent et al. (1998) and later by Voinchet et al. (2004). The sample is divided into 10 to 15 aliquots artificially irradiated to different doses allowing the building of ESR intensity vs added doses growth curve. D_e is determined by extrapolation of this growth curve to zero intensity using a mathematical function. In quartz, three paramagnetic centres are frequently used: the Germanium centre (Ge), the Aluminium centre (Al) and the Titanium centres (Ti-Li and Ti-H). Each centre has different characteristics (e.g. differences in optical bleaching kinetics and/or radiation sensitivity), so it is useful to combine studies of more than one centre in the same investigation (e.g. Al − Ti centres are usually present in most of the quartz grains, allowing a multi-centres approach) to evaluate the reliability of the obtained D_e (Toyoda et al., 2000; Rink et al., 2007; Tissoux et al., 2007; Duval and Guilarte, 2015). Exposure of the quartz grains to sunlight leads to a release of trapped electrons, but it should be noted that, while Ti signals are zeroed during such exposure, the Al centre is not fully bleached and thus a 'residual' ESR signal exists at the time of deposition of the quartz grains after their transportation. It is therefore necessary to determine this residual signal intensity that should be subtracted from the intensities of natural and irradiated aliquots before the total dose fitting, in order to determine the dose accumulated after the deposition of the unit under consideration. According to Voinchet et al. (2015) the bleaching quality of quartz is dependent on the selection of grain-size fractions and the identification of transportation modes, especially in relation to the Al centre. In the present work, we have used both Al and Ti-Li centres to provide D_e and ages following the multi-centre approach proposed by Toyoda et al. (2000) and recently developed (Duval et al., 2015; Voinchet et al., 2020). All the samples show very weak Titanium signals, sometimes making the measurement of Ti-Li difficult and the measurement of Ti-H always impossible. For the Ti-H centre, the signal in the natural aliquot is not distinguishable from the background noise.

The following sampling and analytical protocol was used in the present study. At each site, sediment samples of around 1 kg were sampled from freshly cleaned sections. Systematic *in situ* gamma-ray measurements were provided for each sediment sample using a portable gamma spectrometer (a Canberra Inspector 1000 at Warren Hill and an Ortec Scintipack 296 at Rampart Field and Sapiston), to evaluate the γ dose rate. The α and β contributions to the dose rate were determined from radioelement (U, Th, K) contents of the analysed sediments, measured by laboratory high precision gamma spectrometry, using the dose conversion factors of Guérin et al. (2011) and taking into account the attenuation tables of Brennan et al. (1991) and Brennan (2003), an alpha efficiency of 0.15±0.10 according to Yokoyama et al. (1985) and a water content of 15±5%. Cosmic contributions were determined from the Prescott and Hutton (1994) tables.

ESR measurements were performed on 100–200-µm quartz grains (the best grain size for ESR studies; Voinchet et al., 2015). The extraction and preparation protocol of these quartz grains is described by Voinchet et al. (2004). After extraction, each sample was split into 11 aliquots. Nine of these were irradiated at different doses ranging from 264 to 12,500 Gy with a gamma 60Co source (CEN (CEA) Saclay, France). One aliquot was conserved as a natural reference and the eleventh aliquot was exposed for 1000 h to light in a Dr Honhle SOL2 solar simulator to determine the unbleachable part of the ESR-Al signal and corresponding bleaching rate. The bleaching rate δ_{bl} (%) is determined by comparison of the ESR intensities of the natural and bleached aliquots (δ_{bl}=((I_{nat} $\delta_{bl\ bl}$)/ I_{nat})_100).

D_e is then determined from the intensity data set after subtraction of the residual intensity evaluated from the maximum bleaching value. An exponential + linear fitting function was used for this evaluation using Microcal OriginPro8 software with $1/I^2$ weighting for both Al and Ti-Li signals.

When the obtained age estimates were similar for the two centres of the same quartz sample, weighted mean ages were calculated

3. Sites investigated for this research

3.1 Warren Hill, Mildenhall

The gravel workings at Warren Hill are located at the southern end of a low north-south aligned ridge, which reaches over 30 m OD, though in the vicinity of Warren Hill the ground surface is between 23 m and c. 15 m, dropping to around 11m OD in the River Lark valley (Figures 1-3). This is one of the most important sites in the early development of Palaeolithic archaeology in Britain and the pits were frequented by collectors in the late 19th century (Prigg, 1868; Evans 1872). However, despite its early prominence, there are few accounts of the geology of the site. Solomon (1933) provided a brief description of the gravels, stating that "[t]heir stratification is either rude or absent; the bedding planes, where present, are often steeply inclined, but there is no current bedding of the usual type. Their constituents are quite unsorted, pebbles of all sizes being mixed more or less indiscriminately with material of sand grade. Their general character thus points to their glacial or glacieluvial deposition at no great distance from the edge of the transporting ice-sheet" (p.101). Solomon also noted the abundance of quartzite pebbles of Triassic origin, but rejected a fluvial origin for these gravels as it required "a very peculiar ancient course for the River Trent, for which there is no evidence whatsoever" (p.102).

Following Solomon (1933) the status of the Warren Hill deposits as glaciofluvial gravels was largely accepted until the 1990s. The identification of the gravels at Warren Hill as possible Bytham River deposits in the late 1980s was followed by a small-scale reinvestigation of the site in advance of the 1991 QRA Annual Field Meeting (Wymer et al., 1991; Lewis, 1993; Bridgland et al., 1995). Four sections (91/1 – 91/4) were exposed and the basic stratigraphy of the site and the clast lithological character of the gravels were established (Figure 2; Bridgland et al., 1995). A further field investigation was conducted by J Rose and J Wymer in 2002, and though this remains unpublished, it is referred to by Hardaker (2012) in a study of the surface finds of Palaeolithic artefacts and also by Gibbard et al. (2009).

A further phase of fieldwork was conducted at Warren Hill between 2013 and 2016, with the particular purpose of investigating the wider distribution of the Warren Hill deposits, their relationship to the glacial succession and the terraces of the present River Lark, and also to explore the archaeological content of the gravels in a more systematic manner (Figures 2-3). This fieldwork consisted of excavation of a series of test pits (TP 1-12), dug along a north-south orientated forest track to the west of the former gravel pit, together with a number of boreholes drilled using Cobra percussion (BH 13/1-4) and cable percussion methods (BH 13/5-12). In 2016, two sections (16/1 and 16/2) in the western edge of the old gravel pit and TP 13-18 on the forest track were opened to enable sampling of the deposits for ESR dating purposes.

The 1991 work showed that the succession within the old gravel workings consists of a lower unit, the Warren Hill sands and silts, and an upper unit, the Warren Hill sands and gravels (Figure 2B; Wymer et al., 1991; Bridgland et al., 1995). The sands and silts overlie Chalk and are up to 5.5 m in thickness, consisting of horizontally and ripple bedded fine sands and laminated silts. The sands and gravels overlie a sharp erosional lower bounding surface and consist of 6.5 m of predominantly medium to coarse gravels, displaying prominent large scale, steeply dipping, foreset bedding, though in places the unit is sandier in character. The clast lithology of the gravel fraction consists mainly of flint, but also contains significant quantities of quartzite, vein quartz and Carboniferous chert (Table 2). Palaeocurrent measurements indicate flow to the east and south-east.

The new sections in 2016 confirmed these observations (Figure 2B). Section 1 (16/1) exposed c. 1 m of medium-coarse massive gravels, overlying horizontally and ripple bedded, partly decalcified sands. Section 2 (16/2) exposed c. 2 m of gravelly sands with well-developed large scale cross-stratification, with an easterly palaeoflow direction. Clast lithological analysis of two samples from section 1 are consistent with previous analyses of the gravels within the old gravel workings. The gravels are predominantly flint, with quartzite, vein quartz and Carboniferous chert also present in significant quantities (Table 2).

A borehole transect (transect A–B, Figure 3A) indicates that the stratigraphy established in the gravel pit (Chalk, Warren Hill sands and silts, overlain by Warren Hill sands and gravels) can be traced northwards. The contact between the sands and gravels with the underlying sands and silts rises slightly from c. 16 m to c. 20 m OD. The sands are brown (7.5YR 5/4) in colour and the gravels display clast lithological composition consistent with those exposed in the old gravel workings (Table 2). Towards the northern end of the borehole transect, two additional units, a chalky diamicton immediately overlying the Chalk bedrock and overlying flint-rich gravels, are present beneath the Warren Hill sands and silts. The chalky diamicton is up to 4.5 m in thickness and consists of a poorly sorted mix of chalk and flint clasts in a light olive brown to pale yellow (2.5Y 5/4-7/4) coloured, fine-grained matrix. Samples from the gravel underlying the Warren Hill sands and silts in boreholes 13/8 (7.5-7.7m) and 13/9 (10.0-10.5m) have a different lithological character to the Warren Hill sands and gravels, with abundant flint and chalk clasts, lower quantities of quartzite, vein quartz and Carboniferous chert and, among the minor constituents, *Rhaxella* chert, a lithology that is largely absent from the Warren Hill sands and gravels (Table 2).

A second borehole transect (B–C, Figure 3B) orientated in a north-east to south-west direction demonstrates that this succession of Chalk, chalky diamicton and gravels, Warren Hill sands and silts, Warren Hill sands and gravels extends westwards, though the lowermost two units (chalky diamicton and gravels) pinch out against the rising Chalk bedrock in the vicinity of BH 13/5. The lithological character of the Warren Hill sands and gravels is maintained and samples of the basal gravels in BH13/12 show a consistent lithological composition to the basal gravels in transect A–B. At the western end of transect B–C this succession is cut out as the surface elevation falls by c. 3 m from BH13/5 to TP7, which exposed a unit of c. 3 m of horizontally bedded, yellowish brown (10YR 5/6) sands. In the adjacent TP13 this sand unit was seen to overlie chalky gravels and chalky diamicton.

Test pit 7 is at the mid-point of transect D–C–E, located along the north-south orientated forest track (Figure 3C). The transect runs northwards from the road for around 700 m. At the southern end, the ground surface elevation is around 12 m OD (TP 1), rising to around 30 m OD at the northern end (TP12). In the southern part of the transect (between TP1 and TP3), the test pits exposed between 2 and 3.5 m of sub-horizontally bedded sands. They form a consistent set of deposits at a similar height. The test pits from TP4 to TP7, revealed sub-horizontally bedded sands with occasional gravel and in TP5 and TP13 overlie chalky diamicton. Only samples from TP13 provided sufficient gravel for lithological analysis, which showed a relatively high quartzose content (Table 2). Little can be deduced from the sediments in the test pits north of TP7, which consist of thin, predominantly sandy deposits, with some disturbed gravelly units, beneath the sandy soil layer, overlying disturbed Chalk or chalky diamicton.

A number of armoured mud balls were collected from within the Warren Hill sands and gravels exposed in the 2002 sections and similar mud balls were found in borehole samples. Gibbard et al. (2009) described the occurrence of “chalk-rich diamicton clasts (till balls) up to 10 cm in diameter widely distributed through the sediment” (p. 507). However, the mud balls described here are rather different in character. The exterior surface is armoured by an adhering layer of sand, but the interior consists of a predominantly reddish brown coloured, finely laminated, silt/clay deposit. Eight mud balls were recovered from the 2002 exposures, from which six were selected for particle-size analysis. The results indicate fairly similar particle size distributions, with around 47-63% silt and 37-53% clay, and no sand (Figure 4).

The present investigation has provided evidence of the stratigraphy and the wider stratigraphic context of the succession in the old gravel workings at Warren Hill. The succession of Warren Hill sands and silts overlain by Warren Hill sands and gravels was previously interpreted as a fluvial depositional environment (Bridgland et al., 1995). However, the sedimentology is more consistent with deposition in a lacustrine setting, with initial deposition of the sands and silts in a low energy environment, followed by deposition of the sands and gravels in a prograding, high energy, delta setting. This interpretation of the depositional environment is similar to that offered by Gibbard et al. (2009). The clast lithological signature of the Warren Hill sands and gravels is consistently flint-dominated, but with significant quantities of quartzite, vein quartz and Carboniferous chert. This distinctive and consistent lithological character suggests that the gravels are part of the suite of sediments deposited by the Bytham River, as previously proposed (Wymer et al., 1991; Bridgland et al., 1995) and they are quite distinct from both glaciofluvial gravels and post-Anglian terrace gravels in the area.

The mud balls that are present within the Warren Hill sands and gravels are potentially of some significance. Their particle size distribution is different to the matrix component of chalky diamictons in the area (Figure 4). Comparison of the particle-size distributions of these mud-balls with samples of the chalky diamicton from TP5 and TP8 shows that they are dissimilar. They are also texturally dissimilar to the chalky diamicton at the nearby site of High Lodge (Lewis, 1992). Neither do they resemble the Starston Till Member at Knettishall (Lewis et al., 1999). Comparison with samples of the High Lodge clayey-silts (Lewis, 1992), show similarities, though the mud balls are consistently finer, with more fine silt and a higher clay component. Given the close colour, presence of laminations and textural match with the High Lodge clayey-silts, it is reasonable to suggest that this deposit has been reworked into the Warren Hill sands and gravels. The mud balls are protected by the surface layer of sand armouring the otherwise non-durable fine-grained sediment, enabling them to survive short distance transport in a high energy fluvial environment before being deposited. The presence of High Lodge clayey-silts within the Warren Hill sands and gravels provides a relative stratigraphic relationship between these two sets of sediments, with the former pre-dating the latter.

Beyond the old pit the relationship between the Warren Hill deposits and the likely glacigenic chalky diamicton and associated gravels can be demonstrated. The presence of glacigenic sediments underlying the Warren Hill deposits, indicates that, if a Bytham River origin for the latter is correct, and if the glacigenic sediments are Anglian, the river was experiencing disruption by ice entering the catchment. The Warren Hill sands and gravels therefore represent the last phase of fluvial deposition by the Bytham River.

The interpretation of the sediments exposed in transect D-C-E is more complex. At the southern end of the transect (TP1 to TP3) the ground surface is at c. 12 m OD, and is underlain by at least 3.5 m of sands which are thought to relate to a terrace of the River Lark. South of TP1 on transect F-G, BGS borehole records indicate Lark terrace and floodplain sediments overlying glacial sands and gravels (Figures 2C, 3D). The fluvial sands recorded in TL77SW34 probably relate to the sands exposed between TP1 and TP3 and form a single terrace aggradation. A lower terrace may be indicated by a 2 m drop in ground surface height to the south of the A1101, but this cannot be verified by the borehole record. Higher up the track, between TP4 and TP7, the ground surface morphology is suggestive of one, and possibly two, further terraces. Although the sands exposed in the test pits in this part of the transect could relate to deposition by the Lark, the sedimentology is less clear and there may be some mixing of gravel from the Warren Hill sands and gravels, such as in TP13. If there are further terraces, there is a possible bench around TP4 where the Chalk surface height is c. 13 m OD and the ground surface is c. 16 m OD. In addition, there might be a higher bench between TP5 and TP7 at c. 16.5 m OD, where the ground surface rises from c. 18.5 to c. 20 m OD. Further work would be required to establish more clearly whether these sediments form a further two terraces of the River Lark.

Of importance is the stratigraphic relationship of the Lark terrace sediments with the Warren Hill sands and gravels. Although a direct stratigraphic relationship could not be identified, the interpretation offered here based on the stratigraphy is that Warren Hill sands and gravels are Bytham sediments that show an easterly flow and were deposited during the Anglian Glaciation, while the sands are part of the Lark terraces sediments with a westerly flow and are post-Anglian in age (see ESR Chronology, below).

3.2 Maidscross Hill, Lakenheath

The site at Lakenheath lies on the crest and eastern flanks of Maidscross Hill (Figure 5). The summit of the hill is at 31 m OD and the ground drops away into the Fens on the west side, to the River Little Ouse 4.5 km to the north, and to the River Lark 9 km to the south. On the eastern side is a flat sandy plain at about 4-5 m OD, on which RAF Lakenheath is situated. During the late 19th century Maidscross Hill was visited by archaeologists, notably J.W. Flower, who provided the first description of the Pleistocene deposits at Lakenheath and reported the discovery of Palaeolithic artefacts from the gravels. Flower (1869) describes the gravels at Maidscross Hill as containing quartzite and quartz, extending over an area of about 60 acres (24 ha), to a depth of 2-3 m, resting upon Chalk. During the mid-20th century larger gravel pits were active on the eastern side of Maidscross Hill, but were abandoned by the 1980s.

Following the initial identification of the gravels at Maidscross Hill as deposits of the Bytham River (Rose, 1987; Lewis, 1993), further work was undertaken in 2004-05 to investigate the deposits at Maidscross Hill (Ashton and Lewis, 2005, Figure 5). This comprised the excavation of three test pits (TP1-3) on the summit of Maidscross Hill and at an intermediate position between the top of the hill and the largest of the former gravel pits (TP4). Two sections were opened in one of the old gravel pits and three boreholes were sunk at locations to prove the height of bedrock and to enable the reconstruction of the sediment body geometry at this locality. Where suitable sediments were exposed samples were taken for clast lithological analysis and palaeocurrent determinations were made.

The Pleistocene sediments in the immediate vicinity of Maidscross Hill can be divided into three distinct units on the basis of their elevation, internal structure and texture (Figure 5C). They have been named: the Maidscross Hill sands and gravels; the Lakenheath sands and silts; and the Lakenheath sands and gravels. The Maidscross Hill sands and gravels are present over the summit area of Maidscross Hill. These were visible in TP3 which exposed yellowish brown to strong brown (10YR 5/6 – 7.5YR 5/6) medium coarse, cross-stratified sands and horizontally bedded gravelly sands. An adjacent borehole (BH1) proved a thickness of c. 7 m of sands and gravels resting on Chalk at an elevation of c. 25 m OD, this is somewhat lower than, but not inconsistent with, the observations of Flower (1869). In TP4, 180 m south-east of the summit trig point, Chalk bedrock is at c. 22 m OD. Palaeoflow determined on cross-stratified units was in a broadly southerly direction.

The Lakenheath sands and silts, and the Lakenheath sands and gravels are found in the old gravel pits at a lower elevation on the eastern flank of Maidscross Hill (Figure 5C). In section 1 Chalk was revealed at c. 11.6 m OD. The succession consists of two units; the lower unit, the Lakenheath sands and silts overlie weathered Chalk at 11.6 m OD in section 1 and consist of up to c. 5 m of calcareous sands and silts, with small scale cross-stratified units and ripple bedding, with silt/clay laminae draped on the ripple surfaces in places. They reach a maximum elevation of c. 16 m OD. These are overlain by the Lakenheath sands and gravels which in section 2 have a sharp, horizontal, erosional lower bounding surface. These sediments consist of medium-coarse sands and gravels, and their sedimentology is dominated by large scale foreset beds, with alternating gravels and sandy facies in marked fining upwards sequences. These gravels were exposed to a thickness of 3 m in section 2 and attain a maximum elevation of c. 20 m OD. They are distinguished from the Maidscross Hill sands and gravels on the basis of their differing sedimentology and clast lithology (below) and by the altitudinal separation between the two sets of deposits.

