Fluvial response to Late Pleistocene and Holocene environmental change in a Thames chalkland headwater: the Lambourn of southern England

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ABSTRACT

This paper describes the Late Pleistocene to Holocene stratigraphy of the River Lambourn; a minor headwater of the River Thames in the Berkshire Downs. The Quaternary valley-fill comprises around 5-8 m of Late Pleistocene gravels overlain by Holocene peats and chalky clays. Quaternary deposits overlie an irregular rockhead erosion surface with deep scouring particularly evident on prominent bends in the valley. The gravels subdivide into a lower unit of chalky gravels overlain by coarse flint gravels. Ground penetrating radar suggests that gravels at depth are relatively structureless, but at the top show well-developed point-bar accretion surfaces which occur in association with peat-filled sinuous channels. These probably date from around the Pleistocene-Holocene boundary and may have formed in response to climate change and increased groundwater outflow as stream hydrology changed from the short-duration, high-magnitude flows of the Lower Dryas to the uniform, low-magnitude flows of the Holocene. Holocene peats initially infilled abandoned floodplain channels at around 10 kyr BP but later encroached over much of the Lambourn floodplain. A progressive upward decrease in organic material and an increase in the proportion of chalky clays from around 4 kyr BP probably occurred in response to floodplain accretion coupled with increased erosion of the chalk catchment related to agricultural clearance and a wetter climate.

Keywords:

Quaternary; Late Pleistocene; Holocene; Thames; Lambourn; chalk; Berkshire Downs; fluvial

1. Introduction

Late Pleistocene to Holocene fluvial deposits of north-west Europe form an important record of evolving terrestrial environments and major changes in climate since the last glacial cycle which terminated at 11.7 ka (Anderson et al., 2007; Hughes et al., 2013; Lespez et al., 2015). Most fluvial deposits of this age in north-west Europe show a broadly similar stratigraphy, with an abrupt switch from high-energy gravelly deposits of the Late Pleistocene cold stages into fine-grained and often organic-rich floodplain deposits of the temperate Holocene (Gibbard, 1985; Murton and Belshaw, 2011). Fluvial sediments of this age also record the increasing importance of anthropogenic landscape modification in the later parts of the Holocene (Lewin, 2010; Macklin et al., 2010) and in this respect they have an important part to play in the current debate on the existence and timing of the 'Anthropocene', the proposed geological epoch in which human activity has dominated many of the processes acting on the surface of the planet (Waters et al., 2014). While some advocate that the base of the Anthropocene lies within the industrial debris (Waters et al., 2014) and chemical pollution (Vane et al., 2011) of the 20th century the fluvial stratigraphic record often shows the strong effect of agriculture and land clearance much earlier in the Holocene (Macklin et al., 2010).

In most cases, Late Pleistocene to Holocene fluvial deposits underlie the modern floodplain which immediately imposes difficulties in their observation and sampling. In the Thames Catchment much of our understanding of these deposits is based on information gained from gravel pits which tend to be located on the wider floodplains of trunk rivers and major tributaries (Bridgland, 1994; Collins et al., 1996; Collins et al., 2006). This has introduced a bias against the late Quaternary record of minor headwaters, particularly those in chalkland settings, although as noted by Collins et al. (1996) this information is required to understand the full longitudinal variability of river behaviour.

This paper considers the Late Pleistocene to Holocene evolution of the River Lambourn, which drains a small (269 km^2) chalk catchment in the Berkshire Downs of southern England (Grapes et al., 2006). The Lambourn is a minor headwater in the much larger (16,133 km^2) River Thames basin, whose Quaternary history has been studied for over one hundred years and whose fluvial sediments provide a framework for this part of the geological record in Britain (Bridgland, 1994). The primary aims of this paper are to, (1) show how boreholes and non-invasive geophysical techniques can provide an understanding of the stratigraphy and three-dimensional (3D) geometry of the latest Quaternary fluvial record in poorly-exposed headwater settings and, (2) determine the extent to which the Late Quaternary fluvial stratigraphy of minor headwaters compares or contrasts to better known downstream locations (Collins et al., 2006). The paper adds to a growing body of recent hydrogeological work in the Lambourn catchment (Allen et al., 2010; Gooddy et al., 2006; Grapes et al., 2006; Griffiths et al., 2006; House et al., 2015; Mullinger et al., 2007; Musgrave and Binley, 2011) and an additional aim of the paper is to show how a knowledge of the Late Quaternary fluvial stratigraphy has great practical importance in understanding groundwater-surface water interactions in modern chalkland streams; one of Britain's most highly-valued natural environments (Wheater et al., 2007).

2. Background to the River Lambourn

2.1 Modern river and catchment morphology

The River Lambourn is a chalk stream in the Berkshire Downs of southern England (Figure 1). It rises near Lambourn and is a tributary of the River Kennet, which is itself a tributary of the River Thames. The River Lambourn flows southeast down the regional slope of the Berkshire Downs, a gently tilted block of Cretaceous Chalk approximately 250 m thick which is incised by many valleys, the majority of which are dry with only a few containing perennial rivers (Figure 1). The Lambourn catchment is elongated in a NW-SE direction and is approximately 30 km long and 10 km wide, covering an area of 269 km^2. It has a mean elevation of 157 mAOD (standard deviation 36 m), ranging from a maximum of 260 m in the northwest to a minimum of 68 m in the southeast at the confluence between the rivers Lambourn and Kennet at Newbury (Figure 2A). The river falls at a rate of around 2.4 m per kilometre from source to outflow. The river has a perennial length of approximately 16 km, and an upper seasonal section of around 7 km which exhibits characteristic bourne behaviour, where there is absence of flow for around three months of the year coincident with low groundwater levels, typically in late summer (Grapes et al., 2006). This is a predominantly groundwater-fed river, with a baseflow index of 0.96 and a mean flow of 1.73 m^3/s (Griffiths et al., 2006; Hannaford and Marsh, 2008). The modern River Lambourn is mainly a single thread channel commonly around 5 m wide and 1.5 m deep which meanders across a narrow, confined floodplain typically around 200 m wide. The river splits into anastomosing channels in two anthropogenically-modified flood meadow areas at Welford and Boxford (Allen et al., 2010). The whole river is designated as a Site of Special Scientific Interest (SSSI) as it is a classic example of a lowland chalk river (Old et al., 2014).

2.2 Catchment geology

The Lambourn catchment is underlain by Cretaceous Chalk (Figure 2) which dips at an angle of less than one degree toward the southeast into the western termination of the synclinal London Basin (Bloomfield et al., 2011). Most of the exposed chalk belongs to the Seaford Chalk Formation, a low density and high porosity (up to 50 %) fine-grained carbonate rock which includes many horizons of flint nodules, which can range up to 0.5 m in diameter (Aldiss et al., 2006; Bloomfield et al., 1995).

Older chalks, which include the high-density chalkstones of the Holywell Nodular Chalk and Lewes Nodular Chalk formations occur in the northwest portion of the catchment, upstream from East Garston (Figure 2B). Chalks typically have a dense network of joints and fractures which, particularly where they are enhanced by dissolution, contribute nearly all of the aquifer permeability in the high-porosity but low-permeability fine-grained carbonate rock (Bloomfield et al., 1995). The common development of a rectilinear pattern of dry valleys in the Lambourn catchment may reflect an underlying structural control by an orthogonal fracture set with a northeast and southeast orientation (Figure 2). The River Lambourn itself follows a strongly linear, southeast trending valley for most (but not all) of its length strongly suggesting some underlying structural control. While there is no evidence for the offset of Chalk formations which would indicate a fault (Aldiss et al., 2006), linear fracture swarms often develop where stresses from reactivated basement structures propagate upwards into the Chalk. The Lambourn catchment is located north of the Pewsey-Kingsclere Anticline, a major anticline in the Chalk developed over reactivated Mesozoic extensional faults during late Paleogene to early Neogene compression and basin inversion (Newell, 2014).

