Quaternary Environments and Humans 2 (2024) 100045

Contents lists available at ScienceDirect

Quaternary Environments and Humans

journal homepage: www.journals.elsevier.com/quaternary-environments-and-humans

A revised terrace stratigraphy and chronology for the Little Ouse River as a framework for interpreting the late Lower and early Middle Palaeolithic of central East Anglia, UK

Rob Davis[a,*], Simon G. Lewis[b], Marcus Hatch[b], Nick Ashton[a], Pierre Voinchet[c], Jean-Jacques Bahain[c], Luke Dale[a,d], Frederick Foulds[d], Aaron Rawlinson[a,d], Mark White[d]

[a] Department of Britain, Europe and Prehistory, British Museum, 38-56 Orsman Road, London N1 5QJ, UK
[b] School of Geography, Queen Mary University of London, Mile End Road, London E1 4NS, UK
[c] UMR7194, Histoire Naturelle de l'Homme Préhistorique (HNHP), Muséum national d'Histoire naturelle de Paris, Département Homme et Environnement, Institut de Paléontologie Humaine, 1 rue René Panhard, Paris 75013, France
[d] Department of Archaeology, Durham University, Durham DH1 3LE, UK

ARTICLE INFO

Keywords:
Middle Pleistocene
Palaeolithic
Handaxes
Levallois
Fluvial archive
Breckland

ABSTRACT

The Breckland of central East Anglia has a Pleistocene geological sequence spanning c. 1 million years, providing a framework for assessing changes in human technology and behaviour within a single changing palaeolandscape. The geological record and its associated Palaeolithic archaeology divides into three chronological periods: the fluvial deposits of the River Bytham, which span c. 1 ma to 450 ka; the Hoxnian interglacial sites (c. 400 ka); and the fluvial terraces of the post-Anglian drainage network, which records the past c. 400,000 years. This paper focuses on the third of these periods, presenting results from new work on the fluvial sediments and Palaeolithic archaeology associated with the Little Ouse River. Fieldwork was conducted at four Palaeolithic sites; Barnham Heath, Redhill, Santon Downham, and Broomhill Pit. The new sedimentological and stratigraphic data are used in conjunction with existing borehole records to construct long profiles for the river terrace aggradations and establish a terrace stratigraphy for the Little Ouse. Correlation with the marine isotope record is supported by age estimates from electron spin resonance (ESR) dating of sand units within the terrace aggradations. The results provide an age-constrained lithostratigraphic framework for understanding the Lower and Middle Palaeolithic records of the Little Ouse. The results can be added to previous work on the Bytham and Hoxnian sites, enabling an assessment of human activity in the region from c. 800–200 ka.

1. Introduction

The Pleistocene rivers of southern Britain provide an archive of Palaeolithic artefacts from which chronological patterns of human presence/absence and technological change have been identified (Wenban-Smith, 2004; Bridgland, 2010; Bridgland and White, 2014, 2015; White et al., 2018; Davis et al., 2021a, 2021b). For some time periods, the secondary context assemblages from river gravels provide a framework for interpreting primary context sites. For example, the typological homogeneity of the handaxe assemblages from Boxgrove (García-Medrano et al., 2019) and High Lodge (Ashton et al., 1992) are shown not to be site-specific, but part of the widespread manufacture of ovate handaxes in Britain during Marine Isotope Stage (MIS) 13, demonstrated by the preponderance of ovate handaxes in the Anglian (MIS 12) gravels of the Thames, Solent, and Bytham (Wymer, 1999; Davis et al., 2021a, 2021b). For other time periods, such as MIS 9, for which primary context sites are rare or absent, the fluvial archive provides the clearest view of the character of lithic technology (White and Bridgland, 2017; White et al., 2018, 2024; Rawlinson et al., 2022; Dale et al., 2024). Together, the primary and secondary context records reveal some chronological variation in lithic technology but only very limited evidence of regional variation. However, there remain some regions for which parts of the record are poorly understood.

Central East Anglia is a key region for our understanding of the British Lower and Middle Palaeolithic record. It has a long Pleistocene sedimentary sequence spanning approximately 1 million years. The pre-

* Corresponding author.
E-mail address: rdavis@britishmuseum.org (R. Davis).

https://doi.org/10.1016/j.qeh.2024.100045
Received 19 June 2024; Received in revised form 26 November 2024; Accepted 26 November 2024
Available online 29 November 2024

Anglian sediments consist of the sands and gravels deposited by the erstwhile River Bytham prior to the destruction of that river during the Anglian glaciation (Lewis et al., 2021). The associated archaeology provides a record of human occupation from c. 800–500 ka (Davis et al., 2021a). Anglian glacigenic sediments are widespread and represent a period of significant alteration to the palaeogeography and topography of the region during MIS 12 (Bridgland et al., 1995), and also provide an important stratigraphic marker. The post-Anglian record consists of a series of basins formed in the surface of Anglian deposits and infilled with sediments deposited during MIS 11 (Singer et al., 1993; Ashton et al., 1998, 2005, 2008, 2016; Gowlett et al., 2005; Preece et al., 2007), and the sands and gravels and floodplain sediments deposited by the modern rivers. The present drainage network emerged following the retreat from the region of Anglian ice sheets c. 425 ka, and the evolution of the post-Anglian fluvial system is reflected in sequences of poorly-defined and fragmentary terraces preserved on the valley sides above the modern floodplain. Associated archaeological assemblages provide evidence of human activity in the river valleys, most notably at Lynford, a later Middle Palaeolithic site dated to MIS 4/3 (Boismier et al., 2012).

This paper focuses on one of these rivers, the Little Ouse, which rises east of Thelnetham, Suffolk, and flows west into the Fens, where it is confluent with the Great Ouse (Fig. 1). The study area extends from the river's source to Brandon. Along this stretch of the river, there are four key Palaeolithic sites associated with fluvial deposits: Barnham Heath, Redhill, Santon Downham, and Broomhill. Three of these are of historical significance with much of the material collected from gravel workings during the 1860s as the discipline of Palaeolithic archaeology emerged and the Palaeolithic record in Britain was becoming established (Flower, 1867, 1869; Evans, 1868, 1872; Prigg, 1869). The fourth site, Barnham Heath, relates to later gravel extraction during the 1940s and 1950s, and has produced the largest assemblage of Levallois artefacts in central East Anglia (Wymer, 1999). This paper reports the results of fieldwork conducted at these sites for the Breckland Palaeolithic Project (BPP). The new sedimentological and stratigraphic data are used in conjunction with existing borehole records to construct long profiles for the river terrace aggradations and establish a terrace stratigraphy for the Little Ouse. Age estimates from electron spin resonance (ESR) dating of

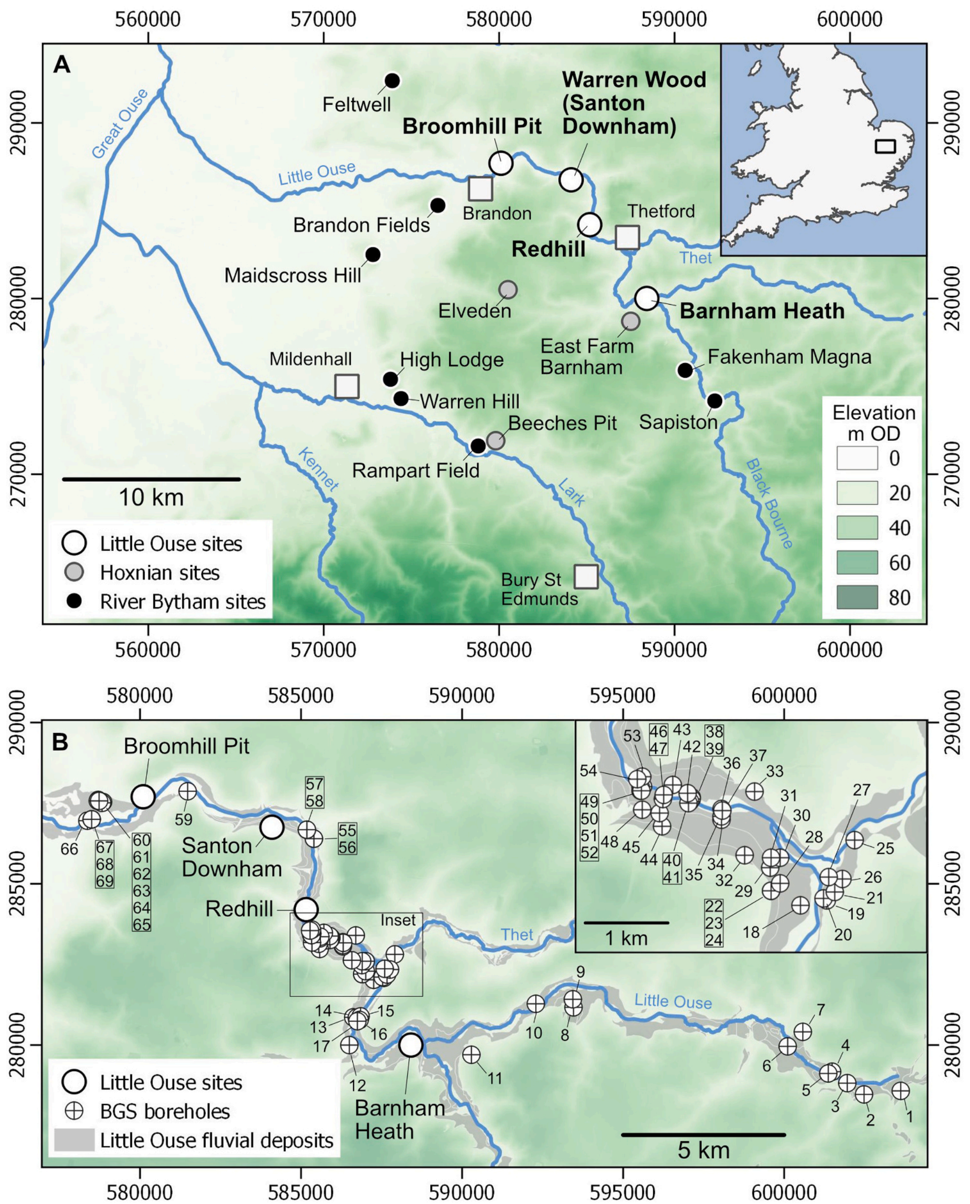

Fig. 1. Study area location map. A) The Breckland of central East Anglia, showing key Palaeolithic sites. B) The valley of the River Ouse. For details of BGS boreholes, see Table 2. (Coordinate system = OSGB 1936 British National Grid, 5 m DTM © Crown copyright and database rights 2024 Ordnance Survey (AC0000851941)).

sand units allow the proposal of correlation with the MIS record. The results provide an age-constrained lithostratigraphic framework within which the Little Ouse Palaeolithic record can be considered, and, with the Bytham and MIS 11 sites, enable an assessment of human occupation of the region from c. 800–200 ka.

2. Materials and methods

Fieldwork was undertaken at five locations in the Little Ouse Valley between July 2017 and January 2019. From east to west in the downstream direction, these were: Barnham Heath, Redhill, Warren Wood (east), Warren Wood (north) and Broomhill (Fig. 1). Warren Wood (north) is the approximate location from which the Santon Downham Palaeolithic material was collected.

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 a cable-percussion drilling rig. All sections and sediment cores were recorded, photographed and located in relation to the OSGB grid and Ordnance Datum using GNSS and total station surveying. Bulk samples taken from sections and boreholes for clast lithological analysis were washed and sieved and the 11.2–16.0 mm fraction retained for clast lithological analysis. A c. 0.5 m^3 bulk sample of each gravel unit encountered was sieved on site through a 20 mm mesh. All potential artefacts were retained.

2.2. River terrace long profile construction

The sediment logs from sections, test pits and boreholes were supplemented with existing borehole records to construct long profiles of the Little Ouse terraces from its source to Brandon, based on sedimentology, and surface and bedrock elevation. All publicly available borehole records for the study area were downloaded from the British Geological Survey (BGS) Geoindex Onshore resource. These were then filtered using a 500 m buffer around the river terrace deposits as mapped by the BGS, resulting in 360 boreholes to review. The logs for each of these were consulted and any boreholes that either did not record fluvial deposits, or lacked key stratigraphical or geographical information were omitted. Surface heights were determined using LiDAR in the case of borehole logs that lacked accurate ground level records. A total of 69 BGS boreholes were used in the analysis. Where multiple boreholes were situated in close proximity to each other and on the same terrace, the average ground level, thickness of deposits and bedrock elevation were calculated for use in the construction of long profiles. The results of this analysis necessitate modification of the existing BGS mapping of three Little Ouse terraces, numbered in descending order from Terrace 3 to Terrace 1, and the introduction of a new terrace nomenclature based on type sections (see Section 4).

2.3. Electron spin resonance (ESR) dating of quartz grains

Electron spin resonance (ESR) dating is a ‘trapped charge’ method; i.e. the sample, having recorded the total radiation dose received since the time of sediment deposition, is used as a dosimeter for dating through the quantification of electrons trapped in mineral defects within quartz grains in relation to irradiation (Grün, 1989; Ikeya, 1993). In this case, the dated event is the last sunlight exposure of quartz grains during transportation by water or wind before deposition and geological burial. This light exposure leads to the release of trapped electrons and a zeroing of the ESR signal (optical bleaching), which then reaccumulates after burial. 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 post burial.

At each site, sediment samples of around 1 kg were taken from freshly cleaned sections. Systematic *in situ* gamma-ray measurements were provided for each sediment sample using an Ortec Scintipack 296 portable gamma spectrometer, to evaluate the γ dose rate. Data was extracted using the threshold approach (Mercier and Falguères, 2007). 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 0.07 ± 0.01 (Bartz et al., 2019), 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 optimal grain size for ESR studies according to 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 ^{60}Co 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 dataset after subtraction of the residual intensity evaluated from the maximum bleaching value. An exponential + linear fitting function was used for the calculation of D_e 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.

2.4. Archaeological investigations

Archaeological investigations were based on analysis of the artefacts recovered during the field investigations, and the study of museum collections and archives. Six museum collections were studied: Ashmolean Museum, British Museum, Cambridge Archaeology and Anthropology Museum, Ipswich Museum, Pitt Rivers Museum Oxford, and West Stow Visitor Centre (formerly part of the Moyse’s Hall Museum collection). For Barnham Heath, documents in the Euston Estate archive and the Basil Brown Archive held at the Suffolk Records Office and Suffolk Archaeological Service were reviewed. Artefacts were recorded using a standard set of metric measurements and attributes, following Ashton (1998) for flakes and cores, Scott (2011) for Levallois cores and flakes, Inizan et al. (1999) for retouched tools, and Roe (1969) and Wymer (1968) for handaxes.

3. Field investigations

3.1. Barnham Heath, Suffolk

Barnham Heath is situated at the confluence of the Little Ouse and the Black Bourne (Fig. 1). It has two disused gravel pits, Barnham Old Pit, operational from 1947 to 1951, and the River Pit, open from c. 1952–1957 (West’s 2009 Brown’s Pit and Northern Pit respectively). Basil Brown frequently visited the gravel workings on behalf of Ipswich Museum. His notes include section drawings, site plans, photographs and reports of Palaeolithic artefacts. Wymer (1985) described the collection, which includes Lower and Middle Palaeolithic elements.