The clast lithological composition of the Maidscross Hill sands and gravels and the Lakenheath sands and gravels (Table 1) are dominated by flint, quartzite, vein quartz and Carboniferous chert (Table 2). The Maidscross Hill sands and gravels contain 55-65% flint, with 28-42% vein quartz and quartzite, with the percentage of quartzite exceeding vein quartz. Carboniferous chert content is variable up to 8.5%. The Lakenheath sands and gravels have a slightly lower proportion of flint and high proportion of vein quartz and quartzite, again with quartzite percentages greater than vein quartz. Carboniferous chert percentages are low and *Rhaxella* chert is present in trace quantities (two pebbles out of over 2000 counted). Chalk is consistently present in significant quantities in these gravels but is absent from the Maidscross Hill sands and gravels.

The height distribution of the deposits at Maidscross Hill suggests that two separate aggradations are present, separated by an incision phase. The higher, and older, Maidscross Hill sands and gravels are separated by around 10 m of incision into Chalk bedrock from the lower, younger deposits, the Lakenheath sands and gravels and the underlying Lakenheath sands and silts. The Maidscross Hill sands and gravels are fluvial sediments that were deposited in a southerly-flowing river. The clast lithology of the gravel fraction is consistent with the quartzite, vein quartz and Carboniferous chert rich character of Bytham River deposits.

The lower deposits, the Lakenheath sands and silts and overlying Lakenheath sands and gravels, are remarkably similar to those exposed at Warren Hill. A low energy depositional environment for the sands and silts is indicated by their textural and sedimentological properties, and deposition in a lacustrine environment is suggested. The coarse nature and foreset structures of the overlying sands and gravels are consistent with deposition of coarse gravel on top of the sands and silts in a prograding delta setting.

3.3 Brandon Fields (Gravel Hill), Brandon

Brandon Fields, lies 5 km to the north east of Maidscross Hill, Lakenheath and is a low hill rising to around 32 m OD. The gravel workings were frequented by collectors of Palaeolithic archaeology in the late 19th century and the location of the pits is given by Flower (1869), who described gravels over an area of some 30-40 acres (12-16 ha), c. 27 m above the river level (i.e. c. 30 m OD), "usually not more than 10 feet [3 m] in thickness, and often less, resting immediately upon the chalk" and “the larger proportion (perhaps four fifths of the whole mass of gravel) consists of rounded quartzites, and a few jasper pebbles" (Flower, 1869, p.450). Little further work had been undertaken on the deposits here until 2005 when a small scale borehole and test pit investigation was undertaken as part of the current research (Figure 6).

A transect of boreholes and test pits extended from the summit of Brandon Fields in a south-easterly direction for approximately 500 m. At the summit the ground surface is at an elevation of c. 32 m OD, falling to around 11 m OD where the track joins the road. Near to the summit, TP1 revealed 3.2 m of sandy gravels, resting on weathered Chalk at 28.4 m OD. The gravel fraction is made up mainly of flint, but also significant quantities of quartzite/sandstone, vein quartz and smaller quantities of Carboniferous chert (Table 2).

Downslope from the summit, sands are present on the south-eastern flank of Brandon Fields; BH3 proved 5.5 m of sands and BH4 proved 2.0 m of sands, both overlying Chalk, at elevations of 23.5 m and 21.5 m OD respectively.

The limited information currently available from Brandon Fields indicates that in the vicinity of the summit there is a quartzite and quartz rich gravel deposit, around 3 m in thickness resting on Chalk. This is consistent with the early observations of Flower (1869). The clast lithological composition of the gravels is consistent with deposition by the Bytham River.

3.4 Rampart Field, Icklingham

Rampart Field is a small former gravel working, located on the northern side of the present Lark valley, and another historically significant location; the gravel workings were active in the mid-late 19th century and were visited by collectors. Palaeolithic artefacts from this site were among the first to be recognised and reported in Britain (Evans, 1872). Again, despite its early archaeological significance, the site received little attention until the 1980s, when the deposits were investigated and attributed to the Bytham River on the basis of their clast lithological composition (Lewis, 1993, 1998; Bridgland et al., 1995).

In 2018 a section was opened in the northern face of the former gravel pit at Rampart Field, about 50 m east of the location of the section exposed in 1993 (Figure 7; Bridgland et al., 1995). The ground surface at this point is at 25 m OD and the section revealed 5.25 m of *in situ* sediments resting on rubbly weathered Chalk at an elevation of 18.5 m OD. At the base of the succession are sub-horizontally bedded yellowish brown sands. These are overlain by facies ranging from medium-coarse, massive, clast-supported gravels to horizontally bedded and ripple cross-stratified sands and silts. The upper 1.5 m of the deposit displayed involutions. The clast lithological composition of gravel facies in the upper, middle and lower parts of the section consists mainly of flint, but with substantial quantities of quartzite, vein quartz and Carboniferous chert (Table 2). The sedimentology, bedrock surface height and clast lithology of the deposits in this section are consistent with the section opened in 1993 (Bridgland et al., 1995).

These sediments were deposited in a fluvial environment, with a mixed bedload and variable flow energy, ranging from high energy flow transporting and depositing coarse gravels, to fine-grained facies requiring low flow or still water conditions, suggesting deposition in pools within the channel system. The clast lithological composition of the gravels suggests that these sediments form part of the Bytham River.

3.5 Sapiston and Fakenham Magna

These two former gravel pits, located in the valley of the Black Bourn, a south bank tributary of the Little Ouse River, were active in the mid-20th century as small-scale commercial gravel quarries operated by Allen Newport and Co (Figure 8). Neither site appears to have attracted much geological interest while active pits, though more recently, investigation of the gravels at Fakenham Magna has identified them as Bytham River deposits (Rose, 1987; Lewis, 1993).

Two sections were opened in the former gravel pit at Sapiston and two boreholes were drilled adjacent to the sections to establish the height of the top of the Chalk bedrock (Figure 8A-B). The ground surface in the vicinity of the sections is at 30.4 m OD and the Chalk bedrock is at c. 20 m OD. The deposits consist of medium-coarse gravel facies, massive and poorly sorted in the upper part of the exposures, but with indications of horizontal bedding lower down, and sub-horizontally bedded and planar cross-stratified sand facies. Palaeocurrent determinations on cross-stratified sands indicate a north-easterly flow direction. The clast lithological composition indicates that, while flint is the main lithological component, there are also significant quantities of quartzite, vein quartz and Carboniferous chert in the gravels. The sedimentology indicates deposition in a predominantly high energy, easterly-flowing, fluvial environment, which together with the clast lithology, indicates that these deposits form part of the Bytham River.

Two sections were opened in the old gravel pit at Fakenham Magna (Figure 8C-D). Section 1, which re-exposed a section previously recorded by Rose (2007), revealed 3.5 m of sands and gravels, resting on undulating Chalk at an elevation of c. 37.0 m OD. The gravels consist of medium-coarse, poorly-sorted, clast-supported quartzite and vein quartz rich gravel, with a clay-enriched matrix in the upper part of the unit. A 0.4 m thick unit of slightly gravelly sand immediately overlies the Chalk bedrock. The gravels are overlain by glacial sediments, comprising a lower brown sandy diamicton, 0.5 m in thickness, and an upper chalk and flint rich grey-coloured diamicton, c. 4 m in thickness and extending to the ground surface. A second section exposed c. 1.2 m of medium-coarse, poorly-sorted, clast-supported gravel. The clast lithological composition of the gravels is dominated by quartzite, vein quartz and flint. Among the minor lithological components are Carboniferous chert and ironstone (Table 2).

Although diagnostic sedimentary structures are absent, the gravels are most likely to be deposited in a high energy fluvial environment, and the clast lithological composition is consistent with deposition by the Bytham River. The clay enrichment of the upper part of the gravels may indicate soil formation on the surface of the gravels, prior to deposition of the overlying glacial sediments. These deposits are the Starston Till and the Lowestoft Till, members of the Happisburgh and Lowestoft Formations respectively. The evidence for soil formation and the details of the glacigenic sediments have been the subject of investigations by Rose (2007).

3.6. Other important Bytham River sites in the area

In addition to the sites investigated during the current research and described in detail above, a number of other sites in the region have been the subject of earlier investigations and are of significance in the reconstruction of the Bytham River. In most cases, these have been reported in detail in previous publications and are summarised here (Figure 1).

3.6.1 Ingham

The gravel pits at Ingham were first described by Clarke and Auton (1984), who noted quartzite and quartz rich gravels overlying Chalk and underlying glacial sediments of the Lowestoft Formation. The gravels were referred to as the Ingham sand and gravel and the site is the type locality for the Ingham Formation (Bowen, 1999). Sections at Ingham were again recorded in the late 1980s which confirmed the stratigraphic position of the Ingham sand and gravel in relation to the overlying Lowestoft Till Member and associated glaciofluvial sands and gravels, the latter infilling a deeply-incised, steep sided channel cut through the Ingham sand and gravel and into the underlying Chalk bedrock (Lewis and Bridgland, 1991; Lewis, 1993).

Around 4 m of Ingham sand and gravel overlie Chalk bedrock, the surface of which is generally between 40.0-41.0 m OD though affected by solution in places. The gravels are massive, with no internal structure visible and are deformed as a result of solution of the Chalk. The sandy facies display either cross-stratification or sub-horizontal bedding. The clast lithological composition is dominated by quartzite and quartz, which together make up over 50.0% of the totals in all cases. Flint and chert are also present in significant quantities, and schorl and ironstone are present in very small quantities.

A second gravel unit, consisting of coarse sand and gravel, with large-scale crudely horizontal bedded gravels and cross-stratified sands, infills a channel cut through the Ingham sand and gravel and into the underlying Chalk to a depth of below 27.0m OD. The clast lithological composition consists mainly of flint, with low percentage of quartzite and quartz and trace amounts of *Rhaxella* chert. A chalky diamicton unit, the Lowestoft Till, overlies both these gravel units and consists of flint and chalk clasts in a silt/clay matrix.

3.6.2 Knettishall

Sections at Knettishall were recorded in detail in the late 1980s (; Lewis et al., 1999). Here the quartzite and quartz rich Knettishall sands and gravels overlie Chalk, with a bedrock surface at c. 25 m OD. The gravels are around 5 m in thickness, and their sedimentology indicates fluvial deposition in an easterly flowing river system. The upper part of the deposits displays evidence for soil formation which indicates that there was a stable land surface on which pedogenesis took place prior to the deposition of the overlying glacial sediments (Lewis et al., 1999). Clast lithological analysis of the Knettishall sands and gravels indicates that they contain a significant quartzite and quartz and Carboniferous chert component, typical of Bytham River sediments. These deposits are overlain by glaciogenic sediments including the Starston Till Member and Coney Weston sands and gravels Member of the Happisburgh Formation, and the Lowestoft Till Member of the Lowestoft Formation. As at Ingham, this site also demonstrates the lithological distinctiveness of the Bytham River sediments when compared with glaciofluvial gravels at the site. The latter are dominated by flint, have a more diverse lithological suite and also have a distinctly different heavy mineral assemblage (Lewis et al., 1999).

3.6.3 Timworth

The succession at Timworth consists of sands and gravels which overlie Chalk bedrock at c. 22 m OD and are separated into two units by an intervening diamicton unit (Lewis and Bridgland, 1991; Lewis, 1993). The lower sands and gravels consist of up to 10 m of predominantly horizontally bedded gravels, with planar and trough cross stratified sands and ripple drift lamination. The sedimentology indicates fluvial deposition in a high, but variable flow regime with a palaeoflow direction towards the east-south-east, a direction that is essentially opposite to that of the north-westerly flowing River Lark. The clast lithological composition is dominated by flint, with smaller amounts of quartzite and quartz. Carboniferous chert and Chalk are also present, and a single pebble of *Rhaxella* chert was identified, though none was found in the 16.0-32.0 mm fraction (Bridgland and Lewis, 1991).

The diamicton that separates the gravels into upper and lower units is blue grey to buff brown in colour, conspicuously chalky, with flint and other clasts, in a compact matrix of silty clay and is up to 8 m in thickness. This unit is interpreted as a till, and is equated with the Lowestoft Till Member.

A second gravel unit overlies the chalky diamicton, though further south, the upper sand and gravel lies directly upon the lower sand and gravel, the till having been cut out. This gravel consists of flint, with significant quantities of quartzite, quartz and Carboniferous chert. Jurassic limestones and *Rhaxella* chert are absent. These gravels were deposited in a fluvial environment; the clast lithology is atypical of glaciofluvial deposits in the area, and the gravels are interpreted as a terrace deposit of the stream that now flows westward to join the Lark at West Stow, the lithological composition is the result of reworking of quartzite and quartz rich gravels to the north, such as those around Ingham and Honnington (Bridgland and Lewis, 1991).

3.6.4 Lackford

The site lies c. 2 km to the south of the River Lark, where exposures were examined in 1989 (Lewis, 1993). The land surface is c. 37-40 m O.D. at this point, sloping down to the river to the north, and rising to the south. Sections exposed massive or crudely bedded to planar cross-stratified sands and gravels overlying Chalk bedrock at an altitude of 29.8 m OD. Sandy facies within this unit consist mainly of planar cross-stratified facies, with some trough cross-stratified and horizontally bedded sands, with palaeoflow in a south-easterly direction. The gravels are made up mainly of flint, with significant quantities of quartzite, quartz and chert. The sedimentology suggests deposition in a fluvial environment, flowing in the opposite direction to that of the modern River Lark. The clast lithological composition shows affinities with the Bytham River.

3.6.5 Frimstone's Pit, Feltwell

Frimstone's Pit, Feltwell was a sand and gravel quarry, active in the 1980s-1990s, that has yielded an important Palaeolithic assemblage, which has been reported by MacRae (1999), Hardaker and MacRae (2000), Bolton (2015) and Hardaker and Rose (2019). Wymer (2001) also discussed the site, though detailed descriptions of the geological context of these finds is lacking.

Exposures in the gravel pit, recorded (by SGL) in 1998 and 1999, revealed c. 8 m of sands and gravels overlying Chalk bedrock at an elevation of c. 20 m OD (Figure 9). The deposits consist of some 5 m of medium-coarse horizontally bedded and cross-stratified gravels in the lower part and c. 3 m of reddish-brown, cross-stratified, horizontally stratified and ripple bedded sands in the upper part of the deposit. Palaeocurrent determinations on cross-stratified gravelly and sandy facies and on ripple structures indicate a flow direction towards the south-west. The clast lithological composition of the gravels is predominantly flint, with quartzite, vein quartz and Carboniferous chert also present in significant quantities. Chalk is also present in the gravels, but *Rhaxella* chert was not found in any of the samples (Table 2).

Towards the eastern side of the quarry, glacial sediments consisting of sands and gravels and tills of the Lowestoft Formation are exposed. A section visible in 2013 exposed bedded sands and gravels overlain by a stratified diamicton, infilling a shallow channel, and above this a massive chalky diamicton around 2 m in thickness, decalcified in the upper part and displaying involution structures (Figure 9C).

3.6.6 Shouldham Thorpe

This site lies approximately 4 km east of the eastern margin of the low lying Fen basin, and has a surface elevation of c. 32 m. Rose (1987, 1989) included this site in the reconstruction of drainage from the West Midlands into East Anglia prior to glaciation of the region and formation of the Wash and Fen basin, using the lithology of the gravels to correlate these deposits with gravels to the west of the Fen basin. A description of the deposits and their lithology is also given by Lewis (1989, 1991, 1993). The deposits at Shouldham Thorpe were informally named the Shouldham sands and gravels by Rose (1992) and the Shouldham Formation by Lewis (1999).

The stratigraphy comprises sands and gravels and overlying sands, resting on Lower Cretaceous bedrock at an altitude of 24.3 m O.D. The gravels (Shouldham sands and gravels) attain a maximum observed thickness of 2.8 m and consist of alternating sand and gravel and sand facies, and consist of massive, planar and horizontally bedded units. The gravels are composed primarily of quartzite, quartz, flint, chert and ironstone, with trace quantities of sandstone and schorl.

The overlying sands (Shouldham sands) were observed to a thickness of 3 m and consist of yellowish red (5YR 4/6) to brownish yellow (10YR 6/6) cross-stratified sands, with minor facies of sand and gravel occurring as thin (<10 cm) layers. The sands are made up mainly of planar cross-stratified units, with additional horizontally and ripple bedded facies. The gravelly facies within the sands comprise quartzite, quartz, flint, chert and ironstone. Palaeoflow measurements on planar cross-stratified facies in the sands and gravels and sands indicates flow towards the east-south-east.

The sedimentology of these deposits indicates fluvial deposition in a south-easterly flowing river system. The clast lithological composition indicates significant derivation from bedrock sources west of The Wash and is consistent with deposition by the Bytham River.

3.7 High Lodge, Mildenhall

High Lodge is only 1 km north of Warren Hill and provides further evidence of Bytham River sediments. From the discovery of artefacts during clay and gravel extraction in the 1860s, there was widespread interest and several investigations of the archaeology and geology (Evans, 1872; Whittaker et al.,1891; Marr, 1921). The largest fieldwork programme was by the British Museum in the 1960s with additional fieldwork in 1988, which form the basis of our current understanding of the geological, environmental and archaeological succession (Ashton et al., 1992). The deposits lie on a gently sloping Chalk surface rising west to east c. 18 to 25 m OD over a 300 m distance. Brown clayey silts are the oldest sediments at the site which, from sedimentology, lithology, heavy minerals and palynology, are interpreted as Bytham floodplain deposits that were laid down during an interglacial (Hunt, 1992; Hunt and Rose, 1992; Lewis, 1992; Rose et al., 1992). A pre-Anglian age for the clayey silts is supported by the recovery of part of a tooth from an extinct rhinoceros attributed to *Stephanorhinus hundsheimensis* (Stuart, 1992; Lewis et al., 2019b). Large artefact assemblages were excavated from the clayey silts and from silts and sands immediately overlying these deposits. The clayey silts were subject to subglacial deformation and transport, resulting in their emplacement above Lowestoft Till during the Anglian glaciation. Sands and gravels at the top of the sequence are glaciofluvial in origin and also attributed to the Anglian glaciation.