Across the northwest half of the Lambourn catchment, the deeply-eroded chalk bedrock is concealed only beneath thin rendzina soils (Catt and Hodgson, 1976) across large areas (Figure 2). In the southeast half of the catchment, downstream from East Garston (Figure 2), younger Chalk formations have a much greater cover of Palaeogene and Quaternary sediments. These deposits which include parts of the Reading and London Clay formations, clay-with-flints, head and alluvium are formed from variably stratified admixtures of gravel, sand, silt and clay up to around 25 m thick (Aldiss et al., 2006). They represent a sequence of siliciclastic sediment recycling and redistribution within the catchment which is important for understanding the origin of the fluvial valley fills. The clay-with-flints typically occurs as flat-lying or gently inclined sheets up to around 5 m thick on low-gradient interfluve plateaus and represents the largely *in situ* modification of thin Palaeogene deposits by freeze-thaw processes under Pleistocene periglacial conditions, with local collapse into solution hollows developed on the underlying Chalk (Catt and Hodgson, 1976). The downslope translation of clay-with-flints around plateau margins is the primary means of producing ‘head’, a term often used to describe diamicton comprising poorly-sorted admixtures of chalky gravel, sand, silt and clay with mantle the sides and base of many valleys across the chalk downlands of southern England. Head is thought to be primarily a periglacial mass-flow deposit where the downslope movement of debris was modulated by seasonal cycles of freeze and thaw (Ballantyne and Harris, 1994). Where valleys contain rivers, or where valleys formerly contained rivers as many are now dry, slope deposits and material eroded from the valley floor could be reworked and sorted by fluvial processes into coarse-grained channel bar and fine-grained floodplain deposits (Murton and

Belshaw, 2011). Some of the siliciclastic material forming the alluvial fills of chalk downland valleys thus has an origin from Palaeogene deposits (modified or reworked by a variety of Pleistocene periglacial processes), with an additional contribution from first-cycle flint nodules (supplying cobble and boulder grade material), clays and fine-grained carbonates eroded from the Chalk. There is no evidence for ice-contact deposits in the Berkshire Downs, which throughout the cold climatic phases of the Pleistocene was located south of the overall glacial maximum (Figure 1) under periglacial conditions characterised by permafrost, mass wasting and, depending on the prevailing humidity, arid aeolian processes or short-duration, high-magnitude stream flows (Ballantyne and Harris, 1994; Murton and Belshaw, 2011). The Thames catchment, of which the River Lambourn is a part, is in general a tectonically-stable region apart from relatively high-magnitude glacio-isostatic uplift during the Quaternary (Bridgland and Schreve, 2009). Uplift, in combination with an oscillating climate (Murton and Belshaw, 2011), has created a flight of terraces (Bridgland, 1994) which occur elevated above the sub-floodplain river deposits under discussion here.

2.3 Study sites

Two sites from the central, perennial part of the River Lambourn are described in this paper (Figure 1). The first site (Ordnance Survey National Grid Reference (NGR) 441455 172577) is located where the M4 Motorway crosses the River Lambourn 750 m south of Welford. Here archived geotechnical borehole records from construction of the M4 motorway cross-over provide a detailed record of the alluvial stratigraphy and chalk bedrock beneath the modern floodplain in a straight segment of the valley. The second site (NGR 442856 172131) is located 1.5 km downstream from the M4 motorway cross-over at a very conspicuous bend in the Lambourn valley just to the north of Boxford (Figure 1). This Boxford site is a Special Area of Conservation (SAC) due to the habitat it provides for Desmoulins whorl snail (*Vertigo moulinsiana*) and is also as a SSSI because of its wetland habitats (Old et al., 2014). Here the alluvial stratigraphy of the River Lambourn has been investigated using a number of new boreholes (Allen et al., 2010) in addition to a range of non-invasive geophysical methods including electrical resistivity tomography (Chambers et al., 2014) and ground penetrating radar. The Boxford site has been the subject of much recent work aimed at understanding the functioning of the wetland (House et al., 2015).

3. M4 crossing: a straight reach of the Lambourn

3.1 Site description and methods

Nine site investigation boreholes (BH) drilled in 1968 prior to the construction of the M4 motorway provide information on the alluvial stratigraphy in this straight segment of the Lambourn valley. The boreholes form a staggered array across the floodplain, which here is approximately 180 m wide (Figure 3). The boreholes range from 18-24 m deep, with all extending into the Chalk for some distance. The course of the River Lambourn and its floodplain were strongly modified by the emplacement of motorway embankments but historical Ordnance Survey maps (the earliest dating from 1882) show the original configuration of the floodplain and the location of channels (Figure 3). The borehole records provide concise geotechnical descriptions of samples recovered using a shell and auger technique, together with Standard Penetration Test (SPT) *N-values* (Clayton, 1995). Nine boreholes were linked into a cross-section which shows the stratigraphy of the alluvial fill (Figure 4).

3.2 Alluvial stratigraphy

Borehole records show that at the M4 crossing the Quaternary superficial deposits of the Lambourn valley have a maximum thickness of 6 m with an undulating base that lies between 88.1 to 91.5 metres above ordnance datum (mAOD). The superficial deposits are predominantly gravel and peat which are cut into flinty Seaford Chalk Formation, whose strength description (Anon, 1999) varies from stiff to hard. Highly-weathered, rubbly chalks occur along the flanks of the valley in intervals up to 6 m thick immediately beneath the superficial gravels (Figure 4). SPT tests of the rubbly chalks produced *N-values* of 10-15 indicating very weak chalk (Clayton, 1995). Boreholes in central parts of the floodplain (BH 16-19) show that here the chalk beneath the gravels was hard and jointed with SPT *N-values* in the range 30-50 indicating weak chalk (Clayton, 1995).

Between rockhead and the modern floodplain, the Quaternary fluvial succession divides into three main parts. At the base is a layer of flint and chalk gravel which ranges up to 3 m thick. Some of the chalk within these gravels is disaggregated into a clayey chalk. The thickness of this layer is variable and it appears to thicken into hollows (BH 16 and 19) and thin over highs (BH 17 and 18) on the chalk rockhead. The chalk-rich gravels are overlain by a layer of flint gravel up to 3 m thick. Borehole records indicate that flint particles are predominantly gravel (2-63 mm), but cobble (63-200 mm) and even boulder (200-630 mm) grade material is present. There are lateral changes into gravel containing sand (BH 16) and some boreholes (BH 17, 18, 19) show the progressive incorporation of more chalk with depth, suggesting a gradational contact with the flint and chalk-rich gravels. The flint gravels are capped by a layer of peat and organic clay which reaches a maximum thickness of 1.6 m (BH 17) toward the centre of the floodplain. The organic deposits incorporate some gravel and toward the margins of the floodplain brown silty clay. Slope deposits occur along the valley margins and comprise an admixture of stiff orange or brown clays, flint gravel, chalk and flints. Slope deposits reach a maximum thickness of 3.7 m in BH 20 and it is likely they interdigitate with river-deposited gravels on the valley floor.

