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Organic and soil material between tills in east-midland England – direct evidence for two episodes of lowland glaciation in Britain during the Middle Pleistocene

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ABSTRACT: This paper provides a record and analysis of a site in east-midland England, at which organic and soil material are found between two Middle Pleistocene tills. This is the first discovery of its kind in the area, and demonstrates unequivocally that the region was glaciated on two separate occasions, something that has long been inferred and articulated, but not actually demonstrated. The landforms, sediments and soils are studied with respect to their geomorphological, lithological, pedological, palaeobotanical and structural properties. The organic and soil material along with soil structures indicate, sequentially, a periglacial climate, a long period of warm temperate weathering and a cool temperate climate. Evaluation of this evidence in terms of existing published work identifies a number of problems with existing models and suggests that the most likely model for the glacial history of this part of midland England is an early Middle Pleistocene glaciation which is represented only by trace erratics, a Marine Isotope Stage (MIS) 12 age glaciation which moved across the area from the NW and deposited a chalk-free till, and an MIS 8 age glaciation that transported and deposited an upper chalky till from the NE.

KEYWORDS: Middle Pleistocene glaciations; midland England; MIS 12 glaciation; MIS 8 glaciation; organic and soil material

Introduction

The scientific issue

The glacial history of lowland east-Midland and Eastern England, before the Last Glacial Maximum (LGM Marine Isotope Stage (MIS) 2) is the subject of a large body of historical research (Geikie, 1894; Wright, 1937; Bowen *et al.*, 1986; Bowen, 1999; Clark *et al.*, 2004; Rose, 2009; Gibbard and Clark, 2011; Lee *et al.*, 2011), yet there is still no consensus as to the number, timing or extent of the glacial episodes. Indeed, recent papers have highlighted different interpretations (Gibbard *et al.*, 2009, 2012; Preece *et al.*, 2009; Rose, 2009; White *et al.*, 2010, 2017; Gibbard and Clark, 2011; Lee *et al.*, 2011, 2017; Bridgland *et al.*, 2014, 2015). These interpretations have been based, primarily, on the succession of glacial deposits and their association with related landforms leading, initially, to the proposal that there were two glaciations across the region (the Anglian/Elsterian and Wolstonian/Saalian) (Mitchell *et al.*, 1973; Shotton, 1983; Straw, 1983). This model was replaced, on the basis of till lithological studies, by a single glaciation model (Perrin *et al.*, 1979; Rose, 1989a) attributed to the Anglian Stage (MIS 12), but this, in turn, was challenged by Hamblin *et al.* (2000, 2005), and Lee *et al.* (2004) who, on the basis of field mapping, collectively proposed a multi-stage glacial model with glacier expansion over lowland England during MIS 16, 12, 10 and 6. Currently, based on amino acid racemisation (AAR) and optically stimulated luminescence (OSL) studies this multi-stage model has been rejected in favour of: (i) a single MIS 12 stage model (Pawley *et al.*, 2008; Preece *et al.*, 2009); (ii) a double MIS12 and 8 glaciation model (White *et al.*, 2010, 2017; Bridgland *et al.*, 2014, 2015), or (iii) an MIS 12 and 6 glaciation model (Gibbard *et al.*, 2009, 2012) of which (i) and (iii) are supported to some extent by a glaciotectonic process model that explains the relative juxtaposition of the key glacial units (Lee *et al.*, 2013, 2017).

The key reasons for these conflicting views are:

(i) Glacial deposits within the area are discontinuous and *not* separated by *direct* evidence that represents non-glacial conditions, so that there is no unequivocal case for more than one glacial episode.
(ii) Methods of dating the glacial deposits are either controversial (geomorphological dating by correlation with river terrace sequences) (Bridgland, 1994; Sumbler, 1995, 2001; Keen, 1999; Lee *et al.*, 2004; Rose, 2009; White *et al.*, 2010; Bridgland *et al.*, 2014), or are based upon geochronometric determinations that are at the limit of the age range (U-series, electron spin resonance (ESR), OSL), have limited replication (U-series, Rowe *et al.*, 1997, 1999), or are only now beginning to be replicated at a number of sites (AAR, Preece and Penkman, 2005; Penkman *et al.*, 2007, 2008, 2011; Preece *et al.*, 2007, 2009).

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(iii) The use of lithostratigraphy to correlate glacial units spatially, because glaciation is a tectonic rather than sedimentary process. Thus, glacial sequences do not always conform to lithostratigraphic principles, and may exhibit stratigraphic replication (vertically and horizontally), inversion and out-of-sequence ordering of units. Stratigraphy can only be reconciled by an integrated understanding of the geomorphological, sedimentological and glaciotectonic processes that determine the properties of a sequence (Lee *et al.*, 2013, 2017).

This paper seeks to address this problem by describing a site at Clipsham in east Midland England where organic deposits, soil properties and soil material have been observed directly between two tills. The study provides clear evidence for two glacial episodes, an intervening period of periglacial soil formation, warm temperate soil formation and cool temperate vegetation development. The tills are discussed in terms of patterns of ice movement in the region, and a proposal is made for the most likely ages of the glacial and non-glacial events.

Location and geology of the site (Supporting Information S1)

Clipsham Quarry is located in Rutland, eastern Midland England, 1 km south of Clipsham village and 10 km NNW of Stamford (Fig. 1). The critical sections are located where superficial deposits fill a buried channel. The Quaternary deposits in the area are dominated by till which covers the higher parts of the plateau (Woodland, 1978). Early Middle Pleistocene Bytham Sands and Gravels are located between 4 and 5.5 km north of the site in the NW–SE-trending buried valley of the Bytham River (Rose, 1987, 1989b, 1994, 2009) (Figs. 1 and 2).

Previous research

Although the glacial deposits at Clipsham have not previously been studied, the site is within a region where research has been carried out previously and is important to our understanding of the glacial history of lowland Britain (Fig. 3). Initial studies by Geikie (1894) (Fig. 3A) inferred a predominantly NE–SW direction of ice flow, although local studies such as that of Jukes-Browne (1910) noted that the tills of south–east Lincolnshire typically contained chalk and flint, whereas the tills of south–west Lincolnshire were rich in Jurassic rocks, especially harder beds of the Lias and Inferior Oolite. Lamplugh and Gibson (1910) recognized both NE–SW and NW–SE directions of ice flow across parts of the region as a result of field mapping and till lithology. This view was also supported by Harmer (1909, 1910, 1928) (Fig. 3B) who recorded the distribution of indicator erratics across midland and eastern England to infer the directions of glacier transport.

Detailed work on erratic clasts by Hollingworth and Taylor (1946) and Sabine (1949) recorded the presence of a Pennine- and NW-sourced chalk-free basal till in Northamptonshire, highlighting an ice-source which had not travelled over Cretaceous chalk. This deposit has subsequently been called the Bozeat Till (Barron *et al.*, 2006). Nevertheless, the importance of a chalky till, deposited by NE–SW-flowing ice and named the Oadby Till, has dominated most studies of the region (Shotton, 1953, 1968, 1976, 1983; Rice, 1968, 1981). Lithological and geomorphological studies by Straw (1983) in the east Midlands reinforced these findings. Rice (1968, 1981) also noted the presence of a reddish

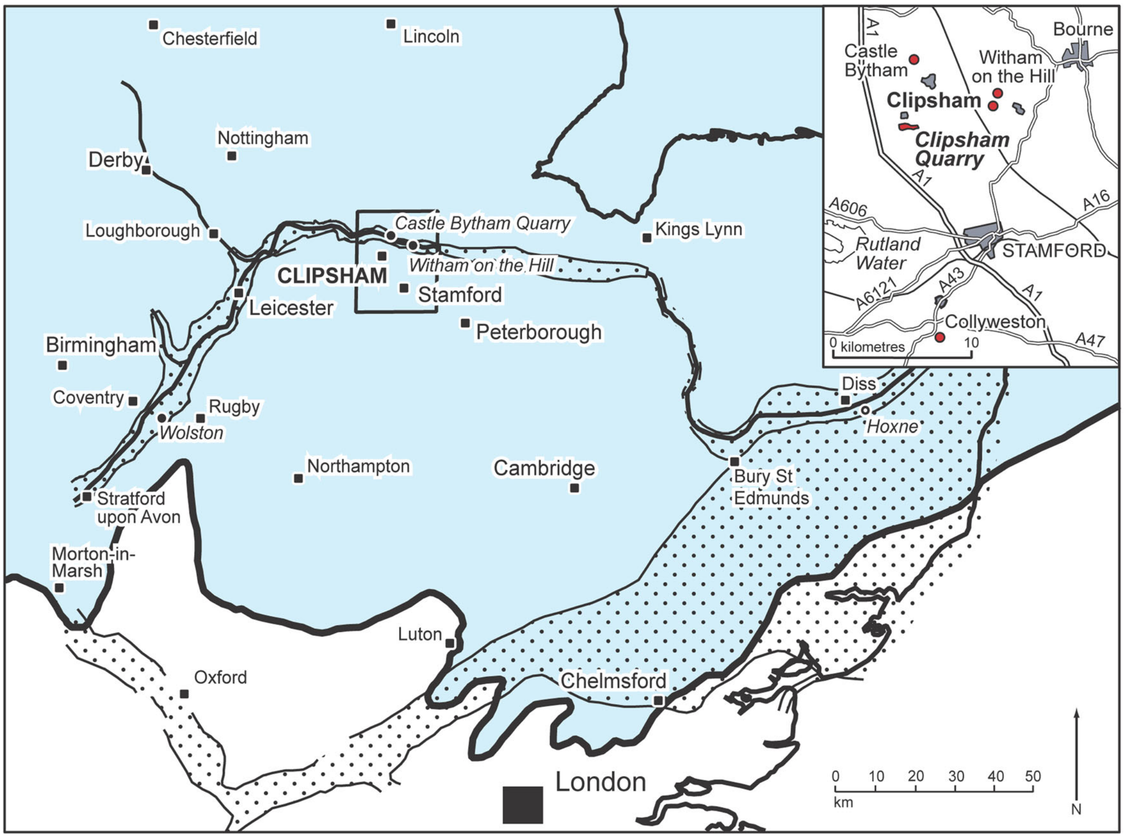

Figure 1. Location of the study site at Clipsham, north of Stamford, east Midland England. The dotted areas show the extent of the pre-glacial Bytham and Thames river systems. Area of ice cover is shown in blue. Details of the location of Clipsham Quarry and adjacent sites mentioned in the text are shown in the inset. [Color figure can be viewed at wileyonlinelibrary.com]

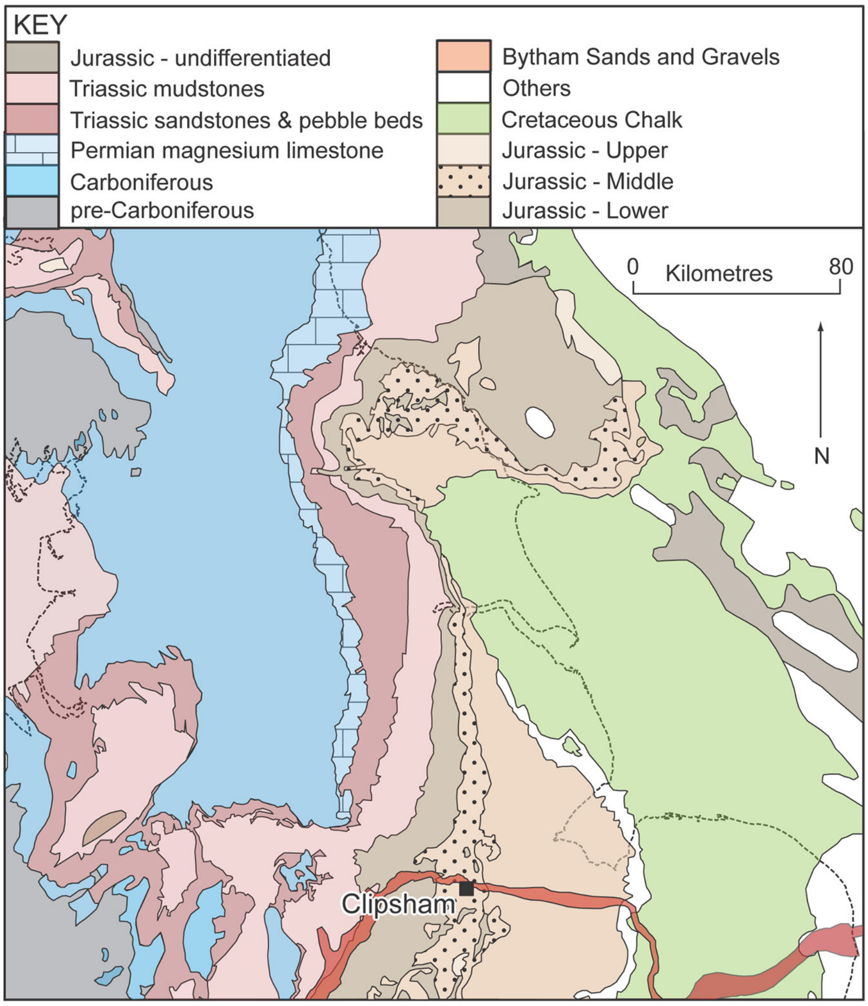

Figure 2. Bedrock geology of the area around and to the north of Clipsham, extending from the west coast of England to the western part of the North Sea region. Also shown is the location of the Bytham river valley and Sands and Gravels, the site of Clipsham and the present English coastline (shown by a dashed line). The geology is taken from British Geological Survey, Bedrock Geology UK South (1: 625 000 scale) and Geology of the UK, Ireland and continental shelf (1: 1000 000 scale) and is defined according to the rock-types identified in the lithological analyses reported in the text. [Color figure can be viewed at wileyonlinelibrary.com]

Triassic-sourced till, known as the Thrussington Till, beneath the chalky till and attributed it to a NW ice source. At some localities the Thrussington Till is interdigitated with the grey, Lias-rich and the grey, chalk-rich tills indicating mixing during entrainment or deposition (Rice, 1981).

West and Donner (1956) used lithology and clast fabric patterns of the tills across midland and eastern England (Fig. 3C) to derive ice-flow directions. This study identified: (i) a NW–SE ice flow which deposited the Triassic till in Leicestershire and a chalky till across east Midland England and East Anglia named the Lowestoft Till and (ii) a NE–SW, N–S and NW–SE ice flow that deposited a chalky till across Midland England and East Anglia named the Gipping Till. The Gipping Till and the Oadby Till refer to deposits of the same glacial event and eventually attributed to the Wolstonian Glaciation (Mitchell *et al.*, 1973). The glacier limits of West (1977) (Fig. 3C) do not coincide with the distribution of the Gipping Till of West and Donner (1956). This discrepancy is readily explained by: (i) the similarity of the ice flow paths of the Lowestoft and Gipping Glaciations in south-east East Anglia and (ii) the fact that interpretation of the pollen assemblage biostratigraphy applied at the time (Mitchell *et al.*, 1973; Rose, 1989a) indicated that all the glacial deposits in south-eastern East Anglia pre-date deposits attributed to the pollen-defined Hoxnian Stage.