4. The terrace stratigraphy of the Bytham River

Rose (1987) first postulated the drainage route for what has become known as the Bytham River. This was based on the recognition of a distinctive suite of quartzite and quartz rich fluvial gravels, overlying bedrock and overlain by Anglian glacigenic sediments that could be traced from Warwickshire in the west into East Anglia and to the North Sea coast. Subsequent work has generated a considerable body of data on the stratigraphy, sedimentology and clast lithology of these fluvial sediments and the Bytham River has become an established component of the early Middle Pleistocene stratigraphy and palaeogeography for southern Britain (Wymer, 1999; Lee et al., 2004; Westaway, 2009; Hosfield, 2011; Moncel et al., 2015; Lewis et al., 2019a).

The altitudinal distribution of the gravels of the Ingham Formation indicates that they are disposed as a series of attitudinally distinct aggradations, though there is little or no geomorphological expression of these as fluvial terraces as the deposits are mostly buried beneath glacigenic sediments. Lewis (1993) identified four aggradations; the Seven Hills (oldest), Ingham, Knettishall and Timworth (youngest). These were defined as members of the Ingham Formation (Lewis, 1999). Lee et al. (2004) produced a different model, proposing six separate aggradations, adding the Castle Bytham and Warren Hill members, with some individual locations being assigned to different terrace bodies. By contrast, Westaway (2009) identified only three aggradations of the Bytham River in East Anglia.

Utilising the key reference sites described above for the Bytham River deposits in the region, together with other information from boreholes and outcrops, five and possibly six aggradations can now be recognised in the Breckland. These are the Rushbrooke, Seven Hills, Ingham, Knettishall, Timworth and Warren Hill aggradations (Figure 10). The long profiles of these gravel aggradations have been constructed by projecting a line along the axis of the Bytham River with the downstream distance for each site determined with reference to Shouldham Thorpe, and the Chalk surface and top of gravel body are plotted. In the case of outcrops with no upper and lower boundary data the height of the outcrop, determined by surveying or estimation from Ordnance Survey 1:25,000 scale contours, is used.

The oldest deposits in the area that may be attributable to the Bytham River are gravels cropping out at the surface or identified in boreholes in the area south and east of Bury St Edmunds. Some of these gravels have been assigned to the Crag Group by the BGS, though they have a distinctly quartzose lithological character. Others have been mapped as Kesgrave sands and gravels or, in more recent BGS mapping, as the Croxton Sand and Gravel Member. A borehole at Rushbrooke revealed c. 2.5 m of quartzite and quartz rich gravel, overlying Chalk and overlain by chalky tills of the Lowestoft Formation, with a Chalk surface height of 60 m OD (Table 1). Examination of field debris by Hey (1980) also identified quartz and quartzite rich gravel deposits in the Bury St Edmunds area. The quartzite rich gravels identified in the borehole at Rushbrooke and three other boreholes c. 5 km to the west (SW38, 40 and 41) may represent a high level aggradation of the Bytham River, with a Chalk surface height in this area of around 60 m OD. There are no other deposits in the area that could be correlated with these high-level gravels, other than an outcrop of quartzite and quartz rich gravels around Wattisfield (Hey, 1980), although these were mapped as Kesgrave sands and gravels by the BGS.

The Seven Hills Gravel Member is recognised from a small outcrop of gravel, mapped as Ingham sand and gravel, at Seven Hills, on the interfluve between the Lark and Little Ouse valleys. A borehole at this location (Lewis, 1993) proved 4.3 m of quartzite and quartz rich gravel resting on Chalk at an elevation of 50.7 m OD, some 10 m higher than in the pit at Ingham (Table 1). Equivalent gravels may be present elsewhere; remnant quartzite and quartz rich gravels were recorded in a small pit near to Ingham (Lewis, 1993) and three boreholes south-east of Bury St Edmunds (TL86SE175, 178 and 179) record sands and gravels resting on Chalk at a similar elevation to that at Seven Hills. Mapped outcrops of Ingham sand and gravel near Stanton and Bardwell, with a high quartzite and quartz content (Hey, 1980), may also form part of the Seven Hills Gravel Member.

The Ingham Gravel Member is identified at Ingham, with a Chalk surface at 40 m OD. Equivalent deposits are found at Fakenham Magna some 7 km to the east, with a Chalk surface at 37 m OD. Outcrops of quartzite and quartz rich gravels, mapped as Ingham sand and gravel, around Honnington also fall within this altitudinal range. To the east, a mapped outcrop of Ingham sand and gravel near Wortham with a high quartzite and quartz content (Hey, 1980), may be a downstream continuation of the Ingham Gravel Member.

The Knettishall Gravel Member is well represented at Knettishall, where gravels rest on a Chalk surface at c. 25 m OD. Equivalent deposits are found at Sapiston, around 4 km to the west, where the sands and gravels are 10 m in thickness and rest on Chalk at c. 20 m OD. Outcrops of Ingham sand and gravel in this area are also considered to be part of this gravel aggradation. Gravels at Hengrave and Lackford, with Chalk surface heights of 28 m OD and 30 m OD respectively are also interpreted as part of this gravel aggradation.

The Timworth Gravel Member is found at Timworth (Chalk surface at 18 m OD) and also at Rampart Field (Chalk at 20.5 m OD). The Maidscross Hill sands and gravels rest on Chalk at c. 25 m OD and at Brandon Fields the Chalk surface beneath the gravels is at around 28 m OD.

The lowest gravel aggradation that can be identified is represented by the Warren Hill sands and gravels, with upstream equivalents at Lakenheath, Feltwell and Shouldham Thorpe. At Maidscross Hill and Warren Hill, these gravels are underlain by sands and silts which were deposited in a lacustrine environment. The evidence of lacustrine sedimentation at Warren Hill and Maidscross Hill suggests that a lake formed in the river valley. The most likely mechanism for this would be by blocking of the river downstream as ice advanced into the Bytham River valley. As the river was still flowing into the lake at the upstream margin, the coarse component of the river’s load was deposited forming a delta, which prograded over the lacustrine sands and silts. The presence of both lacustrine and deltaic deposits at both Warren Hill and Maidscross Hill indicates the formation of a substantial water body, with delta progradation over several kilometres. Upstream of Maidscross Hill at Feltwell, some 9 km to the north, the Bytham River deposits are fluvial and there is no evidence of lacustrine deposition. This suggests that the up-valley extent of the lake is somewhere between Lakenheath and Feltwell. The advancing glaciers impinged on the river valley, though initially flow was not disrupted, as seen at Warren Hill. However, it can be assumed that the advance of glaciers over the area eventually brought about the demise of the Bytham River. Elsewhere, interactions between fluvial and lacustrine deposition have been identified at Shouldham Thorpe and in the upstream correlative deposits to the west of the Wash/Fen basin in Lincolnshire, Leicestershire and Warwickshire (Bowen, 1999).

The clast lithological composition varies between the terrace aggradations, with a trend of increasing flint content down the terrace flight, with flint:quartzose ratios of around 0.3-0.5 in the highest three terraces, around 1.0 in the Knettishall terrace and 1.4-1.6 in the Timworth and Warren Hill aggradations. This probably reflects progressive dilution of quartzite and quartz with flint. The lowest two aggradations also contain variable quantities of Chalk. Chalk is largely absent from the gravels of the higher terraces, though as it is non-durable during fluvial transport and also prone to dissolution, its presence or absence may not be indicative of primary lithological differences between terrace aggradations.

Downstream gradients are calculated for the Ingham, Knettishall, Timworth and Warren Hill aggradations, using the data for the top of the gravel body and outcrop height where necessary (Table 1). The gradients are 0.28, 0.36, 0.20 and 0.27 m km^{-1} respectively. Gradients calculated using the bedrock surface height for these aggradations are somewhat steeper at 0.55, 0.39, 0.47 and 0.38 m km^{-1} respectively. It is not possible to calculate gradients for the two oldest aggradations (Seven Hills and Rushbrooke) as there are insufficient data points.

5. The ESR chronology of the Bytham River deposits

Recent application of ESR dating of quartz grains to Pleistocene fluvial deposits across Europe, including a number of sites in southern Britain, has demonstrated that this technique can provide useful age estimates on sediments that are difficult to date by other dosimetric, radiometric or geochemical means, or provide important corroboration and checks on other methods (Moncel et al., 2013; Moreno et al., 2015; Pereira et al., 2015, 2017; Voinchet et al., 2015, 2020; Antoine et al., 2019). Previous work on samples from the Warren Hill sands and silts and from the Lakenheath sands and silts yielded age estimates between 631-529 ka using the Al centre and suggest that these sediments predate the Anglian (MIS 12) glaciation in Britain (Voinchet et al., 2015). The age estimates from the Ti-Li centre for these samples were not published in 2015 paper but are now also given in Table 4 and are consistent with the Al centre results.

Further samples from Warren Hill, together with those from Sapiston and Rampart Field, provide an enhanced dataset of ESR age estimates that constrain the chronology of the Bytham River deposits in the Breckland. The full results are given in Tables 3 and 4. In the summary below, the mean age is given where both Al and Ti-Li ESR centres could be used. In five samples the Ti-Li signal had high background noises of between 15 and 30%, giving overestimates of age. For these samples just the age estimate from the Al centre is given below, although both are shown in Table 4.

Sapiston is attributed to the Knettishall Gravel Member, and is the highest and oldest of the dated sites, providing four samples for dating. SPN1703 produced a weighted mean age of 775 ± 52 ka. Samples SPN1705 and SP1709 produced ages of 745 ± 140 and 696 ± 130 ka using the Al centre. The last sample SPN1704 produced ages of 1178 ± 200 (Al)/1168 ± 180 (Ti-Li) ka. The sample was from the same unit as SPN1709, but with far older age estimates. The discrepancy seems to be due to the high D_e (Gy) reading, which may be due to incomplete bleaching of the Al and Ti-Li centres. The reason for the poor bleaching is not clear from the sedimentology at the site, although hypothetically could be due to processes such as localised slippage of older sediment. Other than SPN1704, the results give a mean age of 761 ± 45 and suggest that the Knettishall Gravel Member dates to somewhere between MIS 20 and MIS 18 (Figure 11).

The Timworth Gravel Member is represented by Rampart Field where two dating samples were analysed. The weighted means were 683 ± 28 ka and 661 ± 73 ka, with an overall mean age of 680 ± 26 ka for this member. This places the aggradation somewhere between MIS 17 and MIS 16 (Figure 11).

The lowest Bytham sediments are from Maidscross Hill (Lakenheath sands and silts) and Warren Hill sands and silts. Three new samples from Warren Hill produced weighted mean ages of 590 ± 91 ka, 583 ± 37 ka and 579 ± 49 ka. Two further samples produced age estimates from the Al centre of 432 ± 76 ka and 368 ± 51 ka. The new dates are in good agreement with previously reported ages for Maidscross Hill and Warren Hill (Voinchet et al., 2015; Table 4) and the whole set of data allows the calculation of a weighted mean age of 542 ± 34 ka, that places the deposition of the sediments before the MIS 12 glacial stage (Figure 11).

The age estimates for the Lark River terrace deposits (TP17) at Warren Hill have weighted means of 143.5 ± 9.7 ka and 124.6 ± 7.8 ka. A further sample produced an age estimate on the Al centre of 145 ± 9 ka. The results produce a weighted mean age of 136 ± 14 ka, suggesting that this terrace was deposited during MIS 6 (Figure 11).

Three other samples from TP18 and TP13 at the top of the transect produced ages of 270 ± 40 ka (Al)/204 ± 20 ka (Ti-Al) for TP18, and 492 ± 48 ka (Al)/400±78 ka (Ti-Li) and 417 ± 63 ka (Al)/300 ± 56 ka (Ti-Li) for TP13. Weighted means cannot be given due to the discrepancy between the Al and Ti-Li results. As indicated above, there is uncertainty about the stratigraphic interpretation of these deposits, which although resembling sands from the River Lark may have intermixing of Bytham River sediments. If this is the case, as the Lark was a much smaller river with weaker current, reworking of older sediments over a short distance would lead to insufficient bleaching of the Al. For these samples the Ti-Li estimates may give a better indication of age. If correct, the sediments in TP13 were deposited between MIS 12-7, while those in TP18 were deposited during MIS 7. However, the stratigraphic uncertainty remains an issue and further work is required to ascertain how these sediments and their estimated ages fit in with the overall interpretation of the site.

Taken as a whole the results provide additional support for the interpretation that the sediments attributed to the Bytham River pre-date the Anglian (MIS 12) glaciation and the ESR dates also support the stratigraphic age order of the aggradations, with dates from the Knettishall Gravel Member at Sapiston, generally the oldest, dates from the Timworth Member at Rampart Field younger and those from the Warren Hill Member generally the youngest. The dates also support the interpretation that the Warren Hill Bytham deposits pre-date the sands attributed to the River Lark terrace deposits exposed between TP1 and TP3, which are post-Anglian and attributable to MIS 6.

6. Discussion

Fieldwork in the Breckland over the past twenty years has provided a wealth of new data from six sites that contain gravels with the distinctive suite of far-travelled rocks, most notably quartzite, quartz and carboniferous chert. They are quite different from other sites in the Breckland that are dominated by flint and largely reflect local bedrock. The flint gravels are usually glaciofluvial in origin or relate to the modern drainage with rivers flowing west and north-west into the Fen Basin. In contrast, the quartzose gravels consistently reflect drainage to the south-east and east. The new work provides strong support for the interpretation of the quartzose gravels as being deposited by an eastward flowing river from central England, that has been named the Bytham (Rose 1987; Lewis 1993). The course of the river from central England to the East Anglian coast can be traced from a series of sites that contain the distinctive lithologies. The sites include the upstream sites of Castle Bytham, Brooksby and Waverley Wood to the west of the Breckland, and the downstream sites of Flixton, Norton Subcourse and Pakefield to the east (Rose, 1989; Shotton et al., 1993; Lee et al., 2004; Keen et al., 2006; Parfitt et al., 2005; Silva et al. 2009).

The deposits are best-represented in the Breckland area, where marked differences in the heights of the gravel bodies suggest a series of former terrace units. The new work has revised previous models of the terrace formation and suggests that at least five and possibly six separate aggradations can be recognised, the lowest four of which contain archaeology. It is widely agreed that terrace formation is caused by down-cutting events in response to global changes in climate. In some river systems such as the Thames and the Somme, the terraces can be correlated through biostratigraphy, amino-stratigraphy, or geochronology to Marine Isotope Stages with each terrace aggradation usually related to a glacial-interglacial cycle (Bridgland, 1994, 2006; Antoine, 1994; Antoine et al., 2007, 2019). If this model applies to the Bytham River, then as many as six major cold stages might be represented by the gravel aggradations in the Breckland.

The age of the Bytham River is constrained in the Breckland by the relationship with sediments of Anglian glacial age, in particular the Lowestoft Till. This till overlies Bytham sediments at Fakenham Magna, Ingham, Knettishall, Timworth, Lackford and Feltwell, indicating a pre-Anglian age for those aggradations. Critically, the Warren Hill sands and gravels overlie Lowestoft Till, which in combination with the lithology and sedimentological evidence of a pro-glacial lake, suggests that the Warren Hill sands and gravels are also Anglian in age. Warren Hill therefore provides an important tie-point for the Bytham river system. The Anglian glaciation is one of the best dated cold-stage events in the British Pleistocene and through stratigraphy, biostratigraphy, amino-stratigraphy and geochronology is widely attributed to MIS 12 (Bowen, 1999; Bridgland, 2006; Preece et al., 2009; Toucanne et al., 2009; Penkman et al., 2011; Lewis et al., 2019a). Therefore, the age of the Bytham sediments in the Breckland could range from as early as MIS 22 through to MIS 12.

The new ESR dating work that is reported in this paper provides strong support for an Anglian and pre-Anglian age for the Bytham River sediments in the Breckland, and for a post-Anglian (MIS 6) age for at least one terrace of the river Lark at Warren Hill (Figure 11). However, if the geological interpretation is correct, then many of the dates have an overestimation of age. This appears to be due to incomplete bleaching of the Al-centre for some samples and to an overestimation of the Ti-Li intensities of the natural aliquot in relation to the high signal-to-background noise ratio for others. Despite the likely overestimation in age of some samples, importantly they are in the right order and broadly adhere to the model of Bytham terrace formation that is presented in this paper.

Bytham river deposits have also been identified at High Lodge, although here the interglacial flood-plain sediments (clayey silts) were interpreted as being glaciotectonised and displaced by Anglian ice (see above; Lewis, 1992). The armoured mudballs found at Warren Hill, only 1 km to the south of High Lodge, have very similar colouration and particle size properties to the clayey-silts at High Lodge (see above). The mudballs also display laminations, conforming with their interpretation as being derived from the same floodplains sediments as that site. This provides a stratigraphic relationship, showing that the Bytham River sediments at High Lodge pre-date those at Warren Hill. The clayey-silts at High Lodge are temperate in character, have been suggested to date to MIS 13, an age that is supported by the tooth of *Stephanorhinus hundsheimensis* contained within those sediments (Ashton et al., 1992; Stuart, 1992; Lewis et al., 2019b).

A series of papers, published over the last 10 years, has provided a radically different interpretation of several Breckland sites, including Warren Hill, Maidscross Hill, Brandon Fields and Feltwell (Gibbard et al. 2009, 2012, 2018, 2019). These authors interpret the deposits as a series of glacial outwash fans formed at the margin of a late Middle Pleistocene (MIS 6) ice sheet, the so-called 'Skertchly Line', on the eastern side of the Fen Basin. Furthermore, they argue that the High Lodge clayey-silts were the infill of a doline that formed during MIS 7 on top of Anglian till (West et al. 2014).

A rebuttal of the suggested later date for the High Lodge clayey-silts, taking into account the lithological, sedimentological and biostratigraphic data, was presented in Lewis et al. (2019b), while the evidence presented in the current paper also rejects Gibbard and colleagues interpretation of Warren Hill, Maidscross Hill, Brandon Fields and Feltwell as dating to MIS 6. There are several lines of evidence which Gibbard et al. (2009) do not properly consider. Despite providing clast lithology data for Maidscross Hill and Warren Hill, the authors take little account of the high quartzose content and the distinctiveness of these gravels compared to other sites with more local lithologies in their study. Nor do they distinguish the different cherts in their analysis; as previous and current research has shown, of significance is the higher ratio of Carboniferous chert and the virtual absence of *Rhaxella* chert in the quartzose-rich gravels (Lewis 1993; Bridgland et al. 1995). The former derives from the southern Pennines of central England and forms part of the suite of exotic rocks from this region, while the latter was transported into the Breckland area from North Yorkshire by Anglian ice. Therefore, analysis of the cherts is also important for distinguishing between pre-Anglian and post-Anglian gravels.

The interpretation of a late Middle Pleistocene age for these sites is based on an unpublished OSL age estimate of c. 160 ka on the sands at Warren Hill, sampled in 2002 and cited in Gibbard et al. (2009). The much more extensive and detailed dating programme presented here and in Voinchet et al. (2015) clearly suggests a pre-Anglian age for the sites, which fully supports their interpretation as Bytham River sediments.