4. Boxford: a curved reach of the Lambourn

4.1 Site description and methods

The Boxford site is located at a conspicuous bend in the Lambourn valley with an apex located approximately 650 m north of Boxford village (Figure 2). The curved valley is incised into Seaford Chalk and encloses a floodplain that is 250 m wide and includes a number of anastomosing channels which divide the area into three zones (Figure 5). In an upstream location on the outside of the bend is Westbrook Farm where a number of monitoring boreholes were installed adjacent to the river for the Lowland Catchment Research programme (LOCAR) (Allen et al., 2010; Wheater et al., 2007) (Figure 6). Downstream from Westbrook Farm the river divides into an outer main channel and a sinuous side branch which re-joins the Lambourn 500 m downstream. Two densely-vegetated wetland areas (North Meadow and South Meadow) occur on either side of this subsidiary channel (Figure 6). A historical Ordnance Survey map published in 1913 (Figure 7) shows the former presence of numerous minor channels crossing the wetland area, which was formerly managed as a water meadow, an area of floodplain subject to controlled flooding in winter which protected grass from frost and encouraged early spring growth (Everard, 2005). The site has not been grazed for a number of years, and many of the historic channels do not appear on current Ordnance Survey maps but a Global Positioning System (GPS) survey of modern floodplain elevation (using real-time kinematic GPS and a Total Station) shows that many of the linear and herring-bone pattern carrier channels are still present (Figure 7), beneath the now dense cover of tall herbaceous vegetation (Roberts et al., 2014).

In addition to boreholes at Westbrook Farm, drilling was undertaken using a small crawler-mounted Dando Terrier percussion rig at three locations in the North and South Meadows (Figure 6). Cores were recovered using a hollow stem auger in U100 tubes for logging, ^{14}C AMS radiocarbon dating and total organic carbon determination. The depth of peat overlying the gravels in the North and South meadows was determined by pushing a 6 mm diameter steel rod to the contact between the penetrable peat and impenetrable gravels. This was undertaken at 2815 locations at sample spacing of approximately 4 m (Figure 6). The peat depth exceeded the rod length (1.86 m) at six locations which were assigned the maximum proven value of 1.86 m.

Two blocks within the North and South Meadows were surveyed using 3D electrical resistivity tomography (ERT) which provides high-resolution areal and volumetric subsurface information with minimal environmental impact. Full details on the ERT survey at Boxford can be found in Chambers et al. (2014) and are not repeated here. ERT determines the subsurface distribution of electrical resistivity using multiple resistance measurements. The interpretation of ERT data for the purpose of delineating sedimentary bodies requires care because the electrical resistivity is a function of many properties such as porosity, structure, clay content, water content, pore-fluid salinity and temperature. However, Chambers et al. (2014) shows that it is possible to use ERT to discriminate and map the chalk, gravel and peat components of the Quaternary valley fill at Boxford.

A number of ground penetrating radar (GPR) profiles were also available at the Boxford site. Full details on the configuration and processing of GPR data at Boxford are published elsewhere (Crook et al., 2008; Musgrave, 2006; Musgrave and Binley, 2011). GPR is a geophysical technique that detects electrical discontinuities in the shallow subsurface by transmitting and receiving discrete pulses of high frequency electromagnetic energy in the megahertz frequency range (Neal, 2004). GPR works particularly well in sediments with a low electrical conductivity and has been widely used to map bedding structures within fluvial sand and gravel deposits (Huggenberger, 1993).

Laboratory analysis of recovered borehole materials included sieving of gravels in one borehole (PL26X) to determine the grain-size distribution, ^{14}C AMS radiocarbon dating of three peat samples (Table 1) and the determination of total organic carbon (TOC) from the peat profile of one borehole (BHN). Total organic carbon (TOC) content was determined using an Elementar VarioMax C, N analyser after acidification with HCl (50% v/v) to remove carbonate. The limits of quantification for a typical 300 mg sample were 0.18%. Details of this method have been described previously (Vane et al., 2014). No palaeoecological work such as pollen analysis was undertaken as part of this study which focusses on sediment sequences and geometries. Riverine peats in the chalkland of southern England have been shown to have extremely poor preservation of pollen probably related to seasonal water table fluctuations and high pH (Waton, 1982). Information on the dryland vegetation succession in the Lambourn catchment since around 4.4 kyr BP is provided by Waton (1982) who undertook pollen analysis on a core from a polleniferous valley mire at Snelsmore situated in an interfluve position on Palaeogene deposits (Figure 2).

4.2 Quaternary stratigraphy

The total thickness of the alluvial valley-fill deposits at Boxford ranges from 1-9 m, with a median thickness of 5.8 m. A thickness map based on the combined evidence of boreholes and ERT (Figure 8) shows considerable variation in thickness around the valley bend, with the thickest superficial deposits located under the North Meadow (toward the apex of the valley bend) and a marked thinning toward the south under the South Meadow and toward the lateral limits of the floodplain. Borehole evidence shows that the stratigraphy of the Boxford site is broadly similar to that of the M4 crossing with a general threefold division into chalk and flint gravels, flint gravels and peaty alluvium (Figure 9).

4.2.1 Gravels

Gravels range from 0.3 to 8.3 m thick with a median thickness of 5.3 m (Figure 10). The base of the gravels is a markedly irregular erosion surface on the underlying chalk with a particularly deep zone of scouring toward the apex of the bend under the North Meadow, and an increase in elevation in a downstream direction toward the South Meadow (Figure 11). The form of the surface is clearly imaged by 3D ERT where the gravels are distinguished by their high (150-200 Ωm) resistivity values relative to the peats above and the chalk below (Figure 12). The chalk generally shows an increase in resistivity with depth which probably reflects the presence of an irregular and variably developed weathered rockhead layer below the superficial deposits (Chambers et al., 2014). Borehole core shows that chalk near the contact with the gravels comprises weak aggregates of angular and solution-rounded blocks giving a rubbly appearance (Figure 13). The closely-spaced fractures surrounding the blocks are often brown stained and infilled with water-saturated chalk clay.

The lower part of the gravel is usually an admixture of flint and chalk clasts in approximately equal proportions, or sometimes with a predominance of chalk (Figure 9). Many of the chalk clasts are degraded to water-saturated chalk clay which fills the porosity between the flints. Where chalk predominates, flint clasts float within a matrix of disaggregated chalk and it can be problematic to distinguish this material from the largely *in situ* but highly weathered Chalk rockhead. Evidence that the chalky gravels form a valley-wide sheet is less clear than at the M4 crossing (Figure 4). Chalky gravels are present in boreholes along the valley margins (e.g. BHS2, PL26X) but may not be present within more centrally-positioned boreholes (BHS1, BHN), although core recovery is incomplete and this is not certain (Figure 9).

Chalky gravels (where present) are overlain by gravels composed almost entirely of angular to subrounded black, grey and white flints (Figure 13). Sieve analysis of bulk samples from borehole PL26X shows that the gravels are coarse to very coarse (Blott and Pye, 2012) and very poorly to moderately sorted (Figure 14). Occasional outsize flints clasts up to boulder size occur and probably represent local derivation from the coarse flint horizons of the Seaford Chalk (Aldiss et al., 2006). Intervals of brown sandy gravels and gravelly sands (Figure 13) were recovered from the thicker gravel sequences of boreholes BHS1 and BHN (Figure 9). Missing intervals within these boreholes probably correspond to coarse, openwork gravels (which are extremely difficult to recover) suggesting a gravel stratigraphy of alternating coarse gravels and sandy fine gravels.

GPR profiles suggest the presence of well-developed stratification only in the uppermost 1-2 m of the gravel body beneath the clear continuous reflector of the overlying peats (Figure 15). Within the gravels strong, well-defined reflections are likely to indicate an alternation of poorly-sorted sandy gravels or gravelly sandy and matrix-free, open-work gravels (Huggenberger, 1993). Reflectors show a range of flat, undulating and inclined morphologies with numerous truncations, as might be expected in a fluvial deposit. Particularly well-developed sets of down-lapping reflectors terminating in concave channel-like fills are present just below the peats and probably indicate the preservation of relatively-complete fluvial point bars formed by the lateral accretion of thin gravel sheets (Figure 15).