3.1.1. Barnham Old Pit

Barnham Old Pit straddles a bluff between two terrace-like surfaces (Fig. 2). The deposits to the south of the bluff were investigated in Sections 3 and 4, Borehole 19/1, and Test Pit 1. Ground level adjacent to the southern edge of the pit is c. 21 m OD. Chalk bedrock was

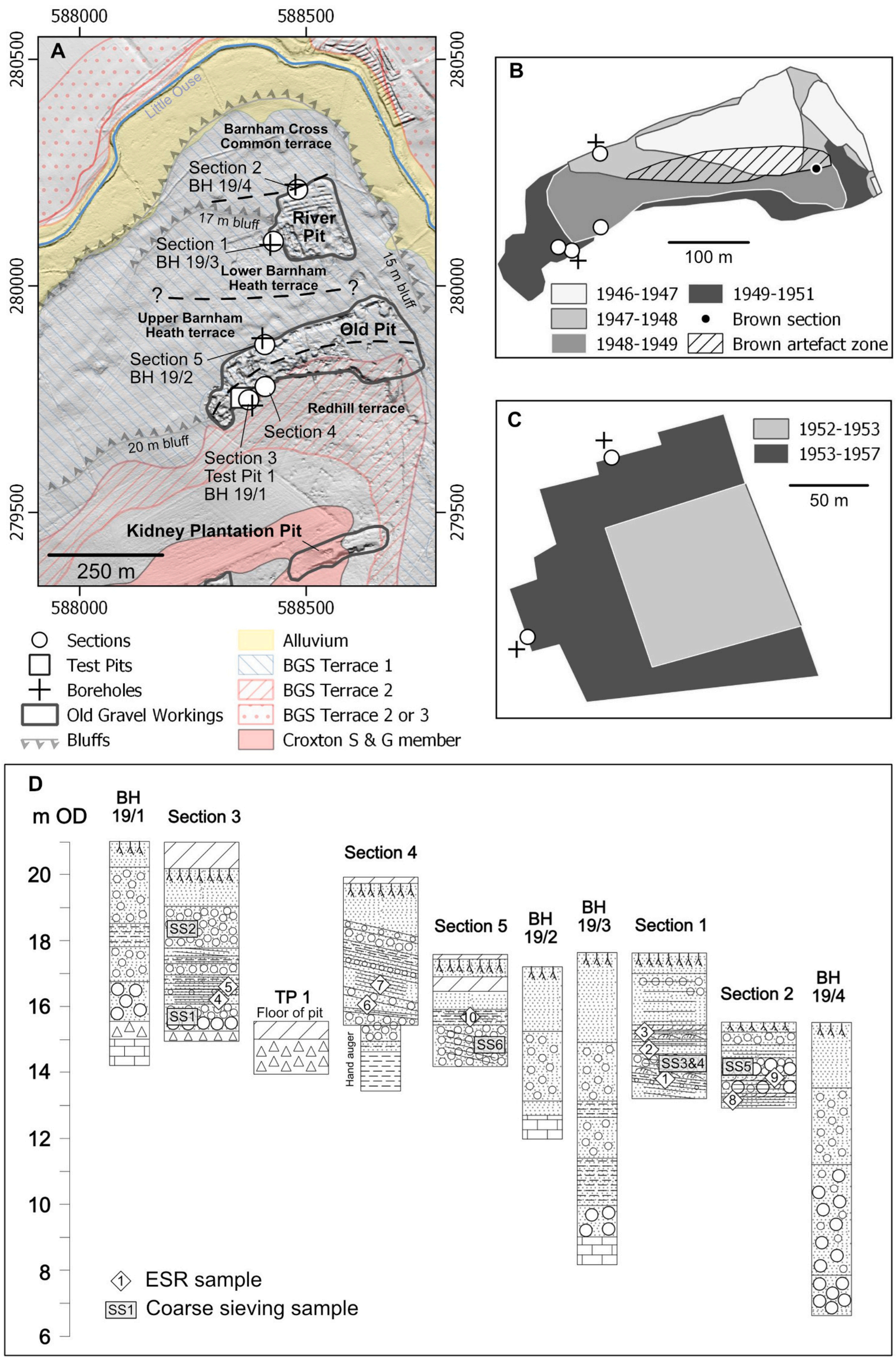

Fig. 2. Barnham Heath. A) Hillshade elevation model (© Environment Agency copyright and/or database right 2022) showing location of sections and boreholes, former Alan Newport Ltd. gravel pits, BGS terrace mapping, and terrace margins and nomenclature proposed by this study (coordinate system = OSGB 1936 British National Grid). B) The development of Barnham Old Pit between 1946 and 1951, showing the location of Basil Brown's section and artefact collection zone. C) The development of the River Pit between 1952 and 1957. D) The section and borehole logs, showing ESR and coarse sieving sample locations. (BH = Borehole, TP = Test Pit).

encountered at 14.8 m OD. The basal deposit is a stony silty clay, with large flint cobbles and nodules in a chalky silt/clay matrix. This may be a till, though it is more likely to be a soliflucted chalky diamicton, with till material reworked downslope following incision of Chalk bedrock. This is overlain by a series of interbedded gravel and sand facies, varying from poorly sorted medium-coarse flint gravel in a sandy matrix, to horizontally and sub-horizontally bedded sand. Towards the middle of the sequence there is a 0.3 m thick sand and silt/clay deposit with sub-horizontal laminations and some clay layers. The upper 1 m of the sequence consists of a stony sandy deposit interpreted as coversand. The clast lithological composition of the gravels (Table 1) is dominated by flint, with occasional quartzite, vein quartz, chert (including *Rhaxella* chert) and sandstone. Chalk clasts are common in the basal deposits. In Section 4, a similar sequence was encountered, but dipping to the west,

Table 1
Clast lithological analysis from sites discussed in the text, with lithological composition expressed as a percentage of total clasts (11.2–16.0 mm fraction) in each sample. (qtz = quartzite, vq = vein quartz, chrt = Carboniferous chert (may contain other undiagnostic chert, Mesozoic and older), Rhx = Rhaxella chert, sld lst = silicified limestone, sst = sandstone, ig + met = igneous + metamorphic, fest = ironstone, schlite = schorlite, lst = limestone.).

Site and sample	qtz	vq	flint	chrt	Rhx	sld lst	sst	ig + met	fest	schlite	lst	chalk	others	Total
Barnham Heath														
Section 3 (2.3–2.6 m)	7.7	4.1	85.7	0.6	0.1	0.1	1.5	0.0	0.0	0.0	0.0	0.1	0.0	782
Section 3 (5.0–5.2 m)	2.1	2.4	91.9	1.2	0.4	0.3	1.0	0.3	0.3	0.0	0.0	0.0	0.0	991
BMH19/1 (2.0–2.5 m)	5.1	5.1	85.6	1.7	0.8	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	118
BMH19/1 (3.5–4.0 m)	3.1	0.0	87.5	1.4	0.7	0.0	2.0	0.0	0.0	0.0	0.0	5.4	0.0	295
BMH19/1 (4.0–4.5 m)	2.1	3.1	80.3	0.5	0.0	0.0	2.6	0.0	0.0	0.0	0.0	10.9	0.5	193
BMH19/1 (4.5–5.0 m)	3.3	4.9	69.9	1.4	0.4	0.0	1.0	0.4	0.4	0.0	0.0	18.2	0.0	489
BMH19/1 (5.0–5.5 m)	1.9	2.6	59.4	0.0	0.0	0.4	1.1	0.0	0.4	0.0	1.1	33.1	0.0	266
BMH19/2 (3.0–3.5 m)	2.9	1.6	93.2	1.0	0.2	0.0	0.7	0.0	0.3	0.0	0.0	0.0	0.0	577
BMH19/2 (3.5–4.0 m)	3.8	2.7	89.9	1.3	0.0	0.0	1.5	0.1	0.7	0.0	0.0	0.0	0.0	744
BMH19/2 (4.0–4.5 m)	7.1	4.3	85.1	1.4	0.0	0.0	1.4	0.0	0.7	0.0	0.0	0.0	0.0	141
Section 1 (3.1–3.5 m)	4.7	4.3	87.1	0.9	0.5	0.3	1.5	0.3	0.5	0.0	0.0	0.0	0.0	1054
BMH19/3 (4.0–4.5 m)	6.0	5.1	84.4	1.7	0.6	0.0	1.3	0.4	0.4	0.0	0.0	0.0	0.0	468
BMH19/3 (5.5–6.0 m)	5.6	3.3	86.3	1.4	0.2	0.2	2.9	0.0	0.0	0.0	0.0	0.0	0.0	483
BMH19/3 (8.0–8.5 m)	4.5	4.2	84.5	1.1	0.4	0.0	1.9	0.0	0.0	0.0	0.0	3.4	0.0	264
BMH19/3 (8.5–8.7 m)	2.6	4.3	82.1	1.0	0.3	0.0	1.5	0.0	0.0	0.0	0.9	7.2	0.0	582
Section 2 (1.4–1.7 m)	11.3	11.3	71.4	1.5	0.1	0.3	2.4	0.2	1.0	0.4	0.0	0.0	0.0	997
BMH19/4 (3.5–4.5 m)	4.9	5.3	87.5	1.8	0.0	0.0	0.4	0.2	0.0	0.0	0.0	0.0	0.0	567
BMH19/4 (4.5–5.5 m)	4.5	2.6	87.8	2.2	0.3	0.0	1.6	0.6	0.3	0.0	0.0	0.0	0.0	312
BMH19/4 (5.5–6.5 m)	1.3	4.5	90.9	1.9	0.3	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	308
BMH19/4 (6.5–6.8 m)	1.3	2.2	91.4	2.7	0.3	0.3	1.6	0.0	0.0	0.0	0.0	0.3	0.0	372
BMH19/4 (7.5–7.8 m)	2.5	3.6	88.4	1.8	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.7	277
BMH19/4 (8.0–8.5 m)	4.9	3.6	88.5	1.5	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	390
Redhill														
Section 1 (2.5 m)	2.9	2.9	92.2	0.7	0.0	0.0	0.8	0.0	0.2	0.0	0.0	0.0	0.1	851
Section 1 (4.0 m)	1.9	1.9	94.0	0.6	0.2	0.0	1.0	0.0	0.3	0.0	0.0	0.0	0.0	1078
Section 1 (5.0 m)	0.9	2.6	77.8	0.6	0.0	0.0	1.0	0.3	0.2	0.0	0.0	16.7	0.0	1019
Test Pit 1 (2.0 m)	4.1	5.4	88.3	0.4	0.1	0.4	1.2	0.1	0.0	0.0	0.0	0.0	0.0	984
Warren Wood														
Test Pit 2 (1.2–1.6 m)	3.0	3.9	89.3	0.7	0.5	0.1	1.5	0.2	0.6	0.1	0.0	0.0	0.0	812
WNW19/2 (3.5–4.0 m)	2.6	3.6	91.3	0.0	0.5	0.5	1.0	0.0	0.5	0.0	0.0	0.0	0.0	195
WNW19/2 (5.0–5.5 m)	1.2	0.7	90.8	0.7	0.2	0.7	1.0	0.0	0.0	0.0	0.0	4.5	0.0	404
WNW19/2 (6.0–6.5 m)	2.6	0.5	60.5	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.0	35.4	0.0	195
WNW19/2 (7.5–7.8 m)	3.8	1.1	49.7	0.4	0.0	0.0	1.3	0.1	0.3	0.0	1.1	42.2	0.0	720
WNW19/2 (8.5–9.0 m)	3.3	2.2	73.6	1.1	0.0	0.0	1.6	0.0	0.0	0.5	0.0	15.9	1.6	182
Test Pit 3 (1.4–1.8 m)	0.9	2.0	94.7	0.2	0.4	0.2	1.3	0.2	0.2	0.0	0.0	0.0	0.0	545
Test Pit 6	0.2	0.3	99.2	0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	648
Test Pit 7	5.8	6.0	85.4	0.5	0.1	0.2	1.8	0.0	0.1	0.1	0.0	0.0	0.0	1043
Test Pit 9	0.5	0.6	98.2	0.2	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	945
Test Pit 10 upper gravel	1.4	2.5	93.3	0.7	0.7	0.0	1.2	0.1	0.0	0.0	0.0	0.0	0.0	985
Test Pit 10 lower gravel	2.1	1.8	91.4	0.7	0.5	0.0	0.5	0.0	0.0	0.0	0.0	2.9	0.0	947
Broomhill Pit														
Section 1 (4.6–4.8 m)	1.4	2.2	93.8	0.5	0.6	0.1	0.7	0.5	0.0	0.0	0.0	0.0	0.1	808

presumably indicating some localised solution of the Chalk bedrock, and overlying a white calcareous silt.

Two gravel facies in Section 3 were sieved for artefacts (Fig. 2). The upper sample (sieve sample (SS) 2) contained three moderately rolled flint flakes. The lower sample (SS1) contained one core fragment, 11 flakes, of which one is retouched, and one retouched natural spall.

The sequence to the north of the 20 m bluff was investigated in Section 5 and Borehole 19/2. Here, ground surface is at 17.6 m OD and the Chalk bedrock is at 12.7 m OD. The sequence consists of structureless fine-medium gravel facies in a silt/clay matrix and bedded sands, overlain by 2 m of stony sand showing involution structures. The gravel clast lithology was similar to Section 3 and Borehole 19/1, except the absence of chalk clasts, including from the basal sediments immediately above the Chalk. The gravel at the base of Section 5 was sieved (SS6) and a single flake was identified.

3.1.2. *Barnham River Pit*

Barnham River Pit is situated towards the northern end of Barnham Heath (Fig. 2). It straddles a bluff that divides two terrace-like surfaces. Investigations to the south of the bluff consisted of Section 1 and Borehole 19/3. Ground surface height is at 17. 5 m OD and the Chalk bedrock is at 8.8 m OD. The lower part of the sequence consists of 1.0 m of coarse gravel resting on Chalk bedrock and overlain by 1.5 m of silty sands with traces of chalk towards the bottom, and a further 1.3 m sandy gravel. Above this, Section 1 shows a silty sand with sub-horizontal bedding and an inclined erosional contact with the sand facies above, which consist of coarse-medium sand, sand/silt laminations and ripple-bedded sand, with pebbly horizons, and an inclined erosional surface. This is overlain by a sandy fine-medium flint gravel with clear bedding dipping 30° to the north-northwest. A series of sand facies overlie the gravel, consisting of a coarse-medium sand fining upwards, horizontally-bedded medium sand and a ripple-bedded fine sand becoming silty sand at the top. Further sand facies overlie an erosional surface, consisting of medium coarse sand with alternating trough cross-bedding and horizontal bedding. Towards the top of the sequence, black staining has formed on horizontal bedding planes. There are some flint pebble horizons within the sands, and isolated larger flint pebbles occur on the contacts or within the sand units. Deformation of bedding planes immediately beneath some flint pebbles suggest these are dropstones.

The clast lithological composition of gravels in this sequence is dominated by flint, with occasional quartzite, vein quartz, chert (including *Rhaxella* chert) and sandstone (Table 1). Occasional chalk clasts occur in the basal gravel. The bedded sandy gravel towards the base of Section 1 was sieved for artefacts. This included material taken from the upper (SS3) and lower part of the unit (SS4). No artefacts were recovered.

Section 2 was located to the north of the bluff. Ground surface here is at 15.6 m OD. The water table was encountered at c. 13 m OD, so only the upper 2.5 m of the sequence was seen in section. These consisted of medium-coarse gravel facies, massive and clast supported in the upper part, but with indications of horizontal bedding and some sorting lower down, and horizontally-bedded and shallow cross-stratified sand facies. Palaeoflow determined on the cross-stratified sands indicate a north-westerly flow direction. The clast lithology of the flint gravel facies in Section 2 at 1.0–1.5 m below the surface is characterised by relatively frequent quartzite and vein quartz clasts (Table 1). This may reflect the input of the Black Bourne, which cuts through the quartzose-rich gravels of the River Bytham near Sapiston (Lewis et al., 2021). This gravel facies was sieved for artefacts (SS5), but none were identified.

Borehole 19/4 was drilled 7.5 m to the northwest of Section 2 to a depth of 9.0 m. It stopped in a coarse flint gravel, indicating Chalk bedrock surface in this area below 6.6 m OD. Overlying the coarse gravel, which included some nodular flint, was c. 4.0 m of medium-coarse gravel, c. 2.0 m of sandy gravel and c. 2.0 m of fine-medium sand. Clast lithology is dominated by flint with the same suite of rarer lithologies as seen elsewhere at Barnham Heath (Table 1). The upper part of this sequence is distinctly different from the sediments exposed in Section 2.

3.1.3. Interpretation of the Barnham Heath Pleistocene geology

The stratigraphy, sedimentology and elevation of the Barnham Heath deposits indicates the presence of four fluvial terrace aggradations, rather than the two currently recognised on BGS mapping (Fig. 3). The youngest aggradation was encountered in Borehole 19/4. The thick coarse gravel deposit here is unlike anything seen elsewhere at Barnham Heath, but is similar to deposits recorded in boreholes from elsewhere in the Little Ouse valley, either in areas mapped as Terrace 1 by the BGS or sub-alluvial gravels (e.g. at Barnham Cross Common). At Barnham Heath, these gravels form a low terrace 1–2 m above the floodplain, with bedrock below 6.6 m OD, potentially around 4.0 m OD.

The second and third packages of sediment consist of the deposits encountered in Sections 1, 2, and Borehole 19/3, and Section 5 and Borehole 19/2. These deposits form the main terrace-like surface of Barnham Heath at c. 17.5 m OD, c. 4–5 m above the modern floodplain. The division into two terrace aggradations is based on bedrock height, which is at c. 9.0 m OD at Borehole 19/3, and c. 12.7 m OD at Borehole 19/2. The absence of a surface expression may be due in part to the bedded sands with dropstones at the top of the Section 1 sequence, which West (2009) correlated with the Lopham sands, suggesting they formed in a lacustrine depositional environment resulting from the blocking of the Little Ouse downstream by ice during a post-Anglian cold stage. This unit is absent from Section 2, however the bedded sands and gravels of Section 2 are very similar to the deposits seen in the lower 2 m of Section 1, suggesting they are part of the same package of fluvial sediment. If this is the case, the upper sand unit may have been eroded, creating an offset between the position of the 17 m bluff, located between Section 1 and Section 2, and the likely position of bedrock incision between Section 2 and Borehole 19/4.