The Bytham River sediments in the Breckland form an important stratigraphic framework for understanding the earliest occupation of northern Europe. The higher deposits in the Rushbrooke and Seven Hills Members provide the potential to test for human presence or absence through large-scale sieving programmes for flint artefacts, although this work has yet to be undertaken. Small-scale archaeological investigations have taken place at Fakenham Magna in the Ingham Member and at Sapiston in the Knettishall Member (Davis et al., submitted). Several flakes were found at these sites, thinly distributed in the sediments, but with no evidence of handaxes. This work potentially takes human presence in the area back to MIS 19 or 18 with occupation again in MIS 17 or 16.

The Timworth Member includes the sites at Brandon Fields, Rampart Field and the Maidscross Hill sands and gravels at Lakenheath. They were all first recognised in the mid-19th century and noted for the collection of handaxes. A limited sieving programme at Rampart Field confirmed the presence of handaxes in Timworth Member deposits and also showed a higher density of artefacts than at Sapiston and Fakenham Magna (Davis et al., submitted). The sites are suggested to date to MIS 15 or 14, probably indicating the introduction of handaxe technology at this time. From the abundance of handaxes found in the historic collections from these sites, there is perhaps a more sustained human presence. Further human occupation is suggested during MIS 13 at High Lodge, while the derived assemblages at Warren Hill might also date to this or earlier marine isotope stages. The archaeological work on the Bytham River is fully described in Davis et al. (submitted).

The Bytham archaeological sites therefore show repeated evidence of human occupation from possibly MIS 19 through to MIS 13. The first part of this record is beginning to compare with the recent work on the East Anglian coast. The earliest evidence is of simple cores and flakes from Happisburgh Site 3 dating to either MIS 25 or MIS 21 (Parfitt et al., 2010), while a similar assemblage from Pakefield is thought to date to late MIS 19 (Parfitt et al., 2005). The latter would be comparable in age to the small number of flakes from Fakenham Magna. The presence of handaxes from sites in the Timworth Member in MIS 15 or 14 is the first well-dated occurrence of these tools in Britain. Comparable evidence might be found in the Solent (Davis, 2013; Hatch, 2014; Davis et al., submitted), but there is little dating control. In mainland Europe, Moulin Quignon in north-west France (Antoine et al., 2019) and La Noira in central France (Moncel et al., 2013) both show handaxe use during MIS 16. Therefore, the Bytham evidence and possibly other British sites fit with the French sites and seem to reflect the introduction of handaxe technology during MIS 15 from neighbouring Europe.

7. Conclusions

The deposits of the Bytham River in the Breckland of East Anglia provide an important stratigraphic framework for understanding the Lower Palaeolithic archaeology contained within its sediments. The new work has provided a revised scheme with the identification of up to six sand and gravel aggradations that can be separated on the basis of altitude. They are interpreted as terrace remnants of the Bytham River that were deposited during the early Middle Pleistocene. If the terrace remnants were formed in relationship to glacial-interglacial cycles, then the highest terrace (Rushbrooke) may date back to MIS 22, with the final aggradation at Warren Hill deposited during MIS 12. ESR dating at four sites on the lowest three aggradations (Knettishall, Timworth and Warren Hill) supports the stratigraphic framework. The dating also indicates that sediments interpreted as a terrace of the River Lark, in an area adjacent to Warren Hill, are later in date than the Warren Hill deposits, and can be attributed to MIS 6. The archaeology, which is fully reported elsewhere (Davis et al., submitted), shows that flakes are present in the Ingham and Knettishall aggradations, and that handaxes are present in the Timworth and Warren Hill aggradations. In combination with the archaeological evidence from the sites on the East Anglian coast, they make an important contribution to understanding of the early occupation of north-west Europe.

Acknowledgements

Much of the work that contributed to this paper was undertaken by Dr Peter Hoare. He sadly died prior to the submission of the manuscript. This paper is dedicated to his memory. We would like to thank the Euston Estate for permission to conduct fieldwork at Sapiston and Fakenham Magna, John Browning and Icklingham Parish Council for Rampart Field, and the Forestry Commission for Warren Hill. Thanks also to Joshua Hogue and Claire Harris for their assistance with fieldwork. This research was funded by Leverhulme Trust Research Project Grant (RPG-2016-039) for the Breckland Palaeolithic Project and the Calleva Foundation for the Pathways to Ancient Britain project.

References

Antoine, P., 1994. The Somme Valley terrace system (Northern France); a model of river response to quaternary climatic variations since 800 000 BP. Terra-Nova 6, 453–464.

Antoine, P., Limondin Lozouet, N., Chaussé, C., Lautridou, J-P., Pastre, J-F., Auguste, P., Bahain, J-J., Falguères, C., Galehb, B., 2007. Pleistocene fluvial terraces from northern France (Seine, Yonne, Somme): synthesis and new results from interglacial deposits. Quaternary Science Reviews 26, 2701–2723 (2007).

Antoine, P., Moncel, M.-H., Locht, J.-L., Bahain, J.-J., Voinchet, P., Herisson, D., Hurel, A., 2019. The earliest record of Acheulean Human occupation from Northern Europe and the rediscovery of the Moulin Quignon site. Nature Scientific Reports 2019 9:13091 https://doi.org/10.1038/s41598-019-49400-w

Ashton, N.M., Cook, J., Lewis, S.G., Rose, J. (Eds.), 1992. High Lodge: Excavations by G. de G. Sieveking, 1962–68 and J. Cook, 1988. British Museum Press, London.

Ashton, N.M., Lewis, S.G., 2005. Maidscross Hill, Lakenheath. Proc. Suffolk Institute of Archaeology and Natural History XLI (1), 122–123.

Bateman, R.M, Rose, J., 1994. Fine sand mineralogy of the Early and Middle Pleistocene Bytham Sands and Gravels of Midland England and East Anglia. Proceedings of the Geologists' Association 105, 33-39.

Bolton, L., 2015. Assessing the origins of Levallois through lower Palaeolithic core variation: a comparative study of simple prepared cores in northwest Europe. Unpublished PhD, University of Southampton.

Bowen, D.Q., 1999. A revised correlation of Quaternary deposits in the British Isles. Geological Society London, Special report No. 23.

Brennan, B.J., 2003. Beta doses to spherical grains. Radiation Measurements 37, 299–303.

Brennan, B.J., Lyons, R.G., Phillips, S.W., 1991. Attenuation of alpha particle track dose for spherical grains. International Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation Measurements 18, 249–253.

Bridgland, D.R., 1994. The Quaternary of the Thames. Chapman and Hall, London.

Bridgland, D.R., Lewis, S.G., 1991. Introduction to the Pleistocene geology and drainage history of the Lark Valley. In Lewis, S.G., Whiteman, C.A., Bridgland, D.R. (Eds.). Central East Anglia and the Fen Basin. Field Guide. Quaternary Research Association, London, pp. 37–44.

Bridgland, D.R., 2006. The Middle and Upper Pleistocene sequence in the Lower Thames: a record of Milankovitch climatic fluctuation and early human occupation of southern Britain: Henry Stopes Memorial Lecture. Proceedings of the Geologists' Association 117, 281–305.

Bridgland, D.R., Lewis, S.G., Wymer, J.J., 1995. Middle Pleistocene stratigraphy and archaeology around Mildenhall and Icklingham, Suffolk: report on the Geologists' Association field meeting, 27 June, 1992. Proceedings of the Geologists' Association 106, 57–69.

Clarke, M.R., Auton, C.A., 1984. Ingham sand and gravel. Field guide to the Gipping and Waveney valleys, Suffolk. Quaternary Research Association, Cambridge, pp. 71–72.

Davis, R.J., 2013. Palaeolithic Archaeology of the Solent River: Human Settlement History and Technology. Unpublished PhD thesis, University of Reading.

Davis, R.J., Lewis, S.G., Ashton, N.M., Parfitt, S.A., Hatch, M.T., Hoare, P.G., 2017. The early Palaeolithic archaeology of the Breckland: current understanding and directions for future research. Journal of Breckland Studies 1, 28–44.

Davis, R.J., Ashton, N.M., Hatch, M., Hosfield, R., Lewis, S.G., submitted. Lower and early Middle Palaeolithic of Southern England: the evidence from the River Test. *Journal of Palaeolithic Archaeology*.

Davis, R.J., Ashton, N.M., Lewis, S.G., Hatch, M., Hoare, P.G., submitted. The archaeology of the Bytham River: human occupation of Britain during the early Middle Pleistocene and its European context. *Journal of Quaternary Science*.

Duval, M., Guilarte, V., 2015. ESR dosimetry of optically bleached quartz grains extracted from Plio-Quaternary sediment: Evaluating some key aspects of the ESR signals associated to the Ti-centers. Radiation Measurements 78, 28-41.

Duval, M., Sancho, C., Calle, M., Guilarte, V., Peña-Monné, J.L., 2015. On the interest of using the Multiple Centre approach in ESR dating of optically bleached quartz grains: some examples from the Early Pleistocene terraces of the Alcanadre River (Ebro basin, Spain). Quaternary Geochronology 29, 58–69.

Evans, J., 1872. The Ancient Stone Implements, Weapons and Ornaments of Great Britain. Longmans, Green & Co, London.

Flower, J.W., 1869. On some recent Discoveries of Flint Implements of the Drift in Norfolk and Suffolk with observations on the Theories accounting for their Distribution. Quarterly Journal of the Geological Society, 25, 449-460.

Gale, S.J., Hoare, P.G., 2011. Quaternary Sediments: Petrographic Methods for the Study of Unlithified Rocks. The Blackburn Press, Caldwell.

Gibbard, P.L., West, R.G., Boreham, S., Rolfe, C.J., 2012. Late Middle Pleistocene ice marginal sedimentation in East Anglia, England. Boreas 41, 319-336.

Gibbard, P.L., West, R.G., Hughes, P.D., 2018. Pleistocene glaciation of Fenland, England, and its implications for evolution of the region. Royal Society Open Science. https://doi.org/10.1098/rsos.170736

Gibbard, P.L., Hughes, P.D., West, R.G., 2019. Human occupation of northern Europe in MIS 13: Happisburgh Site 1 (Norfolk, UK) and its European context: A response to Lewis et al. (2019). Quaternary Science Reviews 223. https://doi.org/10.1016/j.quascirev.2019.07.026

Gibbard, P.L., Pasanen, A.H., West, R.G., Lunkka, J.P., Boreham, S., Cohen, K.M., Rolfe, C., 2009. Late Middle Pleistocene glaciation in East Anglia, England. Boreas, 38, 504–528.

Grün R., 1989. Electron spin resonance (ESR) dating. Quaternary International 1, 65–109.

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

Hardaker, T., 2012. The artefacts from the present land surface at the Palaeolithic site of Warren Hill, Suffolk, England. Proceedings of the Geologists Association 123, 692-713.

Hardaker, T., MacRae, R.J., 2000. A lost river and some Palaeolithic surprises: new quartzite finds from Norfolk and Oxfordshire. Lithics 21, 52 –59.

Hardaker, T., Rose, J., 2019. The Lower Palaeolithic artefacts of the Bytham River system of Central England. Lithics 40, 41-58.

Hey, R.W., 1980. Equivalents of the Westland Green Gravels in Essex and East Anglia. Proceedings of the Geologists' Association, 91, 279–290.

Hosfield, R., 2011. The British Lower Palaeolithic of the early Middle Pleistocene. Quaternary Science Reviews 30, 1486-1510.

Hunt, C.O., 1992. Pollen and algal microfossils from the High Lodge clayey-silts. In: Ashton, N.M., Cook, J., Lewis, S.G., Rose, J. (Eds.), High Lodge: Excavations by G. de G. Sieveking 1962-68 and J. Cook 1988. British Museum Press, London, pp. 109-115.

Hunt, C.O., Rose, J., 1992. Recycled palynomorphs from the High Lodge clayey-silts. In: Ashton, N.M., Cook, J., Lewis, S.G., Rose, J. (Eds.), High Lodge. Excavations by G. de G. Sieveking, 1962-68 and J. Cook, 1988. British Museum Press, London, pp. 103-108.

Ikeya, M., 1993. New Applications of Electron Spin Resonance: Dating, Dosimetry and Microscopy. World Scientific, Singapore.

Keen, D.H., Hardaker, T., Lang, A.T.O., 2006. A Lower Palaeolithic industry from the Cromerian (MIS 13) Baginton Formation of Waverley Wood and Wood Farm Pits, Bubbenhall, Warwickshire, UK. Journal of Quaternary Science 21, 457–470.

Laurent, M., Falguères, C., Bahain, J.J., Van Vliet-Lanoé, B., 1998. ESR dating of quartz extracted from quaternary and neogene sedimentsmethod, potential and actual limits. Quaternary Science Reviews 17, 1057–1062.

Lee, J.R., Rose, J., Hamblin, R.J.O., Moorlock, B.S.P., 2004. Dating the earliest lowland glaciation of eastern England: the pre-Anglian early Middle Pleistocene Happisburgh Glaciation. Quaternary Science Reviews 23, 1551-1566.

Lewis, S.G., 1989. Shouldham Thorpe, Norfolk. In Keen, D.H. (Ed.), The Pleistocene of the West Midlands: Field Guide. Quaternary Research association, Cambridge, pp. 134-5.

Lewis, S.G., 1991. Shouldham Thorpe, Norfolk (TF657085). In Lewis, S.G, Whiteman, C.A., Bridgland, D.R. (Eds.), Central East Anglia and the Fen Basin: Field Guide. Quaternary Research association, London, pp. 127-30.

Lewis, S.G., 1992. High Lodge – stratigraphy and depositional environments. In: Ashton, N., Cook, J., Lewis, S.G. and Rose, J. (Eds.), High Lodge. Excavations by G. de G. Sieveking (1962–68) and J. Cook (1988), British Museum, London, pp.51-85.

Lewis, S.G., 1993. The status of the Wolstonian glaciation in the English Midlands and East Anglia. Unpublished PhD thesis, University of London.

Lewis, S.G., 1998. Quaternary Stratigraphy and Lower Palaeolithic Archaeology of the Lark Valley, Suffolk. In: Ashton, N., Healey, F. and Pettitt, P. (Eds.), Stone Age Archaeology. Essays in honour of John Wymer. Oxbow Monograph 102, pp. 43–51.

Lewis, S.G., 1999. Eastern England. In: Bowen, D.Q. (Ed.), A revised correlation of Quaternary deposits in the British Isles. Geological Society London, Special report No. 23, 10-27.

Lewis, S.G., Ashton, N.M., Field, M., Hoare, P.G., Kamermans, H., Knul, M., Mücher, H., Parfitt, S.A., Roebroeks, J.W.M., Sier, M., 2019a. Human occupation of northern Europe in MIS 13: Happisburgh Site 1 (Norfolk, UK) and its European context. Quaternary Science Reviews 211, 34-58.

Lewis, S.G., Ashton, N.M., Hoare, P.G., Parfitt, S.A., 2019b. Human occupation of Northern Europe in MIS 13: a response to comments by Gibbard et al. (2019). Quaternary Science Reviews 223, 105851.

Lewis, S.G., Bridgland, D.R., 1991. Ingham (TL 855715) and Timworth (TL853692), Suffolk. In Lewis, S.G., Whiteman, C.A., Bridgland, D.R. (Eds.). Central East Anglia and the Fen Basin. Field Guide. Quaternary Research Association, London, pp. 71–83.

Lewis, S.G., Rose, J., Davies, H., 1999. Pre-Anglian fluvial and Anglian glaciogenic sediments, Knettishall, Suffolk, England. Proceedings of the Geologists' Association 110, 17–32.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic d^{18}O records. Paleoceanography 20, PA1003, doi:10.1029/2004PA001071.

MacRae, R.J., 1999. New Lower Palaeolithic finds in Norfolk. Lithics 20, 3-10.

Marr, J.E., 1921. Excavations at High Lodge, Mildenhall in 1920 A.D. Report of the geology. Proceedings of the Prehistoric Society of East Anglia 3, 353 373.

Moncel, M-H., Ashton, N., Lamotte, A., Tuffreau, A., Cliquet, D., Despriée, J., 2015. North-west Europe early Acheulian. Journal of Anthropological Archaeology 40, 302-331.

Moncel, M-H., Despriée, J., Voinchet, P., Tissoux, H., Moreno, D., Bahain, J-J., Courcimault, G., Falguères, C., 2013. Early evidence of Acheulean settlement in north-western Europe - la Noira site, a 700 000 year-old occupation in the Center of France, PlosOne 8 (Issue 11), e75529.

Moreno, D., Falguères, C., Pérez-González, A., Voinchet, P., Ghaleb, B., Despriée, J., Bahain, J.-J., Sala, R., Carbonell, E., Bermúdez de Castro, J.M., Arsuaga, J.L., 2015. New radiometric dates on the lowest stratigraphical section (TD1 to TD6) of Gran Dolina site (Atapuerca, Spain). Quaternary Chronology 30B, 535-540.

Parfitt, S.A., Ashton, N.M., Lewis, S.G., Abel, R.L. Coope, G.R., Field, M.H., Gale, R., Hoare, P.G., Larkin, N.R., Lewis, M.D., Karloukovski, V., Maher, B.A., Peglar, S.M., Preece, R.C., Whittaker, J.E., Stringer, C.B., 2010. Early Pleistocene human occupation at the edge of the boreal zone in northwest Europe. Nature 466, 229–233.

Parfitt, S.A., Barendregt, R.W., Breda, M., Candy, I., Collins, M.J., Coope, G.R., Durbidge, P., Field, M.H., Lee, J.R., Lister, A.M., Mutch, R., Penkman, K.E.H., Preece, R.C., Rose, J., Stringer, C.B., Symmons, R., Whittaker, J.E., Wymer, J.J., Stuart, A.J., 2005. The earliest record of human activity in northern Europe. Nature 438, 1008–1012.

Penkman, K.E.H., Preece, R.C., Keen, D.H., Meijer, T., White, T.S., Collins, M.J., 2011. A chronological framework for the British Quaternary based on calcitic Bithynia opercula. Nature 476, 446-449.

Pereira, A., Nomade, S., Falguères, C., Bahain, J-J., Tombret, O., Garcia, T., Voinchet, P., Bulgarelli, G-M., Anzidei, A-P., 2017. 40Ar/39Ar and ESR/U-series data for the La Polledrara di Cecanibbio archaeological site (Lazio, Italy). Journal of Archaeological Science Reports 15, 20-29.

Pereira, A., Nomade, S., Voinchet, P., Bahain, J-J., Falguères, C., Garon, H., Lefèvre, D., Raynal, J-P., Scao, V., Piperno, M., 2015. The earliest securely dated hominin fossil in Italy and evidence of Acheulian occupation during glacial MIS 16 at Notarchirico (Venosa, Basilicata, Italy). Journal of Quaternary Science 30, 639–650.