4.2.2 Peat and chalky clay

The gravels at Boxford are sharply overlain by peats and chalky clays. Probed thickness measurements (Figure 16) in the North and South meadows show that the peats and clays have a mean thickness of 0.88 m (standard deviation 0.27 m) and range from 0.14 to 1.86 m (although this value was exceeded at six locations). The elevation of each probed location was established using differential GPS allowing the construction of an elevation map on the base of the peats (Figure 17). This map shows the highly-variable topography developed on the underlying gravels and, in particular, the presence of a sinuous channel which is most conspicuous in the South Meadow, but probably continues upstream into the North Meadow. The location of this channel does not correspond to the position of modern or historic channels on the wetland (Figure 7). Borehole BHS1 was drilled in the centre of the channel in the South Meadow and recovered 1.7 m of peat passing upwards into chalky clay (Figure 9).

Radiocarbon dating of peat at the base of the channel produced an age of 9916-10117 cal yr BP (Table 1) showing that the peats at Boxford started to accumulate toward the beginning of the Holocene. Borehole BHN was drilled in an out-of-channel location in the North Meadow and proved a 1 m succession of peats overlying the gravels and passing upwards into pale brown chalky clay (Figure 18). Radiocarbon dating indicated that the base of the peats were 3932-4144 cal yr BP and the top of the peats were 332-513 cal yr BP, where they start to grade into pale brown chalky clays (Table 1). The transition from fibrous organic-rich peats at the base of BHN to chalky clays at the top is shown both by a progressive colour change from black to pale brown and by an upward decrease in the total organic carbon (50%) from around 50 percent at the base to less than 10 percent in the clays (Figure 18).

The chalky clays overlying the peats are pale brown or olive grey in colour when wet, drying to pale grey or white (Figure 13). They are typically around 20 cm thick and have a sharp but transitional contact with the underlying peats in most boreholes, although in borehole BHS2 the base of the clays is a sharp, inclined iron-stained discontinuity (Figure 9). The clays are massive, with no obvious lamination, and contain many dispersed unidentifiable molluscan shell fragments mostly less than 1 mm in size. Roots and root traces occur throughout the clays (Figure 13).

Above the chalky clays are typically 20 cm of sedge peat below the tussocky vegetation of the modern floodplain surface. Boreholes in positions along the margins of the floodplain such as PL26X at Westbrook Farm (Figure 6) have 1 m of slope wash comprising brown and yellow clayey sandy gravel (Figure 9).

5. Discussion

Like the majority of lowland British (and northwest European) rivers, the River Lambourn occupies a valley that was partially infilled by gravel during the youngest cold climatic stages of the Late Pleistocene (Gibbard, 1985). Gravels are sharply overlain by fine-grained, organic-rich deposits which accumulated as temperatures rapidly increased in the Holocene (Figure 19). The gravels in the Lambourn valley have not been dated directly but are contiguous with sub-floodplain gravels of the Late Devensian Woolhampton Formation in the Kennet valley (Collins et al., 1996), 16 km downstream from Boxford at an elevation of around 50 mAOD (Figure 20). Note that in later work Collins et al. (2006) refer to the Woolhampton Formation as the Heales Lock Member of the Kennet Valley Formation. Further downstream again, the Woolhampton or Heales Lock gravels of the River Kennet merge with the Kempton Park and Shepperton gravels, which underlie the floodplain of the River Thames (Collins et al., 1996; Gibbard, 1985). The Woolhampton Formation includes the Wasing Sand Bed toward the base, an organic silty sand deposited during the Windermere (Allerød) Interstadial, suggesting that gravels above this unit were deposited during the Younger Dryas (Collins et al., 1996) (Figure 19). Older gravels below the Wasing Sand Bed are of uncertain age, but were probably deposited in the later part of the previous stadial at around 14.5 kyr BP (Collins et al., 1996). These older gravels represent a renewed phase of valley aggradation that followed the major episode of river downcutting at around 20-13 kyr BP which created the Beenham Grange Terrace (Collins et al., 1996). This terrace flanks the modern floodplain of the River Kennet and a degraded fragment of the Beenham Grange Terrace is also present at Boxford (Figure 5).

Throughout the Pleistocene the Lambourn catchment remained south of the overall glacial maximum (Figure 1) and periglacial conditions would have prevailed during colder periods. It has long been recognised that the development of frozen ground conditions in the Pleistocene was particularly significant for Chalk catchments such as the River Lambourn in that it allowed rapid run-off on otherwise permeable bedrock (Goudie, 1990). Under a regime of highly-variable, seasonal stream discharges this favoured the transport and deposition of gravel in bedload-dominated rivers which are radically different from the clear chalk streams of today. Freeze-thaw cycles were also important in maintaining an abundant supply of sediment through the rapid near-surface brecciation of chalk (Murton, 1996) and in promoting mass wasting on hillslopes (Ballantyne and Harris, 1994). It is likely that most of the gravelly sediments in the Lambourn valley were deposited during the relatively warm permafrost conditions of the Younger Dryas, when where was sufficient humidity to generate precipitation (Murton and Belshaw, 2011). Conversely, erosional down-cutting and scouring of the valley floor was probably most vigorous during the arid permafrost conditions of the last glacial cycle (MIS stages 2-4), when sediment supply from hillslopes into valley bottoms was restricted and limited river discharges had low sediment loads (Murton and Belshaw, 2011). As seen elsewhere in the Thames catchment there is evidence for highly-irregular scouring of the valley floor (Collins et al., 1996), with particular evidence at Boxford for deep scouring on the apex of river bends.

In the Lambourn catchment shattered chalk bedrock was incorporated into a basal layer of chalky gravels which, at straight valley locations such as the M4 crossing, forms a valley-wide sheet several metres thick. Comparable chalky gravels are not reported from downstream locations on the River Kennet (Figure 20) where chalk pebbles form less than 0.5 percent of clasts in gravels dominated by first- or second-cycle flints (Collins et al., 1996). This probably reflects the low strength of chalk clasts which are present only close to source within chalk-bedrock catchments. Within the Lambourn catchment many of the chalk clasts are degraded to a clay paste which occludes pore space within the otherwise highly-permeable flint gravels. This has important hydrogeological implications in that it reduces the storage capacity of sub-floodplain gravels (which may make a significant contribution toward stream flow and the maintenance of wetlands) and, through their reduced permeability may impede the free exchange of water between streams and underlying aquifers (Allen et al., 2010).

Given the absence of gravel pits or other exposures in the Lambourn catchment there is little direct evidence for the types of sedimentary structure and barforms within the gravels. Information on the barforms is required to establish whether the river was braided (with mid-channel bars) or meandering (with bank-attached point bars). It is often assumed that most cold-stage Pleistocene gravelly alluvium was the product of braided rivers, but coarse-grained meandering channels are equally probable (Kostic and Aigner, 2007), as are compound rivers which switch between braided and meandering styles depending on flow stage. Chambers et al. (2014) discuss possible evidence for braided structure within the gravels at Boxford from 3D ERT and Collins et al. (1996) suggest a predominantly braided style for the Late Pleistocene gravels in the Kennet valley at Woolhampton, although here the floodplain is substantially wider than in the relatively confined Lambourn valley 16 km upstream.