The highest terrace aggradation at Barnham Heath, is found on the south side of Barnham Old Pit (Sections 3 and 4, Test Pit 1, and Borehole 19/1). The terrace surface is at c. 20 m OD, c. 7–8 m above the floodplain, with bedrock at c. 14.8 m OD. The basal solifluction deposit indicates a phase of slope action following downcutting into the bedrock and prior to the accumulation of the fluvial sediments. According to Basil Brown's notes, this unit was rich in archaeology. In his section located towards the southeast corner of Barnham Old Pit (Fig. 2), Brown recorded an underlying white sand with white thin clay layers resting on Chalk. This deposit may be the same as the white calcareous silt encountered in the auger hole at the base of Section 4. Wymer (1985) suggested this may be a glacial outwash deposit cut by the overlying fluvial deposits. West (2009) suggests they represent sedimentation in shallow pools formed in the surface of the chalk following post-Hoxnian downcutting but preceding the formation of the solifluction deposit and overlying fluvial terrace deposits.

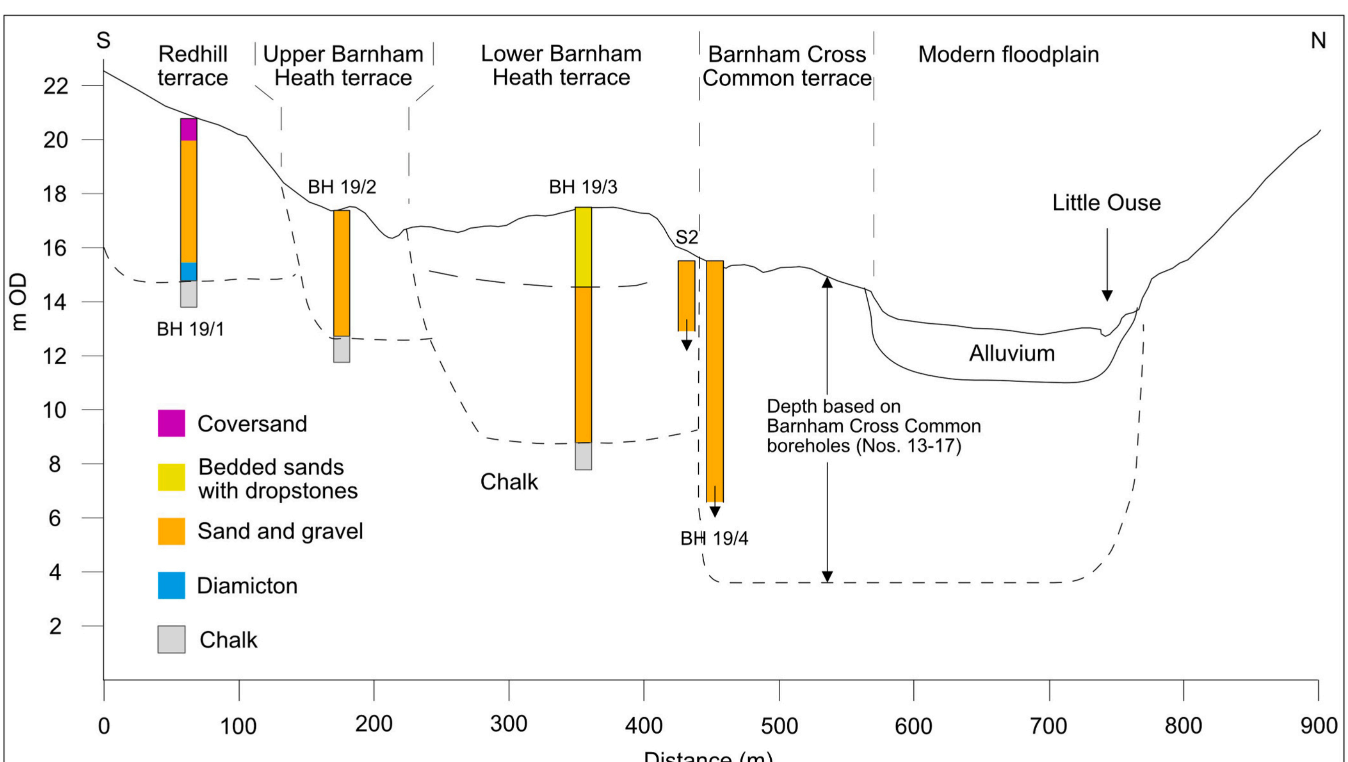

Fig. 3. Interpretation of the Barnham Heath Pleistocene geology.

3.2. Redhill and Warren Wood (east)

3.2.1. Redhill, Thetford, Norfolk

The gravel pits at Redhill became a major focus of Palaeolithic artefact collection during the 1860s (Flower, 1867; Prigg, 1869; Evans, 1872; Wymer, 1985). Located on Abbey Heath to the west of Thetford and on the Norfolk (north) side of the Little Ouse valley (Fig. 4), the disused pits are on a north-south alignment along the front edge of a terrace feature mapped by the BGS as Terrace 3.

Section 1 was excavated to a depth of 5.8 m, with ground surface at 17.3 m OD. Putty chalk with large flint nodules was encountered at the base of the section, interpreted as the weathered surface of the underlying Chalk bedrock. This is overlain by a 1.6 m thick coarse chalk-rich flint gravel, with a grey chalky sand matrix, fine to very coarse subrounded to angular flint clasts, frequent tabular flint and occasional flint boulders. Above the basal deposit is a series of interbedded sand and gravel facies. The sand facies typically consist of fine to medium sand, often horizontally bedded but with some planar cross-bedding, with silt/clay laminae in places, some seams of fine flint pebbles with occasional angular to well-rounded flint cobbles. Palaeoflow measurements on the cross-stratified units indicate a northerly flow direction. The gravel facies are generally poorly sorted fine to coarse flint gravels,

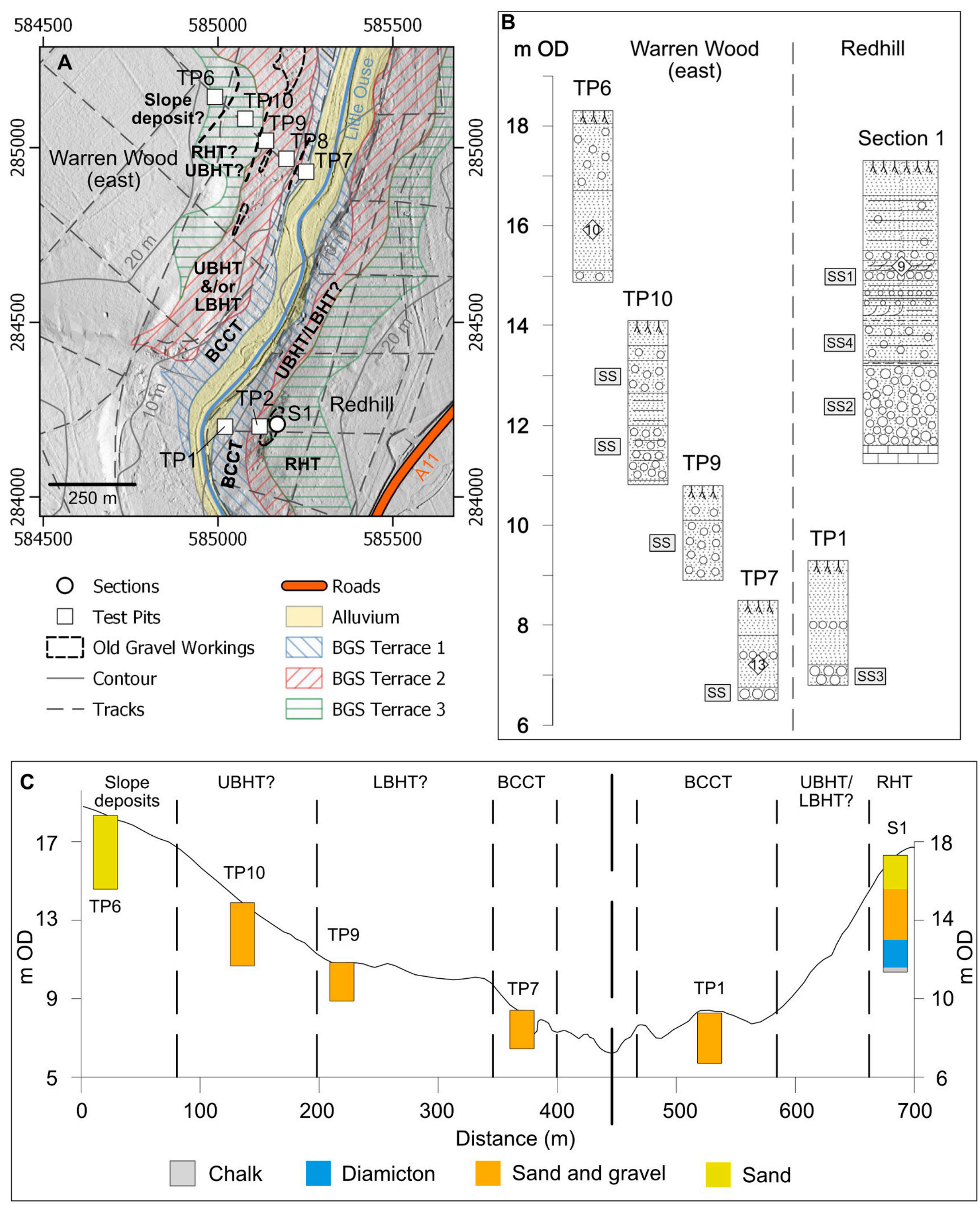

Fig. 4. Redhill and Warren Wood (east). A) Hillshade elevation model (© Environment Agency copyright and/or database right 2022) showing location of section and test pits, former gravel pits, BGS mapping, and terrace margins and nomenclature proposed by this study (coordinate system = OSGB 1936 British National Grid). B) The section and test pit logs, showing ESR and coarse sieving sample locations. C) Interpretation of the Redhill and Warren Wood (east) geology. (BCCT = Barnham Cross Common terrace, LBHT = Lower Barnham Heath terrace, UBHT = Upper Barnham Heath terrace, RHT = Redhill terrace, WWT = Warren Wood terrace, BH = Borehole, S = Section, TP = Test Pit).

angular to sub-rounded with some weak horizontal bedding. Clast lithology (Table 1) is dominated by flint, with occasional vein quartz and quartzite clasts, and rare sandstone and chert clasts (including *Rhaxella* chert). The basal deposit is also characterised by the presence of chalk clasts. The sequence is capped by a well-sorted fine-medium sand, with some weak horizontal bedding, with rare flint cobbles, including some vertical clasts, and significant iron and manganese staining, overlain by an organic-rich topsoil.

Three gravel units encountered in Section 1 were sampled and sieved for artefacts (Fig. 4). SS1 contained 23 flint flakes. Three are retouched, two with scraper retouch and the other is a notch. SS4 had five flakes, one denticulate, and two cores. The third sample (SS2; 1.1 m^3) was remarkably rich in archaeology, with 2 cores, 2 knapping fragments, and 97 flakes, of which 16 are retouched. The condition of the artefacts is also remarkable, with 35 % in fresh condition, and a further 45 % with minimal abrasion to their scar ridges.

Test Pit 1 was located 150 m west of Section 1 on a lower terrace-like surface mapped by the BGS as Terrace 1. The ground surface here is 9.2 m OD. The test pit reached a depth of 2.5 m before encountering water, stopping in a coarse flint gravel. The gravel is overlain by 1.5 m of sand, with fine gravel at the base becoming cleaner and greyish yellow in colour above, with 0.5 m of dark brown sandy soil capping the sequence. The gravel at the base of the test pit was sieved but no artefacts were identified. Test Pit 2 was excavated between Section 1 and Test Pit 1 in an area mapped as Terrace 2 by the BGS, which corresponds with a slight flattening of the slope. Dug to a depth of 2.6 m, it revealed a very loose, stony and dirty sand with clear tip lines that include roots and soil material, interpreted as backfill.

3.2.2. Warren Wood (east), Suffolk

The Pleistocene deposits on the opposite (Suffolk) side of the valley were investigated by a series of test pits along a NW-SE oriented forest track at the eastern end of Warren Wood (Fig. 4). The transect is located approximately 750 m downstream (north) of Redhill and traverses three terraces as mapped by the BGS, from Terrace 3 in the northwest to Terrace 1 in the southeast.

Test Pit 6 and Test Pit 10 were located within the area mapped as Terrace 3. Test Pit 6 was situated at the top of a significant break of slope, while Test Pit 10 was situated on a much more ephemeral break in the slope. Ground surface at Test Pit 6 is at 18.3 m OD and the test pit was dug to a depth of 3.5 m. At the base is a compact pale yellow gravelly sand, with fine to medium flint clasts and chalk pellets. This is overlain by 1.8 m of massive orange sand, with rarer flint clasts, and 1.35 m of loose gravelly sand with clasts of angular flint, frequently vertical, possibly indicating frost action. None of the sediments encountered in Test Pit 6 are unambiguously fluvial in origin. Surface height at Test Pit 10 is 14.2 m OD, and it was dug to a depth of 3.3 m. A chalky sand was revealed at the base of the test pit, overlain by a series of interbedded gravel and sand facies, varying from poorly sorted coarse flint gravel to horizontally bedded sand. Clast lithology is dominated by flint, with occasional vein quartz, quartzite, sandstone and chert, including *Rhaxella* chert. Chalk clasts were absent from the upper gravel, but occasionally present in the lower gravel. The gravel facies were sieved for artefacts, producing three and two flakes from the lower and upper gravels respectively.

Test Pits 8 and 9 were located within the area mapped as Terrace 2. Test Pit 8 encountered disturbed sediments, but Test Pit 9 revealed a moderately well-sorted matrix-supported sandy gravel, coarsening upwards, which is likely to be fluvial in origin. Ground surface is at 10.8 m OD. Clast lithology mirrored the gravels in Test Pit 10. The sandy gravel was sieved and one hard hammer flake was recovered.

Test Pit 7 was located within the area mapped as Terrace 1. Ground surface is at 8.6 m. It was excavated to a depth of 2.0 m, stopping due to water in a coarse flint gravel, which is overlain by a buff coloured medium sand, fining downwards, with a gravelly seam. Above this is a heavily rooted dirty silty sand with occasional flint pebbles, interpreted as coversand, and topsoil. The gravel was sieved for artefacts, producing one rolled hard hammer flake.

3.2.3. Interpretation of the Redhill and Warren Wood (east) Pleistocene geology

At least three, and possibly four, fluvial terrace aggradations can be proposed at Redhill and Warren Wood (east). Sediments of the lowest of these were encountered in Redhill Test Pit 1 and Warren Wood (east) Test Pit 7, where coarse gravel overlain by sand forms a well-defined low terrace feature either side of the river between 1.0 and 1.5 m above the modern floodplain. A second terrace surface can be identified at Warren Wood (east) at c. 10.5 m OD, c. 3 m above the modern floodplain. Only the upper part of the sedimentary sequence was seen in Test Pit 9, a sandy gravel likely to be of fluvial origin. The slight break of slope and fluvial sands and gravels at Test Pit 10 represent a third terrace aggradation, c. 6 m above the modern floodplain. The sediments in Test Pit 6 are more likely to be the result of solifluction processes rather than fluvial activity.

At Redhill, the former pits were dug into the edge of a higher terrace surface at c. 17.3 m OD, c. 10 m above the modern floodplain. The sequence at Redhill revealed in Section 1 closely matches previous descriptions of the Redhill deposits (Flower, 1867; Prigg, 1869; Paterson, 1942; Gibbard et al., 2008). Paterson (1942) interprets the basal layer as a solifluction deposit, which on balance seems a fair interpretation. Flower notes that it is in this deposit that most of the artefacts occur. Our sieving confirmed that this was the richest unit, although artefacts occurred in gravels throughout the sequence. Above the basal deposit, the inter-bedded sands and gravels appear to be fluvial in origin, although in places there may be some inputs from slope processes as identified by Gibbard et al. (2008). It is not clear whether the Redhill Section 1 and Warren Wood (east) Test Pit 10 sediments are part of the same or different aggradations.

3.3. Warren Wood (north) and Santon Downham, Suffolk

A large number of Palaeolithic artefacts were collected during the 1860s from gravel workings near Little Lodge Farm, 2.5 km east of Santon Downham (Flower, 1867; Prigg, 1869; Evans, 1868, 1872). Fieldwork in this area focussed on disused gravel and clay pits, and a forest ride in the northern part of Warren Wood (Fig. 5).

3.3.1. Warren Wood (north) test pit and borehole transect

A series of terrace-like surfaces were investigated in a SW-NE orientated test pit transect. The transect was 600 m long, ending c. 60 m from the top of the steep bluff that drops down to the modern floodplain at c. 6 m OD. Boreholes were sunk adjacent to the first three test pits to attempt to establish depth to bedrock.