These views were revised in 1979 as a result of a major study of till lithologies from 289 sample points across midland and eastern England, and the statistical evaluation of the results using three-dimensional regression (Perrin *et al.*, 1979) (Fig. 3D). Interpretation of these results suggested only one glacial deposit and hence only one glaciation across the region. In line with the pollen-based biostratigraphy (outlined above), all the deposits were considered facies of the Lowestoft Till located below the Hoxnian interglacial deposits at the type site, and hence attributed to the Anglian Stage.

The single ice-flow direction proposed by Perrin *et al.* (1979) was revised by Rose (1992) as a result of additional fieldwork and reference to the work of Hollingworth and Taylor (1946) and (West and Donner, 1956) (Fig. 3E). It was proposed that the early stages of glaciation during MIS 12 were represented by ice that flowed into the region from the north and north-west, respectively depositing chalk-free and Triassic-sourced tills, and that later in the same glacial event a chalky till was deposited by ice that moved through the Wash and Fen Basin then spread-out in a radial ice-flow pattern as a piedmont glacier lobe: two separate ice-flow directions in the single (Anglian/MIS 12) glaciation. Within the Clipsham area, the study of ice-flow indicators in till at Witham on the Hill, 6.5 km to the NE, and Castle Bytham, 5 km to the N (Fig. 1), indicated a chalk-free till deposited by a glacier with a north–south movement above Bytham Sands and Gravels (Lewis, 1989; Rose, 1989c).

Additional chronometric and stratigraphic methods provided independent means of establishing the age of glacial deposits beyond stratigraphic correlation with a ‘Hoxnian style’ pollen assemblage. Correlation of the glacial deposits with the geomorphologically, biostratigraphically and geochronometrically dated aggradations of the rivers Thames, Avon and Severn (Sumbler, 1983, 1995, 2001; Bridgland, 1994; Keen, 1999; Schreve, 2001) suggested that the chalky till of East Anglia (Lowestoft Till) was formed during MIS 12, while the chalky till of Midland England (Oadby Till) was

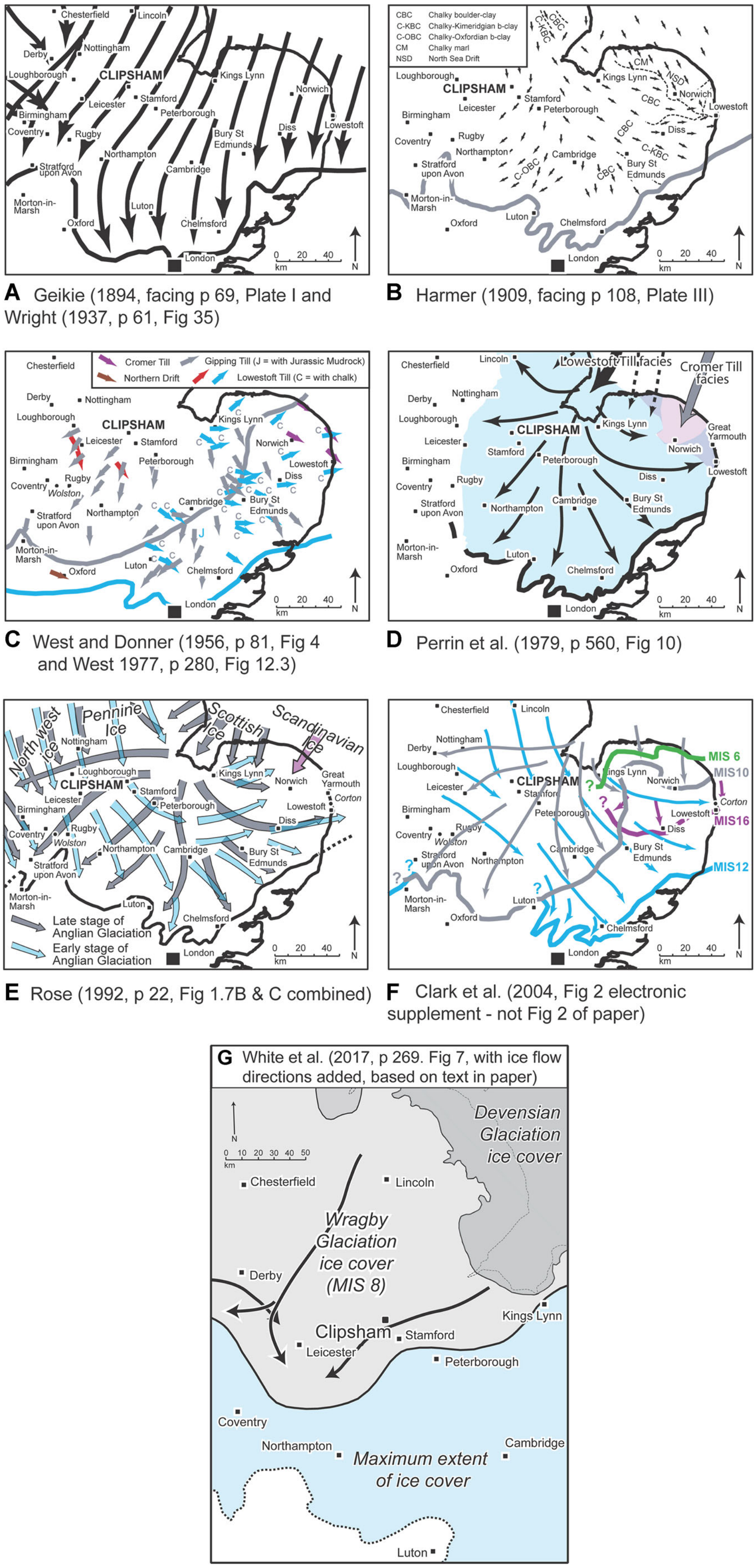

Figure 3. A–G. Published maps of ice flow patterns across Midland and Eastern England. Each figure (A to G) is taken directly from the publication named on each diagram. (A) Taken from Wright (1937), which is largely, but not entirely, based on Geikie (1894). (B) Taken from Harmer (1909) and based the distribution of indicator erratics. (C) Taken from West and Donner (1956), which is based on the results of clast fabric analysis of tills. The names allocated to the till are those used in the paper. The ice limits are taken from West (1977) and do not follow directly from the till fabric results (see text for explanation). (D) Taken from Perrin *et al.* (1979) based on statistical analysis of lithological properties of tills. (E) Taken from Rose (1992) based on lithological properties of tills including the data in West and Donner (1956) and Perrin *et al.* (1979). (F) Taken from Clark *et al.* (2004, electronic supplement) based on the lithological properties used in E and subsequent field mapping throughout eastern and midland England (Hamblin *et al.*, 2000, 2005). Figure 3G. (G) Taken from White *et al.* (2017), with additional information added. The interpretation is based on the relationship of the glacial deposits with dated river deposits, and the relationship to the glacial deposits to the pre-existing landscape. [Color figure can be viewed at wileyonlinelibrary.com]

formed during MIS 10, thus returning to the two-stage glacial model first proposed by West and Donner (1956). Likewise, a study of till lithologies and their distribution in East Anglia (Hamblin *et al.*, 2000, 2005, Rose in Clark *et al.*, 2004) (Fig. 3F) also supported this two-stage model (but proposed additional glacial events in northern Norfolk, although this is beyond the scope of this paper). The glacial history of this part of lowland Britain therefore returned to the models of the 1950–1970s with ice limits very similar to those proposed by West (1977).

Most recently, evidence has been presented that suggests that glaciation occurred in Midland England during MIS 8 (White *et al.*, 2010, 2017; Bridgland *et al.*, 2014, 2015). This Wragby Glaciation follows a model established by Straw (1983, 1991, 2011) and proposes that ice moved across midland England from the north-east and from the north-west (Fig. 3G). The reasons for this revision are based primarily upon the relationship of the glacial deposits to geomorphologically, biostratigraphically and geochrometrically dated river deposits, and in turn the morphology of the pre-existing landscape.

Clearly, the study of the glacial history of east Midland England is complex and the issues of how many glaciations and when the glacial events occurred remain unresolved. Papers by Westaway (2010) who summarizes this problem and the subsequent discussion (Langford, 2012a,b; Westaway *et al.*, 2012) are recommended to acquire an independent perspective of the problem. In some papers, a 'Saalian' age is given to the event, a geochronometric term which relates to the Quaternary of northern Europe. It is defined in Gibbard and Cohen (2008) as the period including MIS 10–6, and is correlated with the Wolstonian of Britain (Cohen and Gibbard, 2020). However, the age range attributed to the Saalian includes two different temperate stages (MIS 9 and 7) and three different cold stages (MIS 10, 8 and 6) which means that the terms 'Saalian' and 'Wolstonian' have little value for the definition of glacial episodes and understanding the processes over the time period concerned. Furthermore, there is dispute about chronological definition of the Elsterian and Saalian Stages, with evidence-based interpretations (Vandenberghe, 2000; Böse *et al.*, 2012; Lee *et al.*, 2012; Lang *et al.*, 2018) attributing the Elsterian to MIS 12 or to MIS 12 and 10, and the Saalian to MIS 10–6 or to MIS 8–6. Thus, in this paper the term Saalian is not used and the findings are placed in temporal context by reference to geochronometry (see below) and Marine Isotope Stages.

Recently, independent geochronological methods have been used to date the glacial history of the region. OSL results from north Norfolk, north Suffolk and the Vale of St. Albans support a single-glaciation model placing all the glacial deposits at these localities in MIS 12 (Pawley *et al.*, 2008, 2010). Similarly, although primarily concerned with the dating of proposed MIS 16 glacial deposits from north Norfolk, Preece *et al.* (2009) have indicated, using AAR analyses, that all the glacial deposits in the area are also of MIS 12 age (Penkman *et al.*, 2011, 2013).

The key facts that emerge from this review are that there should be two tills in the Clipsham area: a chalk-free till with Carboniferous erratics that must have been deposited by ice that travelled from the north and did not cross the Chalk bedrock, and a chalky till that must have been deposited by ice that travelled either from the NE (following the interpretations of Harmer and Straw) or E (following the interpretations of Perrin, Rose and Hamblin). Incorporating these ice-flow directions, a number of models have been developed and the case has been made for *both* multiple-stage and single-stage glacial histories. To a large extent this problem has arisen because the studies have depended upon: (i) the interpretation of the lithology of glacial sediments, a property that is subject to very complex geomorphological, deformational and sedimentological processes (Benn and Evans, 1998); (ii) dating by correlation with river aggradations, which is an approach that may still involve unresolved problems (Rose, 2006, 2009; Preece and Parfitt, 2008); and (iii) the results of a number of geochronometric studies which are still subject to development and not always capable of independent ratification (Preece *et al.*, 2007). The most important problem, however, is that hitherto there has been no site with non-glacial/subaerial deposits between two sets of glacial deposits. The sections at Clipsham redress this problem.

Methods (Supporting Information S2)

A typical example of the sediments and stratigraphy as represented by the exposure at Clipsham 1 (C1) (Fig. 4). All sites were levelled into Ordnance Datum (OD) and the sections were created with a mechanical excavator and cleaned by hand. A number of sections have been described and three are recorded as lithofacies logs (Fig. 5) with the full stratigraphy shown in a schematic composite log (Fig. 6). Details of the sedimentary and deformational structures were recorded by measured section drawings (see Fig. 11) and photography, and any structures measured for direction and dip were carefully cleaned with a trowel to reveal a clear, unambiguous 3D form. Non-sorted deposits are described as diamicton until interpreted, when they are known according to their process of formation as till, debris flow or mudflow, as appropriate. Details of the evidence availability and sedimentary methods are given in Supporting Information S2.

Geomorphology of the site and Lithofacies Unit 1 – limestone sand and gravel

The sediments at Clipsham are located in a buried channel cut into Lincolnshire Limestone Formation (Fig. 7B). This channel trends and slopes from the SW to the NE and is cut into the low-relief, eastward-dipping bedrock surface. The base of the channel slopes from 84.4 m OD in the SW to 79.5 m OD in the NE over a distance 500 m (Fig. 7B), giving a mean gradient of 0.98% (1 in 102, 9.8 m km^{-1}) typical of headwater streams in Britain (Ferguson, 1981). The maximum depth of the channel in the section studied is between 7 and 8 m and the width is between 35 and 55 m. Basal sediments within the channel consist of a fining-upward sequence of gravel, capped with sand and clayey silt (Figs. 5 and 6; Table S2). The size distribution changes from 98% gravel at the base, through 67% gravel, to 56% gravel at the top, and the percentage sand increases upwards in an inverse fashion (Fig. 8; Table S2) from 1.6% at the base to 38% at the top. The clasts are predominantly very angular (96–84%) with the greatest proportion of edge rounding in the middle part of the bed (Table S5), and gravel is composed overwhelmingly of local Jurassic limestone (99–96%). However, there is non-local material in the form of rare (<2%), far-travelled material (quartzite, vein quartz and flint) (Fig. 8; Table S3). The sand is composed of limestone grains and in places the sand and clayey silt are partially cemented (Fig. 11). Palynomorphs from the silts are rare and difficult to identify, but possibly of Quaternary age (Table S4). The direction of dip of the a–b plane (imbrication) is towards the SSW changing progressively upwards towards the W (Figs. 5 and 8; Table S6).