GPR profiles at Boxford provide the main evidence for sedimentary structure within the gravels and these suggest that at depths below 2 m the coarse-grained gravels are relatively unstructured. Toward the top, however, there are clearly-defined sets of inclined reflectors which pass laterally into concave-up channel-form features. The sets of inclined reflectors may represent laterally-accreted point-bars developed adjacent to meandering channels. The reconstructed topography on top of the gravels clearly shows the presence of curved channel segments now infilled with thick peats. The presence of well-stratified gravels with features suggesting the presence of laterally-accreted point bars and sinuous channels has interesting parallels with the latest Pleistocene succession at Woolhampton (Collins et al., 1996). Here the top of the gravels is marked by the local development of channels with alternating fine gravel, sand and silt in lateral accretion units (HLM4 of Collins et al. 2006) which Collins et al. (2006) suggest indicates a reduction in flow competence and a shift in flow regime at the Pleistocene-Holocene transition. The palaeoecology of this unit at Woolhampton is broadly stadial in nature, but some aspects suggest an amerlioration of conditions, consistent with radiocarbon dates which overlap the Pleistocene-Holocene transition (Collins et al., 1996).

Evidence for channel readjustment at the Pleistocene-Holocene boundary is of interest because of the rapidity of the climate change during this interval, which had a duration of less than 50 years (Alley, 2004; Anderson et al., 2007) (Figure 19). In many rivers of northwest Europe there is evidence that cold-climate braided channels of the Younger Dryas had insufficient time to readjust their morphology to the new temperate climate regime and fine-grained, organic deposition initially took place within relict braided channels (Boreham and Gibbard, 2007). However it is possible that small river systems such as the Lambourn and Kennet were sufficiently responsive to change their form during this short (50 year) time interval. Collins et al. (2006) postulate that channel readjustment at the Pleistocene-Holocene transition could also have been driven by an increase in groundwater supply to the river network and thus this could be feature of groundwater-dominated rivers such as the Lambourn.

The Lambourn shows the typical pattern of fluvial change at the beginning of the Holocene in northwest Europe with an abrupt shift toward the accumulation of peats and fine-grained sediments on floodplain wetlands, usually associated with low-energy meandering channels with regular flow patterns (Boreham and Gibbard, 2007; Macklin et al., 2010). A radiocarbon age of peats preserved within the deepest channels at Boxford indicates a Holocene succession that dates back to around

9916-10177 cal kyr BP. Younger radiocarbon dates for peats overlying gravels in out-of-channel locations show that peat accumulation was initialised within the channels with later onlap of gravelly highs on the undulating Pleistocene surface. Peats were formerly very extensive across the River Kennet floodplain and according to Collins et al. (2006) indicate a significant phase of organic accumulation at around 11-9.8 cal. kyr BP. At Woolhampton peats within the Holocene Midgham Member are underlain by clays and pass upwards into tufaceous carbonates and isolated gravelly channel fills (Collins et al., 2006) (Figure 20). Aside from rapid climatic warming and increased vegetation productivity in the early Holocene, the reasons behind the build-up of organic matter on the floodplains of the Lambourn and Kennet are unclear. Collins *et al*. (2006) consider a number of possibilities including the creation of floodplain wetlands as a consequence of channel blockage by beaver dams, log jams or anthropogenic fish weirs. In rivers such as the Lambourn, which are underlain by permeable chalk, it is possible that groundwater flooding could also have been important in the development of the stagnant floodplain wetlands required for reducing the decomposition of organic matter and allowing peat accumulation. The highly degraded, rubbly chalks below and (in the case of the M4 crossing) at the margins of the gravelly valley-fill probably indicate high fluxes of water between surface channels and the chalk aquifer. Recent work has shown the importance of groundwater input to modern wetland development at Boxford (Gooddy et al., 2006; House et al., 2015).

It is difficult to clearly identify river channels associated with the peats in the Lambourn valley. At Boxford the channel may have remained localised on the outside of the sharp valley bend in broadly its current location. Boreholes at Westbrook Farm include sands interbedded with the peats which might indicate former channels. Peats in the inner part of the bend within the North and South Meadows appear free from sands and gravels. At the M4 crossing, scattered flint pebbles are present within the peats which may indicate the former position of channels, overbank flood events or coarse material rafted by vegetation.

At Boxford there is a progressive reduction in the organic content of peats from around 3932-4144 cal kyr BP culminating in the deposition of 10-20 cm of olive grey, chalky clay across the floodplain. Evidence from one radiocarbon data suggests that the base of the chalky clay is at around 332-513 cal yr BP. There are a number of possible explanations for the cessation of peat accumulation at Boxford and the deposition of a layer of chalky clay. It is possible that by infilling abandoned channels and low areas of the floodplain the accumulated peat simply raised the elevation of the floodplain relative to the water table, causing the decomposition of organic matter within the upper part of the layer. Decay is slowest in waterlogged peat below the water table, fastest in the zone of water table fluctuation and intermediate in sites above the water table (Belyea and Clymo, 2001). Climate change may have played a part through changes in stream discharge, reductions in groundwater level or vegetation productivity. Although the Holocene is often regarded as a relatively unremarkable interglacial from the perspective of climate change there were nonetheless significant fluctuations (Figure 19). The general decrease in organic accumulation broadly coincides with a shift toward a cooler and wetter climate in Britain following the termination of the Holocene Climatic Optimum at around 2.5 kyr BP (Anderson et al., 2007). There are also anthropogenic impacts to consider. From around 5 kyr BP agriculture exerted significant effects on the landscape in most parts of Europe that modified catchment hydrology, particularly from the agricultural revolution of the Middle Ages at around 1 ka BP when ploughing caused a significant increase in floodplain accretion rates (Anderson et al., 2007; Lewin, 2010; Macklin et al., 2010). In the Kennet valley gravelly and tufaceous channel fills (Midgham Member Unit MM5) overlying the peats indicate episodic high-energy flood events at around 2.6 kyr BP and are thought to be related to land clearance for agriculture, with flood events probably enhanced by the wetter conditions of the SubAtlantic Chronozone (Collins et al., 2006). Comparable events in the Lambourn catchment may have increased the deposition rate of chalky clays across the floodplain from around 4 kyr BP, coincident with a progressive decrease in the rate of peat accumulation. Although in contrast to the Kennet, peak erosion and deposition of chalky clays within the Lambourn catchment appears to have occurred within the last 400 years. Pollen evidence from an interfluve valley mire at Snelsmore Common located 4 km southeast of Boxford (Figure 2) indicates significant episodes of forest clearance within the Lambourn catchment at around 2.6 kyr BP (consistent with the presence of a nearby Iron Age hill fort) and at 475 yr BP (Waton, 1982) (Figure 19). Relative to other chalkland catchments, Waton's (1982) pollen analysis indicated that the Lambourn Catchment, or at least the part of the catchment covered by Palaeogene and Quaternary siliciclastic sediments (Figure 2), maintained an extensive wooded cover (Waton, 1982). This factor, together with the predominance of permeable chalk bedrock within the catchment, may explain the relatively progressive response to agricultural land clearance.

At Boxford the re-establishment of an organic-rich layer above the chalky clays is primarily the result of anthropogenic intervention within the past 200 years with the construction of a network of channels which were used for controlled flooding of a wetland meadow. Overall therefore the River Lambourn shows both a number of similarities and differences from the Late Pleistocene and Holocene succession found immediately downstream in the Kennet valley showing the importance of headwater studies in reconstructing the behaviour of the River Thames along its full length.