Test Pit 1 and Borehole 19/1 were located at the southwestern end of the transect upslope of the first terrace-like surface. Ground level is c. 22.7 m OD. Chalk bedrock was encountered in Borehole 19/1 at 18.8 m OD. Resting on the Chalk is a series of chalky diamictons, interpreted as till, and silty sands, capped by coversand and topsoil.

Test Pit 2 and Borehole 19/2 were located on the highest terrace-like surface. Here ground surface is c. 19.7 m OD. Borehole 19/2 was drilled to a depth of 13 m, stopping in a sandy silt. Chalk bedrock at this location must therefore be below 6.7 m OD. The sandy silt was part of a 4 m sequence of silts and clays, occasionally with sandy laminations. This is overlain by an 8 m sequence of interbedded sands and gravels. Clast lithology of the gravels is dominated by flint with rare quartz, quartzite, chert (including *Rhaxella* chert) and sandstone. Below c. 13.7 m OD, the gravels also contain a significant number of chalk clasts. The upper 3.7 m of the sequence was exposed in Test Pit 2. This consists of a yellow/orange sand fining upwards with a gravel band, overlain by a massive poorly sorted flint gravel with a clayey sand matrix, interpreted as a slope deposit, and capped by coversand and topsoil. The gravel was sieved, but no artefacts were recovered.

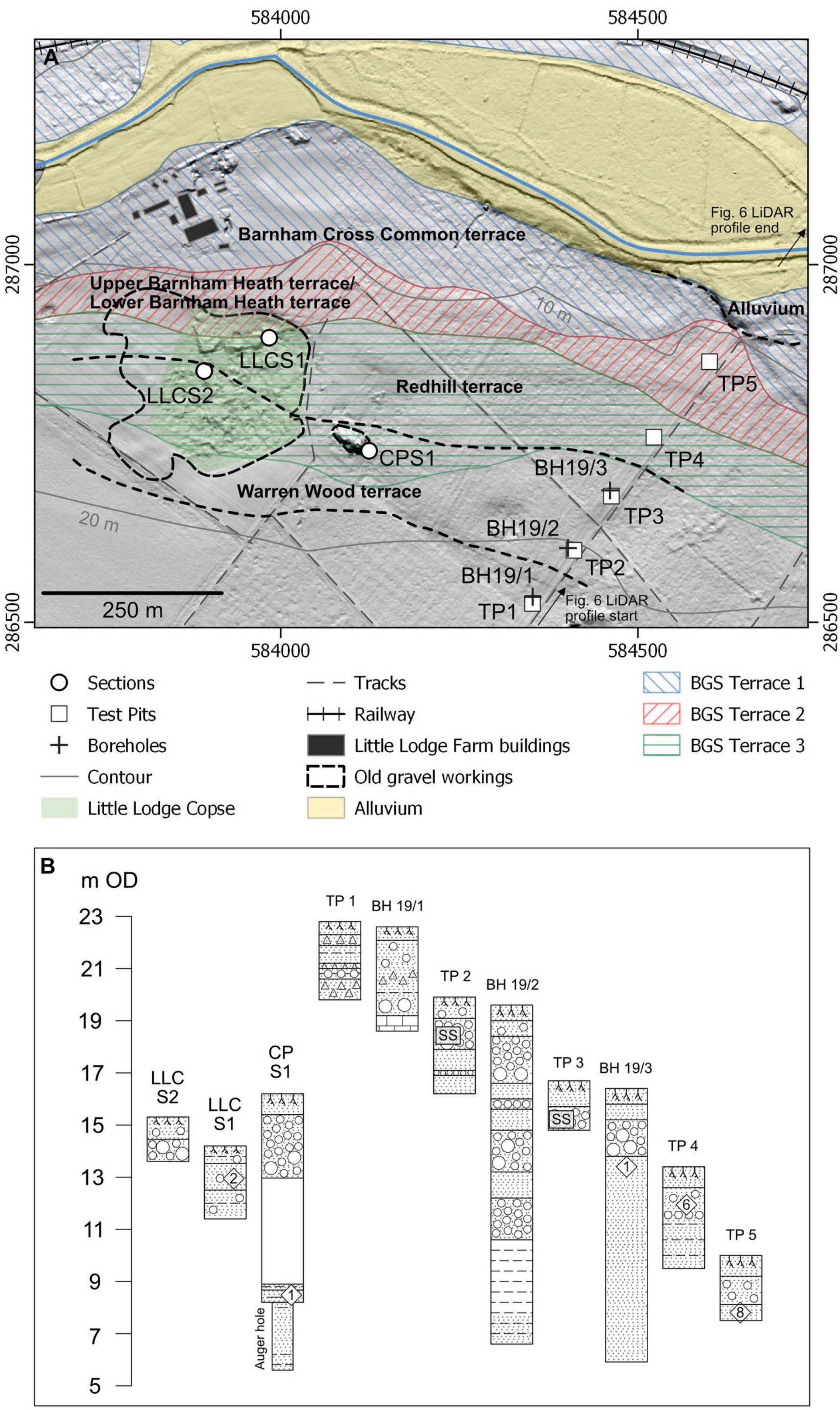

Fig. 5. Warren Wood (north) and Little Lodge Farm. A) Hillshade elevation model (© Environment Agency copyright and/or database right 2022) showing location of sections, test pits, and boreholes, former gravel and clay pits, and BGS mapping (coordinate system = OSGB 1936 British National Grid). B) The section, test pit and borehole logs, showing ESR and coarse sieving sample locations. (LLCS = Little Lodge Copse Section, CPS = Clay Pit Section, BH = Borehole, TP = Test Pit).

Test Pit 3 and Borehole 19/3 were situated on the next break of slope, where ground surface is c. 16.5 m OD. Borehole 19/3 was drilled to a depth of 10.5 m, stopping in a brownish yellow sand, indicating that Chalk bedrock must be below 6 m OD. The lower 8 m consists of brownish yellow sand, chalky in places with a few chalk pebbles at the base of the borehole. Above this is a coarse flint gravel, moderately sorted, with a silty sand matrix. Clast lithology is similar to the upper gravels in Borehole 19/2 (Table 1). The sequence is capped by a medium sand and soil. The gravel was sieved for artefacts, and eight flakes were recovered, of which one had a notch and scraper retouch. A further two flakes and one retouched flake were recovered from the same deposit during cleaning and recording of the sections. Excavation of an area around Test Pit 3 (conducted in 2018 by Mark White, Durham University) recovered a further 56 flakes and 3 cores from the gravel, plus the butt of a broken handaxe.

Test Pit 4 was situated on the next break of slope where surface height is c. 13.4 m OD. The test pit was dug to a depth of 3.9 m. The sequence consists of yellow sand with some silty layers, overlain by a yellow fine silty sand and a massive yellow sand with occasional flint pebble layers, capped by coversand and soil. Test Pit 5 was situated on a well-developed terrace-like surface where ground level is c. 10.2 m OD. The test pit was dug to a depth of 2.5 m, exposing a massive brownish yellow medium sand, overlain by a yellowish brown gravelly sand, coarsening upwards, and a black organic-rich soil.

3.3.2. *Clay and gravel pit sections*

Three sections were excavated in disused pits as part of the Durham University project (Fig. 5). Clay Pit Section (CPS) 1 was excavated in the face of a former clay pit. The sequence was similar to previous sections excavated in the same pit (White, 1997). Ground surface is at c. 16.2 m and the section was excavated to a depth of c. 8.0 m. An auger hole at the bottom of the section went through 2.6 m of sands, silts and clays, stopping in a brown sandy silt. Chalk bedrock is therefore below 5.6 m OD. The sequence revealed in the section consists of a medium to coarse yellowish brown chalky fine sand, weakly bedded with iron-staining and faulting, overlain by a pale brown silt, and c. 4.3 m of clay, pale yellowish brown and slightly silty and calcareous in the lower part, light brown and massive and decalcified above. The clay is overlain by a c. 2.4 m sequence of sands and gravels. The gravel facies are moderately sorted, with a medium to coarse sand matrix but open framework in places. Excavation of the gravel resulted in the recovery of 131 flakes, 2 cores and a broken handaxe. The sequence is capped by coversand and soil.

An area of disused gravel pits is preserved in a copse of trees on the edge of Little Lodge Farm. Ground surface descends from c. 18.0 m OD at the southern edge of the gravel pits to c. 14.0 m OD at the northern edge. Little Lodge Copse Section 1 was situated in a small pit at the edge of a terrace-like surface. Ground level is c. 14.2 m OD and the section was excavated to a depth of 2.8 m. The sequence consists of a series of sand facies, slightly silty in places, with rare sub-angular to rounded, fine to very coarse flint clasts and occasional flint cobbles. Little Lodge Copse Section 2 was excavated in a small pit towards the middle of the copse. Ground surface is c. 15.3 m OD and the section was excavated to a depth of 1.7 m. A compact poorly sorted medium to very coarse flint gravel, with a medium to coarse sand matrix, is overlain by a medium to coarse pale brown sand with occasional flint clasts, capped by coversand and soil.

3.3.3. *Interpretation of the Warren Wood (north) and Santon Downham Pleistocene geology*

Boreholes 19/1 and 19/2 demarcate the southern margin of the fluvial sequence associated with the Little Ouse valley (Fig. 6). In Borehole 19/1, the chalky diamicton is interpreted as Anglian till, resting on Chalk bedrock at c. 19 m OD. There is a relatively steep cut in the Chalk between Borehole 19/1 and 19/2, infilled with clays, silts and sands, as seen in Boreholes 19/2, 19/3, and the clay pit section. These are interpreted as Anglian glaciolacustrine sediments. The depth and extent of the glacial sediments is unknown, but it is clear that at least some of the Little Ouse terraces are cut into the glacial sequence. The chalk-rich gravels overlying the silts and clays in Borehole 19/2 may also be glacial in origin, and are distinct from the overlying flint-rich sands and gravels. These occur at the same altitude as the fluvial sands and gravels in Test Pit 3 and Borehole 19/3, which together represent the first fluvial aggradation of the Little Ouse in this area. The gravel in Little Lodge Copse Section 2 and the clay pit section is likely to be part of the same aggradation. A solifluction deposit lies above the fluvial deposits towards its southern margin, as seen in Borehole 19/2.

A degraded terrace-like surface occurs at c. 13.5 m OD, c. 7.5 m

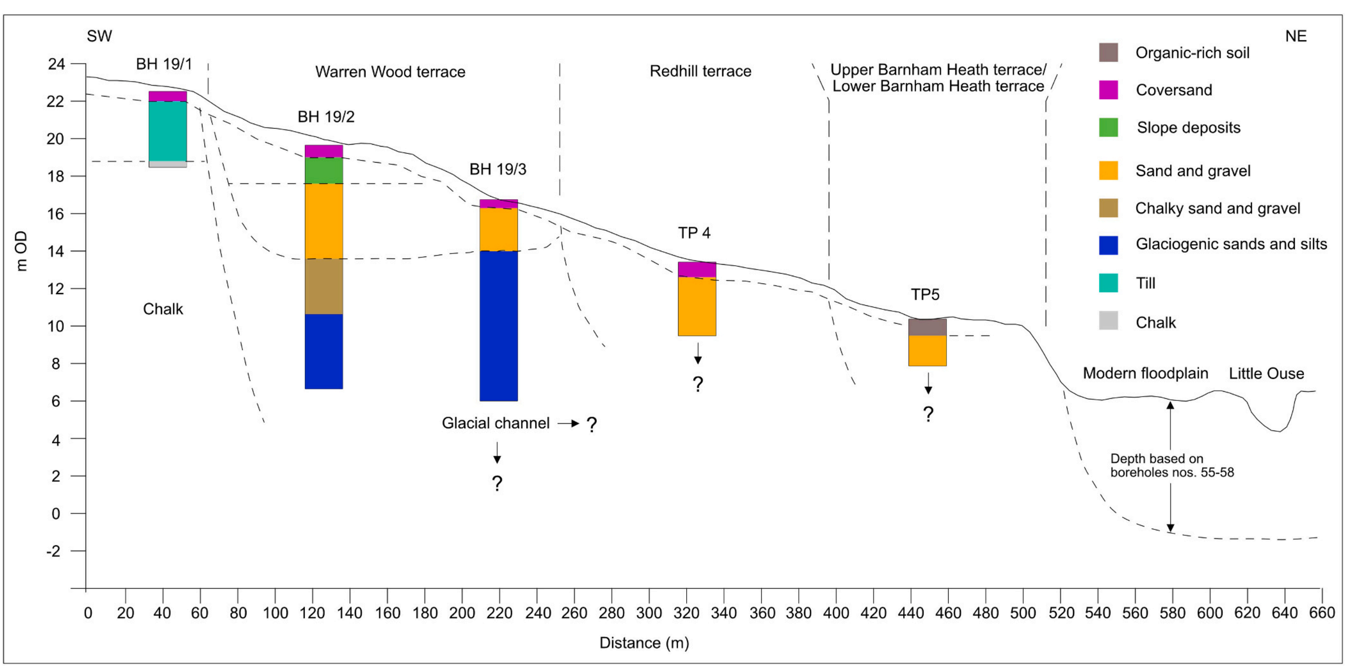

Fig. 6. Interpretation of the Warren Wood (north) geology. (BH = Borehole, TP = Test Pit).

above the floodplain. Only the upper part of the sequence has been recorded, in Test Pit 4, located towards the back edge of the terrace feature, and Little Lodge Copse Section 1, located at the front edge of this terrace. In neither case are the sediments unequivocally fluvial in origin.

A terrace-like surface occurs at the northeastern end of the transect, at c. 10 m OD, c. 4 m above the floodplain. The upper part of the sequence was seen in Test Pit 5. It is clear from the topography that the area mapped as Terrace 1 by the BGS between the end of the transect and the river is in fact part of the modern floodplain (Figs. 5 and 6). However, there is a clear surface expression of a lower terrace to the west at Little Lodge Farm, where a terrace-like plateau lies 1–2 m above the floodplain.

3.4. Broomhill Pit, Norfolk

Broomhill Pit is a large 19th Century gravel pit located on the north side of the river between Santon Downham and Brandon (Fig. 7). Palaeolithic artefacts were recovered from this pit, reportedly from a basal unit of very coarse flint gravel (Flower, 1869).

Section 1 and Test Pit 1 were excavated towards the southwest corner of the pit. Ground surface at Section 1 is c. 13.3 m OD. The section was dug to a depth of 5.2 m. The sedimentary sequence consists of a series of interbedded sand and gravel facies. The sand facies vary from gravelly and cross-stratified at the base of the section, to more silty and horizontally bedded, to having weaker bedding towards the top of the section. The gravel facies consist of thin pebble layers, alternating with sand layers, with a thicker poorly sorted fine to medium angular flint gravel towards the top of the section. Clast lithology is dominated by flint, with occasional quartzite, vein quartz, and sandstone and chert clasts, including *Rhaxella* chert. A hand auger was used at the bottom of the section, going through c. 0.3 m of grey laminated silts and clays, stopping on gravel at c. 7.8 m OD. The floor of the pit at Test Pit 1 is c. 8.7 m OD, which was excavated to a depth of 1.1 m through redeposited chalky gravelly sands. A hand auger was used in the base of the test pit, reaching putty chalk at a depth of 0.87 m, interpreted as the weathered surface of the Chalk bedrock, at an altitude of c. 6.7 m OD. This is c. 1.1 m below the base of the auger hole at the bottom of Section 1, with the intervening sediments not seen in either the test pit or section.

During excavation, one flake and one retouched flake were found in the sand unit at the top of the section, a flake was found in the upper sand and gravel unit, and two flakes were found in the lower sand and gravel unit. Sediments from three gravel units were sieved for artefacts (Fig. 7). The upper sand and gravel contained no artefacts (SS1). One core, four flakes, and one retouched flake were recovered from the middle sand and gravel (SS4). Eight flakes and a retouched natural spall were identified from the lower sand and gravel (SS2).