Preece, R.C., Parfitt, S.A., Coope, G.R., Penkman, K.E., Ponel, P., Whittaker, J.E., 2009. Biostratigraphic and aminostratigraphic constraints on the age of the Middle Pleistocene glacial succession in north Norfolk, UK. Journal of Quaternary Science 24, 557-580.

Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations. Radiation Measurements 23, 497-500.

Prigg, H., 1868. The tumuli of Warren Hill, Mildenhall. Proceedings of the Suffolk Institute of Archaeology, Statistics and Natural History 4(3), 287-299.

Rink, W.J., Bartoll, J., Schwarcz, H.P., Shane, P., Bar-Yosef, O., 2007. Testing the reliability of ESR dating of optically exposed buried quartz sediments. Radiation Measurements 42, 1618-1626.

Rose, J., 1987. The status of the Wolstonian glaciation in the British Quaternary. Quaternary Newsletter 53, 1-9.

Rose, J., 1989. Tracing the Baginton-Lillington sands and gravels from the West Midlands to East Anglia. In: Keen, D.H. (Ed.), The Pleistocene of the West Midlands: Field Guide. Quaternary Research Association, Cambridge, pp. 102-110.

Rose, J., 1992. High Lodge – regional context and geological background. In: Ashton, N., Cook, J., Lewis, S.G., Rose, J. (Eds.), High Lodge. Excavations by G. de G. Sieveking (1962–68) and J. Cook (1988), British Museum, London, pp.13-24.

Rose, J., 1994. Major river systems of central and southern Britain during the early and Middle Pleistocene. Terra Nova 6, 435-443.

Rose, J. 2007. The stratigraphy at Fakenham Magna and Flixton: AHOB sites in East Anglia. In: Stringer, C.B. and Bello, S. (Eds.), First Workshop of AHOB2: Ancient Human Occupation of Britain and its European Context. Abstracts volume, 10-12, viewed 3 April 2019, <https://www.researchgate.net/profile/Christopher_Stringer/publication/228611893_First_Workshop_of_AHOB2_Ancient_Human_Occupation_of_Britain_and_its_European_Context/links/0912f510ba931140a0000000/First-Workshop-of-AHOB2-Ancient-Human-Occupation-of-Britain-and-its-European-Context.pdf>.

Rose, J., 2009. Early and Middle Pleistocene landscapes of eastern England. Proceedings of the Geologists' Association 120, 3-33.

Rose, J., Davies, H., Lewis, S.G., 1992. Heavy mineral composition of the sands at High Lodge. In: Ashton, N.M., Cook, J., Lewis, S.G., Rose, J. (Eds.), High Lodge. Excavations by G. de G. Sieveking, 1962-68 and J. Cook, 1988. British Museum Press, London, pp. 94-102.

Shotton, F.W., Keen, D.H., Coope, G.R., Currant, A.P., Gibbard, P.L., Aalto, M., Peglar, S.M., Robinson, J.E., 1993. Pleistocene deposits of Waverley Wood Farm Pit, Warwickshire, England. Journal of Quaternary Science 8, 293–325.

Silva, B., Candy, I., Rose, J., Schreve, D., White, M., Coope, G.R., Schreve, P., Lewis, M., 2009. Early Middle Pleistocene landscapes of Suffolk: an update on the environmental archaeology of Flixton

Quarry. In Stringer, C.B. & Bello, S. (eds), Abstracts of Second Workshop of AHOB2: Ancient Human Occupation of Britain and its European Context. London: AHOB, p. 39.

Solomon, J.D., 1933. The implementiferous gravels of Warren Hill. The Journal of the Royal Anthropological Institute of Great Britain and Ireland 63, 101–110.

Stuart, A.J., 1992. The High Lodge mammalian fauna. In: Ashton, N.M., Cook, J., Lewis, S.G., Rose, J. (Eds.), High Lodge. Excavations by G. de G. Sieveking, 1962-68 and J. Cook, 1988. British Museum Press, London, pp. 121-123.

Tissoux, H., Falguères, C., Voinchet, P., Toyoda, S., Bahain, J-J., Despriée, J., 2007. Potential use of Ti-center in ESR dating of fluvial sediment. Quaternary Geochronology 2, 367-372.

Toucanne, S., Zaragosi, S., Bourillet, J.F., Cremer, M., Eynaud, F., Vliet-Lanoe van, B., Penaud, A., Fontanier, C., Turon, J.L., Cortijo, E., Gibbard, P.L., 2009. Timing of massive ‘Fleuve Manche’ discharges over the last 350 kyr: insights into the European ice-sheet oscillations and the European drainage network from MIS 10 to 2. Quaternary Science Reviews 28, 1238–1256.

Toyoda, S., Voinchet, P., Falguères, C., Dolo, J-M., Laurent, M., 2000. Bleaching of ESR signals by the sunlight: a laboratory experiment for establishing the ESR dating of sediments. Applied Radiation and Isotopes 52, 1357-1362.

Voinchet, P., Bahain, J-J., Falguéres, C., Laurent, M., Dolo, J.M., Desprieé, J., Gageonnet, R., Chaussé, C., 2004. ESR dating of Quartz extracted from Quaternary sediments: application to fluvial terraces system of Northern France. Quaternaire 15, 135–142.

Voinchet, P., Moreno, D., Bahain, J-J., Tissoux, H., Tombret, O., Falguères, C., Moncel, M.H., Schreve, D., Candy, I., Antoine, P. Ashton, N., Beamish, M. Cliquet, D., Despriée, J., Lewis, S.G., Limondin-Lozouet, N., Locht, J-L. Parfitt, S., Pope, M., 2015. New chronological data (ESR and ESR/U-series) for the earliest Acheulian sites of north-western Europe. Journal of Quaternary Science 30(7), 610–622.

Voinchet, P., Pereira, A., Nomade, S., Falguères, C., Biddittu, I., Piperno, M., Moncel, M-H., Bahain, J-J., 2020. ESR dating applied to optically bleached quartz - A comparison with 40Ar/39Ar chronologies on Italian Middle Pleistocene sequences. Quaternary International 556, 113-123.

West, R.G., Gibbard, P.L., Boreham, S., Rolfe, C.J., 2014. Geology and geomorphology of the Palaeolithic site at High Lodge, Mildenhall, Suffolk, England. Proceedings of the Yorkshire Geological Society 60, 99-121.

Westaway, R., 2009. Quaternary vertical crustal motion and drainage evolution in East Anglia and adjoining parts of southern England: chronology of the Ingham River terrace deposits. Boreas 38, 261-284.

Whitaker, W., Woodward, H.B., Bennett, F.J., Skertchly, S.B.J., Jukes-Browne, A.J., 1891. The Geology of Parts of Cambridgeshire and of Suffolk (Ely, Mildenhall, Thetford). Memoir of the Geological Survey of Great Britain. HMSO, London.

Wymer, J.J., 1999. The Lower Palaeolithic Occupation of Britain (Vol. 1 and 2). Wessex Archaeology and English Heritage, Salisbury.

Wymer, J.J., 2001. Palaeoliths in a lost pre-Anglian landscape. In: Milliken, S. and Cook, J. (Eds.), A Very Remote Period Indeed. Papers on the Palaeolithic presented to Derek Roe. Oxbow Books, Oxford, pp.174-179.

Wymer, J.J., Lewis, S.G., Bridgland, D.R., 1991. Warren Hill, Mildenhall, Suffolk. In: Lewis, S.G., Whiteman, C.A., Bridgland, D.R. (Eds), Central East Anglia and the Fen Basin. Field Guide. Quaternary Research Association, London, pp. 50-58.

Yokoyama, Y., Falguères, C., Quaegebeur, J.P., 1985. ESR dating of quartz from Quaternary sediments: first attempt. Nuclear tracks 10, 921–928.

Figures

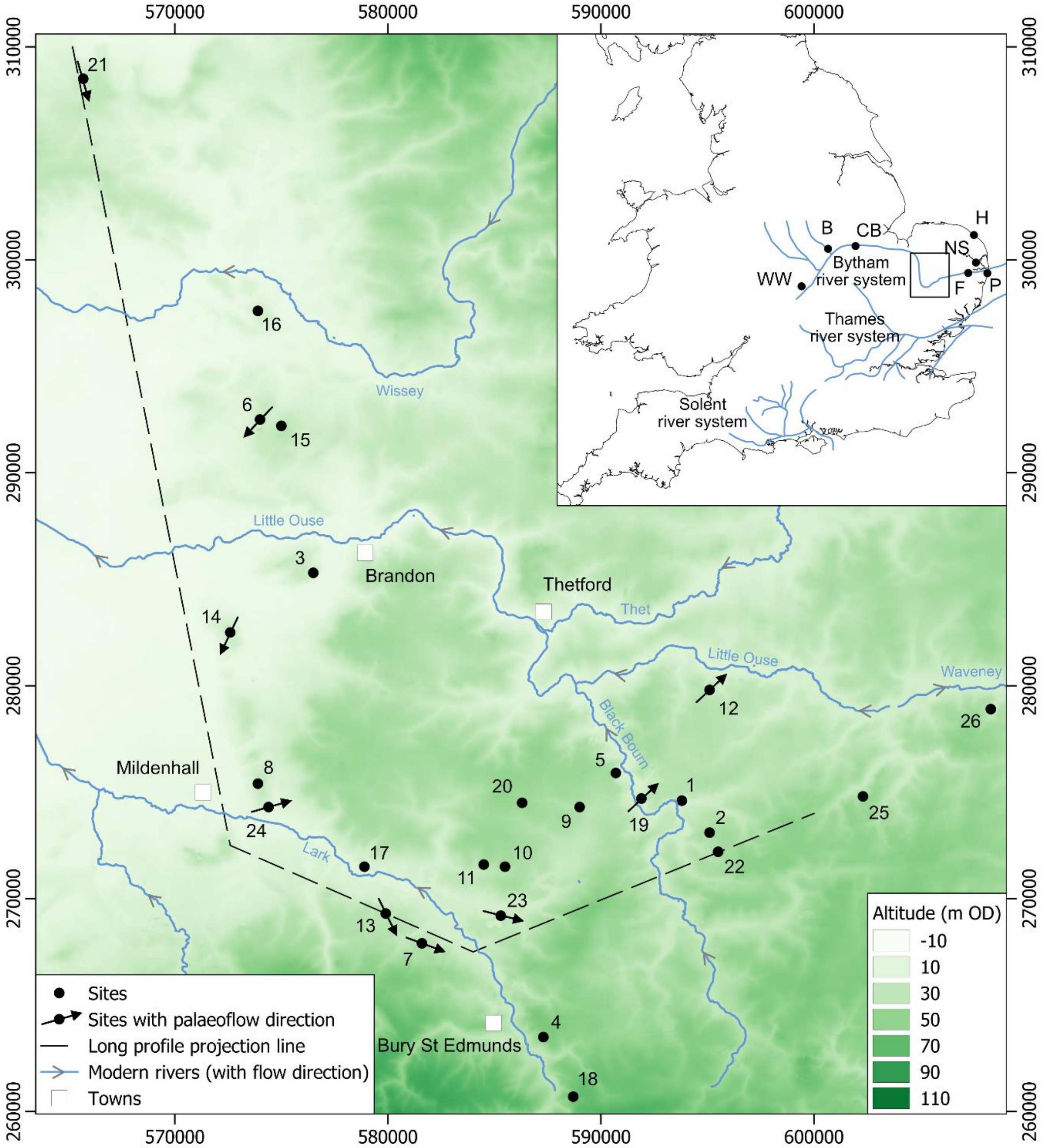

Figure 1. Study area with sites mentioned in the text with the projection line for terrace long profiles. Palaeoflow directions are shown by each Bytham site, where recorded. The direction of flow is also indicated on the modern rivers. Sites: 1 Bardwell (A); 2 Bardwell (B); 3 Brandon Fields; 4 Bury St Edmunds; 5 Fakenham Magna; 6 Feltwell; 7 Hengrave; 8 High Lodge; 9 Honnington; 10 Ingham (Site A); 11 Ingham (Site B); 12 Knettishall; 13 Lackford; 14 Maidscross Hill; 15 Methwold; 16 Northwold; 17 Rampart Field; 18 Rushbrooke; 19 Sapiston; 20 Seven Hills; 21 Shouldham Thorpe; 22 Stanton; 23 Timworth; 24 Warren Hill; 25 Wattisfield; 26 Wortham. Inset map: B = Brooksby; CB = Castle Bytham; F = Flixton; H = Happisburgh; NS = Norton Subcourse; P = Pakefield; WW = Waverley Wood.

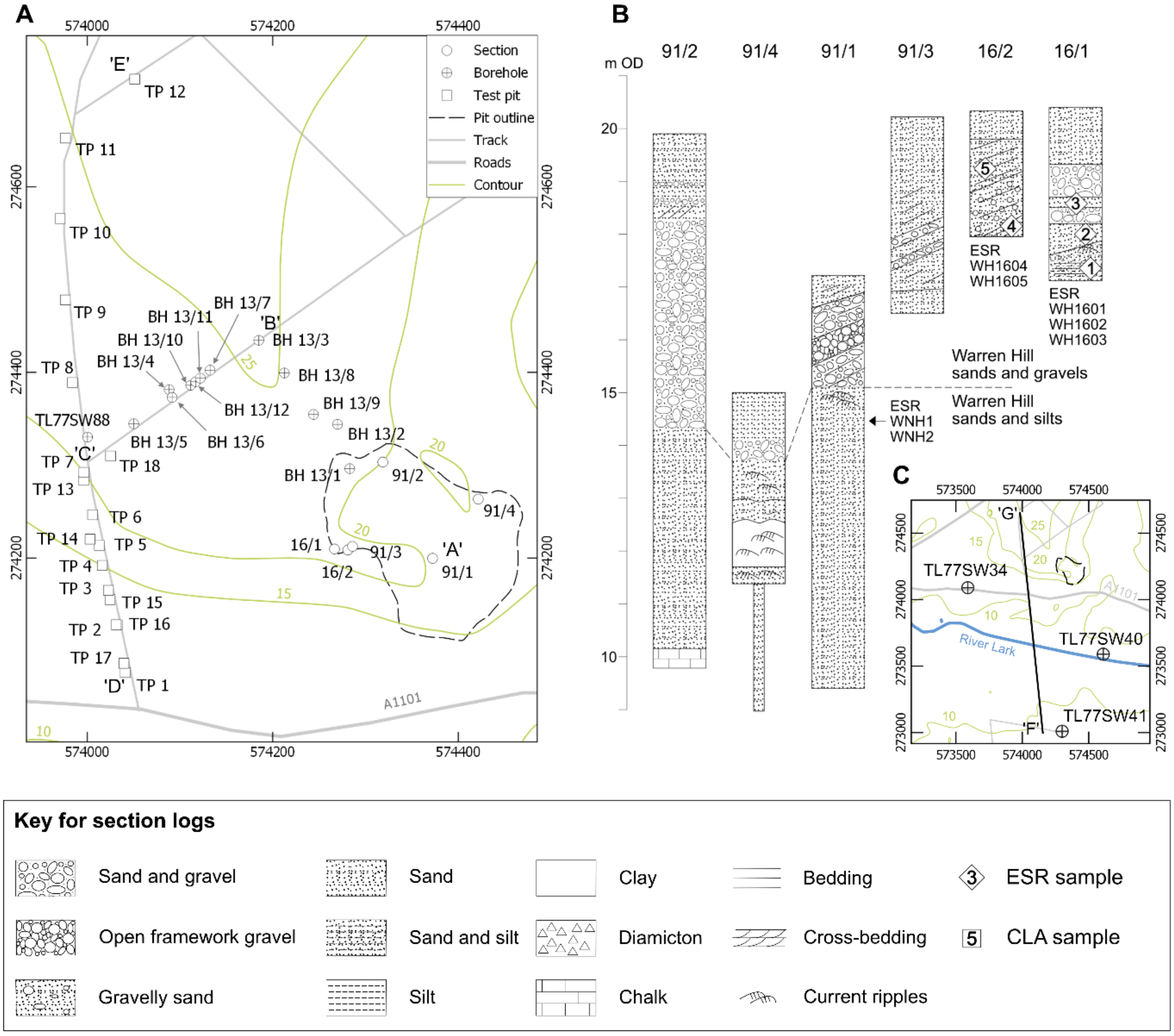

Figure 2. Warren Hill. A. Old gravel pit and adjacent area with location of sections, test pits and boreholes. B. Section logs from QRA fieldwork (91/1 – 91/4) and BPP fieldwork (16/1 and 16/2). C. Position of transect F-G and BGS boreholes. ESR sample locations are given (Table 3).

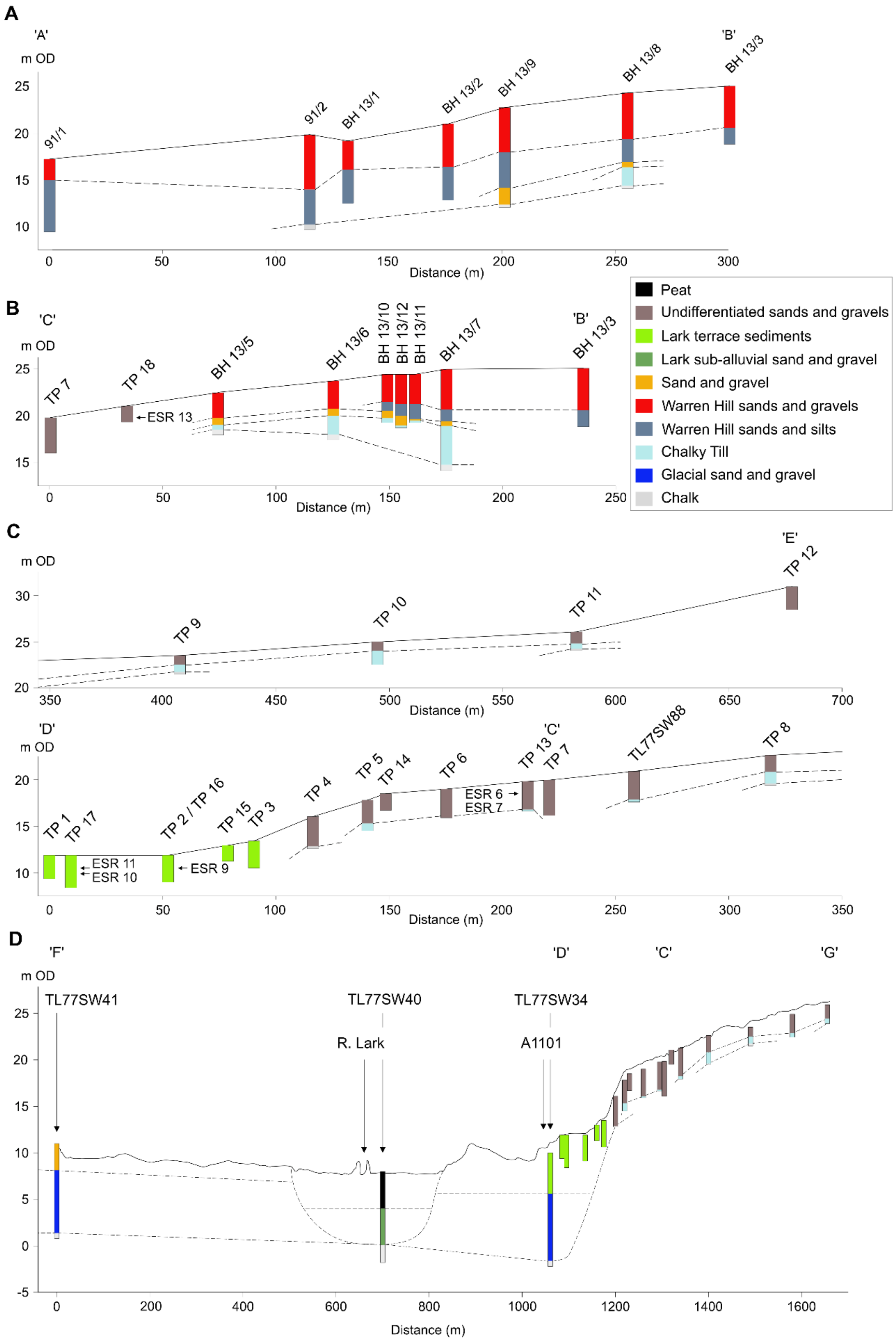

Figure 3. Warren Hill sediment profiles (see Figure 2). A. Transect A-B from Section 91/1 to BH13/3. B. Transect C-B from TP7 to BH13/3. C. Transect D-C-E from TP1 to TP12. Transect F-G showing River Lark sediments and BGS boreholes. ESR sample locations are given (Table 3).