6. Conclusions

- The Late Pleistocene to Holocene fluvial record of northwest Europe is biased toward major trunk channels (primarily because of the location of floodplain gravel pit exposures) with few studies undertaken in minor tributaries. This work is necessary to establish longitudinal variation in fluvial response to the major changes in climate and anthropogenic influence since the Last Glacial Maximum.
- The River Lambourn is located in a minor Chalk catchment in one of the headwaters of the River Thames but shows a full and complex Late Pleistocene to Holocene stratigraphy. An absence of excavated exposures on the small, but ecologically-valuable, chalk-stream floodplain necessitates the use of boreholes and in particular geophysical surveys to understand the stratigraphy.
- The Quaternary valley-fill stratigraphy typically comprises around 5-8 m of Late Pleistocene gravels overlain by Holocene peats and chalky clays. Quaternary deposits overlie an undulating and irregular rockhead erosion surface. Deep scouring of the typically highly weathered chalk rockhead is particularly evident on prominent bends in the valley such as occur near Boxford.
- The gravels subdivide into a lower unit of chalky gravels overlain by coarse flint gravels. Ground penetrating radar surveys suggests that gravels at depths below 2 m are relatively structureless, but at the top show well-developed point-bar lateral accretion surfaces which occur in association with peat-filled sinuous channels. These probably date from around the Pleistocene-Holocene boundary and may have formed in response to increased groundwater discharge as stream hydrology changed from the short-duration, high-magnitude flows of the Lower Dryas to the uniform, low-magnitude flows of the Holocene.
- Holocene peats initially infilled abandoned floodplain channels at around 10 kyr BP but later encroached over much of the Lambourn floodplain. A progressive upward decrease in organic material and an increase in the proportion of chalky clays from around 4 kyr BP probably occurred in response to floodplain accretion (bringing it close to or above the water table) coupled with increased erosion of the chalk catchment related to agricultural clearance and a wetter climate.

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Table Captions

Table 1. Location and depth of peat samples taken for radiocarbon dating. The conversion of radiocarbon ages to calibrated (cal) ages was undertaken using CALIB (Stuiver and Reimer, 1986).

Figure Captions

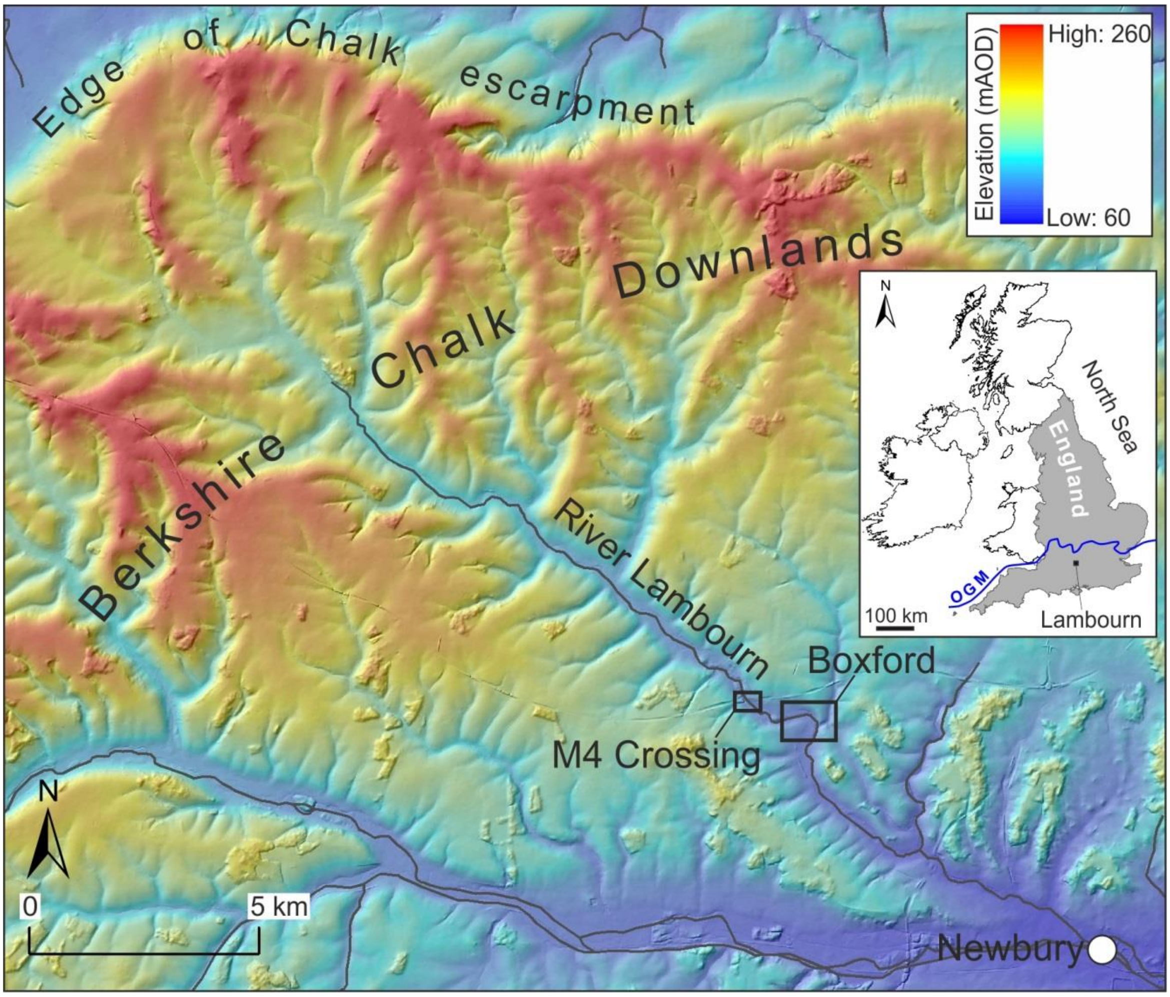

Figure 1. Map showing the location of River Lambourn in the Berkshire Downs of south-central England with the two study sites at Boxford and the M4 crossing. Inset map shows the location of the Lambourn relative to the Overall Glacial Maxiumum (OGM). Contains Ordnance Survey data © Crown copyright and database right (2010). NEXTMap Britain elevation data from Intermap Technologies.

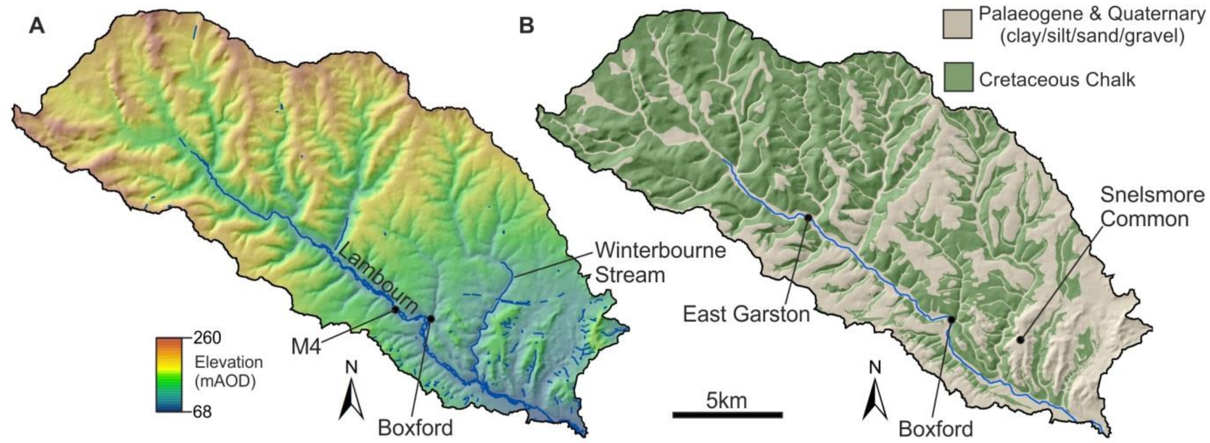

Figure 2. (A) Terrain model showing the elevation of the Lambourn catchment, (B) Simplified catchment geology showing the distribution of chalk where it is at surface (usually concealed beneath a thin soil) and predominantly siliciclastic Palaeogene and Quaternary deposits. Contains Ordnance Survey data © Crown copyright and database right (2010).