The morphology of the channel and properties of the sediment fill suggests that this is a headwater channel cut

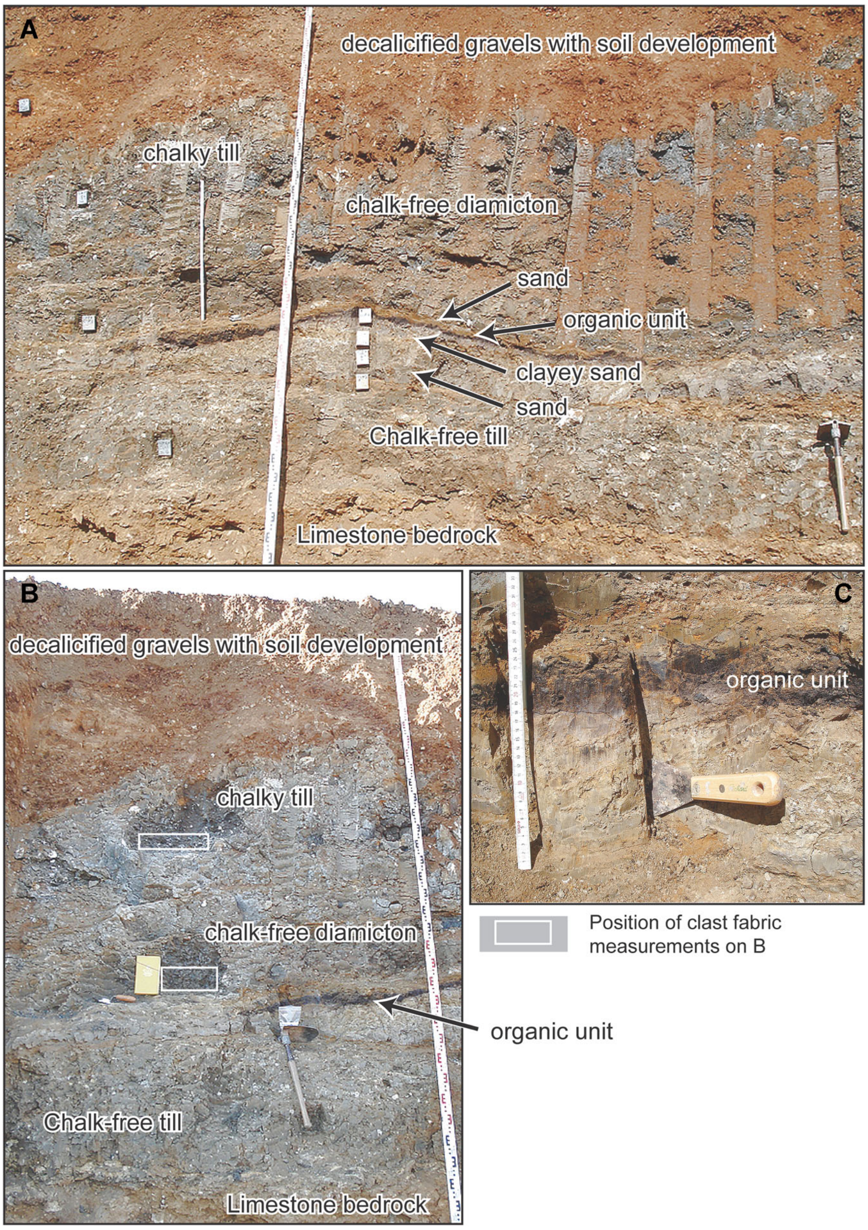

Figure 4. Photographs of Section C1 at Clipsham, north of Stamford. The particular lithological units are identified on the photographs. (A) A general view of the site with the Kubiena tins *in situ*. Limestone is at the base of the section. (B) A view of the sampled area after the Kubiena tins have been removed and clast fabric analysis has been completed. This image gives the most faithful representation of the colours of the units. (C) The soil and organic horizon, showing the monolith before removal for transport back to the laboratory. [Color figure can be viewed at wileyonlinelibrary.com]

into the limestone by a stream flowing towards the north-east. The steep incised form indicates rapid erosion, such as may be established with the onset of permafrost conditions, impermeable ground and high seasonal discharges. The sediments show little sign of abrasion, also suggesting active erosion and very limited transport distances, with the bulk of the material being derived from the local channel-side bedrock and adjacent plateau slope (limestone clasts and Quaternary palynomorphs). The sand and clayey silt cap suggests that high discharges terminated before the deposition of the overlying deposits, but the sand and clayey silt could have been deposited over a very short period, such as a season. The traces of non-local, far-travelled lithologies suggest that the region was glaciated before formation of the channel. However, the scarcity of the far-travelled material and the absence of far-travelled fine material suggest that the channel was formed on a bedrock landscape with an erratic residue, rather than a landscape covered by glacial deposits.

It is suggested that the channel and its fill originated as part of the regional drainage network along with other buried channels recorded across the area (Rice, 1962; Stevenson, 1967; Wyatt, 1971; Wyatt *et al.*, 1971; Rose, 1987, 1989a) (Fig. 7C). The incised form is attributed to erosion of high snow-melt discharges on a periglacial landscape. It is possible that the channel originated as a proglacial or subglacial meltwater channel formed when the basal till at the site was deposited (Stevenson, 1967), but the trend of the channel, transverse to the regional ice movement which deposited the basal till, the relative absence of far-travelled material and the lack of allochthonous palynomorph content in the sands make this proposal less tenable. Within a regional context, the channel is likely to be part of the preglacial river network identified by Wyatt (1971) and Wyatt *et al.* (1971) (Fig. 7C), which relates to the Bytham River system that crosses the region, just north of Clipsham, from west to east (Rose, 1987, 1989c, 1994) (Fig. 1).

The channel is very significant for this study as it is this landform that created a depression that has favoured the accumulation and preservation of the organic material.

Lithofacies Units 2–6

Three facies logs based on Clipsham Sections 1, 2 and 3 (Fig. 5) represent the succession at the site, with other logs recorded in Smith (2003). The logs are taken from a variety of positions

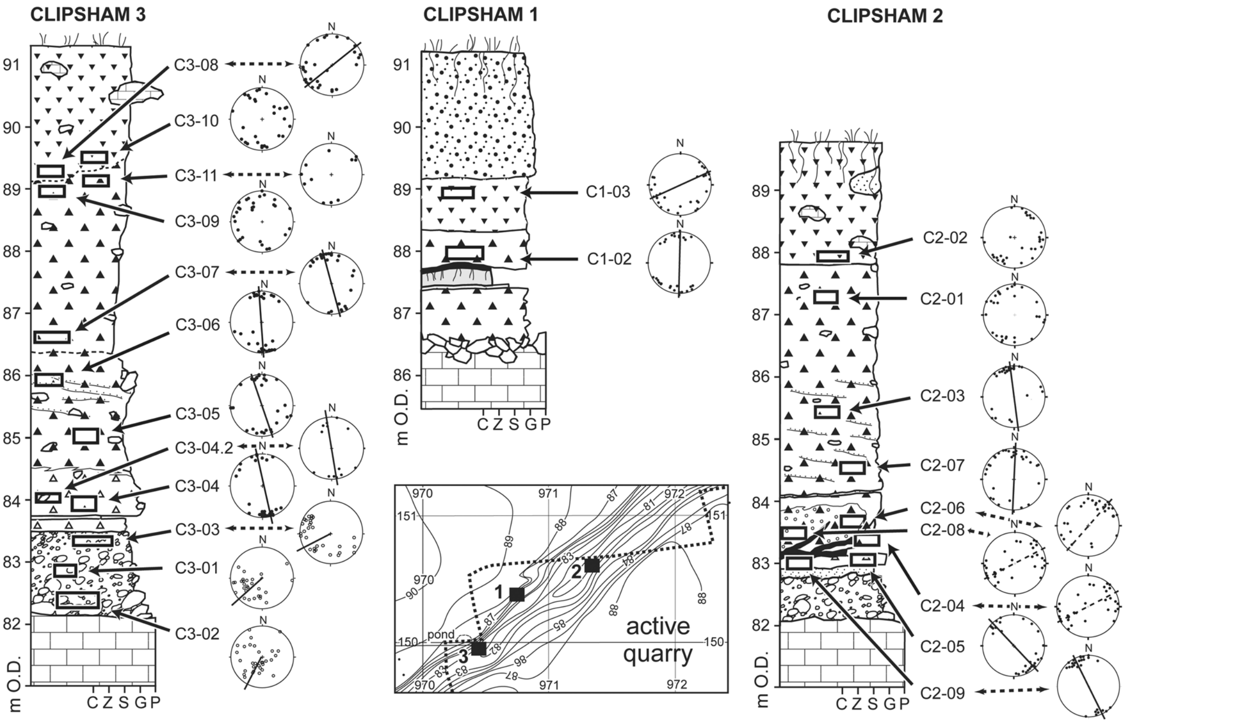

Figure 5. Representative sections from Clipsham, north of Stamford, Lincolnshire, UK, along with the results of clast fabric and imbrication analyses. Three logs are shown as typical of the area shown on the inset. The symbols are standard. Triangles represent diamicton, and sands, gravels and sands and gravel are shown with dots and open circle symbols. Clayey sand is shown with light grey in Log Clipsham 2 and organic material is shown with black. Limestone is indicated by the brick symbol. The rectangles on the figures show the location of sample points with an arrow linking the fabric data to the sample point. Fabric stereograms C3-01, 02 and 03 are the results of imbrication measurements with a mean dip direction shown by a line, and all the other stereograms are the results of elongate clast measurements with a statistically significant trend indicated by a line through the data. Those results that do not have a line through them are not statistically significant at the >95% level.

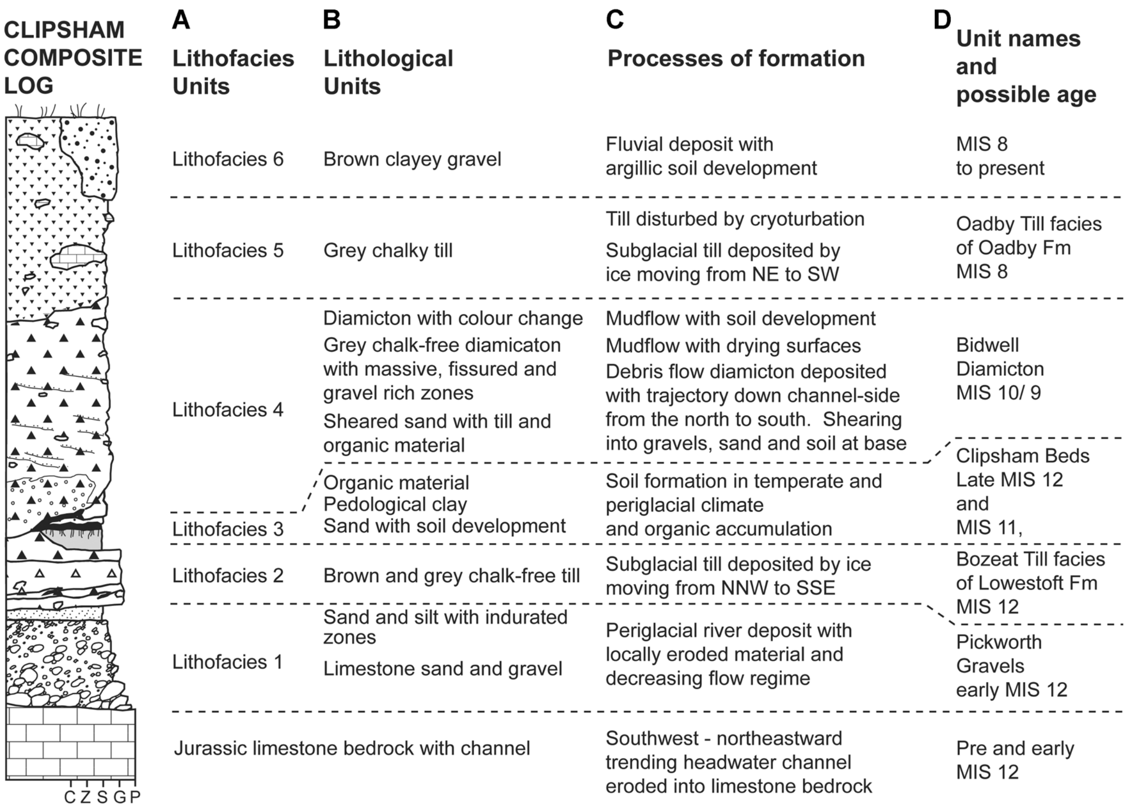

Figure 6. A composite log of the lithologies represented at Clipsham. (A) The Lithofacies Units; (B) the Lithological Units; (C) the processes of formation; (D) the Unit names and possible age (derived either by correlation or defined in this work). The derivation of the processes of formation, unit names and possible ages is explained in the text.

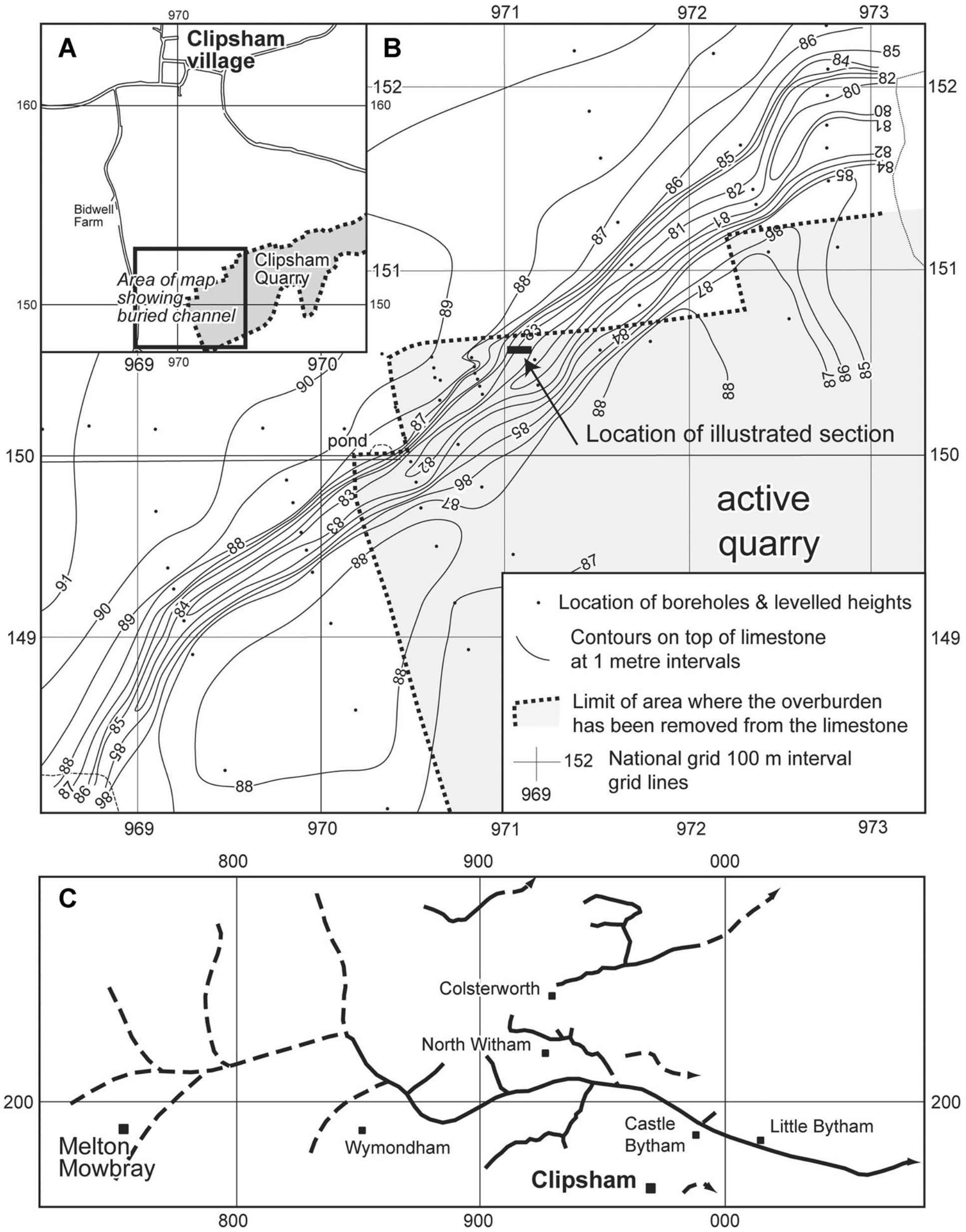

Figure 7. The form and regional context of the buried channel at Clipsham, north of Stamford. (A) The location of the detailed map with respect to the quarry and the local area. (B) A 1 m contour map of the rockhead relief showing the configuration of the buried channel. The rockhead levels were derived from a detailed borehole survey and levelling the surface of the exposed channel. The positions of the boreholes are shown. It can be seen that the buried channel trends and slopes from SW to NE. (C) Buried channels and valleys in north Leicestershire, Rutland and south Lincolnshire. Taken from Wyatt (1971, plate 1). The broken lines indicate that the route and existence is 'uncertain'. The scale and orientation of all the figures is given by the National Grid Coordinates. All are within 100 km grid square SK, and the grid lines on A are at 1 km intervals, those on C are at 10 km intervals and those on B at 100 m intervals.

within the buried channel and cover a range of geomorphological positions, from sites at the deepest part of the channel to others near the margin (Fig. 5 inset). Six lithofacies units can be identified and the main units (2, 4 and 5) are persistent across the site. A summary of the complete stratigraphy is given in Fig. 6 and a summary of all the lithological properties is shown in Fig. 8. The following text describes the geomorphological, sedimentary, lithological and pedological properties of Lithofacies Units 2–6, followed by an interpretation of the processes of formation of that unit.