Section 2 was located at the northern end of the pit. Ground surface is at c. 18.4 m OD. At the base of the section is a very chalky till, sloping up to the north from the base of the section at c. 14.6 m OD, steepening to near vertical contacts with the overlying sediments at c. 16.5 m OD. In the southern part of the section, the chalky diamicton is overlain by a grey chalky clay and a black silt/clay. In the northern part of the section, a hollow of unknown origin is formed in the chalky diamicton, the base of which is at c. 15.6 m OD, infilled with sand with a clay pocket and occasional large flint clasts. Above this is a very poorly sorted sand with large flints, a chalky stony clay and topsoil. During the excavation of Section 2, three long blades were found in close proximity to each other in the topsoil. The blades are made on flint and are in fresh condition, with creamy-white patinated surfaces. One is a crested blade, likely to have been removed to rejuvenate a blade core. Their typology suggests a

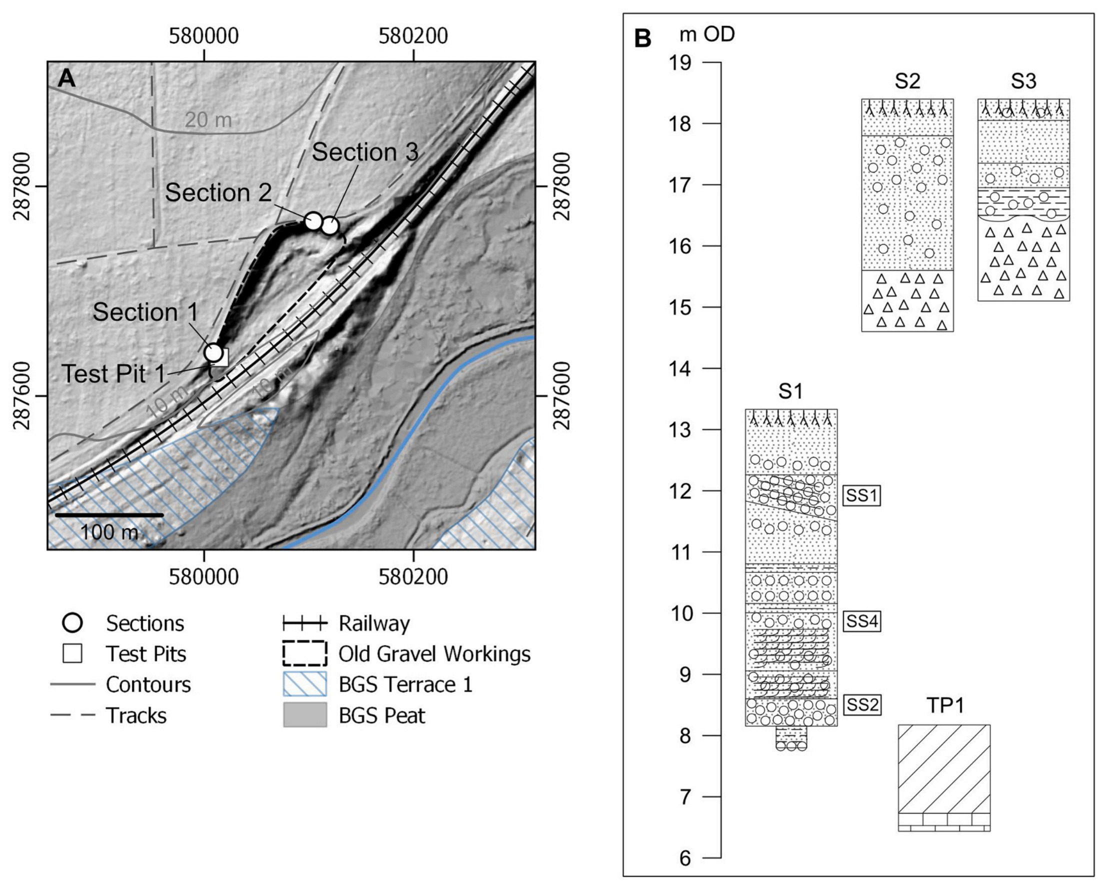

Fig. 7. Broomhill Pit. A) Hillshade elevation model (© Environment Agency copyright and/or database right 2022) showing location of sections, former gravel pit, and BGS mapping (coordinate system = OSGB 1936 British National Grid). B) The section logs, showing coarse sieving sample locations.

late Upper Palaeolithic age.

Section 3 was located on the north side of a gulley cut into the side of the pit. Ground surface is at c. 18.4 m OD. At the base of the section is c. 1.4 m of chalky diamicton, with an undulating surface at c. 16.5 m OD. Resting on this is a brown stony silt/clay, overlain by a slightly stony sand and a medium/coarse sand with iron-stained laminations, capped by a sandy soil. In the process of cutting back Section 3, a large flint hard hammer flake was found in the stony silt/clay.

3.4.1. Interpretation of the Broomhill Pit Pleistocene geology

The sequence in Section 1 closely matches descriptions by Flower (1869) and Evans (1868). The basal deposits, not seen in the recent investigations, were described by Flower (1869) as a very coarse ferruginous gravel, containing some very large flint nodules, mixed with rounded quartzite pebbles and broken chalk, overlain by a less ferruginous gravel containing a greater proportion of chalk fragments. Evans (1868) described the lower beds of gravel as having "a very large percentage of rolled Chalk and seams of chalky sand" (p. 445). It is likely that this sediment formed following erosion of the Chalk bedrock by the river downcutting laterally into the north side of the valley (West, 2009), but whether the coarse gravel is fluvial or a result of solifluction is unclear. The main sedimentary process responsible for the sequence in Section 1 appears to be fluvial, based on the bedding structures of the interbedded sands and gravels. There are close similarities between this section and Section 1 at Redhill and Section 3 at Barnham Heath, and it is likely that these are part of the same fluvial aggradation (see below). The chalky diamicton seen in Sections 2 and 3 is interpreted as till. While a direct relationship between this and the fluvial deposits of Section 1 was not established, the altitude of the deposits indicates the latter is cut through the till. An alternative interpretation for the sediments at the northern end of the pit, not supported by the observations reported in this paper, has been put forward by West (2009). In his view, the stoney sands in Sections 2 and 3 are lacustrine sediments equivalent to the Lopham sands and related to a pro-glacial lake that formed in the Little Ouse valley during a post-Anglian cold stage, and the underlying chalky diamicton reworked into the lake deposits from the valley side.

4. Terrace stratigraphy of the Little Ouse valley

A new terrace stratigraphy for the Little Ouse valley can be proposed on the basis of correlation of the sequences described above, supplemented with information from BGS borehole records (Fig. 1; Table 2). Five post-Anglian fluvial terraces are recognised, referred to in order of descending elevation as the Warren Wood, Redhill, Upper Barnham Heath, Lower Barnham Heath, and Barnham Cross Common terraces (Fig. 8 and Table 3). Following lithostratigraphic procedure adopted elsewhere (e.g. Bowen, 1999), the sediments underlying the terraces can be considered as members of the Little Ouse Valley Formation. There is some correlation between previous mapping and the newly defined terraces, however, there are multiple locations where fieldwork exposures or boreholes are reassigned under the current study (Tables 2 and 3). At present, there are insufficient data points to undertake a complete remapping of the distribution of the terraces.

4.1. Warren Wood terrace

Deposits of the highest and therefore oldest aggradation attributable to the Little Ouse were seen at Warren Wood (north), in Boreholes 19/2 and 19/3, Test Pits 2 and 3, Little Lodge Copse Section 1 and the clay pit section (CPS1), which together provide the stratotype for this terrace. The Warren Wood terrace is formed of c. 4.0 m of sand and gravel overlying glaciolacustrine sediments at c. 14 m OD. The terrace surface at Warren Wood is 11.0–12.0 m above the modern floodplain. Further upstream a borehole (Table 3: BH ID No. 11) records 2.75 m of sand and gravel overlying Chalk at c. 22.4 m OD, with surface height at c. 25.1 m OD, c. 10.5 m above the modern floodplain. These sands and gravels are assigned to the Warren Wood terrace, yielding a long profile gradient of −0.63 m/km.

4.2. Redhill terrace

The sands and gravels seen in Barnham Heath Borehole 19/1 and Sections 3 and 4, Redhill Section 1, Warren Wood (north) Test Pit 4, and Broomhill Section 1 can be correlated on the basis of their altitude, with Redhill selected as the stratotype. Sands and gravels recorded in three BGS boreholes are assigned to this aggradation on the basis of their altitude. The Redhill terrace consists of 2.0–4.0 m of sands and gravels, in places overlying a chalk-rich basal deposit consisting of large angular flint clasts in a sand or silt/clay matrix. The surface and bedrock contact height for the Redhill terrace is typically 6.5–9.0 m and 2.0–4.0 m above the modern floodplain respectively, with a long profile gradient of −0.53 m/km.

4.3. Upper Barnham Heath terrace

This terrace was recognised at Barnham Heath in Borehole 19/2 and Section 5 on the basis of bedrock height, which distinguished the sequence as a separate aggradation from the Lower Barnham Heath terrace. Sands and gravels recorded in seven BGS boreholes are suggested to be part of the Upper Barnham Heath terrace. The terrace surface is typically 3.0–5.0 m above the modern floodplain, and bedrock is at or near to the altitude of the modern floodplain. The gradient of the Upper Barnham Heath terrace is −0.57 m/km. It is unclear whether the sediments seen in Warren Wood (east) Test Pit 9 and Warren Wood (north) Test Pit 5 are associated with this aggradation or the Lower Barnham Heath terrace.

4.4. Lower Barnham Heath terrace

Barnham Heath Sections 1 and 2, and borehole 19/3 provide the stratotype for this terrace aggradation. As mentioned above, it is unclear whether Warren Wood (east) Test Pit 9 and Warren Wood (north) Test Pit 5 are also associated with this aggradation. Nine boreholes can also be assigned to the Lower Barnham Heath gravels. Surface height is c. 2.0–4.0 m above the modern floodplain, and bedrock height is 3.0–5.0 m below the modern floodplain. The aggradation consists of c. 6 m of interbedded sand/silty sand and gravel facies. At Barnham Heath, this is overlain by c. 2 m of horizontally bedded sand with dropstones. The gradient of the Barnham Heath terrace is −0.60 m/km.

4.5. Barnham Cross Common terrace

Barnham Heath Borehole 19/4, Redhill Test Pit 1, and Warren Wood Test Pit 7 are all characterised by a coarse flint gravel, overlain by 1.5–2.0 m of sand, forming a low terrace 1–2 m above the modern floodplain. It is well represented at Barnham Heath and Barnham Cross Common, with a borehole (Table 3: BH ID No. 13) at the latter selected as the stratotype (Fig. 9). The majority of BGS boreholes in the Little Ouse valley are located within areas mapped either as Terrace 1 or alluvium/peat. The Barnham Cross Common terrace boreholes show a range of gravel thicknesses, with bedrock contact height varying between 3 and 10 m below the level of the modern floodplain. Boreholes in areas of alluvium/peat show a similar range of gravel thicknesses, with bedrock contact varying from 5 to 9 m below the modern floodplain. This suggests that the sub-alluvial gravel and Barnham Cross Common terrace deposits are part of the same package of sediments, deposited during the Devensian, into which the modern floodplain and river channel is cut.

5. Chronology of the Little Ouse valley terraces

ESR dating of quartz grains has recently been employed in the

Table 2
BGS borehole records used in this study, with previous BGS terrace assignations and new terrace assignations from the current study.

BH ID	Reference	Length	Ground level (m OD)	Gravel thickness (m)	Gravel top (m OD)	Bedrock height (m OD)	BGS mapping	This study
1	TM07NW 47	7.4	26.4	6.0	26.0	20.0	Terrace 2	Lower Barnham Heath Terrace
2	TM07NW 41	27.5	24.4	6.0	24.0	18.0	Terrace 2	Barnham Cross Common Terrace
3	TM07NW 73	9.5	22.6	-	19.7	-	Peat	Sub-alluvial
4	TM07NW79	40.2	25.3	1.2	24.9	23.7	-	Redhill Terrace
5	TM07NW36	28.4	22.1	5.0	21.4	16.4	Peat	Barnham Cross Common Terrace
6	TM07NW 30	25.6	22.0	5.3	21.5	16.2	Terrace 1	Barnham Cross Common Terrace
7	TM08SW15	11.7	24.7	7.7	24.6	16.9	-	Lower Barnham Heath Terrace
8	TL98SW 10	6.5	22.0	1.0	17.5	16.5	Terrace 2	Redhill Terrace
9	TL98SW 12	95.0	19.9	5.5	19.9	14.4	Terrace 2	Upper Barnham Heath Terrace
10	TL98SW 2	28.3	16.8	7.6	13.4	5.8	Terrace 1	Sub-alluvial
11	TL97NW 10	3.8	25.1	2.8	25.1	22.4	-	Warren Wood Terrace
12	TL88SE80	9.8	15.4	8.3	15.3	7.0	Terrace 1	Lower Barnham Heath Terrace
13	TL88SE 71	11.0	13.8	9.0	12.8	3.8	Terrace 1	Barnham Cross Common Terrace
14	TL88SE 72	8.2	12.7	5.2	10.7	5.5	Alluvium	Sub-alluvial
15	TL88SE 79	8.2	11.2	8.0	11.2	3.2	Alluvium	Sub-alluvial
16	TL88SE 77	9.7	11.3	8.2	10.8	2.6	Alluvium	Sub-alluvial
17	TL88SE 76	9.3	12.1	3.6	7.4	3.8	Alluvium	Sub-alluvial
18	TL88SE137	10.0	12.4	8.0	12.0	4.0	Terrace 1	Barnham Cross Common Terrace
19	TL88SE177	3.0	14.0	0.5	13.6	13.1	Terrace 1	Upper Barnham Heath Terrace
20	TL88SE159	10.0	14.4	2.5	14.0	11.5	Terrace 1	Upper Barnham Heath Terrace
21	TL88SE175	3.0	14.4	1.7	14.1	12.4	Terrace 1	Upper Barnham Heath Terrace
22	TL88SE180	9.0	13.5	4.7	12.7	8.0	Terrace 1 or 2	Lower Barnham Heath Terrace
23	TL88SE181	9.0	13.5	5.0	12.5	7.5	Terrace 1 or 2	Lower Barnham Heath Terrace
24	TL88SE182	9.0	13.5	6.2	12.7	6.5	Terrace 1 or 2	Lower Barnham Heath Terrace
25	TL88SE154	10.0	13.2	6.0	12.9	6.9	Terrace 1	Barnham Cross Common Terrace
26	TL88SE157	12.5	12.3	6.3	11.6	5.3	Terrace 1	Barnham Cross Common Terrace
27	TL88SE158	10.0	11.3	8.3	11.0	2.7	Terrace 1	Barnham Cross Common Terrace
28	TL88SE 242	9.2	12.8	7.3	11.9	3.6	Terrace 1	Barnham Cross Common Terrace
29	TL88SE46	18.3	14.5	9.1	13.9	4.8	Terrace 3	Barnham Cross Common Terrace
30	TL88SE 211	6.1	12.6	4.1	11.6	6.5	Terrace 1	Lower Barnham Heath Terrace
31	TL88SE 212	7.0	12.9	4.8	11.7	6.9	Terrace 1	Lower Barnham Heath Terrace
32	TL88SE 196	6.3	16.8	3.7	15.2	11.5	Terrace 2	Upper Barnham Heath Terrace
33	TL88SE134	10.0	14.5	2.4	13.2	10.8	Terrace 1 or 2	Upper Barnham Heath Terrace
34	TL88SE 8	12.3	14.3	9.8	12.8	3.1	Terrace 1	Barnham Cross Common Terrace
35	TL88SE 7	6.0	10.6	4.3	9.9	5.6	Terrace 1	Barnham Cross Common Terrace
36	TL88SE5	8.5	9.1	3.0	7.6	4.6	Alluvium	Sub-alluvial
37	TL88SE6	10.7	9.7	4.4	9.2	4.8	Alluvium	Sub-alluvial
38	TL88SE 17	8.2	9.0	6.4	8.2	1.8	Terrace 1 or 2	Sub-alluvial
39	TL88SE 2	6.6	8.7	4.3	7.3	3.1	Alluvium	Sub-alluvial
40	TL88SE 3	6.6	8.7	3.8	6.9	3.1	Alluvium	Sub-alluvial
41	TL88SE 4	5.9	8.7	3.7	7.5	3.8	Terrace 1	Sub-alluvial
42	TL88SE 11	7.7	9.0	6.7	9.0	2.3	Terrace 1 or 2	Sub-alluvial
43	TL88SE 9	6.2	9.5	5.2	9.5	4.4	Terrace 1 or 2	Barnham Cross Common Terrace
44	TL88SE 120	3.4	15.9	2.4	15.9	13.5	Terrace 3	Redhill Terrace
45	TL88SE24	14.3	13.0	10.5	10.6	0.1	Terrace 3	Sub-alluvial
46	TL88SE20	18.3	9.0	5.5	7.8	2.3	Alluvium	Sub-alluvial
47	TL88SE21	30.5	8.5	5.6	6.3	0.7	Terrace 1	Sub-alluvial
48	TL88SE 58	7.2	11.5	4.2	9.5	5.3	Terrace 2	Lower Barnham Heath Terrace
49	TL88SE 62	9.3	8.2	7.5	7.4	0.0	Alluvium	Sub-alluvial
50	TL88SE 61	9.7	8.2	8.1	7.6	0.5	Alluvium	Sub-alluvial
51	TL88SE 60	8.5	8.0	6.4	6.9	0.5	Terrace 1	Sub-alluvial
52	TL88SE 59	13.3	10.0	11.8	9.5	−2.4	Terrace 1	Barnham Cross Common Terrace
53	TL88SE 64	9.0	8.4	7.7	8.1	0.4	Terrace 1 or 2	Sub-alluvial
54	TL88SE 63	12.8	8.7	5.7	7.3	1.6	Alluvium	Sub-alluvial
55	TL88NE 6B	14.7	10.5	13.3	10.0	−3.2	Terrace 2	Barnham Cross Common Terrace
56	TL88NE 6 A	13.8	10.5	12.3	10.0	−2.3	Terrace 2	Barnham Cross Common Terrace
57	TL88NE 53	10.2	8.8	7.4	7.0	−0.4	-	Sub-alluvial