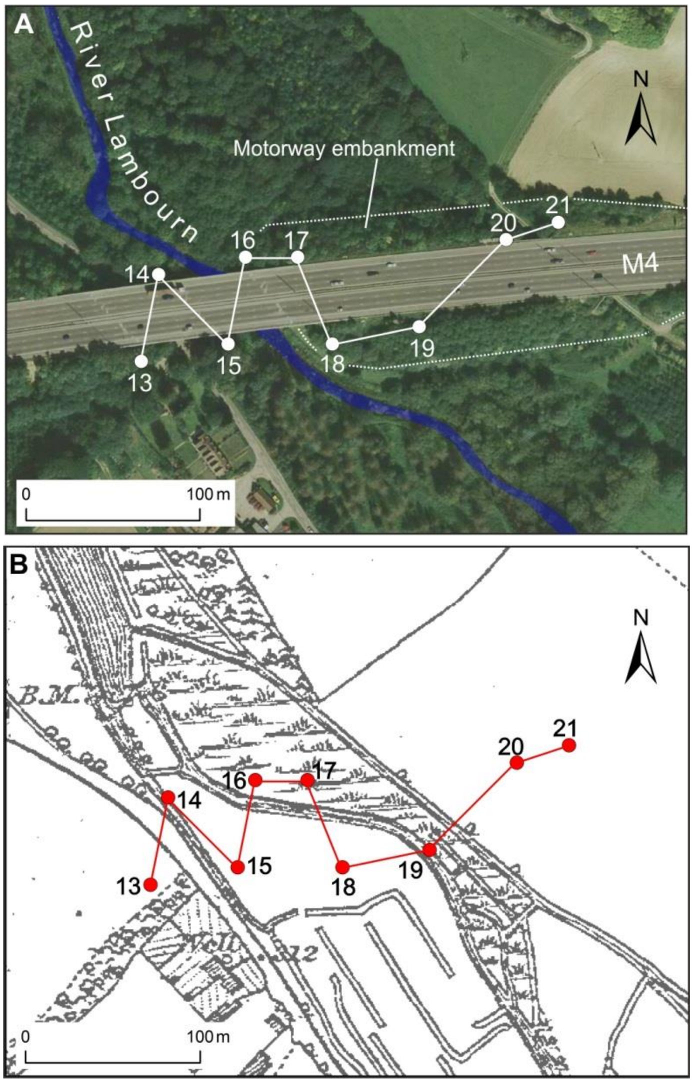

Figure 3. (A) Aerial photograph of the M4 cross-over of the Lambourn valley showing the location of site investigation boreholes drilled 1968 prior to construction. Numbering follows the British Geological Survey (BGS) Single Onshore Borehole Index (SOBI) where all boreholes are prefixed by SU47SW. (B) Ordnance Survey historical map (surveyed in 1878 and published in 1882) showing the configuration of the floodplain and course of the river before motorway construction.

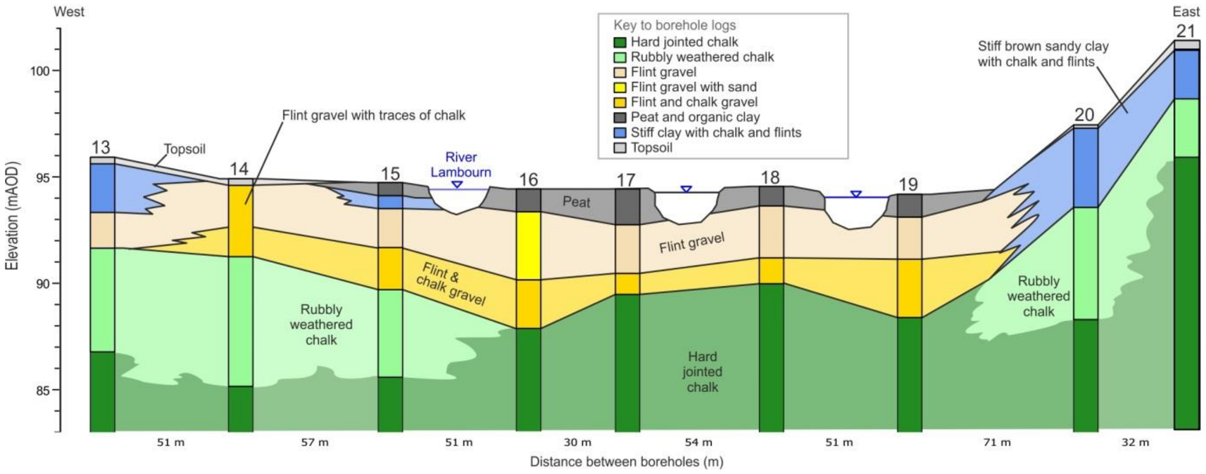

Figure 4. Correlation of site investigation borehole records at the M4 crossing of the River Lambourn (see Figure 4 for location of the boreholes which have a staggered distribution across the 180 m wide floodplain). Borehole records are based on material recovered using a shell and auger method.

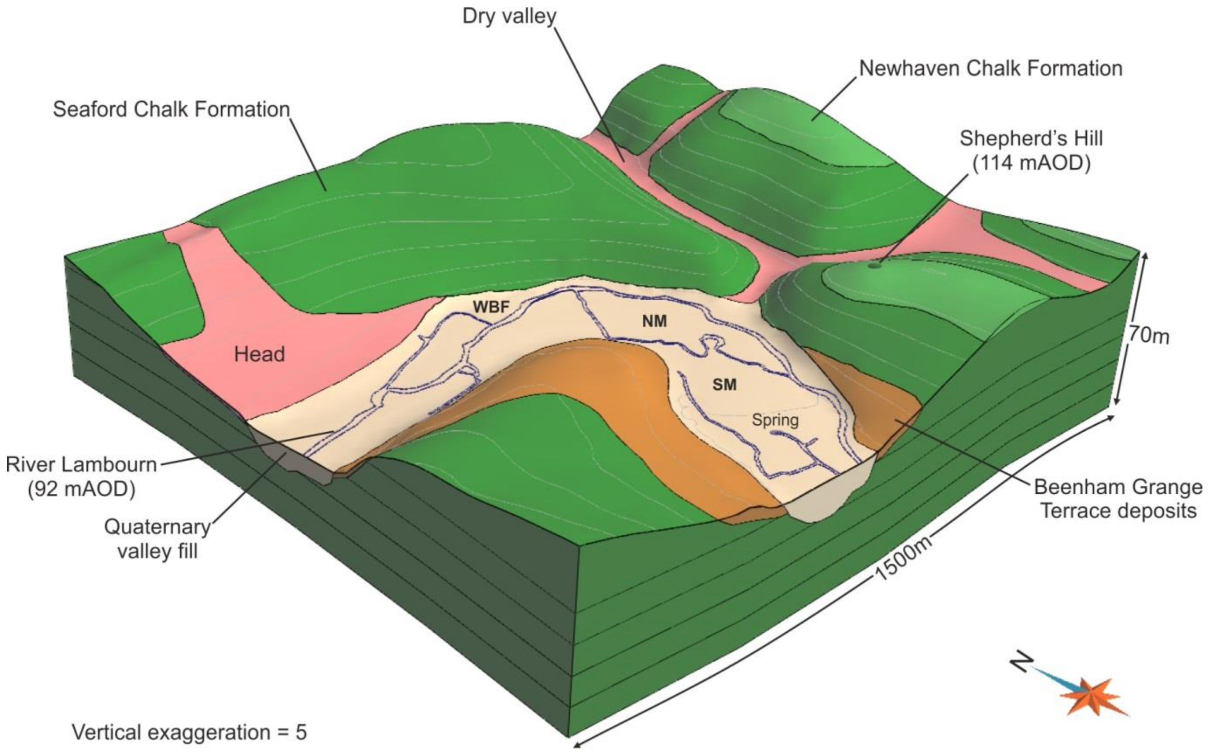

Figure 5. Block diagram of the Boxford site showing the showing the general bedrock and superficial geology at this prominent bend in the Lambourn valley. Note that the vertical scale is exaggerated by a factor of five (WBF=Westbrook Farm; NM=North Meadow; SM=South Meadow).