Lithofacies Unit 2 – brown and grey chalk-free till

Lithofacies Unit 2 has a maximum observed thickness of ~2.5 m (Fig. 5, Clipsham 3) and overlies either the Limestone Sand and Gravel in the centre of the buried channel, or limestone bedrock at and beyond the channel sides. It is a clay-rich diamicton with a brown colour above the gravel, sand and bedrock, and a greyer colour higher in the unit (Table S1). The particle size distribution is consistent, with around 6% gravel, 25% sand, 21% silt and 48% clay (Table S2). Palynomorphs and the trace of organic carbon (Tables S1 and S4) indicate that the diamicton matrix is composed predominantly of Lower, Middle and Upper Jurassic mudrocks, a conclusion supported by the clast content, which is dominated by Jurassic limestones, ironstones and sandstones (Table S3) along with diagnostic fossils from the Middle and Upper Jurassic in the form of *Perisphinctes* sp. (from the Weymouth or Stewartby Mb. of the Oxford Clay Fm) and *Gryphaea* sp. (from the Weymouth Mb of the Oxford Clay Fm) (Table S1). Also present are rounded quartz and quartzite pebbles from the adjacent Bytham river sediments (Fig. 1) and occasional clasts of Carboniferous limestone and chert. Far-travelled igneous rocks are present in all samples in very small

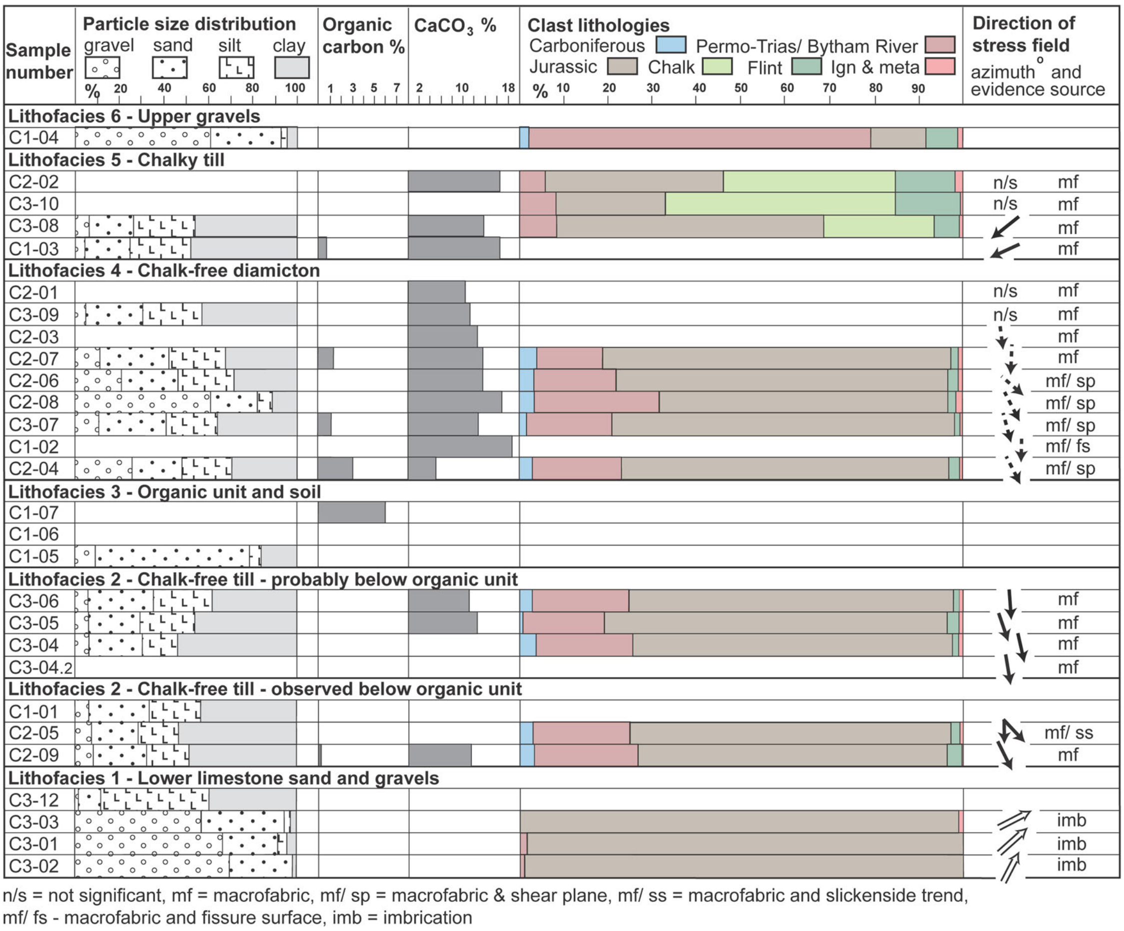

Figure 8. A summary of the lithological properties of all the stratigraphic units recorded at Clipsham, north of Stamford, Lincolnshire, UK. From left to right the columns shows the sample number, particle size distribution, organic carbon content, calcium carbonate content, clast lithological content, and direction of the stress field responsible for emplacing the deposit. All content values are given as percentage of a sample. The property of the stress field indicator is shown as: (i) macrofabric (mf), (ii) macrofabric and shear plane (mf/sp), (iii) macrofabric and slickenside trend (mf/SS), (iv) macrofabric and fissure surface slope and trend (mf/fs), and (v) imbrication direction and dip (imb). Samples that failed to yield a statistically significant fabric direction are indicated as n/s, and those with a statistically significant fabric direction are represented by an arrow showing the azimuth for the direction of the stress field. Stress fields attributed to glacial processes are shown with a solid line and stress fields attributed to gravitational mass movement are shown with a dashed line. [Color figure can be viewed at wileyonlinelibrary.com]

numbers (<1%), and are predominantly basalts and andesites, with occasional granites, all typical of northern Britain.

In places, the contacts between the brown and grey parts of the diamicton show small-scale deformation structures (Figs. 5, 6 and 11). This is supported by the microfabric (Fig. 9a.A) which shows two different, intermixed till lithologies (light and dark brown). Soft-sediment deformation structures including flame-like fold-noses indicate that porewater pressures were elevated during deformation. However, a number of discrete displacement structures are also present, indicating brittle deformation and thrusting, and the thrusts both truncate and are deformed by the ductile deformation. Alternation between ductile and brittle deformation means that during deformation, porewater levels were fluctuating within the till and substrate (cf. Lee and Phillips, 2008). Macrofabric of the diamicton shows a persistent NW–SE preferred orientation of the long axis of the elongate clasts (Fig. 5; Table S6). A comparison of the roundedness of the clasts in this lithofacies unit, with that below, shows that the limestone clasts have greater edge-rounding than the same clasts in the sands and gravels (Table S5). A number of the clasts in Lithofacies 2 show striated surfaces.

Lithofacies Unit 2 indicates non-sorted material composed of source rocks derived from the north-west through to the north-east, laid down and deformed under varying pore-water conditions. Subglacial accretion and deformational processes provide a most likely mechanism, with the resulting deposit typical of a subglacial traction till (Evans *et al.*, 2006). At Clipsham this process is responsible for the entrainment, transport, comminution and deformation of mudrocks, limestone, ironstones and sandstones from nearby Jurassic strata, and distally sourced Carboniferous rocks from the Pennines (Fig. 2). The brown and grey colours reflect entrainment of different bedrock types, with the brown colour being derived from the underlying limestone and the grey colour derived from more distant mudrocks. The absence of any chalk in this till precludes transport from the east, something that is supported by the macrofabric which suggests a NW–SE ice flow direction, and indicates that the Middle Jurassic fossils and palynomorphs are also from the north rather than from the east.

Lithofacies Unit 3 – sand and soil, organic material

Lithofacies 3 consists, from the base upwards, of a strong brown, to brownish-yellow to light, yellowish-brown clayey sand and a black organic mud (Fig. 4; Tables S1 and S2). It is located in the channel (Figs. 5 and 6) and overlies a fresh surface of Lithofacies Unit 2. The sand reaches a maximum thickness of 18 mm and the organic mud a maximum thickness of 5 mm. Each unit is of limited extent: at Clipsham Site 2 the organic unit is c. 2.5 m and the underlying sand c. 4 m. The

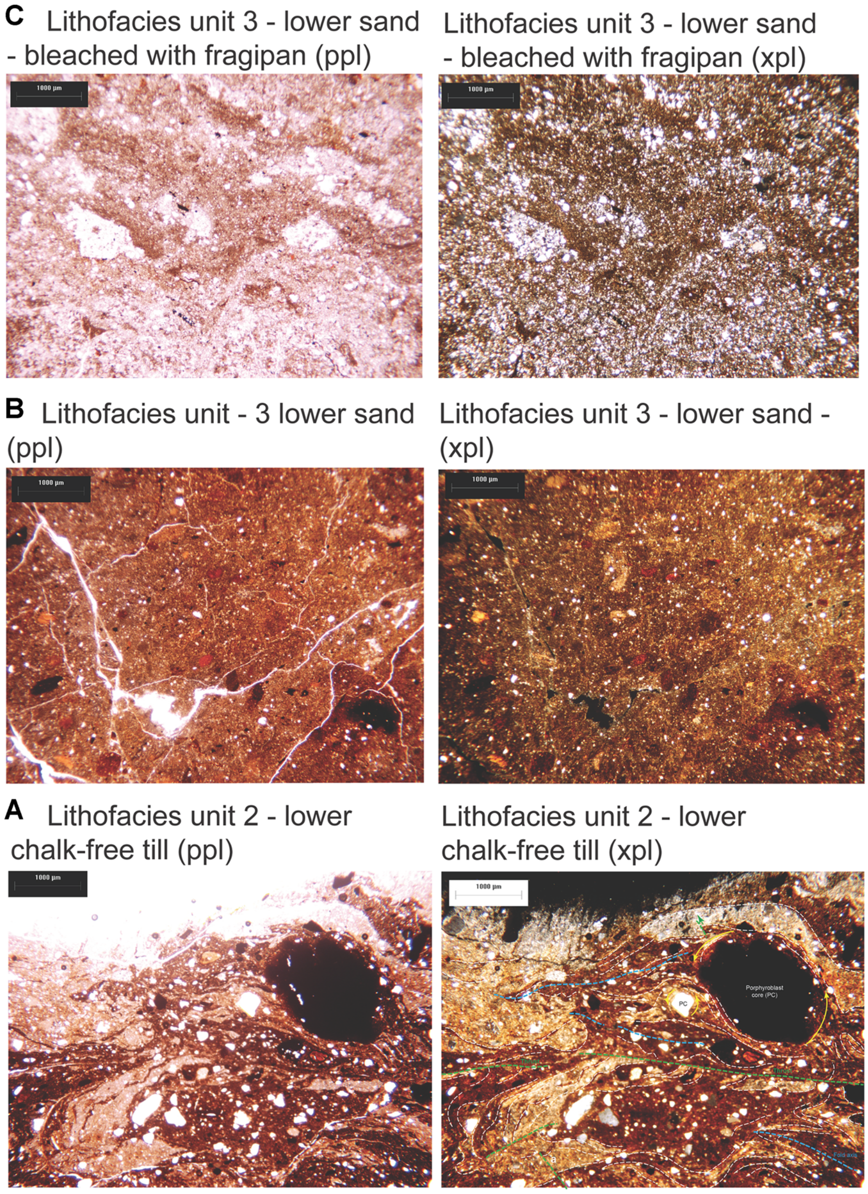

Figure 9a. Micromorphological properties of the sediments and soils at Clipsham, Lincolnshire, UK. (A) Lithofacies Unit 2, brown and grey chalk-free till. This thin section shows two different till lithologies forming soft-sediment deformation structures with flame-like fold-noses. Also, a number of discrete displacement structures indicate thrusting. On the xpl figure the ductile structures are shown by blue lines and the brittle structures by green. This relationship shows that the thrusting both truncates and is deformed by the ductile deformation. For further details see the text. (B) Poorly sorted sand with a variable content of sand and fine gravel. The variability suggests derivation from a fresh, highly variable lithology such as the underlying grey and brown chalk-free till. (C) Brown, well-sorted quartz sand with silty-clay concentration-layers typical of fragipan. These concentrations form in periglacial soils due to the concentration of clay and silt-size material into roughly horizontal bands, by the growth and melt of segregated ice in a poorly drained soil.

whole unit is partially deformed with an upward flexure about mid-point. Carboniferous and Jurassic palynomorphs such as would be derived from the underlying brown and grey chalk-free till (Lithofacies 2) exist in all the units.

Kubiena samples were taken from Lithofacies 3 for micromorphological analysis (Fig. 4A). The lower part of the lower strong brown sand (Fig 9a.B) shows poorly sorted sand with a variable content of sand and fine gravel, as well as a finer fraction suggesting derivation from a fresh, highly variable lithology such as the underlying grey and brown chalk-free till. Above this, the light yellowish-brown sand shows a better sorted quartzitic sand with weathered quartz grains and silty-clay concentration-layers (Fig. 9b.C). These concentration-layers are typical of fragipan (van Vliet and Langohr, 1981), which forms in periglacial soils due to the concentration of clay and silt-size material into roughly horizontal bands by the repeated growth and melt of segregated ice and indicates that a periglacial soil developed at this level in Lithofacies 3.

There is also evidence for root development within this bed (Fig. 9b.D). The root imprint is conspicuous and is associated with a thin, parallel circle of orientated clay and mottling. This root structure may be of recent development, but this is not likely as the section was freshly excavated, is 6.5 m below the present land surface, and there has been no evidence of root structures in the other beds at this depth.