(*continued on next page*)

Table 2 (*continued*)

BH ID	Reference	Length	Ground level (m OD)	Gravel thickness (m)	Gravel top (m OD)	Bedrock height (m OD)	BGS mapping	This study
58	TL88NE 52	10.0	8.8	7.0	6.8	−0.3	-	Sub-alluvial
59	TL88NW4/B	30.5	7.8	4.0	6.9	2.9	Terrace 1	Upper Barnham Heath Terrace
60	TL78NE40	15.0	7.4	13.8	7.0	−6.8	Terrace 1	Barnham Cross Common Terrace
61	TL78NE42	15.0	7.4	11.7	7.4	−4.4	Terrace 1	Barnham Cross Common Terrace
62	TL78NE43	15.0	7.4	10.5	7.4	−3.2	Terrace 1	Barnham Cross Common Terrace
63	TL78NE44	15.0	7.4	13.6	7.3	−6.4	Terrace 1	Barnham Cross Common Terrace
64	TL78NE45	15.0	7.4	13.5	6.9	−7.1	Terrace 1	Barnham Cross Common Terrace
65	TL78NE46	15.0	7.4	13.1	7.4	−5.8	Terrace 1	Barnham Cross Common Terrace
66	TL78NE 17	9.2	5.0	3.9	0.7	−3.2	Peat	Sub-alluvial
67	TL78NE18	15.0	4.8	5.8	1.5	−4.3	Peat	Sub-alluvial
68	TL78NE19	15.0	5.1	6.5	2.7	−3.8	Peat	Sub-alluvial
69	TL78NE20	11.0	5.5	7.6	4.0	−3.6	Peat	Sub-alluvial

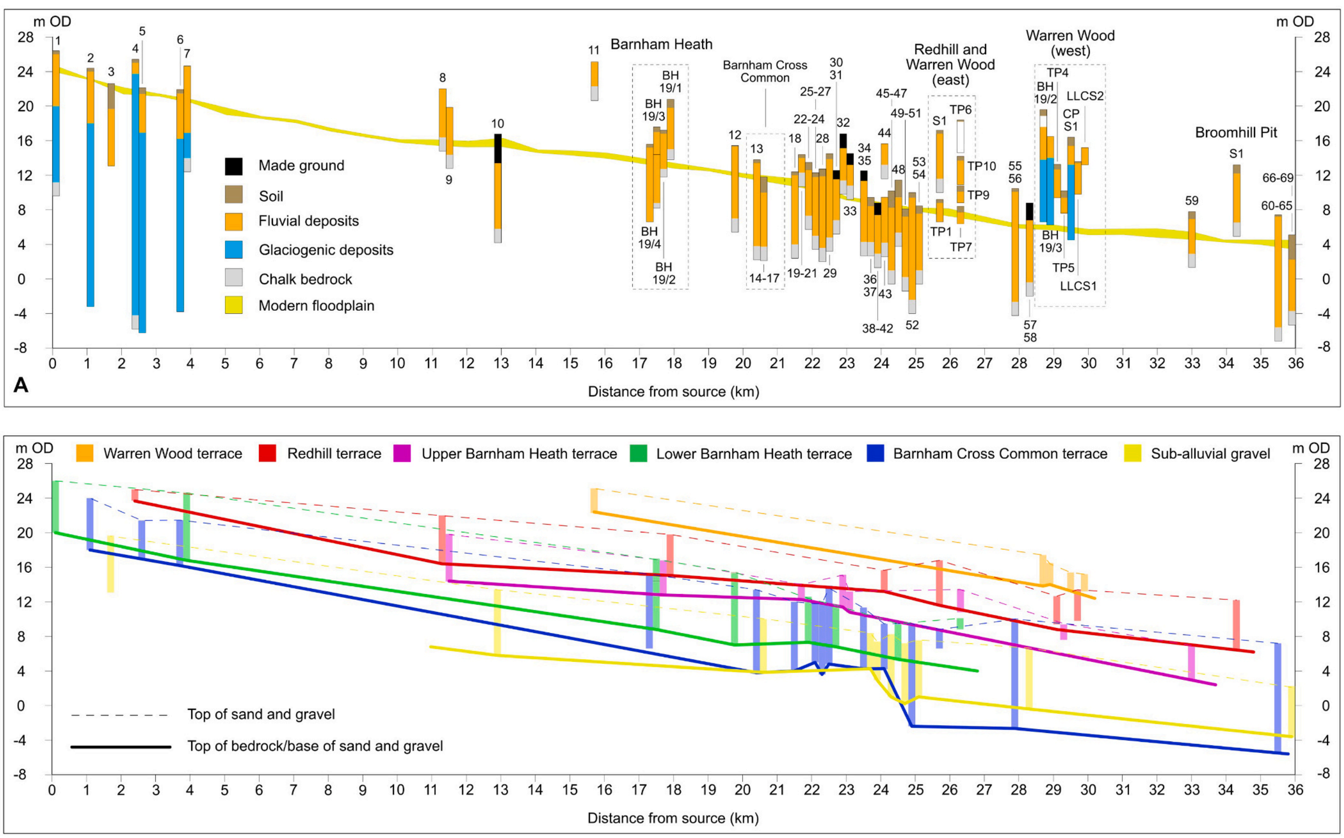

Fig. 8. Interpretation of the development of the Little Ouse. A) BGS boreholes and BPP logs; B) suggested long profiles for the terraces.

Breckland to provide age estimates for the pre-Anglian fluvial deposits of the River Bytham (Voinchet et al., 2015; Lewis et al., 2021), as well as for other Pleistocene fluvial sequences globally (e.g. Voinchet et al., 2019, 2020; Hernando-Alonso et al., 2022; Li et al., 2022). For the Little Ouse, a total of 18 samples were collected from sand units at each of the fieldwork sites. Sample locations are marked on Figs. 2, 4 and 5. The results are summarised in Fig. 10 and Tables 4 and 5. The sample from Section 1 at Broomhill experienced problems during processing, which prevented the production of meaningful results. The results from the other 17 samples are discussed below.

At Warren Wood (north), the sands and gravels assigned to the Warren Wood terrace did not include any suitable sand units for ESR dating. Instead, sands underlying the gravels were sampled. A sample (SDWW1801) was taken from the upper part of the sand sequence immediately below the fluvial gravels in Test Pit 3, producing an age estimate of 3607 ± 723 ka (1175 ± 284 ka when restricting the growth curve) from the Al centre, and 716 ± 60 ka from the Ti-Li centre. A second sample (SD1701) was taken from the top of the sand unit at the base of Clay Pit Section 1. This produced age estimates of 887 ± 68 ka (Al centre) and 972 ± 62 ka (Ti-Li centre). These overestimated ages are interpreted as indicating totally unbleached or poorly bleached pre-Anglian sediments. In both cases, the sands are interpreted as glaciogenic in origin, reworked during the Anglian in a glaciolacustrine environment. The sand unit in Warren Wood (east) Test Pit 6 was

Table 3
Terrace stratigraphic nomenclature of the Little Ouse fluvial terraces defined in this study, together comprising the Little Ouse Valley Formation.

Terrace/Member	Type section	Proposed MIS correlation
Warren Wood	Warren Wood (north) Borehole 19/2, Test Pit 2, Test Pit 3	12–10
Redhill	Redhill Section 1	10–8
Upper Barnham Heath	Barnham Heath Section 5, Borehole 19/2	8–6
Lower Barnham Heath	Barnham Heath Section 1, Borehole 19/3	6–5
Barnham Cross Common	BGS Borehole TL88SE71	4–2

sampled as a potential Warren Wood terrace deposit based on its altitude, although as described above, it is more likely to be a slope deposit. Age estimates from sample WNW1710 are 648 ± 33 ka (Al) and 212 ± 15 ka (Ti-Li). The ESR ages of these likely aeolian or colluvium deposits may be recording initial deposition followed by final reworking/ deposition. The suggested age of the Warren Wood terrace is therefore based on lithostratigraphic reasoning alone. The fluvial sands and gravels at Warren Wood (north) overlie glacial sediments that infill a glacial channel cut through Anglian till, and represent the first iteration of the emergent Little Ouse drainage post retreat of Anglian ice sheets. This suggests a late MIS 12 age for initial aggradation followed by the establishment of the interglacial river during MIS 11.

Age estimates for the Redhill terrace sediments were obtained from seven samples. At Barnham Heath Section 3, the weighted mean average for sample BMH1705 is 332 ± 45 ka. This overlaps with the samples from Warren Wood (north) (WNW1706 = 374 ± 47 ka; SD1702 = 294 ± 16 ka), suggesting aggradation between MIS 11 and MIS 8. Of the four samples for which weighted mean averages could not be calculated, the sample from Barnham Heath Section 3 (BMH1704) produced age estimates of 353 ± 41 ka (Al) and 271 ± 58 ka (Ti-Li), providing additional support for aggradation of these sediments between MIS 11 and MIS 7. The two samples from Barnham Heath Section 4 provide age estimates from the Al centres only, with BMH1706 in good agreement at 335 ± ka while BMH1707 produced an age of 232 ± 74 ka. The Ti-Li centres failed to produce well-fitting growth curves, due to both a very weak natural signal which was difficult to differentiate from background noise and a wide range of sensitivities within grains in irradiated aliquots. The former issue resulted in the natural dose being overestimated, resulting in an artificially increased D_e (Gy) reading, while the latter problem produced an overdispersion of irradiated dose points and large error margins. The sample from Redhill Section 1 (RDH1709) was older, producing age estimates of 468 ± 37 ka (Al) and 501 ± 36 ka (Ti-Li). The Ti-Li centre again produced an overdispersion of points on the growth curve indicative of a mixture of well-bleached, partially bleached, and unbleached grains, possibly indicating a reworked sediment. On balance, the ESR results indicate aggradation of the Redhill terrace deposits between MIS 11 and MIS 8, which, on lithostratigraphic grounds, we suggest is more likely to be constrained to MIS 10 to MIS 8, with initial downcutting of the river early in MIS 10 and subsequent downcutting to the new base level of the Upper Barnham Heath terrace during MIS 8. The ESR age estimate from Redhill, is clearly an overestimate, given that the Little Ouse fluvial sediments can be demonstrated to be younger than MIS 12 both stratigraphically through the relationship to Anglian till, and by the presence of *Rhaxella* chert.

An age estimate for the aggradation of the Upper Barnham Heath terrace is provided by sample BMH1710 from Barnham Heath Section 5, which gave a weighted mean average of 209 ± 10 ka. This suggests deposition of the bedded sands during MIS 7. Similar age estimates were obtained from the sample from Warren Wood (north) Test Pit 5 (WNW1708 = 218 ± 14 ka (Al) and 245 ± 16 (Ti-Li)). This may therefore be a downstream correlate of the Upper Barnham Heath terrace, and together the dates suggest terrace formation during MIS 8 to MIS 7.

Age estimates for the Lower Barnham Heath terrace were obtained from four samples from Barnham Heath Sections 1 and 2. Three of these gave results that are in good agreement. BMH1702 produced a weighted mean average of 116 ± 16 ka. For BMH1703, the Al centre provided an age estimate of 137 ± 14 ka, while the Ti-Li centre provided an age estimate of 105 ± 35 ka. BMH1709 provided a result from the Al centre alone (149 ± 7 ka), as the Ti-Li centre experienced the same issues as described above for sample BMH1707. These results indicate terrace formation during MIS 6–5. BMH1701 produced a mean weighted average age of 211 ± 10 ka. This appears to be an overestimate of the age of terrace formation, being more consistent with the age obtained from Section 5 for the Upper Barnham Heath terrace. This may be due to incomplete bleaching or reworking of older sediments.

Sampling of deposits associated with the Barnham Cross Common terrace was limited to just one location, Warren Wood (east) Test Pit 7 (WNW1713). Age estimates for the sands overlying the coarse gravel are 176 ± 15 ka (Al) and 148 ± 16 ka (Ti-Li). These results are more consistent with the age estimates for the Lower Barnham Heath terrace. The Barnham Cross Common terrace can be assigned to the Devensian on lithostratigraphic grounds. It is clearly a separate, younger aggradation to the Lower Barnham Heath terrace, dated here to MIS 6–5, which is continuous with the sub-alluvial gravel. Furthermore, the presence of a low Devensian terrace just above the modern floodplain is a feature of several other rivers in lowland England, such as the Thames, Trent and Cam (Bridgland, 2010; Gao and Boreham, 2010). The age estimate for WNW1713 suggests that either the deposits in Test Pit 7 are part of the Lower Barnham Heath terrace, but with subsequent erosion at the margin of the Barnham Cross Common terrace having removed the upper part of the sequence, or the gravels are Devensian but are overlain by sands reworked from the Lower Barnham Heath terrace.

6. Evolution of the Little Ouse valley

The Little Ouse evolved as part of the drainage network that emerged at the end of the Anglian glaciation (Fig. 10). During the Anglian, the pre-existing drainage network was destroyed and the region's landscape was remodelled through the deposition of tills, glacial outwash gravels, and the erosion and infilling of sub-glacial valleys. As the ice sheets retreated, the melting of trapped ice created kettle holes in which small lakes or large ponds developed. Streams and rivers would have developed in the depressions left by partially infilled glacial channels, for example the Lark and Black Bourne which in places developed over glacial tunnel valleys (Woodland, 1970). A similar relationship appears to exist between Anglian glaciogenic deposits and the Little Ouse. At Warren Wood (north), the sediments laid down by the earliest iteration of the Little Ouse (Warren Wood terrace) overlie glacial sands and silts that infill a steeply incised channel or basin that cuts through till. Likewise, near the source of the river, boreholes record thick sequences of glaciogenic silt and clay beneath the fluvial sands and gravels (Fig. 8).

Following the establishment of the Little Ouse drainage system during late MIS 12 and MIS 11, downcutting occurred during MIS 10 followed by aggradation of the Redhill terrace gravels between MIS 10 and MIS 8. Further downcutting occurred during MIS 8, followed by aggradation of the Upper Barnham Heath terrace deposits between MIS 8 and MIS 7, and during MIS 6, followed by aggradation of the Lower Barnham Heath terrace and deposition of the overlying bedded sands with dropstones at Barnham Heath during MIS 6/5. West (2009) suggested that the bedded sands at Barnham Heath were deposited in a pro-glacial lake that formed as Fenland ice blocked the outlet of the Little Ouse near Brandon. No further evidence for this was identified in the sections and boreholes examined for the current study. Finally, the Barnham Cross Common terrace was formed following downcutting of the river to its current base level and aggradation during the Devensian, and the subsequent formation of the modern floodplain.