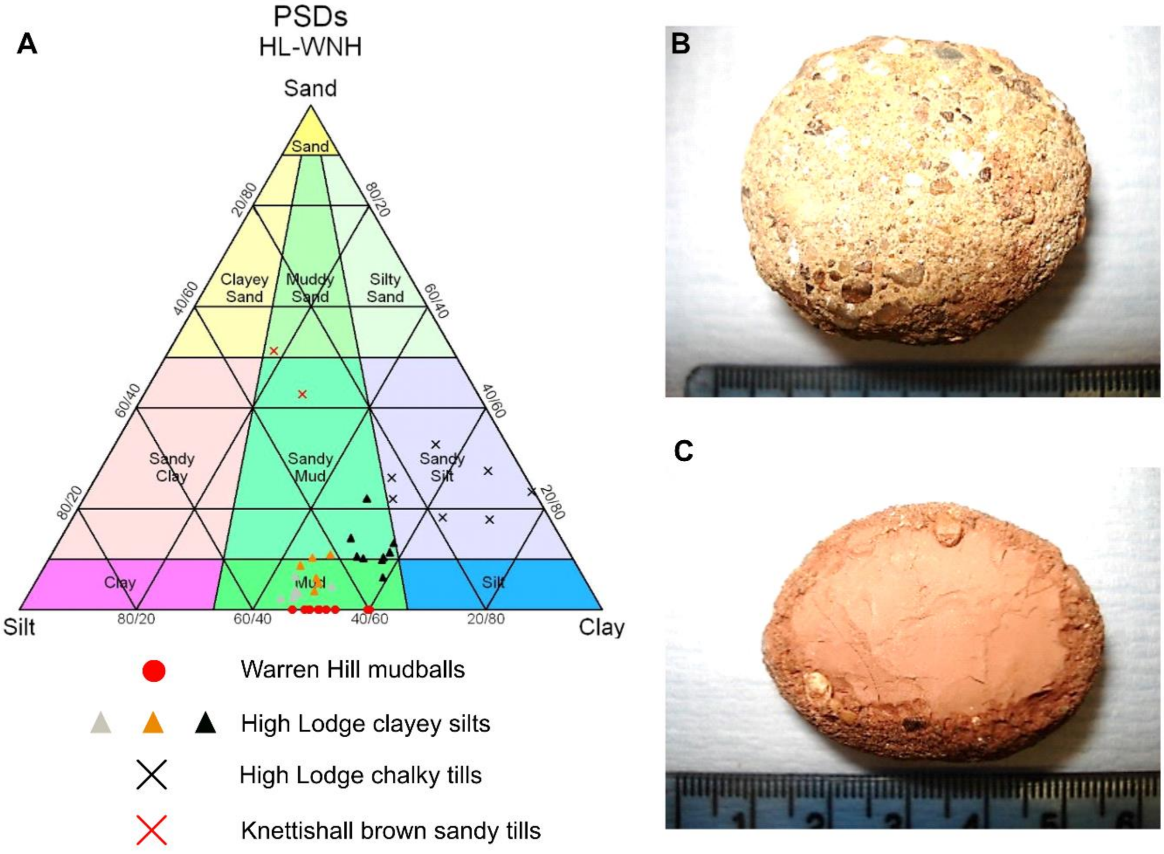

Figure 4. A. Particle size distribution comparing Warren Hill mudballs with samples from the High Lodge clayey silts, High Lodge chalky tills and Knettishall brown sandy tills. B. Warren Hill mudball with armouring. C. Warren Hill mudball with cleaned surface.

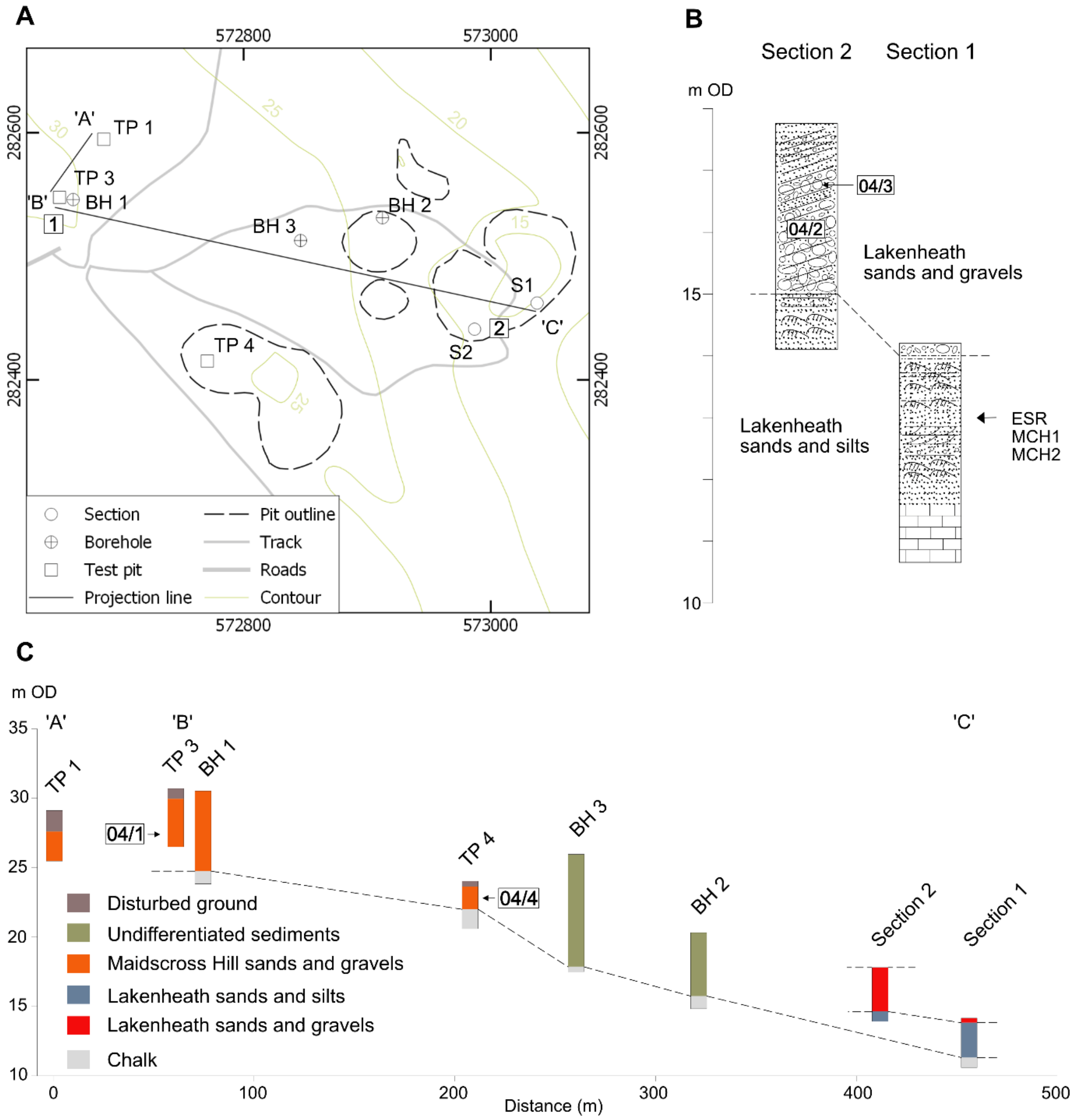

Figure 5. Maidscross Hill, Lakenheath. A. Location of old gravel pits, sections, test pits and boreholes. B. Logs of Sections 1 and 2, showing ESR sample locations. C. Profile of sediments on transect from TP1 to Section 1.

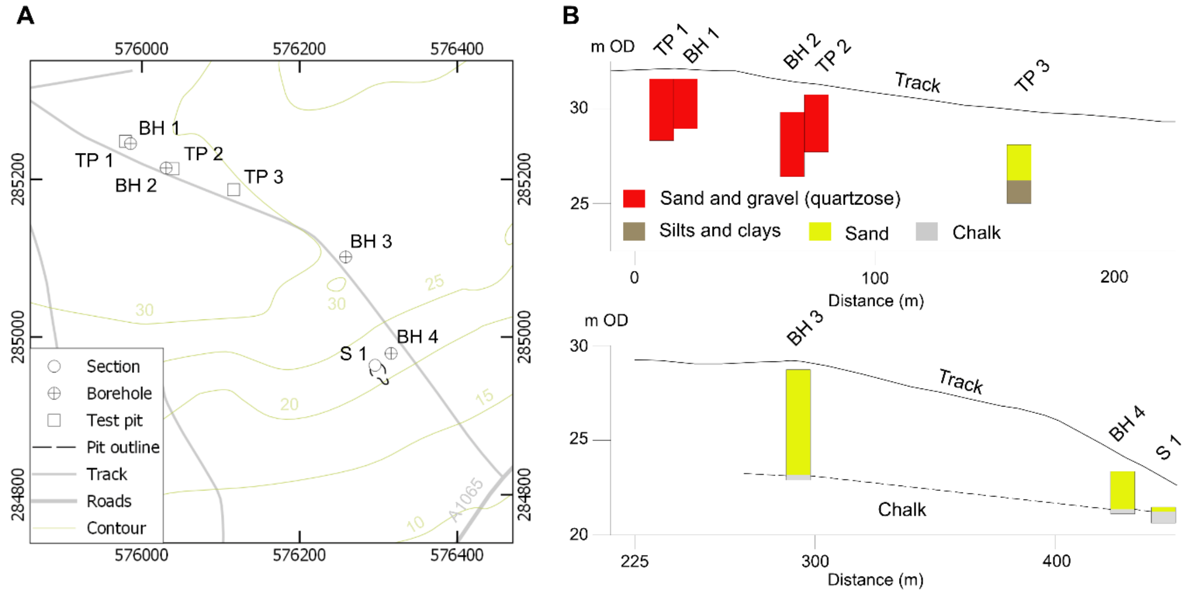

Figure 6. Brandon Fields, Brandon. A. Location of test pits, boreholes and section. B. Profile of sediments on transect from TP1 to Section 1.

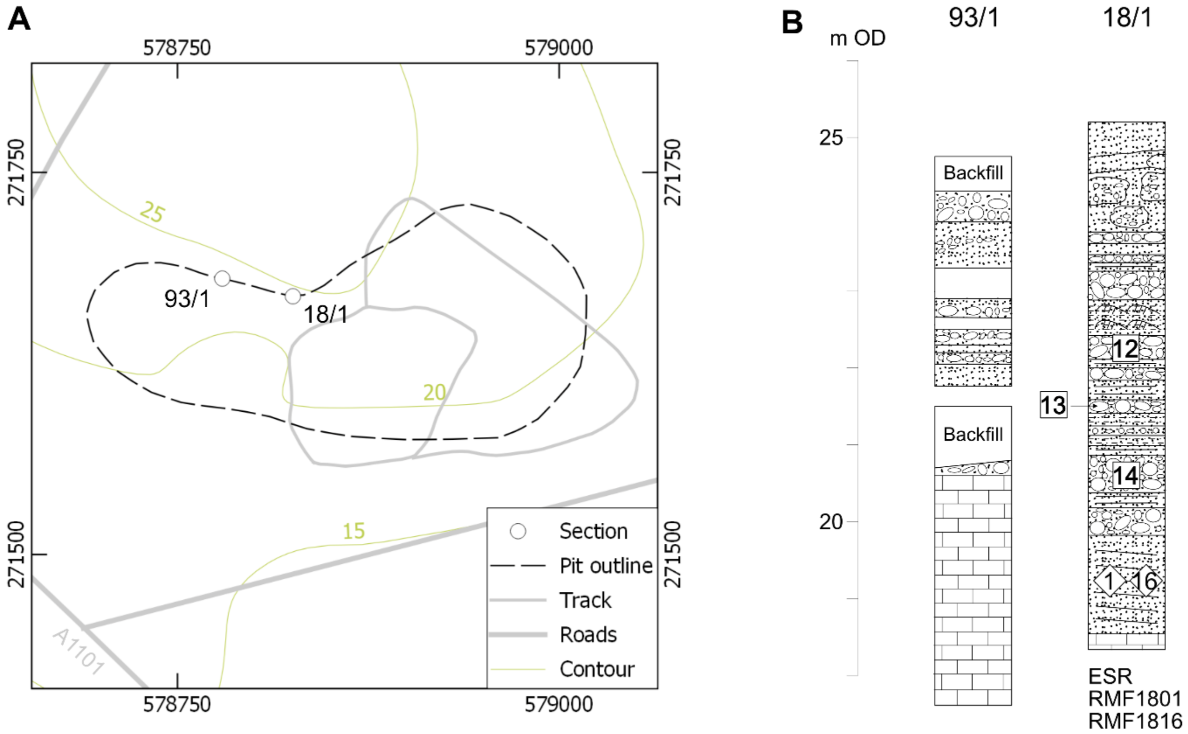

Figure 7. Rampart Field, Icklingham. A. Location of old gravel pit and sections. B. Logs of Sections 93/1 and 18/1 with ESR sample locations.

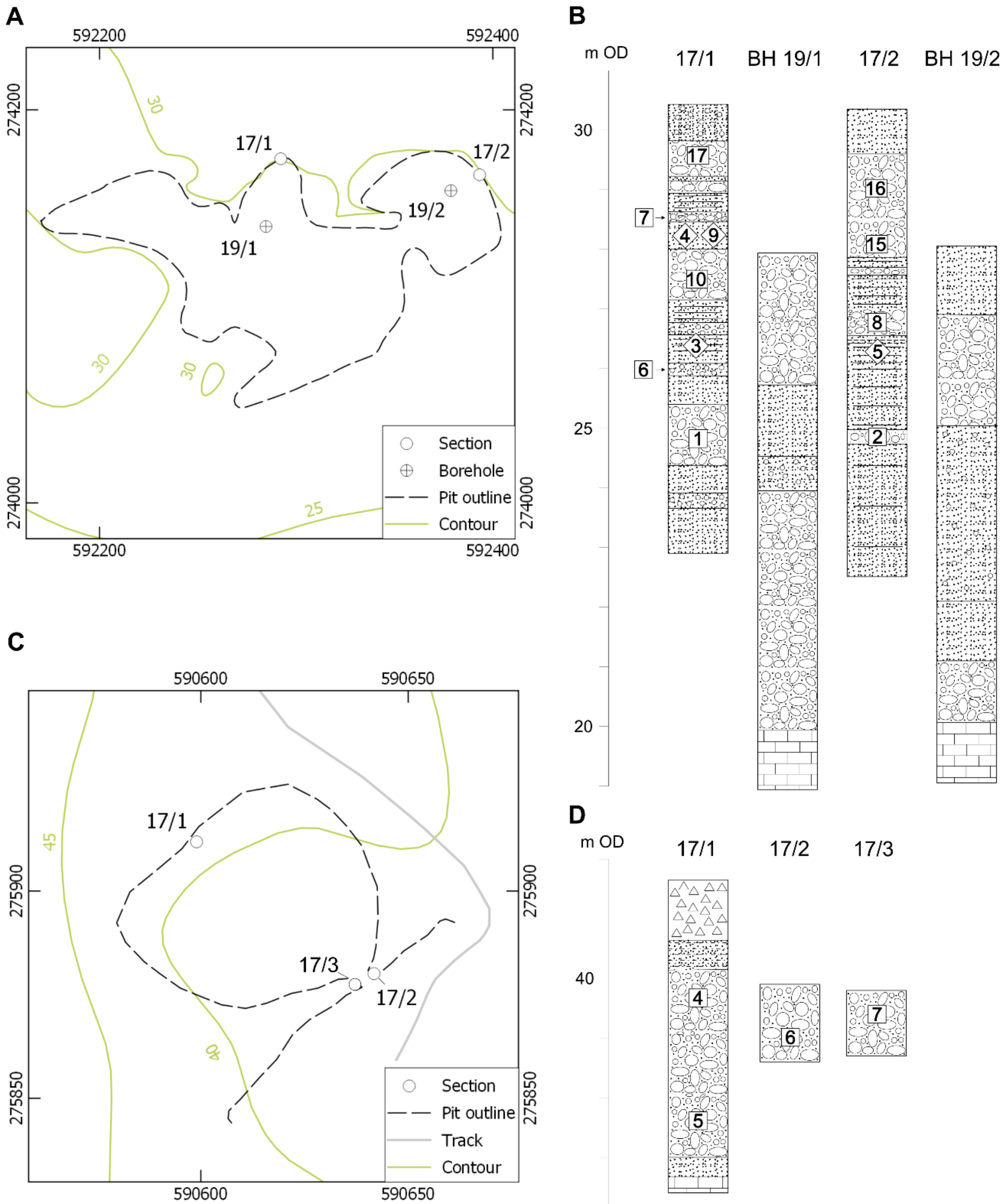

Figure 8. Sapiston and Fakenham Magna. A. Location of old gravel pit, sections and boreholes at Sapiston. B. Sections and borehole logs at Sapiston with location of ESR samples. C. Location of old gravel pit and sections at Fakenham Magna. D. Section logs at Fakenham Magna.