The sand is overlain by the organic bed which is composed of sand, silt, clay and pedogenic clay and forms a conspicuous, black horizon, with a massive appearance (Fig. 4C). The

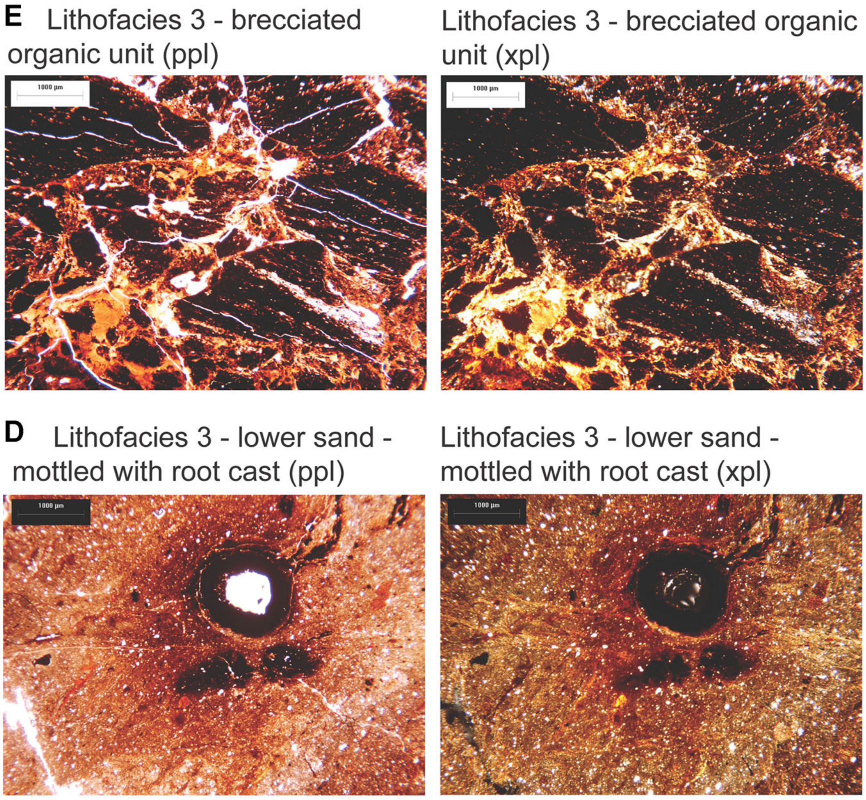

Figure 9b. Micromorphological properties of the sediments and soils at Clipsham, Lincolnshire, UK. (D) Evidence for root development. The root cast is associated with a very thin, parallel, circle of orientated clay and mottling reflecting pedogenesis and local stresses. The association with the buried soil is supported by the fact that the sample point is 6.5 m below the present land surface and there is no evidence of root structures in any of the other beds at this depth. (E) The organic bed. The organic material is represented by the black coloured fragments and the intervening fissures are filled with fragments of organic material, sand, silt and pedogenic clay. The larger organic fragments of organic material show banding with layers of fine sand, fine silt and clay. It is suggested that the organic layer may be due to washing-in and deposition of organic matter along with mineral material. A pool, in a vegetated landscape, is the likely depositional environment. Likewise, the presence of fragments of pedogenic clay suggests that a Bt horizon of an argillic soil existed adjacent to the locality, and was subsequently disturbed and mixed with the other fractions. [Color figure can be viewed at wileyonlinelibrary.com]

carbon content is 6%, which is much higher than other units at the site (Table S1), and this gives the material its dark colour (Hiederer, 2009). The thin section (Fig. 9b.E) shows that the bed is brecciated into larger organic fragments separated by fissures infilled with smaller fragments of organic material, sand grains and pedogenic clay. The larger organic fragments show banding with layers of fine silt and clay. This is not characteristic of a soil, which should be mixed by pedogenic process and it is suggested that at Clipsham the organic bed may be due to washing-in and deposition of organic and mineral matter from the adjacent hillside. A pool, at the base of a vegetated slope, is the likely depositional environment. Likewise, the presence of fragments of pedogenic clay suggests that a former Bt horizon of an argillic soil existed adjacent to the locality, and was subsequently eroded and mixed with the other fractions. This pedogenic clay is formed in a soil and is dependent upon warm, humid climate conditions operating over a substantial period (McKeague, 1983; Bronger, 1991) and the root structures described above are likely to have formed while this type of soil developed.

Pollen analysis

Quaternary pollen is present in the organic bed and the results are presented as pollen concentrations, and percentage diagrams to show, respectively, abundance and vegetation assemblages (Fig 10A,B). The pollen spectra are characterized by three zones, described from the base upwards, but overall the assemblages are similar from bottom to top. Tree pollen ranges between ~50 and 30% throughout, herbs between ~40 and 20%, spores between 0 and ~20%, and pre-Quaternary pollen reaches 40%. *Picea* is the dominant tree species, and *Abies* and *Pinus* are also present.

Zone I

Tree pollen is dominated by *Picea* and *Abies* which declines towards the end of the zone. There are small amounts of Cyperaceae present with a large proportion Poaceae which begins to decrease mid-zone before peaking at the transition to Zone II. The spore assemblage contains three fern species (*Cryptogramma crispa*, *Dryopteris* and *Ophioglossaceae*) and mosses (*Lycopodium* type, *Huperzia* and Sphagnum). These species display a general increase towards the end of Zone I, while *Pteridium* begins to appear mid-zone. There is a significant proportion of pre-Quaternary spores which display an increase throughout the zone.

Zone II

The frequency of *Picea* and *Abies* increases in this zone and shows a pattern that is inversely proportional to *Pteridium*. Cyperaceae, Poaceae and *Huperzia* are also present. Pre-Quaternary spores are present with a generally consistent frequency throughout.

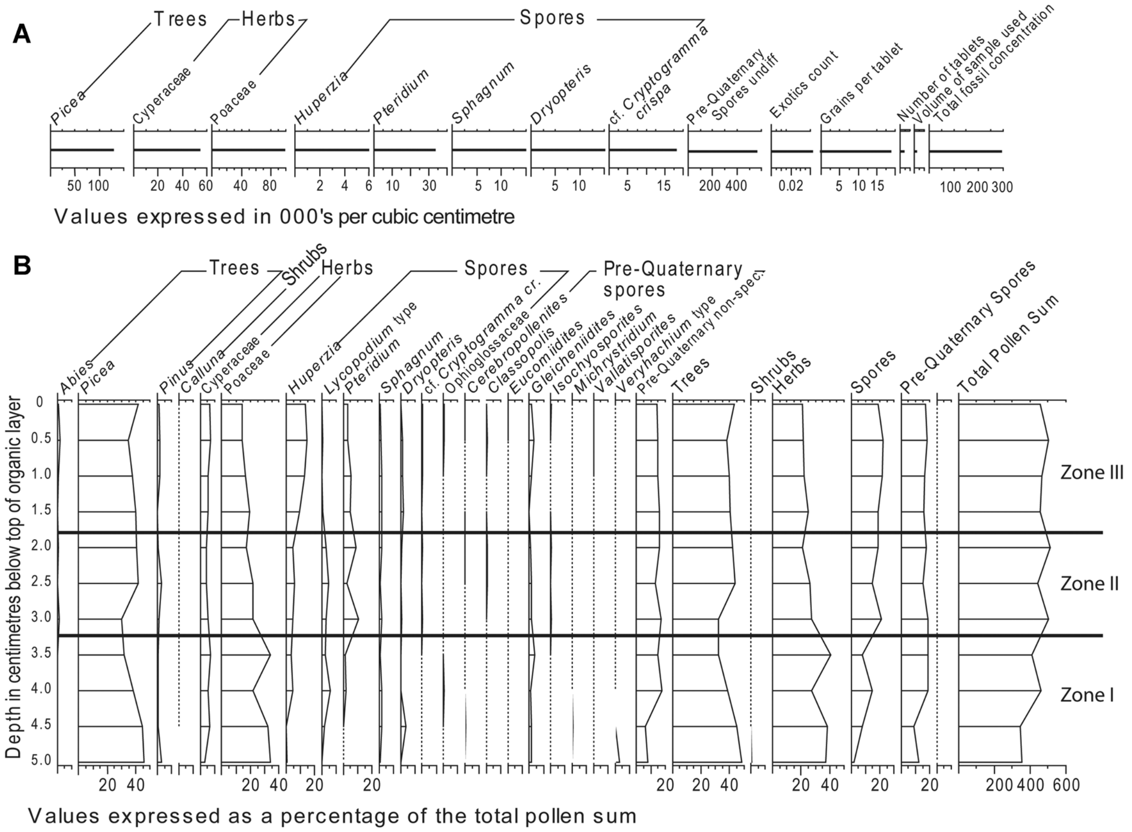

Figure 10. Pollen concentrations and relative pollen frequencies from the organic layer of Lithofacies Unit 3. (A) Pollen concentration (1-cm^3 samples, spiked with two Lycopodium tablets) in order show the abundance of pollen grains within the organic layer. (B) Pollen diagram (counts of c. 300 grains per slide) showing the relative frequency of given taxa expressed as a percentage of the total pollen sum. The pollen spectra are characterized by three zones, although overall the assemblages are similar from bottom to top. Tree pollen ranges between ~50 and 30% throughout, herbs between ~40 and 20%, spores between 0 and ~20%, and pre-Quaternary pollen reaches 40%. *Picea* is the dominant tree species, and *Abies* and *Pinus* are also present.

Zone III

Tree pollen shows little variation throughout this zone. Cyperaceae and Poaceae persist and *Huperzia* becomes dominant in the spore group while *Pteridium* decreases. Pre-Quaternary spores are persistent around the same level.

The interpretation of the pollen assemblages has been arrived at using Balme (1995), Pocock and Jansonius (1961), Wall (1965), Godwin (1975), Stace (1991) and Marrs and Watt (2006). The pollen spectra suggest an open, tundra environment dominated by Cyperaceae and Poaceae and the presence of restricted *Picea* woodland. Open habitats are also indicated by the two clubmosses: *Huperzia* and Lycopodium type (Stace, 1991, pp. 5–6), and these species seem to be competing for the same ecological niche, as their frequencies show an inverse relationship in the upper part of the pollen profile (Zone III). The presence of the tree pollen requires further consideration as the possibility exists that this is far-travelled and trees were absent from the Clipsham area. While this is possible for *Abies* and *Pinus*, which have minimal pollen presence, the relative abundance of *Picea*, which is not a high pollen producer, suggests that woodland is local. It is possible that *Picea* has stratigraphic significance, having been recognized as abundant at Purfleet, Essex, in a unit dated to MIS 9, although as pointed out by Schreve *et al.* (2002, p. 1458) 'the dominance of *Picea* does not compare closely with any other known assemblages' and this relationship is best noted for future research.

The pre-Quaternary pollen does not have a climatic signal, being derived, by erosion, from the Jurassic bedrock and till in the area. Erosion of the Jurassic bedrock is shown by the presence of *Classopolis*, which was abundant throughout the Jurassic. However, the increase in pre-Quaternary pollen, from relatively low values at the base, to persistently higher values up the profile, suggests that erosion increased over time, probably reflecting river incision and slope movement in the region.

Lithofacies 3 is therefore interpreted as a depression infill in which sand, organic and soil material were laid down. The sand hosts evidence for *in situ* periglacial and temperate climate soil development in the form of fragipan and root casts. The pool sediments represent the accumulation of transported soil- and organic-material. The fragipan, root casts, organic material and pedogenic clay are all indicative of subaerial conditions, both at the site (fragipan and root clasts) and on the adjacent slopes from which the organic material and pedogenic clay are likely to have been derived. The soil structures suggest both cold climate (fragipan) and more temperate climate conditions (root casts with pedogenic clay skins, and organic material with pedogenic clay). These climatic inferences are reinforced by the habitat of the vegetation, with open tundra conditions favouring active layer processes, and the milder conditions represented by *Pteridium*, and *Picea* favouring more biomass and cool temperate soil-forming processes. Overall, this complex evidence suggests that pedogenesis took place over a relatively long period as the formation of the pedological clay requires several thousand years of warm and moist temperate climate (FitzPatrick, 1980). However, it must be stressed that the formation of the cooler climate soils and organic materials requires only a relatively short period.

The basin within the channel acted as a local sink accumulating a wide range of palaeoenvironmental information. All the evidence indicates that the site at Clipsham was subject to soil formation and biological activity and was therefore part of a subaerial environment after the deposition of the lower chalk-free till (Lithofacies Unit 2). Interpretation of the soil materials and sediments indicates a period of active layer soil development, a long period of warm temperate conditions followed by a period of cooler climate during which the organic sediments accumulated.

Lithofacies Unit 4 – deformed, sheared, fissured, grey, chalk-free diamicton

This is a structurally complex unit comprising three parts: (i) at the base a sheared sand bed, organic material, diamicton with high organic content and banded brown chalk-free till; (ii) in the middle a diamicton with high, gravel-size clast content, a diamictic gravel, and a massive diamicton; and (iii) a horizontally fissured diamicton at the top (Fig. 11). Despite the structural complexity, the lithology of the Unit is consistent, with all the beds dominated by Jurassic source rocks, both as clasts (46–78%) (Table S3), diagnostic fossils (Table S1) and palynomorphs (Table S4); the presence of Carboniferous limestone and chert (1–6%) and palynomorphs (Table S4); far-travelled igneous and metamorphic rocks (1–2%); flint (1–2%) and an absence of Chalk (Table S3). Carbonate contents of 7–17% (Table S1) for the matrix indicate that the lithologies are not decalcified and that the absence of Chalk is a primary property.

Micromorphology of the lower part of the unit reveals a lower chalk-free diamicton, an organic-rich chalk-free diamicton and sand with gravel, although in this slide the beds are inverted (Fig. 12A). The sand shows no trace of pedogenesis, indicating that it was deposited after the period of soil formation. The mixing of the organic bed and the lower chalk-free till (Lithofacies Unit 2) is also shown on Figs. 11 and 12B where the complex juxtaposition of the organic mud, sand and pre-existing till can be seen. The organic carbon content of the darker diamicton is 3%, which contrasts with values of 1% or less for all other diamicton types, but is lower than that of the organic bed (6%) (Table S1). A lens of brown till, which is derived from below the organic bed, also extends into Lithofacies Unit 4 (Fig. 11).

The middle part of the unit comprises a large fold-nose of massive, black or very dark grey, chalk-free diamicton (Fig. 12C), chalk-free diamicton with a high clast content and a poorly sorted gravel. This extends across the organic-rich chalk-free diamicton, separated in places by shear planes and at one locality a thin layer of organic material (Fig. 11). The preferred orientation of elongate clasts within the fold-nose (C2-08, C2-06, C2-04) trend NE–SW (Table S6, resultant vector of elongate clasts) at right angles to the NW–SE flow direction indicated by shear planes (Table S6, shear planes), confirming that compression has taken place and corroborated by the visual appearance of a fold-nose.

A black, horizontally fissured diamicton overlies all of these beds and forms the upper part of Unit 4. The fissures are discontinuous and slope gently towards the SE. They have a rough surface texture and have the appearance of drying surfaces rather than stress-generated shear planes, which tend to be polished and/or exhibit slickensides. The arrangement of fissure surfaces roughly one-above-the-other (Fig. 11) suggests a stack of thin mudflows each drying at the surface before being over-ridden by a subsequent flow. The observed fissures are interpreted as discontinuous fragments of these drying surfaces that have survived erosion caused by the passage of the subsequent flow. Clast fabric analysis shows a flow direction from the NNW towards the SSE (Table S6), similar to that indicated by the slope of the fissure surface and similar to that of the lower parts of Unit 4.