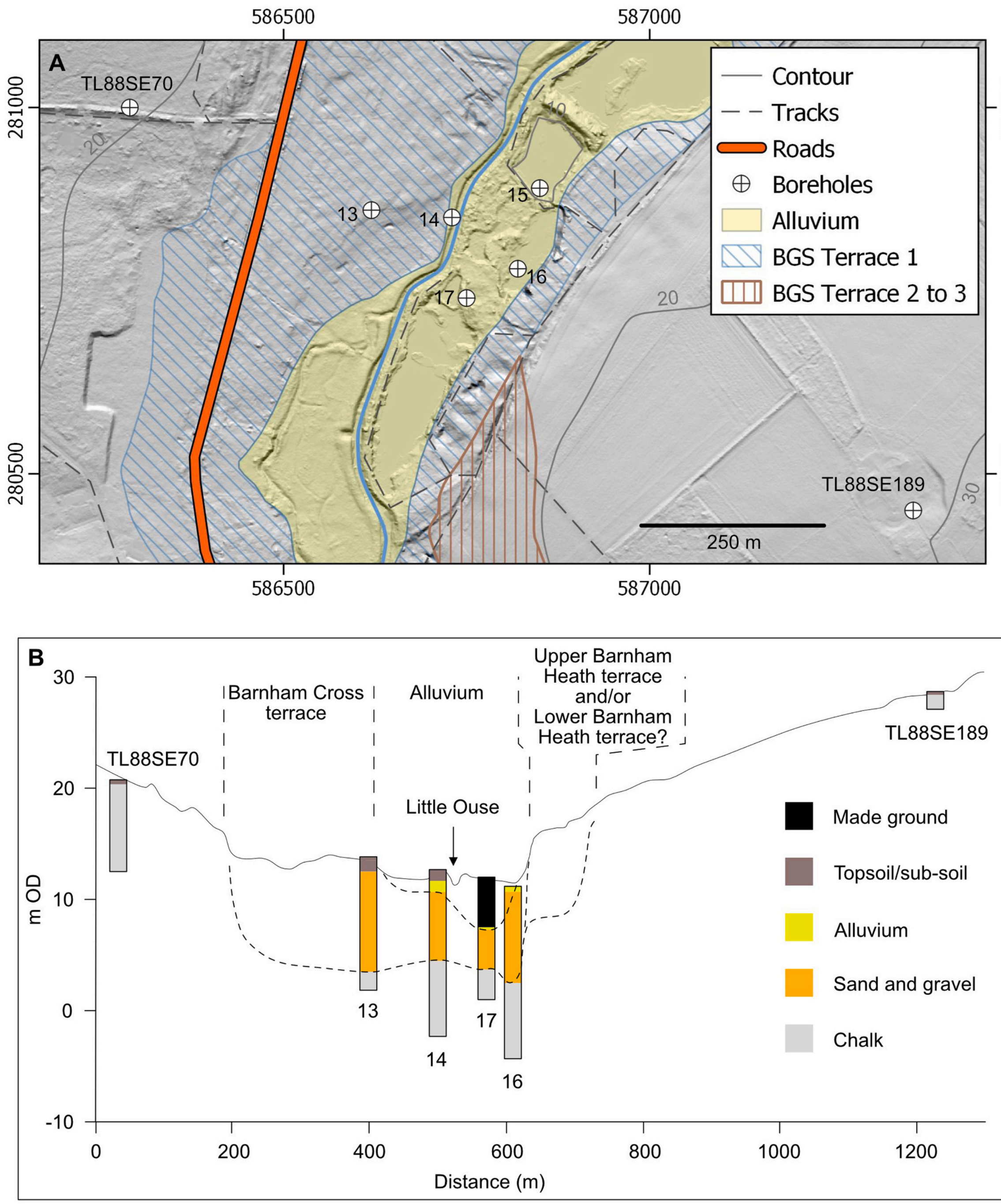

Fig. 9. Barnham Cross Common. A) Hillshade elevation model (© Environment Agency copyright and/or database right 2022) showing location of BGS boreholes and BGS mapping (coordinate system = OSGB 1936 British National Grid). B) Interpretation of the Barnham Cross Common geology. Borehole No. 13 is the stratotype for the Barnham Cross Common terrace.

7. Palaeolithic archaeology

The revised terrace stratigraphy and chronology outlined above provides the framework for interpreting the Palaeolithic assemblages from the Little Ouse sites. These consist of historic collections of material gathered from Barnham Heath, Redhill, Santon Downham, and Broomhill, and the recently excavated assemblages described above (Table 6).

At two locations, quarrying has affected multiple terraces, potentially producing mixed assemblages. However, at Redhill and Broomhill, only gravels of the Redhill terrace were worked, and therefore the collections from these sites provide the clearest view of lithic technology associated with that terrace. The assemblages are similar, with a predominance of pointed, sub-cordate and crude handaxes, and a paucity of ovate and cordate forms (Table 6). Other artefact types are clearly underrepresented in the museum collections, as demonstrated by the recently excavated material, particularly the large numbers of flakes recovered from the basal deposit at Redhill. The assemblage from the coarse basal deposit at Redhill is intriguing. The artefacts are fairly fresh, suggesting limited disturbance of a local occupation site from early in the formation of the Redhill terrace, potentially late MIS 10 or early MIS 9. The assemblage is focussed on the production of large flakes, which are frequently retouched, with handaxe manufacture either absent or a minor component of lithic technology. The relationship between this

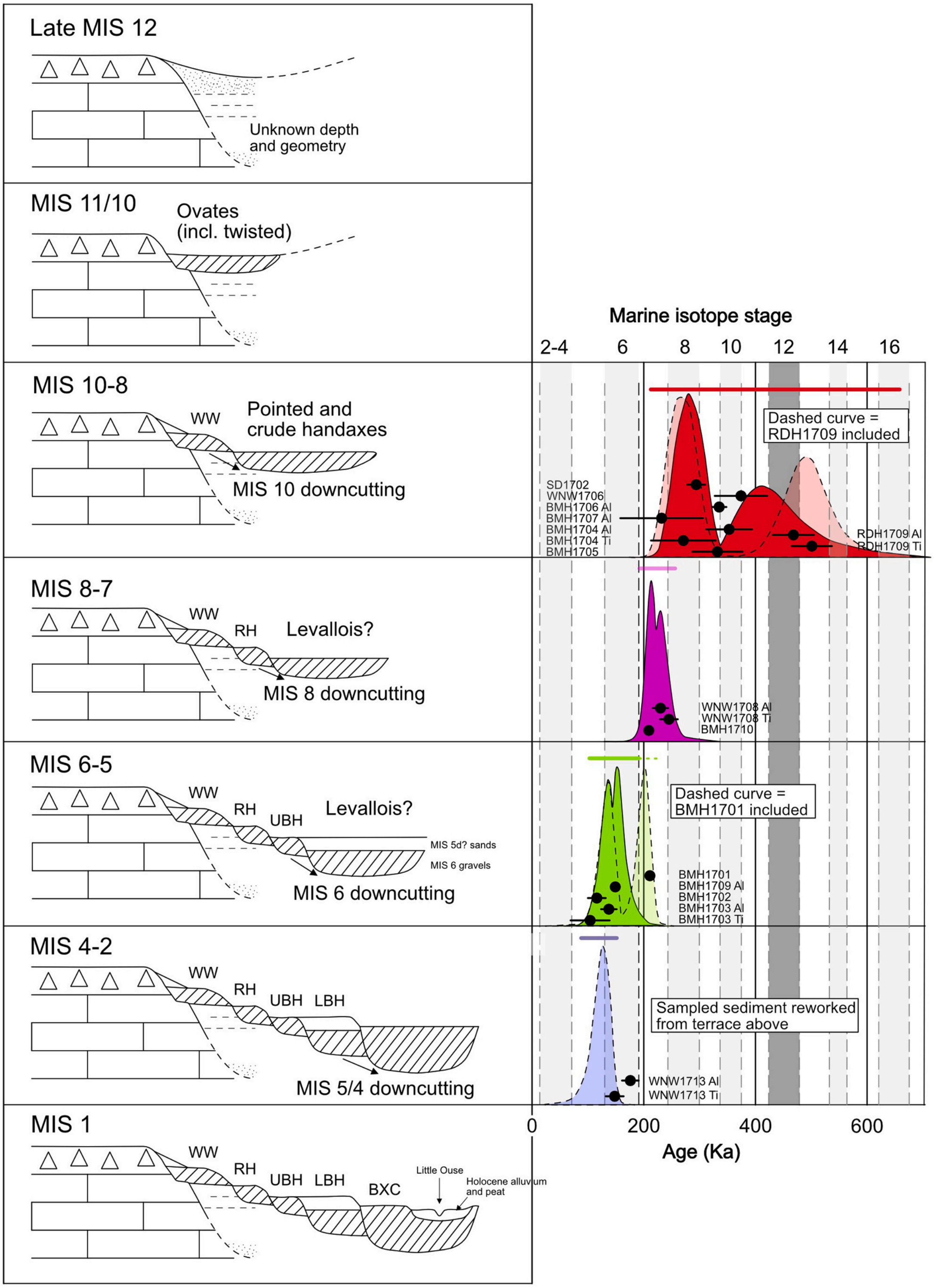

Fig. 10. The development and chronology of the Little Ouse fluvial terraces.

fresher core and flake assemblage and the more rolled handaxes of the historic collections remains uncertain.

There is uncertainty concerning the provenance of the historic artefact collections from Santon Downham. The early descriptions provided by Evans (1868), (1872); Prigg (1869), and Flower (1869), indicate gravel workings of Mr White of Little Lodge Farm as the source of the Santon Downham material. These workings do not appear on contemporary or 1st edition OS maps, and the clay pit that is shown (see above and White 1997) does not match the description of the sedimentary sequence provided by Evans. In fact, the only deposits comparable to the early descriptions are those seen in Warren Wood (north) Borehole 19/2. The Warren Wood terrace can be traced westwards to the southern part of Little Lodge Copse (Fig. 5). The pits here match the early descriptions, and are the most likely source of the Santon Downham artefacts. These gravel workings span the Warren Wood and Redhill terraces. The Santon Downham historic collection is therefore likely to contain material from both terraces. Differences between the Santon Downham and the Redhill and Broomhill collections

Table 4
ESR dosimetric data obtained on quartz extracted from sediments from Little Ouse sites. 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 20 μm) 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((InateIbl)/Inat) 100). Uncertainties are given at 1 σ.

Terrace level	**Sample**	D_α (μGy/a)	D_β (μGy/a)	D_γ (μGy/a)	D_γ in situ (μGy/a)	Cosmic (μGy/a)	D_a (μGy/a)	**Water (%)**	Al Bl. (%)
Sediments underlying Warren Wood Terrace									
Santon Downham CP S1	SD1701	18 ± 1	375 ± 13	247 ± 10	307 ± 15	60 ± 3	761 ± 22	15 ± 5	42
Santon Downham Warren Wood TP3	SDWW1801 (total curve)	33 ± 1	598 ± 14	425 ± 11	180 ± 9	142 ± 7	952 ± 20	15 ± 5	51
Santon Downham Warren Wood TP3	SDWW1801 (restricted)	33 ± 1	598 ± 14	425 ± 11	180 ± 9	142 ± 7	952 ± 20	15 ± 5	51
Warren Wood Terrace									
Warren Wood TP6	WNW1710	25 ± 1	685 ± 17	400 ± 13	406 ± 20	130 ± 6	1246 ± 29	15 ± 5	42
Redhill Terrace									
Barnham Heath S3	BMH1705	16 ± 1	482 ± 13	270 ± 11	492 ± 25	97 ± 5	1086 ± 30	15 ± 5	47
Barnham Heath S4	BMH1704	16 ± 1	625 ± 14	318 ± 11	395 ± 20	90 ± 4	1125 ± 27	15 ± 5	38
Barnham Heath S4	BMH1707	13 ± 1	568 ± 15	278 ± 12	384 ± 19	114 ± 6	1079 ± 27	15 ± 5	41
Barnham Heath S4	BMH1706	6 ± 1	243 ± 12	126 ± 10	241 ± 12	101 ± 5	592 ± 20	15 ± 5	37
Redhill	RDH1709	18 ± 1	547 ± 16	307 ± 13	290 ± 14	137 ± 7	991 ± 25	15 ± 5	45
Santon Downham S3	SD1702	20 ± 1	466 ± 19	291 ± 15	347 ± 17	139 ± 7	973 ± 29	15 ± 5	33
Warren Wood TP4	WNW1706	10 ± 1	436 ± 13	219 ± 10	293 ± 15	150 ± 8	889 ± 22	15 ± 5	40
Barnham Heath Terrace						±			
Barnham Heath S1	BMH1703	10 ± 1	647 ± 14	283 ± 10	299 ± 15	128 ± 6	1084 ± 23	15 ± 5	24
Barnham Heath S1	BMH1702	14 ± 1	608 ± 14	297 ± 10	237 ± 12	121 ± 6	979 ± 21	15 ± 5	25
Barnham Heath S1	BMH1701	10 ± 1	584 ± 14	264 ± 11	278 ± 14	103 ± 5	975 ± 23	15 ± 5	34
Barnham Heath S2	BMH1709	9 ± 1	392 ± 14	192 ± 10	172 ± 9	143 ± 7	717 ± 19	15 ± 5	15
Barnham Heath S5	BMH1710	16 ± 1	664 ± 11	330 ± 9	340 ± 17	140 ± 7	1160 ± 22	15 ± 5	32
Warren Wood TP5	WNW1708	27 ± 1	767 ± 18	439 ± 14	398 ± 20	132 ± 7	1324 ± 30	15 ± 5	40
Barnham Cross Common Terrace									
Warren Wood TP7	WNW1713	8 ± 1	403 ± 14	193 ± 11	271 ± 14	155 ± 8	837 ± 22	15 ± 5	38

Table 5
ESR results obtained on quartz extracted from sediments from Little Ouse sites. Uncertainties are given at 2 σ.

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)	
Sediments underlying Warren Wood Terrace								
Santon Downham CP S1	SD1701	675 ± 101	0.99	887 ± 68	739 ± 184	0.98	972 ± 62	
Santon Downham Warren Wood TP3	SDWW1801 (total curve)	3437 ± 1375	0.98	3607 ± 723	682 ± 18	0.99	716 ± 12	
Santon Downham Warren Wood TP3	SDWW1801 (Al restricted)	1120 ± 539	0.99	1175 ± 284				
Warren Wood Terrace								
Warren Wood TP6	WNW1710	807 ± 80	0.99	648 ± 33	264 ± 35	0.98	212 ± 15	
Redhill Terrace								
Barnham Heath S3	BMH1705	335 ± 71	0.99	308 ± 65	379 ± 63	0.98	349 ± 58	332 ± 45
Barnham Heath S4	BMH1704	397 ± 46	0.99	353 ± 41	305 ± 65	0.97	271 ± 58	
Barnham Heath S4	BMH1707	250 ± 80	0.99	232 ± 74	467 ± 60	0.98	433 ± 56	
Barnham Heath S4	BMH1706	198 ± 15	0.99	335 ± 13	245 ± 65	0.95	414 ± 56	
Redhill	RDH1709	464 ± 73	0.99	468 ± 37	497 ± 70	0.98	501 ± 36	
Santon Downham S3	SD1702	296 ± 30	0.99	304 ± 31	282 ± 14	0.98	290 ± 15	294 ± 16
Warren Wood TP4	WNW1706	335 ± 50	0.99	377 ± 56	328 ± 70	0.97	369 ± 79	374 ± 47
Barnham Heath Terrace								
Barnham Heath S1	BMH1703	149 ± 15	0.98	137 ± 14	114 ± 38	0.96	105 ± 35	
Barnham Heath S1	BMH1702	111 ± 16	0.99	113 ± 16	121 ± 33	0.91	124 ± 34	116 ± 16
Barnham Heath S1	BMH1701	206 ± 13	0.98	211 ± 14	205 ± 71	0.98	210 ± 73	211 ± 10
Barnham Heath S2	BMH1709	107 ± 10	0.99	149 ± 7	131 ± 45	0.97	183 ± 20	
Barnham Heath S5	BMH1710	242 ± 16	0.99	209 ± 14	251 ± 50	0.95	216 ± 43	209 ± 10
Warren Wood TP5	WNW1708	288 ± 18	0.99	218 ± 14	324 ± 21	0.97	245 ± 16	
Barnham Cross Common Terrace								
Warren Wood TP7	WNW1713	147 ± 12	0.99	176 ± 15	124 ± 13	0.98	148 ± 16	

will therefore provide an indication of the character of the Warren Wood terrace Palaeolithic record. Pointed, sub-cordate and crude handaxes, similar to those from Broomhill and Redhill, occur in significant numbers, but cordate and ovate handaxes are by far the most common form, including a significant number with twisted profiles (Table 6). The cordate/ovate component of the Santon Downham material is typically more patinated, supporting the notion that these have a different taphonomic history to the rest of the material and probably derive from the Warren Wood terrace. It is also noteworthy that three of the Santon Downham ovate handaxes appear to have damage incurred through heating.

At Barnham Heath, sediments of the Redhill, Upper Barnham Heath, and Lower Barnham Heath terraces were worked in the Barnham Old Pit and River Pit. It is clear from Basil Brown's notes, that the majority of the material was recovered from the southern part of the Old Pit, indicating their provenance in the basal deposits of the Redhill terrace. It is possible to isolate an assemblage of material that must have come from this pit based on recorded years of recovery – anything found prior to 1952 had to come from the Old Pit, as the River Pit did not open until that year (Fig. 2). This amounts to 139 artefacts (Table 6). As at Redhill and Broomhill, ovates and cordates are rare, and pointed and sub-cordate handaxes are well represented, but here crude handaxes are more common. This may in part reflect more comprehensive collecting of the full range of lithic artefacts at Barnham Heath, which is indicated by the large number of flakes and cores from the site. The latter consist of alternately flaked migrating platform cores (MPCs) and one simple prepared core (SPC) that is similar to the SPCs from Purfleet (White et al., 2024).