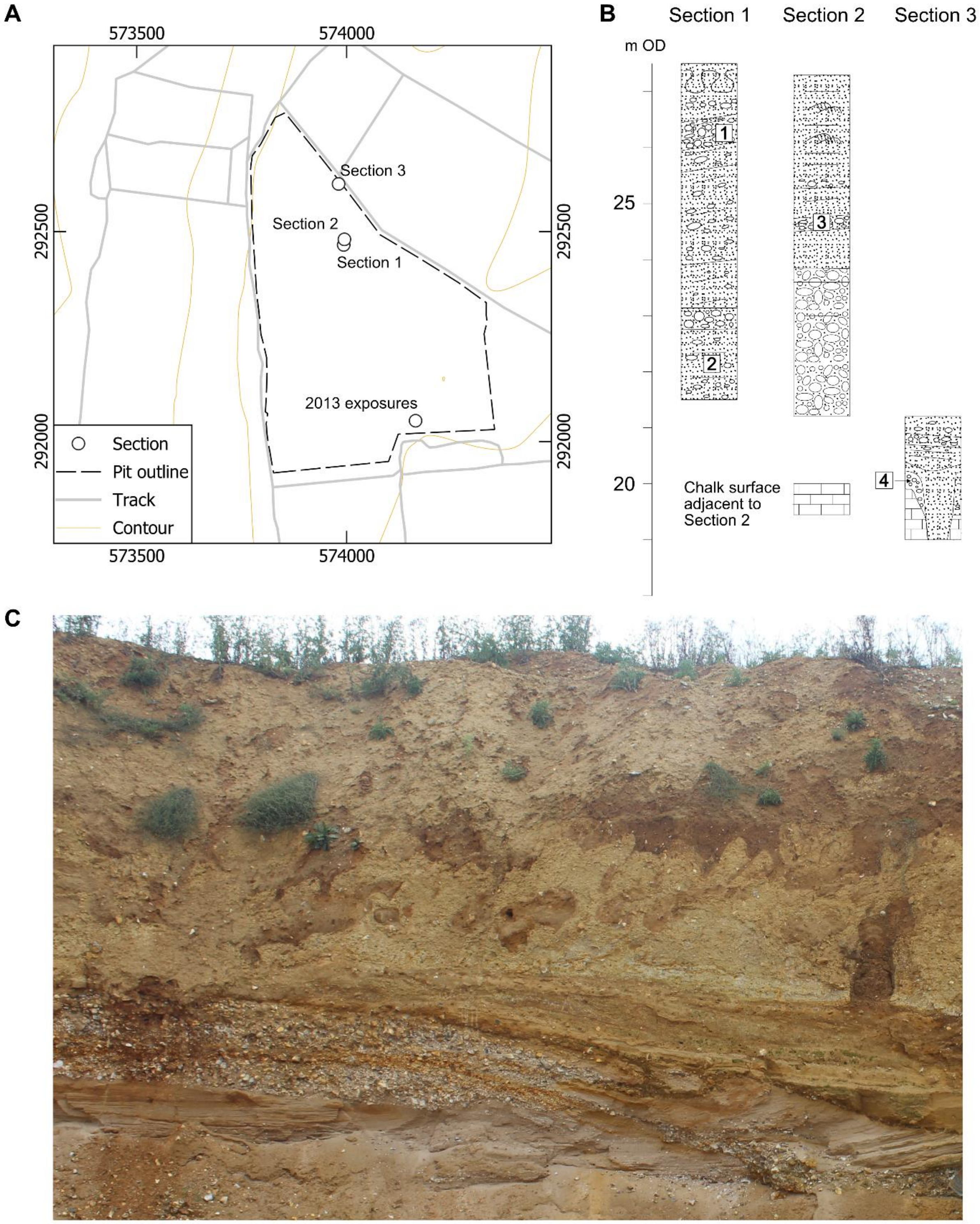

Figure 9. Frimstone's Pit, Feltwell. A. Location of sections. B. Logs of Sections 1 to 3. C. Photograph through exposure of deposits in 2013.

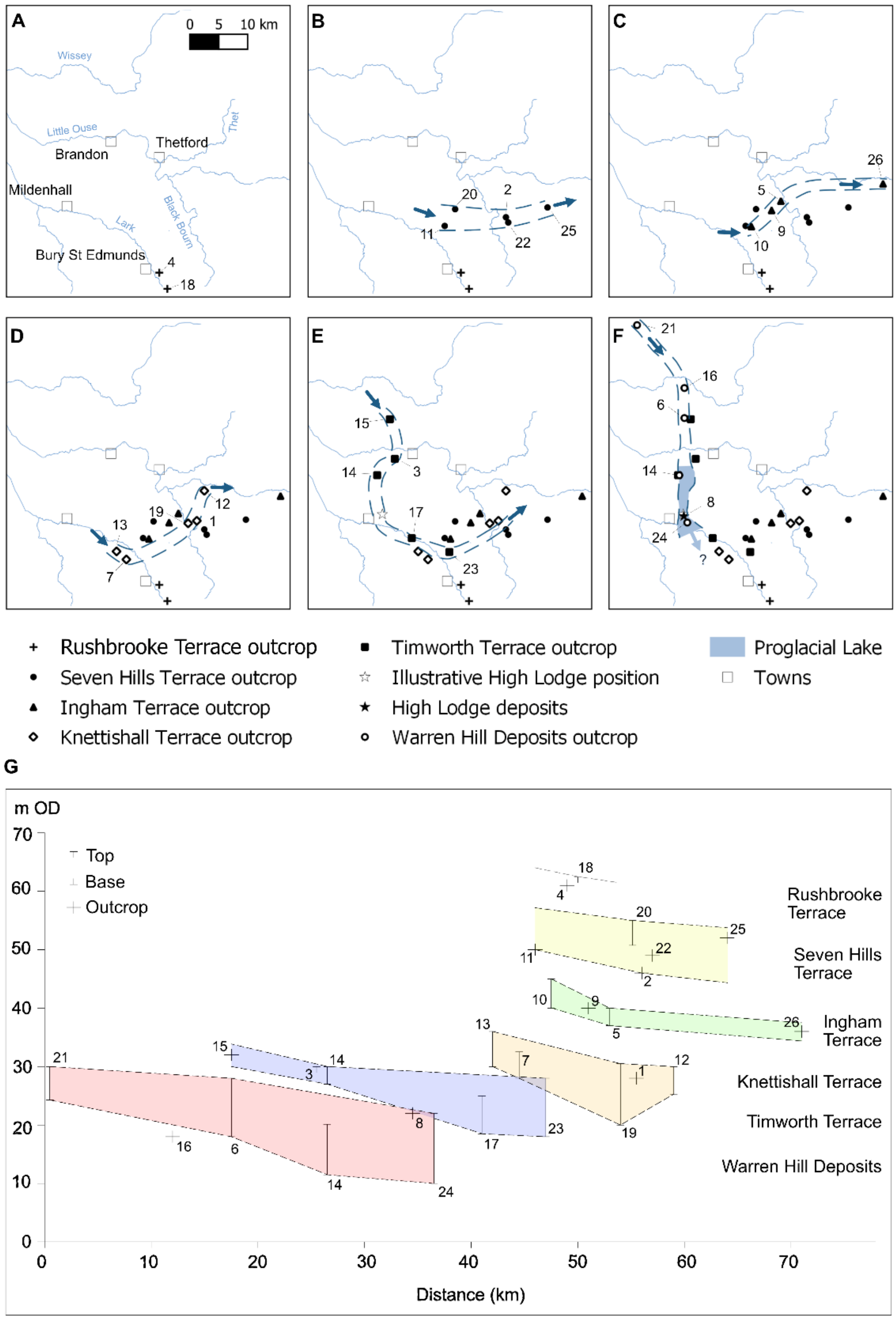

Figure 10. Evolution of the Bytham River in the Breckland with suggested long profiles of terraces. A. Rushbrooke Member sites. B. Seven Hills Member sites. C. Ingham Member sites. D. Knettishall Member sites. E. Timworth Member sites. F. Warren Hill Member sites. G. Suggested long profiles of terraces. Sites: 1 Bardwell (A); 2 Bardwell (B); 3 Brandon Fields; 4 Bury St Edmunds; 5 Fakenham Magna; 6 Feltwell; 7 Hengrave; 8 High Lodge; 9 Honnington; 10 Ingham (Site A); 11 Ingham (Site B); 12 Knettishall; 13 Lackford; 14 Maidscross Hill; 15 Methwold; 16 Northwold; 17 Rampart Field; 18 Rushbrooke; 19 Sapiston; 20 Seven Hills; 21 Shouldham Thorpe; 22 Stanton; 23 Timworth; 24 Warren Hill; 25 Wattisfield; 26 Wortham.

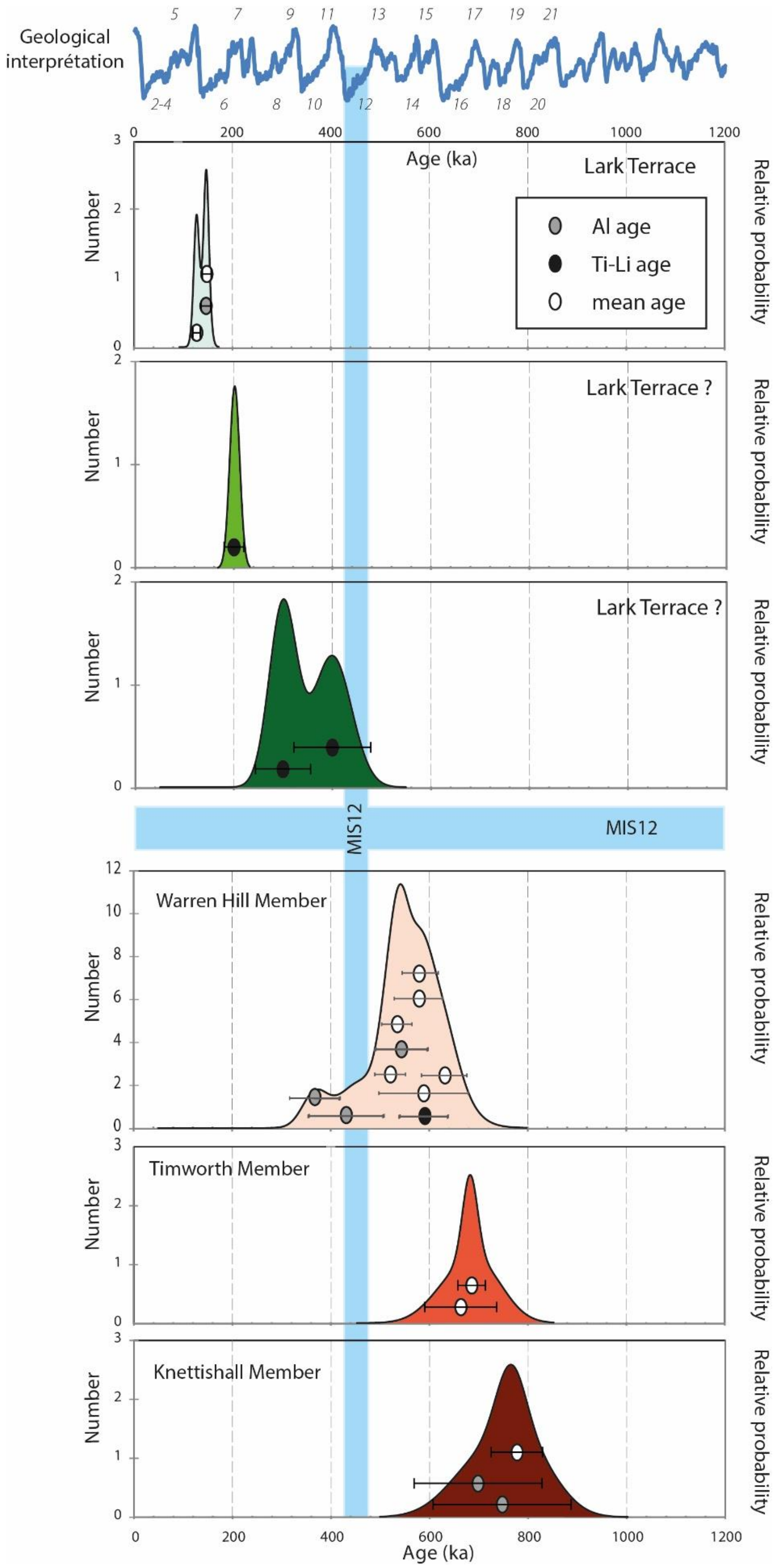

Figure 11. ESR dates with standard deviations plotted by site on the oxygen isotope record (LR04 $\delta^{18}O$; Lisieki and Raymo, 2005) against the geological interpretation of the sediments from which the dating samples were taken.

Table 1. Sites used in the text showing site location number (Figure 1), National Grid Reference, distance along long profile projection (Figure 1), Ordnance Datum (OD) of top and bottom of the deposit, or base of outcrop, references and attribution to Bytham member.

No.	**Site**	**East**	**North**	**Dist. along projection**	**Top OD**	**Base OD**	**Outcrop OD**	**Reference**	**Member**
21	Shouldham Thorpe	565700	308500	0.5	30.0	24.3		Lewis, 1993	Warren Hill
16	Northwold	573900	297600	12.0			18.0	Lewis, 1993	Warren Hill
6	Feltwell	574000	292500	17.5	28.0	18.0			Warren Hill
15	Methwold	575000	292200	17.5			32.0	Lewis, 1993	Timworth
3	Brandon Fields	576500	285300	25.5	30.0				Timworth
14	Maidscross Hill	572600	282500	26.5	30.0	27.0		Lewis & Ashton unpub	Warren Hill & Timworth
8	High Lodge	573900	275400	34.5			22.0	Lewis, 1992	High Lodge
24	Warren Hill	574400	274300	36.5	22.0	10.0		Lewis 1993, Bridgland et al. 1995	Warren Hill
17	Rampart Field	578900	271500	41.0	24.9	18.5		Bridgland et al., 1995	Timworth
13	Lackford	579900	269300	42.0	36.0	30.0		Lewis, 1993	Knettishall
7	Hengrave	581600	267900	44.5	32.5	28.0		Rose & Wymer, 1994	Knettishall
11	Ingham, Site B	584500	271600	46.0			50.0	Lewis, 1993	Seven Hills
23	Timworth	585300	269200	47.0	28.0	18.0		Lewis, 1993	Timworth
10	Ingham, Site A	585500	271500	47.5	45.0	40.0		Lewis, 1993	Ingham
4	Bury St Edmunds	587300	263500	49.0			61.0	Hey, 1980	Rushbrooke
18	Rushbrooke	588700	260700	50.0	62.5			Bridgland, unpub	Rushbrooke
9	Honnington	589000	274300	51.0			40.0	Lewis, 1993	Ingham
5	Fakenham Magna	590700	275900	53.0	40.0	37.0		Rose, unpub; BPP survey	Ingham
19	Sapiston	591900	274700	54.0	30.5	20.0		BPP unpublished	Knettishall
20	Seven Hills	586300	274500	55.1	55.0	50.7		Lewis, 1993	Seven Hills
1	Bardwell (A)	593800	274600	55.5			28.0	Lewis, 1993	Knettishall
2	Bardwell (B)	595100	273100	56.0			46.0	Hey, 1980	Seven Hills
22	Stanton	595500	272200	57.0			49.0	Hey, 1980	Seven Hills
12	Knettishall	595100	279800	59.0	30.0	25.2		Lewis et al., 1998	Knettishall
25	Wattisfield	602300	274800	64.0			52.0	Hey, 1980	Seven Hills
26	Wortham	608300	278900	71.0			36.0	Hey, 1980	Ingham

Table 2. Clast lithological analysis (11.2-16.0mm fraction from sites discussed in the text. (qtz+sst = quartzite+sandstone, vq = vein quartz, chrt = all cherts except Rhx = *Rhaxella* chert, ig+met = igneous + metamorphic, fest = ironstone, schlite = schorlite, lst = limestone.) Data extracted 04/10/2020.