These data suggest that the lower and main part of Lithofacies Unit 4 was deposited by a debris flow which locally deformed and incorporated existing units. The debris flow terminated as a fold-nose in the region of Section 2 with a thickness of 1 m. It is overlain by the fissured diamicton, which appears to have been formed by a number of very liquid mudflows. At Section 2, Lithofacies Unit 4 is nearly 4 m thick, while at Section 1 it is <1 m thick and at Section 3 is c. 5.5 m thick, suggesting different positions within the debris flow/mudflow, or an association with different flow units. The directional indicators show a NW–SE flow direction, which is normal to the trend of the buried channel in which they are located. It is suggested that the flows have moved down the northern side of the channel. The SE direction of slope of

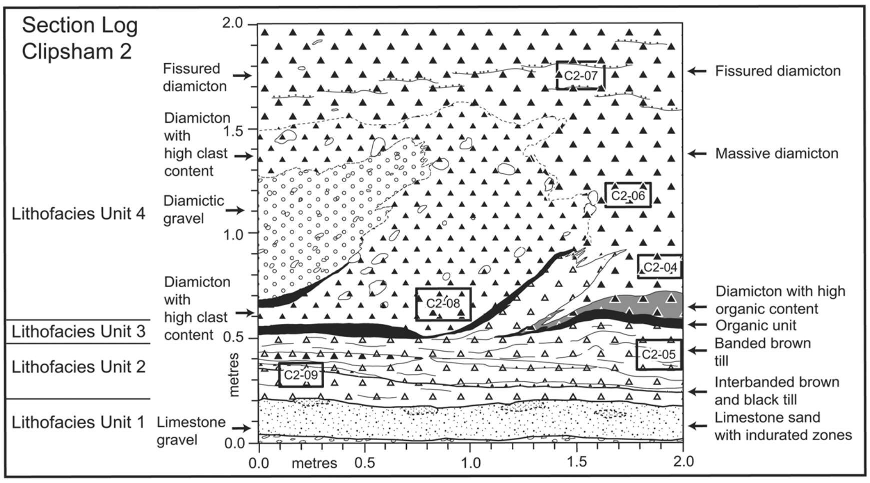

Figure 11. Field sketch of Section Log Clipsham 2 to show deformation structures characteristic of Lithofacies Unit 4. Full details are given in the text, but the main elements of the succession are as follows: Lithofacies Units 1 and 2 are at the base and Unit 2 shows evidence of interbedding of the brown and black tills, also seen in Fig. 9A. This unit is overlain by the organic layer (Lithofacies Unit 3), which, in the centre of the figure, is deformed and extends up into the overlying beds. Lithofacies Unit 4 overlies the organic layer, but also incorporates a fragment of that layer. The structure represents a large fold-nose of massive, black or very dark grey, chalk-free diamicton, chalk-free diamicton with high clast content and a diamictic gravel. This is overlain by a black, fissured diamicton. The figure also shows the location of the sample points for macrofabric analysis, the results of which can be seen Fig. 8 and Table 6. The fold-nose is interpreted as the compressional front of a debris flow and the fissured diamicton is explained as accretionary beds of a number of thin, mobile mudflows.

the fissure surfaces reflects the flow direction of the mudflow pulses and the much lower slope angle of the land surface at the time this unit was deposited.

The topmost part of Unit 4 is free of fissures, but, as indicated by the fabric analyses (Fig. 6; Table S6), shows a similar flow direction to the underlying parts of this unit, indicating perhaps more rapid accretion as one, single, thick mudflow unit, caused by increased water content. However, the top of Unit 4 at Sections 2 and 3, where the unit is thickest, shows colour change from black and very dark grey typical of the unit, to a dark greyish brown and dark yellowish brown and a dispersed fabric with the absence of any directional indication. These properties are interpreted as an effect of pedogenesis suggesting that at these sections, this part of Lithofacies Unit 4 was close to a former land surface.

Taken together, the various parts of Lithofacies Unit 4 are interpreted as the products of a debris flow followed by a more mobile mudflow, and ending with textural disturbance caused by soil formation at the ground surface. Thus, Lithofacies 4 buried and preserved the organic material soon after formation.

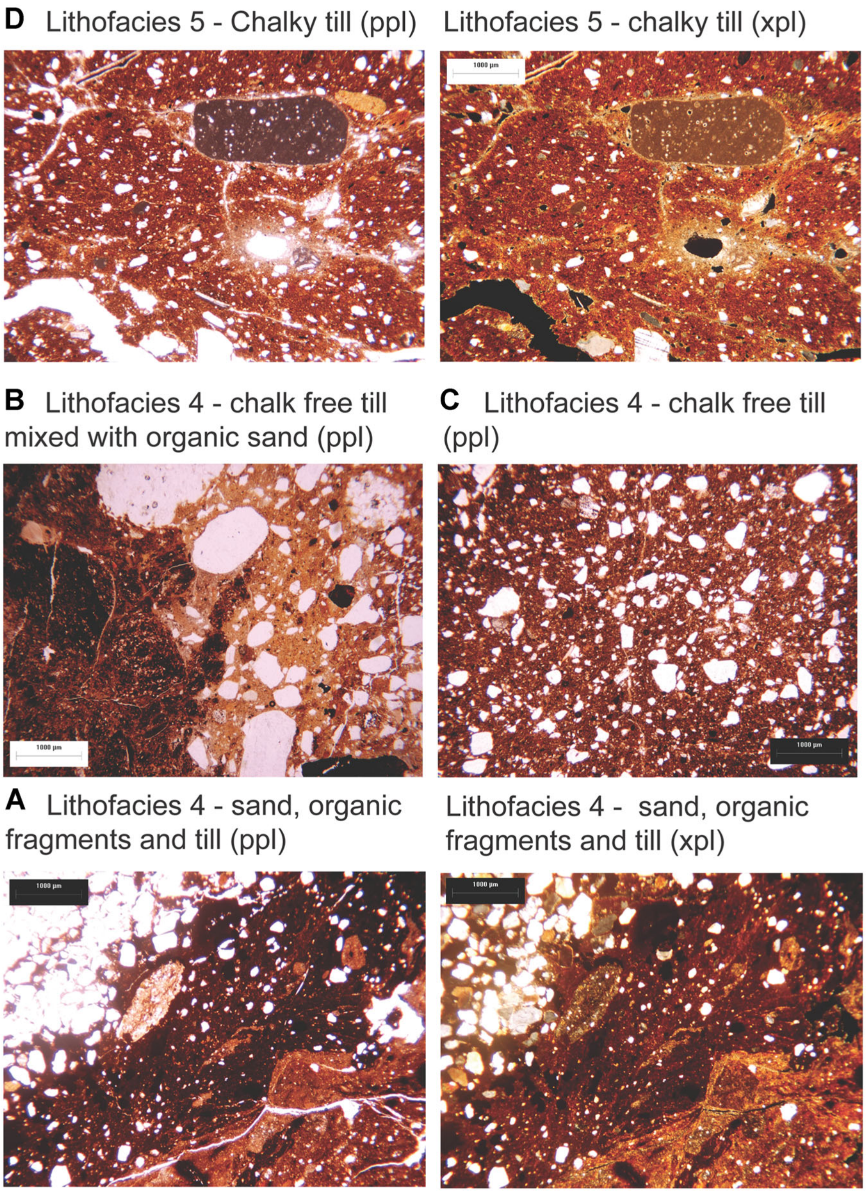

Figure 12a. Micromorphology of the units overlying the organic layer at Clipsham, Lincolnshire. The location of the sample points for these thin sections can be seen on Fig. 11, although because the resolution of Fig. 11 is far less than that of the thin sections some of the finer features shown in the thin sections are not indicated on Fig. 11. (A) Lithofacies 4. The lower part of the Unit showing the mixture of sand, organic fragments and brown till in both ppl and xpl. This succession is inverted. The brecciation of the sand, and the mixing of the organic material with till to form a deformed organic diamicton are visible. The unweathered sand grains indicate freshly deposited material. (B) Lithofacies 4. A ppl image showing mixing of the chalk-free till with the organic sand. (C) Lithofacies 4. An xpl image of chalk-free till which constitutes the massive diamicton that makes up the debris flow deposit. (D) Lithofacies 5. Ppl and xpl images of chalky till. A subrounded clast of chalk is clearly visible in the upper right-hand side of the slide, and both images show rounded ball-like structures, in the diamict matrix separated by linear dislocation structures both formed by subglacial transportation. Some of the linear dislocations show increased orientated clay content, which is likely to be a trace of soil formation. However, apart from the clay concentration around the chalk clast and around the black rootlet void there are no other signs of soil formation. This is typical Oadby Till.

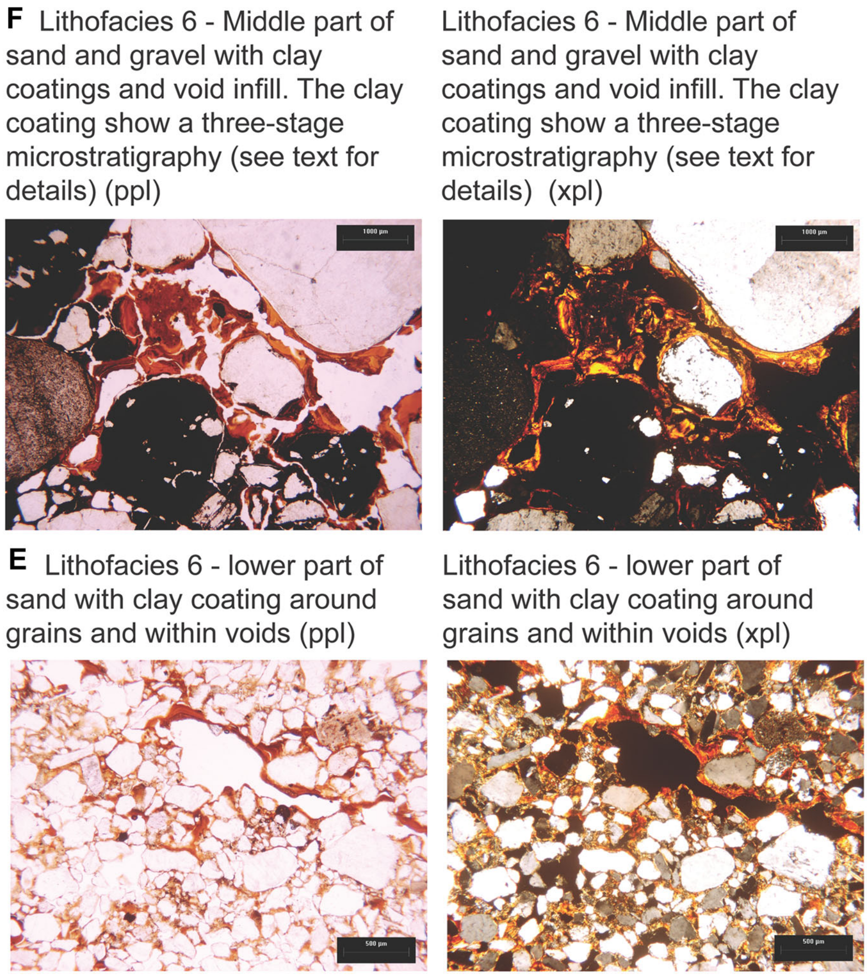

Figure 12b. Micromorphology of the units overlying the organic layer at Clipsham, Lincolnshire. The location of the sample points for these thin sections can be seen on Fig. 11, although because the resolution of Fig. 11 is far less than that of the thin sections some of the finer features shown in the thin sections are not indicated on Fig. 11. (E) Lithofacies 6. Ppl and xpl images of the lower part of the clayey sand and gravel that forms the uppermost Unit at Clipsham. The crenulated edges of a number of the quartz grains show the effects of weathering, and the brown (ppl) and yellow brown (xpl) coating around the sand grains and around the margins of the void (black in xpl) indicate the effects of illuvial clay translocation during long-term humid warm temperate soil formation at the site. (F) Lithofacies 6. Ppl and xpl images of the middle part of sand and gravel with clay coatings and void infill. The clay coating shows a three-stage microstratigraphy with fine pedological clay (bright orange ppl/yellow xpl) translocation, disruption and a final stage of coarser clay translocation (darker orange ppl/dark orange and black xpl) (see text for details). [Color figure can be viewed at wileyonlinelibrary.com]

Lithofacies Unit 5 – grey chalky till

Lithofacies Unit 5 is a grey diamicton with clearly visible chalk clasts. It is present as the surface deposit across the site, except in the area of Log 1 (Fig. 6), where it is overlain by a small body of brown clayey gravel (Lithofacies Unit 6). This diamicton is characterized by about 46% clay, 28% silt, 20% sand and 6% gravel (Table 2) and is typical of the chalky till of east Midland England (Perrin *et al.*, 1979). The lithological content is unique for the site with the presence of chalk clasts (up to 57%, Table S3) and a much higher content of flint than any of the underlying deposits (c. 8%, Table S3). Jurassic-sourced clasts are also abundant (c. 25–60%, Table S3) and Triassic and igneous/metamorphic rocks are also present (c. 7% and c. 1%, respectively, Table S3), but Carboniferous rocks (cherts, limestones, grits) are absent (Table 3). Calcium carbonate content is ~15% (Table S1), and one sample shows the presence of organic carbon (0.7%, Table S1). Palynomorph content is similar to all the other samples analysed except for the presence of taxa from the Chalk Group. There is a trace of Carboniferous palynomorphs in one sample (Table S4). Macrofabric analysis on two samples from lower parts of the unit show a strong preferred orientation with a NE–SW trend (Fig. 5; Table S6), whereas other samples from higher in the unit do not show a preferred orientation. Micromorphological analysis of a sample taken from the lower part of the unit shows a sub-rounded chalk clast, along with rotational structures and linear dislocation structures (van der Meer *et al.*, 2003) which are typical of subglacial transportation (Fig. 12D) (Evans *et al.*, 2006; Evans, 2017).

This clay-rich diamicton shows a provenance and flow direction from the east with characteristics typical of a subglacial traction till (Evans *et al.*, 2006; Evans, 2017) formed by ice moving over Chalk bedrock, Jurassic mudrocks and limestones, and outcrops of Bytham River deposits (there are no *in situ* Triassic pebble beds at the east to provide a source for this material). Ice also transported into the area far-travelled material from distant igneous and metamorphic sources (Fig. 2). The dispersed macrofabrics from the upper part of this unit are attributed to post-depositional disturbance associated with soil formation (see Lithofacies Unit 6 below).

Lithofacies Unit 6 – brown clayey gravel

Lithofacies 6 forms an isolated body of brown, clayey gravel that extends to the surface. It has an irregular base and is surrounded by Lithofacies Unit 5 (Figs. 4–6). The isolated and disturbed nature of this sediment suggests preservation as a consequence of periglacial cryoturbation. The size distribution of this lithology is dominated by gravel (62%), with 31% sand, 3% silt and 4% clay (Table S2), reflecting fluvial sorting and deposition. However, the micromorphology shows that the clay surrounds the coarser particles and binds the particles together (Fig. 12E,F) suggesting post-depositional alteration. The lithology comprises quartzite and quartz (77%), ironstone (11%), flint (7%), Carboniferous chert (2%), and igneous and metamorphic rocks (1%) with trace amounts of limestones and sandstone (Table S3), clearly dominated by chemically durable clasts, implying survival as an insoluble residue. Palynomorphs are present and can be provenanced to Carboniferous, Jurassic and Quaternary sources (Table S4). This residual clast lithology suggests fluvial provenance from the chalk-free till, with the subsequent removal of non-durable lithologies and consequent enhanced frequency of the durable lithologies. Provenance from the chalky till would have resulted in much higher frequency of flint and there is no source for the quartz and quartzite. The high quartz and quartzite content could point to provenance from the Bytham Sands and Gravel (Rose, 1989c; Figure 8), but this is not supported by the low ironstone content and relatively high flint content.