The remaining Barnham Heath material cannot be assigned to a specific terrace with certainty, although it is likely that much of it is also from the basal deposits of the Redhill terrace given Basil Brown's notes on provenance. In general, the potentially mixed material is similar to the Redhill terrace group (Table 6), including the relative proportions of different handaxe types, and large numbers of MPCs, hard hammer flakes, and some SPCs. However, there are four artefact types that appear in the mixed group that are absent from the Redhill terrace group: Levallois cores, Levallois flakes, trihedral handaxes and unifaces. There is evidence in this group for the mixing of different industries with different taphonomic histories. Of the fresher material (fresh or slightly rolled), 16.7 % are related to Levallois technology, 18.8 % are handaxes and 12.5 % are scrapers. The moderately rolled material is dominated by hard hammer flakes (56.9 %), with handaxes accounting for 12.2 % and Levallois just 1.6 %. The heavily rolled material is dominated by handaxes (49.1 %), particularly crude and pointed forms, but Levallois is absent. This suggests the presence of a more derived assemblage dominated by handaxes with MPCs and hard hammer flakes, with a less derived assemblage of which Levallois is a major component.

It is likely that the differences between these two groups of Barnham Heath material is related to the mixing of material from multiple terraces in the mixed group versus a collection of material from the Redhill terrace. The most significant difference is the presence of Levallois cores and flakes, which are therefore likely to be derived from deposits of either the Upper Barnham Heath terrace or Lower Barnham Heath terrace. This is supported by an observation recorded by Brown in his notebook, in which he notes the occurrence of Levallois artefacts and handaxes in the fluvial gravels to the north of the main area of artefacts along the southern edge of Barnham Old Pit. Unfortunately, we do not know if these were rolled handaxes, reworked from older sediments, or fresher artefacts that could be broadly contemporary with the Levallois material.

8. Discussion

8.1. Lower Palaeolithic of central East Anglia

The fluvial aggradations of the rivers Bytham and Little Ouse provide a framework for assessing broad-scale patterns of human presence/absence and technological change from c. 800 ka to c. 200 ka. The archaeological material associated with these deposits is typically in secondary context, time-averaged assemblages. Assuming discontinuity of occupation during (some) glacial periods, variation between terrace assemblages will at least in part be due to the arrival in Britain of new

Table 6
Composition of the Palaeolithic assemblages from sites discussed in the text. Barnham Heath museum collections divided into material assigned to Redhill terrace based on Basil Brown records and discovery dates, and mixed material that cannot be assigned to a specific terrace. Numbers in parentheses are the totals provided by TERPS (Wessex Archaeology, 1996). (* = TERPS totals for Barnham Heath cannot be divided into Redhill terrace and mixed terrace groups, Museum = material in museum collections recorded for this study, BPP = artefacts recovered during Breckland Palaeolithic Project fieldwork).

Site	Santon Downham		Redhill		Broomhill Pit		Barnham Heath		
Terrace	Warren Wood and Redhill		Redhill		Redhill		Redhill		Redhill, Upper Barnham Heath and Lower Barnham Heath
Collection	Museum	BPP	Museum	BPP	Museum	BPP	Museum	BPP	Museum
Handaxes (n)	106 (143)	-	70 (77)	-	54 (87)	-	49 (?*)	-	99 (500 *)
Crude	8.5 %	-	15.7 %	-	25.9 %	-	40.8 %	-	41.4 %
Small crude	4.7 %	-	4.3 %	-	5.6 %	-	6.1 %	-	10.1 %
Pointed	17.0 %	-	47.1 %	-	35.2 %	-	26.5 %	-	22.2 %
Sub-cordate/ovate	12.3 %	-	14.3 %	-	13.0 %	-	10.2 %	-	7.1 %
Cleaver	3.8 %	-	1.4 %	-	1.9 %	-	6.1 %	-	6.1 %
Cordate	27.4 %	-	4.3 %	-	9.3 %	-	2.0 %	-	1.0 %
Ovate	21.7 %	-	4.3 %	-	3.7 %	-	2.0 %	-	4.0 %
(twisted ovate/cordate)	n = 13		n = 1		n = 1		n = 0		n = 0
Ficron	-	-	5.8 %	-	-	-	-	-	-
Flat-butted cordate	1.9 %		-		-		-		-
Uniface	1.9 %	-	-	-	-	-	-	-	2.0 %
Trihedral	-	-	-	-	1.9 %	-	-	-	2.0 %
Unidentifiable	0.9 %	-	2.9 %	-	3.7 %	-	6.1 %	-	4.0 %
Handaxe roughout (n)	0 (6)	-	2 (4)	-	0 (9)	-	2 (0)	-	7 (0)
Levallois									
Levallois flake (n)	0 (1)	-	0 (0)	-	0 (1)	-	-	-	9 (3)
Levallois core (n)	0 (0)	-	0 (0)	-	0 (0)	-	-	-	4 (5)
Cores (n)	0 (0)	-	0 (1)	4	0 (0)	1	9 (?*)	1	46 (120 *)
Migrating platform core	-	-	-	100.0 %	-	100.0 %	88.9 %	100.0 %	73.9 %
Simple prepared core	-	-	-	-	-	-	11.1 %	-	26.1 %
Unretouched flakes (n)	2 (6)	9	11 (11)	107	2 (6)	19	75 (?*)	14	275 (350 *)
Hard hammer	100.0 %	77.8 %	90.9 %	83.2 %	100.0 %	78.9 %	88.0 %	92.9 %	78.2 %
Soft hammer	-	-	9.1 %	4.7 %	-	5.3 %	8.0 %	7.1 %	5.1 %
Indeterminate	-	22.2 %	-	12.1 %	-	15.8 %	4.0 %	-	16.7 %
Retouched flakes (n)	3 (4)	2	6 (5)	20	3 (11)	2	3 (0)	2	18 (0)
Scraper	100.0 %	100.0 %	50.0 %	40.0 %	100.0 %	50.0 %	66.7 %	100.0 %	100.0 %
Denticulate	-	-	16.7 %	25.0 %	-	-	-	-	-
Notch	-	-	33.3 %	35.0 %	-	50.0 %	33.3 %	-	-
Retouched natural spalls (n)	0 (0)	-	0 (0)	-	0 (0)	1	2 (0)	1	0 (0)
Other (n)	1 (0)	-	2 (2)	2	1 (1)	-	0 (?*)	-	6 (20 *)

human groups with their own traditions of stone tool manufacture. This fluvial archive provides a broad framework of chronological variation within which (near) primary context assemblages can be considered (Fig. 11).

At present, the timing of the earliest occupation of the region is unknown, with the oldest Bytham aggradations yet to be systematically searched for artefacts. The earliest evidence comes in the form of a few hard hammer flakes, including one scraper, recovered from gravels of the Ingham and Knettishall terraces, suggesting sparse or short-lived occupation of the area c. 800 and c. 700 ka respectively (Davis et al., 2021a). Handaxes first occur in the Timworth terrace. These are typically crude forms made with hard hammers, and are likely to be reworked from MIS 15 interglacial deposits (Lewis et al., 2021). Rolled crude handaxes are found alongside fresher ovates and scrapers in a mixed assemblage from the MIS 12 gravels at Warren Hill. At High Lodge, River Bytham floodplain sediments have been dated to MIS 13 (Ashton et al., 1992). Two assemblages occur in stratigraphic superposition: a primary context core and flake assemblage with elaborate scrapers in Bed C; and an ovate-dominated handaxe assemblage in Bed E. Crude handaxes are absent. The sequence here helps interpret the handaxe assemblages from Warren Hill and the Timworth terrace sites, while also providing the resolution required to identify the scraper and ovate assemblages as two distinct industries.

The handaxe collection from Santon Downham includes an assemblage of ovate and cordate handaxes, often with twisted profiles, which is likely to relate to occupation during MIS 11. The primary context record enhances our understanding of this period, showing multiple phases of occupation, each with distinct material culture. At East Farm Barnham, two human groups have been inferred from the presence of two industries in stratigraphic superposition, first characterised by a core and flake industry (Clactonian), then later during the same interglacial (Hoxnian; MIS 11c), by the presence of handaxes, including twisted ovates (Ashton et al., 2016; White et al., 2019). Further detail of human behaviour during MIS 11c is provided by Elveden, where twisted ovates form a significant part of lithic technology (Ashton et al., 2005), and Beeches Pit, where the use of fire has been identified (Gowlett et al., 2005; Preece et al., 2007). At Hoxne, two industries have been dated to MIS 11a, the Lower Industry characterised by ovate handaxes, the Upper Industry by pointed handaxes and elaborate scrapers (Singer et al., 1993; Ashton et al., 2008).

The Little Ouse sites provide evidence for occupation during MIS 9. Handaxes are typically crude or pointed forms, with only rare occurrence of cordates and ovates. Core working is also present, but without an accompanying primary context record, it is difficult to discern whether these represent different industries, as Wymer (1985) suggested at Barnham Heath, or were produced alongside handaxes as part of the Acheulean technological repertoire. Perhaps more convincing is the excavated assemblage from Redhill, which is so distinct in terms of condition and technology from the historic handaxe-dominated collections from the same sequence, and is a sufficiently large sample, that it is a good candidate for a distinct core and flake industry early in the interglacial.

In general, this patterning across the Lower Palaeolithic record of central East Anglia finds parallels in the broader record of southern Britain, such as: the early core and flake assemblages from Happisburgh Site 3 and Pakefield (Parfitt et al., 2005, 2010); the occurrence of crude

MIS	Fluvial archive			Primary context sites		
	River	Aggradation	Technology	Site	Layer	Primary technology
1	Little Ouse	Modern floodplain				
2		Barnham Cross Common	?			
3				Lynford	Facies B	Handaxes
4						
5		Lower Barnham Heath	Levallois?			
6						
7		Upper Barnham Heath	Levallois?			
8						
9		Redhill	Pointed handaxes Core and flake?			
10						
11		Warren Wood	Ovates w. twisted			
(11a)				Hoxne	Stratum A	Handaxes w. scrapers
				Hoxne	Stratum B	Handaxes
(11b)						
(11c)				Beeches Pit	Bed 4	Handaxes
				Elveden	Beds 3, 4 & 5	Ovates w. twisted
				East Farm Barnham	Unit 6	Ovates w. twisted
				East Farm Barnham	Unit 5	Core and flake
12		Warren Hill deposits	Ovates w. crude handaxes and scrapers (mixed)	Anglian till		
13	Bytham	Timworth	Ovate handaxes	High Lodge	Bed E	Ovate handaxes
				High Lodge	Bed C	Core and flake w. scrapers
14			Crude handaxes			
15		Knettishall	Core and flake			
16						
17		Ingham	Core and flake			
18						
19		Seven Hills				

Fig. 11. Summary of the secondary and primary context records from central East Anglia.

handaxes in MIS 15 deposits at Fordwich (Key et al., 2022); ovate handaxes in MIS 13 deposits at Boxgrove (Roberts and Parfitt, 1999) and MIS 12 gravels in the Solent (Davis et al., 2021b) and Middle Thames (Wymer, 1999); Clactonian and Acheulean assemblages during MIS 11 (Wenban-Smith, 2013; White et al., 2018); and core and flake assemblages at Purfleet and Cuxton preceding handaxe assemblages dominated by pointed forms with ficrons and cleavers during MIS 9 (Schreve et al., 2002; Wenban-Smith et al., 2007; White et al., 2018; Rawlinson et al., 2022). There are also some differences that point to regional variation: the absence of High Lodge-type scrapers in MIS 12 or 13 contexts outside of the Breckland; and the contrasting modal forms of handaxes during MIS 11c from East Anglia (ovates, including twisted forms) and the Thames (pointed/triangular forms; White et al., 2019).

8.2. *Early Middle Palaeolithic of East Anglia*

The evidence from Barnham Heath indicates that Levallois artefacts first occur in the region in deposits associated with either or both of the Upper Barnham Heath and Lower Barnham Heath terraces, sometime during MIS 8–5. At present it is not possible to refine the chronology nor is it possible to determine the relationship between the Levallois artefacts and the handaxes in similar condition and from the same site.

The paucity of the Levallois record in central East Anglia is part of an imbalance in the distribution of early Middle Palaeolithic sites following the widespread appearance of Levallois in the Palaeolithic record of northwest Europe from late MIS 8 (Hérisson et al., 2016). In Britain, there is a relatively rich record from the Thames where a series of primary context sites are dated to late MIS 8/early MIS 7 and late MIS 7 (White et al., 2006; Scott, 2011). Outside of the Thames, the record is remarkably poor, and tends to be concentrated in the lower reaches of the larger rivers of southern and eastern England (Ashton et al., 2018). For East Anglia, there are just 131 Levallois artefacts from 47 findspots, but only six locations have more than three pieces (Wessex Archaeology, 1996, 1997). Taken as a whole, the British early Middle Palaeolithic record is dwarfed by the number of sites and the size of the assemblages found in mainland northwest Europe (see Hérisson et al., 2016 for a summary). Adding to this picture are the large number of Levallois artefacts being recovered from the submerged river systems of the southern North Sea (Tizzard et al., 2014; Amkreutz and van der Vaart-Verschoof, 2022; Bynoe et al., 2022; Davis et al., 2023; Roberts and Hamel, 2023).

There are a number of potential factors at play. Preservation is one issue, with the extensive and thick loess mantle, associated palaeosols, and dolines of mainland northwest Europe affording protection to archaeological assemblages (Antoine et al., 2003; Roebroeks, 2014). Such deposits are rare in Britain but lithic artefacts should still survive, either as (sub-) surface scatters on interfluves or in secondary context within the gravels of younger river terraces. The fact that Levallois artefacts are so rare outside of the Thames suggests that Britain was a marginal area for early Middle Palaeolithic occupation, and much more so than had been the case during previous interglacials of the Middle Pleistocene (Ashton et al., in press). One reason for this may have been the reductions in land connections to mainland Europe due to the development of the channel river system and the continued subsidence of the North Sea basin (Ashton and Lewis, 2002; Roebroeks, 2014). A further factor is the contrasting surface geology either side of the North

Sea basin. The loess cover of mainland Europe provided a rich biome with large areas of mammoth steppe (Zimov et al., 2012), whereas in Britain, redistribution of the thinner loess cover has formed a mosaic of poorer and richer soils (Catt, 1978), a process that would have created a more fragmented mammoth steppe with more dispersed herds of herbivores. For Neanderthals adapted to exploiting the richness of the Mammoth steppe of mainland Europe, Britain at this time may have presented an unfavourable environment at the edge of the Neanderthal world.

9. Conclusion

The Breckland of central East Anglia has a Pleistocene geological sequence spanning c. 1 million years, providing a framework for assessing changes in human technology and behaviour within a single changing palaeolandscape. The geological record and associated archaeological remains divide into three chronological periods: the fluvial deposits of the River Bytham, which span c. 1 Ma to 450 ka; the Hoxnian interglacial sites (c. 400 ka); and the fluvial terraces of the present drainage network, which records the past c. 400,000 years. New field data, together with the analysis of existing borehole records, and the application of ESR dating, enables a revised terrace stratigraphy and chronology for the Little Ouse to be developed, providing a framework for interpreting the associated Lower and early Middle Palaeolithic archaeology. This can be added to the previous work on the Bytham and Hoxnian sites, as well as the later Middle Palaeolithic site at Lynford (Boismier et al., 2012) to establish the changing character of lithic technology practised in this region from c. 800 ka to c. 60 ka. This reveals patterns of chronological variation, which are often reflected in broader trends across southern Britain, and are likely to reflect the traditions of tool-making of the various Lower and Middle Palaeolithic groups that occupied Britain during different periods of the Middle and Late Pleistocene.

CRediT authorship contribution statement

Luke Dale: Writing – review & editing, Investigation, Formal analysis. **Frederick Foulds:** Writing – review & editing, Supervision, Investigation. **Aaron Rawlinson:** Writing – review & editing, Investigation, Formal analysis. **Mark White:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Rob Davis:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Simon Lewis:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Marcus Hatch:** Writing – review & editing, Visualization, Investigation. **Nick Ashton:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Pierre Voinchet:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Jean-Jacques Bahain:** Writing – review & editing, Validation, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Euston Estate and the Forestry Commission for permission to undertake fieldwork and facilitating access to the fieldwork sites and for access to estate archives. We are grateful to Claire Harris, Joshua Hogue, Anne-Lyse Ravon and Durham University students for assisting with fieldwork. We would also like to thank staff at the Ashmolean Museum, British Museum, Cambridge Archaeology and Anthropology Museum, Ipswich Museum, Pitt Rivers Museum Oxford, and West Stow Anglo-Saxon Village for access to collections and support with data collection. The work reported in this paper was funded by Leverhulme Trust Research Project Grant (RPG-2016-039) for the Breckland Palaeolithic Project, the Calleva Foundation for the Pathways to Ancient Britain project, and Department of Archaeology, Durham University. The ESR and mobile gamma-ray spectrometers of the French National Museum of Natural History were bought with the financial support of the 'DIM MAP Île-de-France' program, the 'Région Centre' and the Labex BcDIV program respectively.

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