Site and Sample	qtz+sst	vq	flint	chrt	Rhx	ig+met	fest	schlite	lst	chalk	others	Total
Brandon, Brandon Fields												
BH1 (0.0-2.5m)	28.3	15.6	52.0	2.7	0.0	0.0	0.9	0.2	0.0	0.0	0.2	442
TP2 (1.0-2.0m)	19.9	9.6	65.4	4.3	0.5	0.0	0.3	0.0	0.0	0.0	0.0	376
Fakenham Magna												
4	48.6	25.1	19.2	5.9	0.0	0.0	0.4	0.6	0.0	0.0	0.1	1082
5	39.3	27.7	27.7	4.4	0.1	0.0	0.5	0.3	0.0	0.0	0.0	960
6	37.8	33.1	22.3	4.6	0.0	0.0	1.1	1.2	0.0	0.0	0.0	1104
7	41.1	29.2	25.1	3.1	0.0	0.0	0.9	0.6	0.0	0.0	0.0	871
Feltwell, Frimstone's Pit												
1	17.1	6.5	58.8	4.2	0.0	0.0	1.9	0.0	0.0	10.7	0.8	738
2	8.9	3.0	63.4	6.7	0.0	0.0	2.2	0.0	0.0	14.8	1.0	595
3	21.6	7.9	58.2	4.4	0.0	0.0	1.5	0.5	0.0	5.0	0.9	661
4	9.0	3.4	57.6	6.5	0.0	0.0	1.1	0.0	0.0	20.6	1.8	557
Icklingham, Rampart Field												
12	20.2	12.1	61.8	5.1	0.0	0.0	0.8	0.0	0.0	0.0	0.0	604
13	24.8	18.7	46.3	8.4	0.0	0.1	1.3	0.4	0.0	0.0	0.0	702
14	39.5	28.0	24.5	5.2	0.0	0.0	2.2	0.1	0.0	0.0	0.5	868
Lakenheath, Maidscross Hill												
1	29.0	5.2	54.1	8.2	0.0	0.0	0.0	0.0	0.0	0.0	3.6	699
2	28.4	13.4	32.2	8.0	0.0	0.0	0.0	0.0	0.0	15.5	2.5	612
04/1	20.6	6.6	62.7	6.1	0.0	0.0	0.0	0.0	0.0	0.0	4.1	807
04/2	37.2	7.0	30.6	4.7	0.1	0.0	0.0	0.0	0.0	15.1	5.3	913
04/3	33.4	7.4	33.8	6.3	0.1	0.0	0.0	0.0	0.0	13.6	5.4	1015
04/4	15.0	5.0	26.5	1.3	0.0	0.0	0.0	0.0	0.0	50.9	1.3	680
Sapiston												
1	25.5	15.2	54.4	1.4	0.0	0.3	0.3	0.0	0.0	2.9	0.0	995
2	20.8	11.1	60.8	4.5	0.0	0.4	0.6	0.1	0.0	1.6	0.1	808
6	18.4	7.7	68.9	3.7	0.2	0.2	0.5	0.2	0.0	0.3	0.0	588
7	30.4	20.4	43.2	4.1	0.0	0.2	1.7	0.2	0.0	0.0	0.0	658
8	28.1	14.4	53.3	3.3	0.1	0.0	0.5	0.3	0.0	0.0	0.0	786
10	20.3	13.4	60.7	3.9	0.1	1.0	0.5	0.0	0.0	0.0	0.0	789
15	28.4	23.7	42.2	4.9	0.0	0.2	0.6	0.0	0.0	0.0	0.0	490
16	25.3	15.1	55.9	2.7	0.0	0.5	0.6	0.1	0.0	0.0	0.0	1196
17	29.8	17.1	47.4	4.8	0.0	0.1	0.4	0.4	0.0	0.0	0.0	914
BH19/1 4.0-5.0m	25.6	15.9	52.7	3.9	0.0	0.5	1.4	0.0	0.0	0.0	0.0	207
BH19/1 5.0-6.0m	24.3	11.4	60.0	3.8	0.0	0.0	0.5	0.0	0.0	0.0	0.0	185
BH19/1 7.0-7.5m	9.2	10.8	69.2	9.2	0.0	0.0	1.5	0.0	0.0	0.0	0.0	65
BH19/2 3.0-4.0m	11.9	11.9	74.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	59
BH19/2 6.0-7.0m	22.6	11.6	61.3	2.5	0.0	1.0	1.0	0.0	0.0	0.0	0.0	199
BH19/2 7.0-7.5m	26.8	15.8	50.3	4.3	0.0	0.0	2.8	0.0	0.0	0.0	0.0	392
BH19/2 7.5-8.0m	26.5	19.0	49.0	3.5	0.0	0.0	0.0	0.0	0.0	1.5	0.5	200
Warren Hill												
BPP Sect 1 1.2m	22.9	18.8	45.6	9.8	0.0	0.0	1.5	0.5	0.0	0.8	0.0	388
BPP Sect 1 2.0m	27.7	23.3	36.9	7.9	0.0	0.0	3.7	0.3	0.0	0.3	0.0	382
TP3 2.8 m	4.5	3.5	64.2	2.2	0.5	0.0	1.6	0.0	0.8	22.7	0.0	629
TP8 1.2 m	34.7	23.4	27.5	10.1	0.0	0.0	3.1	1.2	0.0	0.0	0.0	415
TP9 1.2 m	41.8	23.3	21.0	7.8	0.0	0.2	4.7	0.4	0.0	0.7	0.0	447
TP13 0.6m	29.9	20.6	40.2	6.9	0.0	0.0	1.7	0.3	0.0	0.3	0.0	291
BH 13/3 1.0–2.5 m	17.9	12.0	61.5	3.4	0.0	0.9	2.6	0.9	0.0	0.9	0.0	117

BH 13/3 2.5–4.0 m	17.6	13.9	63.9	2.8	0.0	0.0	0.0	0.0	0.0	1.9	0.0	108
BH 13/3 4.0–4.5 m	13.6	2.3	75.0	6.8	0.0	0.0	0.0	0.0	0.0	2.3	0.0	44
BH 13/5 1.0–2.0 m	16.0	11.2	63.6	8.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	250
BH 13/5 2.0–2.7 m	8.5	12.8	64.9	13.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94
BH 13/6 1.0–2.0 m	22.2	3.7	59.3	14.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27
BH 13/6 2.0–3.0 m	24.6	13.1	57.4	1.6	0.0	0.0	3.3	0.0	0.0	0.0	0.0	61
BH 13/6 3.0–3.5 m	12.8	9.4	72.2	4.4	0.0	0.0	1.1	0.0	0.0	0.0	0.0	180
BH 13/7 1.0–1.5 m	17.9	8.8	65.1	5.9	0.0	0.0	1.6	0.3	0.0	0.3	0.0	307
BH 13/7 1.5–2.0 m	15.0	14.6	62.1	7.5	0.0	0.0	0.8	0.0	0.0	0.0	0.0	240
BH 13/7 2.0–2.5 m	17.6	10.9	62.2	8.8	0.0	0.0	0.5	0.0	0.0	0.0	0.0	193
BH 13/7 2.5–3.0 m	16.2	9.7	68.3	4.7	0.0	0.0	1.1	0.0	0.0	0.0	0.0	278
BH 13/7 3.0–3.5 (4.0) m	12.0	9.6	72.5	3.6	0.0	0.0	1.2	0.6	0.0	0.6	0.0	167
BH 13/8 0.5–1.0 m	15.9	10.6	60.3	8.1	0.0	0.0	1.6	0.0	0.0	3.4	0.0	320
BH 13/8 1.0–1.5 m	12.2	9.0	68.1	8.0	0.0	0.0	1.1	0.0	0.0	1.6	0.0	188
BH 13/8 1.5–2.0 m	15.3	10.6	65.9	2.4	0.0	0.0	0.0	0.0	0.0	5.9	0.0	85
BH 13/8 2.0–2.5 m	19.6	15.2	63.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	46
BH 13/8 2.5–3.0 m	17.5	6.3	65.0	1.3	0.0	0.0	1.3	0.0	0.0	8.8	0.0	80
BH 13/8 3.0–3.5 m	11.3	8.4	70.9	5.4	0.0	0.0	0.0	0.0	0.0	3.9	0.0	203
BH 13/8 3.5–4.5 m	17.3	4.9	67.9	3.7	0.0	0.0	0.0	0.0	0.0	6.2	0.0	81
BH 13/8 4.5–5.3 m	5.4	2.7	86.5	4.1	0.0	0.0	0.0	0.0	0.0	1.4	0.0	74
BH 13/8 7.5–7.7 m	1.9	1.9	19.6	0.0	0.9	0.0	0.9	0.0	0.0	74.8	0.0	107
BH 13/9 0.5–1.0 m	17.6	10.8	64.9	4.1	0.0	0.0	1.4	0.0	0.0	1.4	0.0	74
BH 13/9 1.0–2.0 m	17.2	9.6	63.2	5.7	0.0	0.5	1.9	0.0	0.0	1.9	0.0	209
BH 13/9 2.0–2.5 m	23.8	14.4	51.3	5.6	0.0	0.0	3.1	1.3	0.0	0.6	0.0	160
BH 13/9 2.5–3.5 m	9.6	7.7	75.0	3.8	0.0	0.0	0.0	0.0	0.0	3.8	0.0	52
BH 13/9 3.5–4.5 m	10.6	4.9	73.2	8.9	0.0	0.0	0.0	0.0	0.0	2.4	0.0	123
BH 13/9 4.5–5.0 m	12.5	15.6	51.6	4.7	0.0	1.6	4.7	0.0	0.0	9.4	0.0	64
BH 13/9 10.0–10.5 m	5.2	6.2	70.1	0.5	0.5	0.0	1.5	0.0	0.5	15.5	0.0	194
BH 13/10 0.5–1.0 m	27.1	18.8	32.9	5.9	0.0	0.0	1.2	1.2	0.0	12.9	0.0	85
BH 13/10 1.0–1.5 m	41.0	17.9	28.2	5.1	0.0	0.0	5.1	0.0	0.0	2.6	0.0	39
BH 13/10 1.5–2.0 m	23.1	0.0	69.2	0.0	0.0	0.0	7.7	0.0	0.0	0.0	0.0	13
BH 13/10 2.0–2.3 m	21.1	18.9	48.9	3.3	0.0	0.0	7.8	0.0	0.0	0.0	0.0	90
BH 13/10 2.3–2.5 m	10.9	17.2	62.5	3.1	0.0	0.0	6.3	0.0	0.0	0.0	0.0	64
BH 13/10 2.5–2.7 m	19.6	14.0	57.9	7.5	0.0	0.0	0.9	0.0	0.0	0.0	0.0	107
BH 13/10 2.7–3.0 m	17.0	17.0	56.4	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94
BH 13/10 4.0–4.5 m	19.4	11.1	44.4	0.0	0.0	0.0	11.1	2.8	11.1	0.0	0.0	36
BH 13/11 0.5–1.0 m	30.8	14.0	45.8	4.2	0.0	0.0	3.3	0.0	0.0	1.9	0.0	214
BH 13/11 1.0–1.8 m	12.6	11.6	71.6	3.2	0.0	0.0	1.1	0.0	0.0	0.0	0.0	95
BH 13/11 1.8–2.0 m	11.8	13.4	66.4	6.7	0.0	0.0	1.7	0.0	0.0	0.0	0.0	119
BH 13/11 2.0–2.5 m	14.0	13.3	66.4	3.5	0.0	0.0	0.7	0.0	0.0	2.1	0.0	143
BH 13/11 2.5–2.8 m	11.6	7.0	79.1	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	43
BH 13/11 2.8–3.3 m	8.5	5.3	85.1	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	94
BH 13/12 0.5–0.8 m	34.5	9.2	47.1	5.9	0.0	0.0	3.4	0.0	0.0	0.0	0.0	119
BH 13/12 0.8–1.0 m	10.8	9.6	71.7	7.2	0.0	0.0	0.6	0.0	0.0	0.0	0.0	166
BH 13/12 1.0–1.5 m	16.0	10.5	67.4	5.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	181
BH 13/12 1.5–2.0 m	16.7	11.9	59.5	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42
BH 13/12 2.5–2.8 m	13.8	6.3	70.0	8.8	0.0	0.0	1.3	0.0	0.0	0.0	0.0	80
BH 13/12 2.8–3.0 m	26.7	8.6	56.9	3.4	0.0	1.7	2.6	0.0	0.0	0.0	0.0	116
BH 13/12 3.5–4.5 m	3.1	3.1	53.1	0.0	0.0	0.0	0.0	0.0	0.0	40.6	0.0	32
BH 13/12 4.5–4.6 m	0.9	0.9	55.6	0.9	1.7	0.0	0.0	0.0	0.9	39.3	0.0	117
BH 13/12 4.6–5.0 m	3.8	0.9	11.7	0.6	0.3	0.0	1.9	0.0	1.6	79.2	0.0	317
BH 13/12 5.0–5.5 m	3.6	0.7	20.5	0.3	0.0	0.0	0.7	0.0	1.3	72.8	0.0	302

Table 3. ESR dosimetric data obtained on quartz extracted from sediments from Breckland sites.

Terrace level	**Sample**	**D_α (μGy/a)**	**D_β (μGy/a)**	**D_γ in situ (μGy/a)**	**D_{cosmic} (μGy/a)**	**D_a (μGy/a)**	**Water (%)**	**Al Bl. (%)**
Knettishall Terrace								
Sapiston S1	SPN1709	17 ± 1	624 ± 15	305 ± 15	133 ± 7	1078 ± 24	15 ± 5	47
Sapiston S1	SPN1704	15 ± 1	566 ± 16	296 ± 12	133 ± 7	1020 ± 25	15 ± 5	49
Sapiston S1	SPN1703	10 ± 1	264 ± 13	191 ± 10	101 ± 5	565 ± 19	15± 5	45
Sapiston S2	SPN1705	14 ± 1	356 ± 13	251 ± 13	101 ± 5	722 ± 22	15± 5	44
Timworth Terrace								
Rampart Field S1	RMF1801	15 ± 1	391 ± 10	209 ± 10	86 ± 4	701 ± 16	15± 5	46
Rampart Field S1	RMF1816	42 ± 2	901 ± 20	470 ± 23	75 ± 4	1487 ± 35	15± 5	52
Warren Hill Deposits								
Maidscross Hill S1	MCH1	9 ± 1	750 ± 19	407 ± 20	116 ± 6	1282 ± 32	15± 5	42
Maidscross Hill S1	MCH2	6 ± 1	546 ± 16	314 ± 25	120 ± 6	985 ± 33	15± 5	48
Warren Hill S91/1	WNH1	8 ± 1	565 ± 16	298 ± 15	95 ± 5	966 ± 25	15± 5	46
Warren Hill S91/1	WNH2	7 ± 1	646 ± 18	301 ± 24	100 ± 5	1054 ± 33	15± 5	49
Warren Hill S16/1	WH1601	7 ± 1	324 ± 12	222 ± 11	109 ± 5	663 ± 19	15± 5	53
Warren Hill S16/1	WH1602	11 ± 1	429 ± 14	256 ± 13	118 ± 6	814 ± 21	15± 5	48
Warren Hill S16/1	WH1603	10 ± 1	258 ± 10	209 ± 10	132 ± 7	609 ± 17	15± 5	41
Warren Hill S16/2	WH1604	10 ± 1	255 ± 12	197 ± 10	139 ± 7	601 ± 19	15± 5	48
Warren Hill S16/2	WH1605	11 ± 1	231 ± 9	201 ± 10	164 ± 8	606 ± 15	15± 5	50
Lark Terrace Deposits								
Warren Hill TP16	WH1609	11 ± 1	530 ± 14	285 ± 14	153 ± 8	979 ± 22	15± 5	27
Warren Hill TP17	WH1610	12 ± 1	396 ± 13	231 ± 12	139 ± 7	777 ± 21	15± 5	23
Warren Hill TP17	WH1611	10 ± 1	468 ± 12	264 ± 13	148 ± 7	890 ± 20	15± 5	31
Lark Terrace disturbed?								
Warren Hill TP13	WH1606	9 ± 1	293 ± 12	218 ± 11	156 ± 8	676 ± 19	15± 5	49
Warren Hill TP13	WH1607	11 ± 1	298 ± 12	228 ± 11	158 ± 8	695 ± 19	15± 5	48
Warren Hill TP18	WH1613	11 ± 1	368 ± 9	264 ± 13	150 ± 8	794 ± 18	15± 5	53

Dose rates were determined taking into account alpha and beta attenuations estimated for the selected grain sizes from the tables of Brennan (Brennan et al., 1991; Brennan, 2003); dose rate conversion factors from Guérin et al (2011); k-value of 0.15 (Yokoyama et al., 1985); the internal dose rate was considered as negligible due to the low content of radionuclides from the quartz grains (Murray and Roberts, 1997; Vandenberghe et al., 2008); we removed the external part of the grain (around 20mm) by HF etching; cosmic dose rate was calculated from the equations of Prescott and Hutton (1994) corrected according to altitude and latitude. The bleaching rate dbl (%) is determined by comparison of the ESR intensities of the natural and bleached aliquots dbl¼((Inat–Ibl)/ Inat) 100). Uncertainties are given at 1 σ.

Table 4. ESR results obtained on quartz extracted from sediments from Breckland sites. Uncertainties are given at 2 σ. The age estimates with a grey background are not used in the construction of Figure 11.

Terrace level	Sample	Al centre			Ti-Li centre			Mean weighted ages (ka)
		D_e (Gy)	r^2	Ages (ka)	D_e (Gy)	r^2	Ages (ka)	
Knettishall Terrace								
Sapiston S1	SPN1709 (2)	750 ± 140	0,9695	696 ± 130	1052 ± 200	0,9311	976 ± 190	
Sapiston S1	SPN1704 (3)	1201 ± 199	0,9523	1178 ± 200	1191 ± 178	0,9907	1168 ± 180	
Sapiston S1	SPN1703	432 ± 33	0,9978	764 ± 60	458 ± 60	0,9984	810 ± 110	775 ± 52
Sapiston S2	SPN1705 (2)	538 ± 100	0,9882	745 ± 140	856 ± 120	0,9501	1186 ± 170	
Timworth Terrace								
Rampart Field S1	RMF1801	480 ± 80	0,9899	685 ± 110	450 ± 71	0,9652	642 ± 100	661 ± 73
Rampart Field S1	RMF1816	1057 ± 130	0,9916	711 ± 90	1011 ± 50	0,9967	680 ± 30	683 ± 28
Warren Hill Deposits								
Maidscross Hill S1	MCH1 (1)	678 ± 70	0,9971	529 ± 55	665 ± 44	0.9959	518 ± 38	522 ± 31
Maidscross Hill S1	MCH2 (1)	621 ± 56	0,9938	631 ± 56	626 ± 73	0.9859	635 ± 82	632 ± 45
Warren Hill S91/1	WNH1 (1)	526 ± 51	0,9941	544 ± 53	569 ±45	0.9981	589 ±49	
Warren Hill S91/1	WNH2 (1)	568 ± 40	0,9961	539 ± 38	556 ± 55	0.9899	527 ± 52	535 ± 30
Warren Hill S16/1	WH1601	390 ± 55	0,9879	589 ± 84	380 ± 41	0,9970	573 ± 62	579 ± 49
Warren Hill S16/1	WH1602	489 ± 61	0,9873	601 ± 76	470 ± 36	0,9939	577 ± 44	583 ± 37
Warren Hill S16/1	WH1603 (2)	263 ± 46	0,9641	432 ± 76	367 ± 60	0,9789	603 ± 100	
Warren Hill S16/2	WH1604 (2)	221 ± 30	0,9892	368 ± 51	282 ± 40	0,9761	469 ± 67	
Warren Hill S16/2	WH1605	369 ± 75	0,9696	609 ± 124	343 ± 84	0,9558	566 ± 139	590 ± 91
Lark Terrace Deposits								
Warren Hill TP16	WH1609	138 ± 14	0,9844	141 ± 14	143 ± 14	0,9852	146 ± 14	144 ± 10
Warren Hill TP17	WH1610	96 ± 10	0,9871	124 ± 13	97 ± 8	0,9921	125 ± 10	125 ± 8
Warren Hill TP17	WH1611 (2)	129 ± 8	0,9938	145 ± 9	146 ± 14	0,9848	164 ± 16	
Lark Terrace disturbed?								
Warren Hill TP13	WH1606 (4)	282 ± 42	0,9750	417 ± 63	203 ± 38	0,9818	300 ± 56	
Warren Hill TP13	WH1607 (4)	342 ± 33	0,9903	492 ± 48	278 ± 54	0,9821	400 ± 78	
Warren Hill TP18	WH1613 (4)	214 ± 32	0,9851	270 ± 40	162 ± 16	0,9843	204 ± 20	

(1) Samples which have previously unpublished results for Ti-Li centres. (2) Samples with a high ESR signal/noise ratio for the Ti-Li centre: SPN1709 19% noise; SPN1705 15% noise; WH1603 17% noise; WH1604 18% noise; WH1611 30% noise. (3) sample with very high De readings where both the Al and Ti-Li centres are thought to be incompletely bleached. (4) Samples where the Al centres are thought to be incompletely bleached. For full explanation see text.