Photomicrographs show zones of reddish brown, bright orange (xpl) and yellow (ppl) material in the form of void infills (cutans) and grain coatings (Fig 12E,F). This material is very fine-grained birefringent clay and is the product of soil-forming processes breaking down weatherable minerals into stable illite, smectite and haematite. Because of its very fine texture, this material is susceptible to translocation down a soil profile, and forms the basis of an illuvial horizon (McKeague, 1983). Thus, the pedological clay observed in Lithofacies 6 required a relatively long period in humid, warm temperate interglacial conditions and represents the Bt horizon of an argillic soil (Kemp, 1985a,b; Candy *et al.*, 2014).

The microstratigraphy in the clay coatings (Fig. 12b.F) reveals three stages of soil development: (i) bright yellow (xpl) and yellow-brown (ppl) fine clay coatings around grains and the margins of voids caused by the formation and translocation of fine clay, in a humid warm temperate climate; (ii) fractures of the fine clay due to disruption and fragmentation of the clays, most probably by frost processes in the soil; and (iii) void infilling by mottled brown (ppl) or black with yellow shadows (xpl) of coarser clay demonstrating renewed translocation, but in this case deposition of a coarser-grained clay, probably reflecting less effective clay formation and moderate temperate climatic conditions (cf. Kemp, 1985b). The photomicrograph from lower down the soil profile (Fig. 12b.E) shows only stage (i) clay coatings and suggests that the later processes of soil formation did not reach to this depth below the land surface, due either to a temperate climate that had less warmth, or a warm temperate climate that was of shorter duration.

Thus, the origin of Unit 6 is attributed to fluvial deposition of material eroded from the chalk-free till, and subsequently modified by soil-forming processes over a period that covers at least two temperate episodes and an intervening cold stage. It is preserved at this site by periglacial cryoturbation of the land surface.

Summary of the succession and correlation with regional lithostratigraphy

The presence of a soil and organic material between glacial deposits at Clipsham is important for our understanding of the glacial and environmental history of lowland Britain. This section provides a summary of the stratigraphic sequence, and places the lithological units in a wider lithostratigraphic framework. Due to the absence of absolute and relative dates, this process is based on lithostratigraphic correlation underpinned by an understanding of geodynamic processes.

Lithofacies 1 – periglacial gravels – Pickworth Gravels

The lower limestone sand and gravel, with overlying partially lithified sand is a local unit restricted to the base of the buried channel that crosses the site in a SW–NE direction and is overlain by till. Sedimentological criteria indicate local derivation and deposition by a headwater stream in a periglacial climate. The locally derived lithology means that there is no basis for wider correlation, and the unit is taken as a characteristic lithology for any future discoveries. Lithofacies 1 is known informally as the Pickworth Gravels. Sparse erratic material within the unit does, however, provide evidence for previous glaciation. The local cementation of the sand facies is post-formational.

Lithofacies 2 – chalk-free till – Bozeat Till/ Lowestoft Till

The brown and grey chalk-free diamicton that overlies the Pickford Gravels in the buried channel and the bedrock elsewhere is interpreted as a subglacial traction till, deposited by ice travelling from the NW to the SE. The brown colour is determined, primarily by entrainment of the limestone bedrock and the grey colour reflects a higher proportion of material transported by glaciers from Jurassic mudrocks to the NW. Lithological properties are characteristic of the chalk-free Bozeat Till (Barron *et al.*, 2006), defined at a type-site c. 70 km to the south of Clipsham, and representative of the chalk-free till Lowestoft Till (Hollingworth and Taylor, 1946; West and Donner, 1956; Rose, 1992). The Lowestoft Till is widely accepted as having been deposited in MIS 12 (Anglian Glaciation).

Lithofacies 3 – sand, soil and organic material – Clipsham Beds

The sequence of fresh till surface, sand with a periglacial soil imprint, organic material and soil material includes critical evidence for subaerial conditions after the accretion of the Bozeat Till. The fresh surface of the Bozeat Till indicates that its surface was eroded, probably by the stream that eventually deposited the sand. The fragipan imprint on the sands indicates periglacial climate soil formation, while the rootlet casts with pedological clay coatings and the organic material reflect temperate climate plant cover, soil development and subsequent deposition of organic detritus.

The organic material, which is composed of layered soil material and highly birefringent pedological clay, indicates that vegetation and well-developed soils existed on the adjacent land surface. The products of this ecosystem were subsequently eroded and transported into a pool within the channel. The duration and climate needed to form pedological clay (Fig. 9b.E) means that a relatively long time and humid, warm temperate climate must have occurred before deposition of the organic material. That the pedological clay is inherited from warm temperate climate processes, and the pollen content represents cool temperate vegetation with open spruce woodland, ferns and grasses accord with the scenario whereby the soils preserve the longer-term climate signal and the vegetation records the climate signal just before erosion, transport and deposition. Lithofacies 3 is designated the Clipsham Beds.

Although there is substantial evidence for subaerial conditions and the types of climate in existence at the time, there are no firm chronostratigraphic indicators, either biological (pollen, fauna, insects), lithological or pedological. Climate provides the only evidence of stratigraphic relevance to the extent that the formation of pedogenic clay requires a humid warm temperate climate of relatively long duration, warmer than, for instance, the natural processes of soil formation in the same region within the present interglacial. The change to cool temperate climate followed by slope instability and mass movement may record the oncoming glaciation. On the assumption that the Bozeat Till was deposited during MIS 12 (see above) the simplest interpretation is that subaerial conditions occurred during MIS 11 under a climate that is similar to that proposed for midland England during this period (Candy *et al.*, 2014). However, it must be stressed that this type of climate also existed in a number of interglacials that preceded and followed MIS 12 (Candy and McClymont, 2013).

Lithofacies 4 – deformed, grey, chalk-free diamicton – Bidwell Diamicton

The deformation structures, variable thickness, textural variability and local incorporation of the Clipsham Beds within the base of the unit all suggest that Lithofacies Unit 4 is the nose of a debris flow that moved down the north side of the valley. The fissured chalk-free diamicton at the top of this unit suggests that the debris flow was buried by a series of mobile mudflows, also from the north. This is an entirely locally derived deposit, but it is significant for this study because it buries and preserves the organic materials from further weathering and erosion. As with the Pickworth Gravels there is no basis for wider correlation and it is informally named the Bidwell Diamicton. The unit is also important because the colour change and disturbed fabric of the upper part of the unit suggest modification in the lower part of a soil profile, before burial by Unit 5.

On the assumption (see above) that the soils and organic deposits formed during MIS 11, it is reasonable to propose that the Bidwell Diamicton formed during the colder climate of MIS 10, and that the soil imprint on the upper part of the unit formed during MIS 9, but these proposals must be considered tentative.

Lithofacies 5 – grey chalky till – Oadby Till

Internal structure, indicator lithologies including Chalk, and clast fabric results provide substantial evidence that the grey chalky diamicton is a till, deposited by glaciers moving from the NE to the SW, virtually at right angles to the direction of ice flow that deposited lower chalk-free Bozeat Till. This deposit forms the surface lithology across much of the area and is known as the Oadby Till (Bowen, 1999), which is attributed to deposition by glaciers in MIS 12. However, Hamblin *et al.* (2000, 2005) and Rose (2009) suggest deposition during MIS 10 but retain the name Oadby Till (Rice, 1968), whilst White *et al.* (2010, 2017) and Bridgland *et al.* (2014, 2015) have proposed that it was deposited during MIS 8 and is part of the Wragby Till Formation (Fig. 3).

Clearly, the findings from Clipsham have implications for the age attributed to this Oadby Till. The concept of two glacial episodes with different directions of ice movement during MIS 12 (Rose, 1992; Bowen, 1999) is unlikely, because of the climate and temporal duration needed for the development of pedological clay in the Clipsham Beds between the two tills. The presence of the temperate climate Clipsham Beds suggests that two glacial episodes advanced across the region, either between MIS 12 and MIS 10 (West, 1977; Hamblin *et al.*, 2005; Rose, 2009), or between MIS 12 and MIS 8 (White *et al.*, 2017). From the above, it is not clear whether the Oadby glaciation occurred during MIS 10 or MIS 8, and at present this issue can only by resolved by what is known from the wider extent of the two till lithologies (see 'The glacial history of midland England' below).

Lithofacies 6 – clayey gravel and temperate and cold climate soil formation

Lithofacies Unit 6 is gravel modified by soil-forming processes and surrounded by Oadby Till. Isolation and preservation is attributed to cryoturbation processes at the surface and elsewhere this unit has been removed by erosion. A microstratigraphy within the clay coatings suggests a sequence of humid warm temperate weathering followed by cold climate disruption and a further stage of cool temperate weathering. Apart from the record of soil formation in different climates, over a period longer than one full interglacial, it is not possible to allocate these climatic events to a given Quaternary episode with any confidence. On the assumption that the last period of cool temperate weathering relates to the Holocene (MIS 1) the earlier full interglacial period of soil formation would represent the Last Interglacial (MIS 5e), and this is not an unreasonable conclusion. Because of its isolation Lithofacies Unit 6 is not named although it does confirm that the Oadby Till is older than the Last Interglacial (MIS 5e).

The glacial history of midland England

Number of glaciations recorded at Clipsham

Clipsham provides evidence for the presence of three glacial episodes across this part of eastern Midland England. The first is inferred from the traces of erratic material in the periglacial Pickworth Gravels. The low frequency of such material suggests that the glacial deposits, with the exception of a few residual clasts, had been stripped from the landscape before the erosion of the now buried channel and deposition of the Pickworth Gravels. All that can be said is that lowland Midland England was glaciated and subsequently eroded before the glaciation that deposited the Bozeat Till (the second glacial episode). The third glacial episode is represented by the Oadby Till.

Extent and stratigraphic control of the different glacial deposits

Our understanding of the glacial history of lowland midland England is far from resolved, but the evidence from Clipsham makes a positive contribution to this subject, as it demonstrates, unequivocally, that the two, well-represented, lowland glacial deposits of eastern midland England are separated by non-glacial conditions with a climate and duration equivalent at least to a full interglacial. The earlier glaciation from the NW deposited the chalk-free Bozeat Till and a later glaciation from the NE deposited the chalky Oadby Till (Fig. 13).

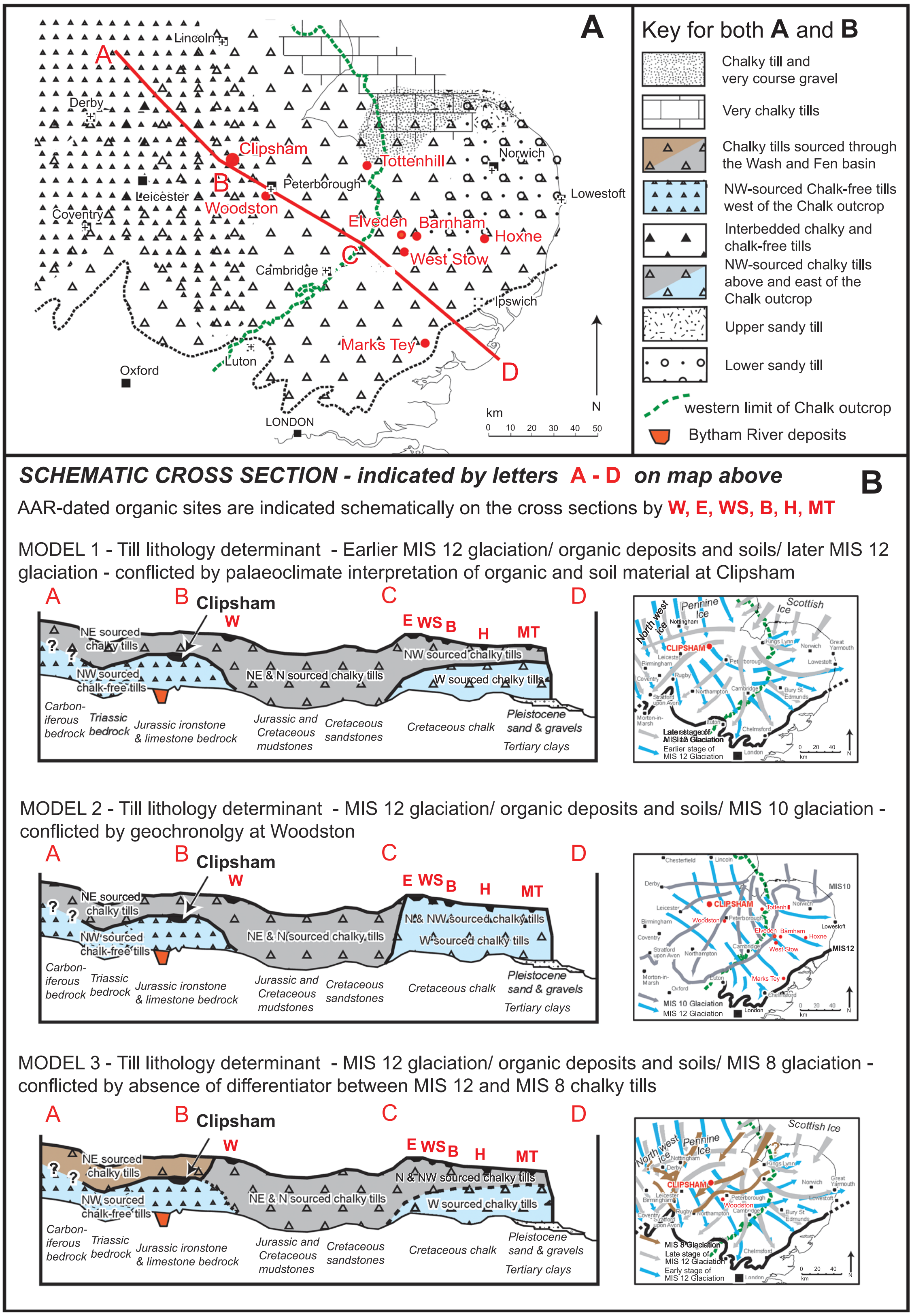

Figure 13. Continued.

The Bozeat Till in Midland England

The lithological content of the brown and grey chalk-free Bozeat Till indicates glacial transport from NW to SE across Carboniferous, Triassic and Jurassic rocks (Fig. 2), along with far-travelled material from the north-west. The bulk of the deposit is made up of local Jurassic mudrocks and limestone. Ice movement of this direction is supported by the record of NNW–SSE-trending striations near Wartnaby WNW of Clipsham (Lamplugh *et al.*, 1909, p. 64). Published records of the lithological properties and fabric direction of tills to the south of Clipsham (Sabine, 1949; West and Donner, 1956; Perrin *et al.*, 1979; Barron *et al.*, 2006) indicate that similar till extends almost as far as the limit of glacial deposits in southern Midland England (Fig 13A,B), but the extent is difficult to determine because the deposit: (i) rarely forms the surface till, (ii) lithological properties are only recorded in a few sections or boreholes and (iii) there are few published records from across the region (see Supporting Information S3). Examination of the results of West and Donner (1956) suggest that Bozeat Till may exist in the region south of the Wash and west of the Chalk outcrop, as four sites show an ice flow direction from the NW to SE or W to E (Numbers: 6, 8, 42 and 43 in List of Sites pp. 72–75), but all these sites are recorded as being blue-grey or brown-grey *chalky* 'boulder-clay', and therefore cannot be Bozeat Till (although where the chalk could have come from with such ice-flow directions is difficult to understand). Thus, it appears that the Bozeat Till is absent from the area south of the Wash and Fen basin (Fig. 13A).

Differentiation of the Bozeat Till and Oadby Till in the region overlying and to the east of Chalk outcrop

The properties of chalk-free and chalky tills described above are no longer applicable in the region overlying or to the east of the chalk outcrop. Once the NW–SE-flowing ice reached Chalk bedrock the Bozeat Till has the capacity to include chalk and the Bozeat and Oadby Tills cannot be readily differentiated in the field. Potentially, the findings of West and Donner (1956) should differentiate the Bozeat and the Oadby tills above and east of the Chalk outcrop by the direction of macrofabric trend, and indeed this is what is used to differentiate the lower Lowestoft and upper Gipping Tills of these authors. The Lowestoft Till shows a NNW–SSE to NW–SE trend and the Gipping Till shows a N–S to NE–SW trend (West and Donner, 1956, fig. 4). Thus, the Lowestoft Till of East Anglia is the down-glacier chalk-rich extension of the Bozeat Till and the Gipping Till was deposited at the eastern side of the piedmont ice-stream that deposited the Oadby Till in Midland England. The results also imply that ice from both flow directions covered the whole of central and southern East Anglia and the northern parts of Hertfordshire and Essex (not just the western part of the region as shown in West, 1977, figure 12.3, p. 280).

In an attempt to resolve this problem, Fish and Whiteman (2001) used Chalk micropalaeontology to correlate tills with the outcrop of particular Cretaceous Stages in east Yorkshire, Lincolnshire, Norfolk, Cambridgeshire and Suffolk. Nine sample points are relevant, and the till lithologies (all of which are ascribed to the Lowestoft Formation) are defined as lower dark facies and upper light facies. The Chalk clasts from the lower facies at most of the sites indicate derivation from the NW and W and are therefore likely to be the regional correlative of the Bozeat Till, whereas the upper facies show a typically NNW to SSE ice flow direction typical of the eastern limb of the ice-stream that deposited the Oadby Till. Like the findings of West and Donner (1956) these results also show that the glaciers that deposited the two tills covered the whole region.

With the same objective, Scheib *et al.* (2011) (Supporting Information S4) analysed the geochemistry of soils developed at the outcrop of glacial deposits at 4187 sites within midland and eastern England and used multivariate statistical analysis to evaluate the importance of adjacent bedrock upon the geochemistry of the glacial deposits, and so determine the direction of ice movement. The first three principal components reported by this study were found to provide 93% of the total variance. The relationship between the geochemistry of the soils developed on glacial deposits, with that developed on bedrock indicates a lower till with a NW–SE to W–E flow path, and an upper unit with a NE–SW and N–S and NW–SE piedmont lobe passing through the Wash and Fen Basin (Scheib *et al.*, 2011, fig. 9) in accordance with the findings of West and Donner (1956), Rose (1992), Fish and Whiteman (2001) and Hamblin *et al.* (2005). However, although these findings indicate that the upper till reached a limit along the western part of the Chalk escarpment (roughly similar to Fig. 3C,F; West, 1977; Hamblin *et al.*, 2005), they do not support the contention that the upper till extended to the glacial limits within the region, and they do not identify two till sources in East Anglia, east of the Chalk outcrop, except within the northern area (West and Donner, 1956; Rose, 1992; Fish and Whiteman, 2001; Scheib *et al.*, 2011, fig. 9).

Other differentiating properties, such as correlation with dated river terrace deposits, relationship to 'pollen stratigraphy' and physical and geochemical geochronology have been discussed above. It must be concluded that despite substantial work, it is not possible at the moment to determine whether the region overlying and east of the Chalk outcrop in central and southern East Anglia was glaciated once (West, 1977; Hamblin *et al.*, 2005; Scheib *et al.*, 2011; Lee *et al.*, 2017) or twice (West and Donner, 1956; Rose, 1992; Fish and Whiteman, 2001).

The place of the MIS 8 age Wragby Till in the succession at Clipsham and the extent of this glacial deposit and its correlatives

Figure 3G shows that Clipsham is located within the area of the MIS 8 age Wragby Glaciation (Bridgland *et al.*, 2014; White *et al.*, 2017), and that the glacial deposits in the Clipsham area are referred to as Oadby Till, considered a regional variant of the Wragby Till. This interpretation is based upon the stratigraphic position of the Wragby Till in relation to dated river terrace deposits within the region, and the position of

Figure 13. Scenarios for Middle Pleistocene glaciation of eastern midland and eastern England as a consequence of the discovery of organic deposits and soils between two tills at Clipsham. The key relates to both A and B. It identifies the different lithologies shown on A according to the symbols applied and on B using colour as well as symbols to represent the lithologies in cross-section. Also shown is the western limit of the Chalk outcrop, interglacial sites that have been allocated to Marine Isotope Stage 11 using AAR, and the location of the study site at Clipsham. The position of the cross-sections shown in part B below is shown and identified on part A by the letters A–D. (A) A map and key showing the glacial deposits and their distribution across midland and eastern England. (B) Three cross-sections presenting scenarios for glaciation of midland and eastern England in light of the presence of organic deposits and soils at Clipsham. **Model 1** presents the case for an earlier MIS 12 age glaciation, organic deposition and soil development, and a later MIS 12 age glaciation. While this model is supported by some lithological interpretations of till distribution across the region, it is rejected because the subaerial evidence from the sediments and soils at Clipsham indicate warm temperate climate conditions characteristic of a full interglacial. **Model 2** presents the case for MIS 12 and MIS 10 age glaciations with intervening MIS 11 sediments and soils and is supported by the organic material and soils at Clipsham and by some lithological interpretations of till distribution across the region, but it is rejected because MIS 11 age (AAR and biostratigraphically determined) deposits at Woodston (W) overly what should be MIS 10 age tills. **Model 3** presents the case for MIS 12 and MIS 8 age glaciations, separated by organic deposits and soils that developed in MIS 11 or 9. This model is favoured and is supported by the distribution of AAR-dated interglacial sites above the tills. However, chalky till extends across the whole area from A to D and there is no direct lithological evidence in the field to discriminate between that which formed in MIS 12 and that which formed in MIS 8. [Color figure can be viewed at wileyonlinelibrary.com]

biostratigraphically and geochronologically dated sites across midland and eastern England (White *et al.*, 2017, fig. 6).

Critically, the Wragby Till is overlain by river terrace deposits attributed to MIS 7 and younger (White *et al.*, 2017, fig. 1) and is therefore, along with associated outwash and lacustrine sediments, considered to be of MIS 8 age. However, there are no direct stratigraphic constraints on the lower boundary for the age of this deposit, other than the presence of underlying preglacial Bytham River deposits, which only indicate an age younger than MIS 13 or early MIS 12 (Rose, 1989c). The age of this glaciation can also be addressed by the distribution of organic deposits attributed to MIS 11 and 9 (White *et al.*, 2017, fig. 6). There is an absence of sites of these ages within the area designated for MIS 8 ice cover, but south and east of this region, sites at Woodston, Barnham, West Stow/Beeches Pit, Hoxne and Marks Tey (Fig. 13) indicate that ice has not covered this area since the MIS 11 interglacial stage (Penkman *et al.*, 2011, 2013). White *et al.* (2017) also shows Frog Hall (MIS 11 or 9), Tottenhill (MIS 11 or 9) and Biddenham (MIS 9) on fig. 6 of their paper, but these sites are not verified by recent geochronological analysis (Penkman *et al.*, 2011, 2013), although an earlier U-series study placed Tottenhill in MIS 9 (Rowe *et al.*, 1997). Thus, the glaciers that deposited the Wragby/Oadby Till did not extend across the area with MIS 11 organic sites at the surface, and could not have extended beyond Woodston (Fig. 13) which is the most northerly and westerly of these localities. This means that the Oadby Till at Clipsham is constrained to MIS 8. While this is stratigraphically straightforward, the distribution of the chalky till in midland and eastern England provides a problem as chalky till extends south of the MIS 11 sites, and in particular underlies the interglacial deposits at Woodston (Horton *et al.*, 1992). There are no known lithological or morphological criteria that differentiate the Oadby Till ascribed to MIS 8 and the Oadby Till that is recorded in the area where MIS 11 sites overlie glacial deposits and an MIS 12 age considered most likely.

Stratigraphic constraints

Following from the above, a number of stratigraphic constraints can be identified:

i. The position of the glacial deposits above Bytham Sands and Gravels means that all glacial deposits in the region under consideration are younger than MIS 13/early MIS 12.
ii. The position of the glacial deposits beneath organic deposits in north-east midland England dated to MIS 7 means that the glacial deposits at Clipsham are MIS 8 or older. This is supported by relationships with dated river terrace deposits.
iii. Lithological studies of the tills in midland and eastern England indicate that both NW-sourced and N-sourced ice flow directions reached either: (a) a zone roughly coincident with the Chalk outcrop, or (b) had similar eastern and southern limits close to the limit of glaciation. This difference has not been resolved.
iv. The position of organic deposits at Woodston dated to MIS 11 means that irrespective of point (iii) above, glacial deposits south and east of Woodston in central and southern East Anglia and south midland England are older than MIS 11. This is supported by relationships with dated Thames river deposits.
v. The organic deposits and soils preserved between the chalk-free and chalky tills at Clipsham provide evidence for periglacial, warm temperate and cool temperate climate conditions.

Potential models for glaciation in midland and eastern England

Considering the constraints outlined above, three models for the glaciation of midland and eastern England are presented (Fig. 13).

Model 1 (Figure 13B.1). Ice flowed across the region in two different directions from two different sources during MIS 12, separated by a non-glacial episode. Both glaciations extended across the whole of midland and eastern England to the limit of the area covered by glaciation. This model is supported by the distribution of the till lithologies and age of organic sites above and beneath the tills across the region, but is conflicted by the evidence for long-duration warm temperate climate between the tills at Clipsham.

Model 2 (Figure 13B.2). Ice flowed across the region in two different directions with two different sources: the earlier glaciation deposited the chalk-free till during MIS 12, and the later glaciation deposited the chalky till during MIS 10. The two events were separated by a long-duration climatic episode typical of an interglacial hemicycle within Britain. In this case it is proposed that the MIS 12 Lowestoft glaciation extended to the limits of the area covered by glaciation and the MIS 10 glaciation extended as far as central East Anglia. This model is supported by the climatic signal from the organic deposits and soils between the till at Clipsham and the distribution of the upper chalky till in midland England, but the proposition is conflicted by the organic site at Woodston that has been ascribed to MIS 11 on the basis of biostratigraphy, AAR and OSL age determinations.

Model 3 (Figure 13B.3). Ice flowed across the region in two different directions with two different sources: the earlier glaciation deposited the chalk-free till during MIS 12, and the later glaciation deposited the chalky till during MIS 8. The two events were separated by a long-duration climatic episode typical of glacial/interglacial cycles within Britain. In this case it is proposed that the MIS 12 Lowestoft glaciation extended to the limits of glaciation in southern and eastern England and the MIS 8 glaciation extended as far as north midland England and north of the Woodston organic site. This model is supported by the climatic signal from the organic deposits and soils between the tills at Clipsham and is also in accordance with the biostratigraphy, AAR and OSL age determinations. This is a realistic model, and indeed it could be possible to relate the Bidwell Diamicton to MIS 10 cold stage and the possible soil at the top of this deposit to MIS 9.

However this proposition is challenged by the finding which indicates that an upper chalky till extends south and east of the study region. This means that in the Clipsham area the upper chalky till is MIS 8 age, but further south and east it is MIS 12 age, and there is no known evidence to differentiate the two. Furthermore, the earlier MIS 12 chalky till of south midland and eastern England does not appear to have existed at Clipsham, and this ice flow-track does not appear to have crossed the Clipsham area as there is substantial, albeit negative, evidence for no chalk within the Clipsham region before MIS 8.

Of the three models, number 3, which proposes an MIS 12 glaciation followed by a non-glacial conditions and an MIS 8 glaciation provides the most convincing scenario for the glaciation of midland and eastern England. With respect to the MIS 12 glaciation this model may be related to that proposed by Rose (1992) and Lee *et al.* (2017) in which both the chalk-free and chalky tills were laid down in MIS 12. However, this association would require that the chalk-rich ice flow path would not have extended as far north as Clipsham during MIS 12.

Conclusions

- Organic sediments and soil materials are recorded from between two tills at Clipsham in eastern midland England. This is the first record of such a succession in the region. This paper presents the results of a detailed geomorphological, lithological, pedological, palaeobotanical and structural study of the site.
- Geomorphological analysis of the site indicates that the succession is preserved in a buried stream headwater channel eroded into limestone bedrock.
- Occasional far-travelled clasts in the gravels at the base of the channel may provide evidence of previous (pre-MIS 12) glaciation
- Clast lithology, clast fabric, sediment chemistry, indicator fossil provenance and palynomorph content indicate that the lower chalk-free till was deposited by ice flowing NW to SE and the upper chalky till was deposited by ice moving NE to SW.
- The lower till, below the organic material, is known as the Bozeat/Lowestoft Till. The upper till, above the organic material, is known as the Oadby/Wragby Till.
- The organic deposits and soil material consist of periglacial soil structures, transported organic matter, transported pedological clays and root casts. Interpretation of the above and a microstratigraphic analysis reveals that the region experienced periglacial soil processes, a long period of warm temperate climate, ending with cool temperate climate conditions. These are interpreted as the product of subaerial processes.
- Debris flow and mudflow sediments, derived from the chalk-free till, bury the organic materials and ensure their survival. These mass-flow deposits show traces of soil development at their surface and are buried by the chalky till.
- Together, the organic deposits, mass-flow deposits and buried soils provide evidence of climate change through an interglacial/glacial/interglacial cycle.
- Evaluation of the stratigraphic sequence from Clipsham in terms of previous work from the area suggests that the lower till was deposited during MIS 12, that the organic material, soils and mass flow materials were formed through MIS 11–9, and that the upper chalky till was formed by an MIS 8 glaciation.
- A complex, well-developed soil in gravel above the MIS 8 Oadby Till provides evidence for warm temperate, cold and cool temperate climate development.
- Although the age attributions are made by correlation with other sites from midland, eastern and southern England, the presence of the subaerial deposits between two tills is of exceptional importance by demonstrating, unequivocally, that midland England was glaciated during two separate cold stages of the Middle Pleistocene, something that hitherto has only been inferred from indirect relationships.

Author contributions—All authors contributed to the research. The site was discovered and excavated by N.S.J.Q.B.; fieldwork was conducted by J.R. and J.T.; lithological and sedimentological analysis was conducted by J.R. and Mark Lewis; palynological, palynomorph and palaeontological analyses were conducted by E.T., J.B.R. and J.K.W.; micromorphology was conducted by A.P., J.R.L. and J.R.

Supporting information

Additional supporting information can be found in the online version of this article.

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Data availability statement

The primary data that support the findings of this study are available from the corresponding author upon request. As far as possible all data are made available in the text, tables and figures.

Abbreviations. AAR, amino acid racemisation; LGM, Last Glacial Maximum; MIS, Marine Isotope Stages; OD, Ordnance Datum; OSL, optically stimulated luminescence.

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