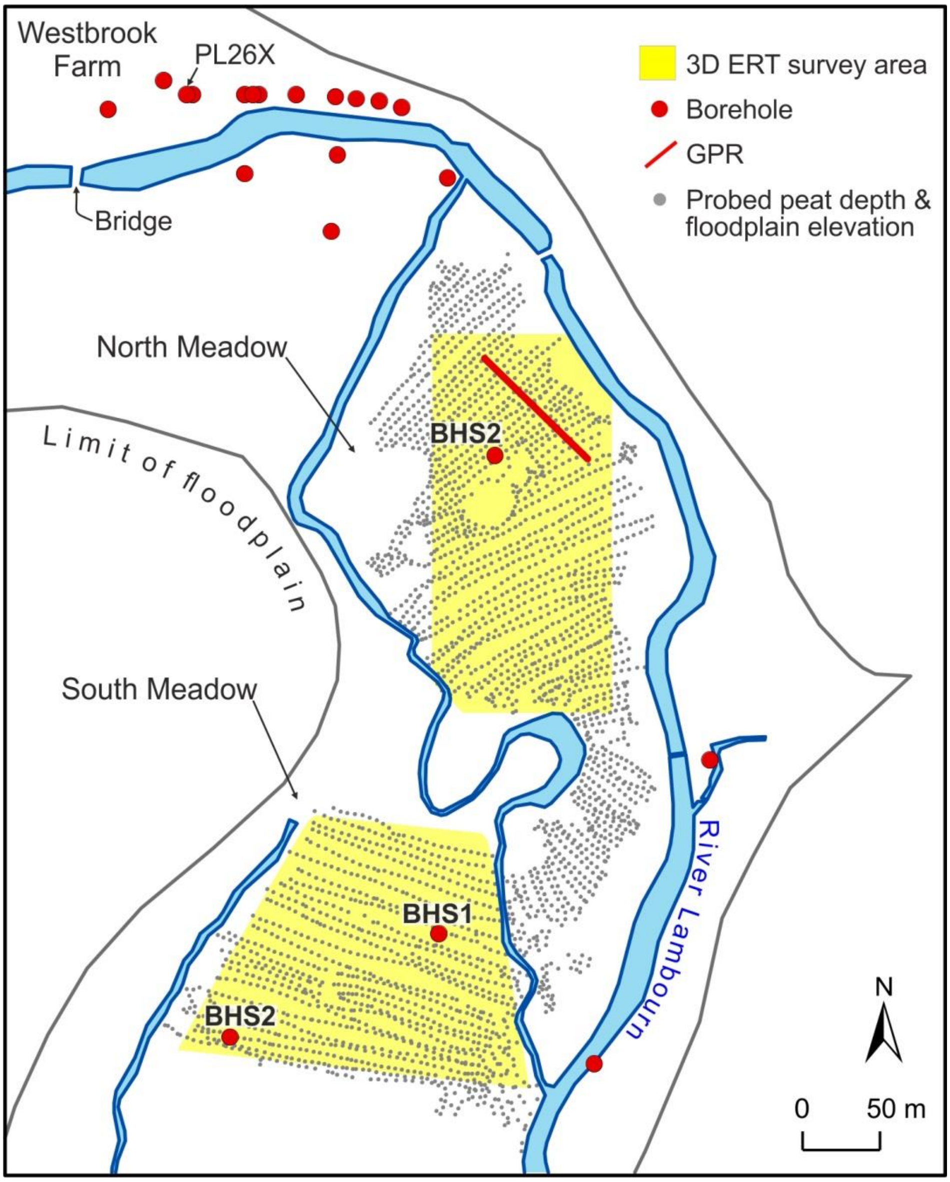

Figure 6. Map showing the Boxford site and the distribution of boreholes, probed peat depths (and floodplain elevation points), 3D ERT survey areas and GPR line. Boreholes discussed in the text are labelled. Contains Ordnance Survey data © Crown copyright and database right (2010).

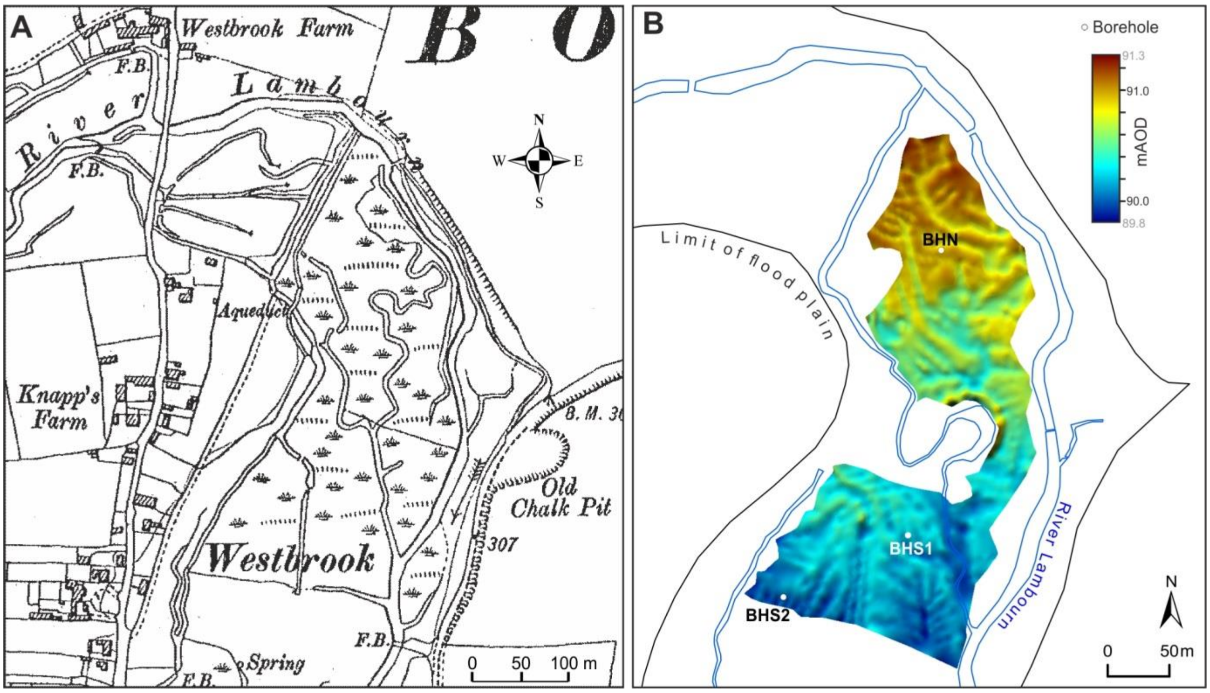

Figure 7. (A) Historical Ordnance Survey map (surveyed in 1878, revised in 1910 and published in 1913) showing numerous channels crossing the wetland at Boxford. (B) Differential GPS survey of floodplain elevation showing the presence of numerous linear and herring-bone pattern drainage channels. Interpolation of survey points (Figure 7) in this figure (and in other maps) is implemented in SKUA-GOCAD^{TM} by Discrete Smooth Interpolation (Mallet, 1989)

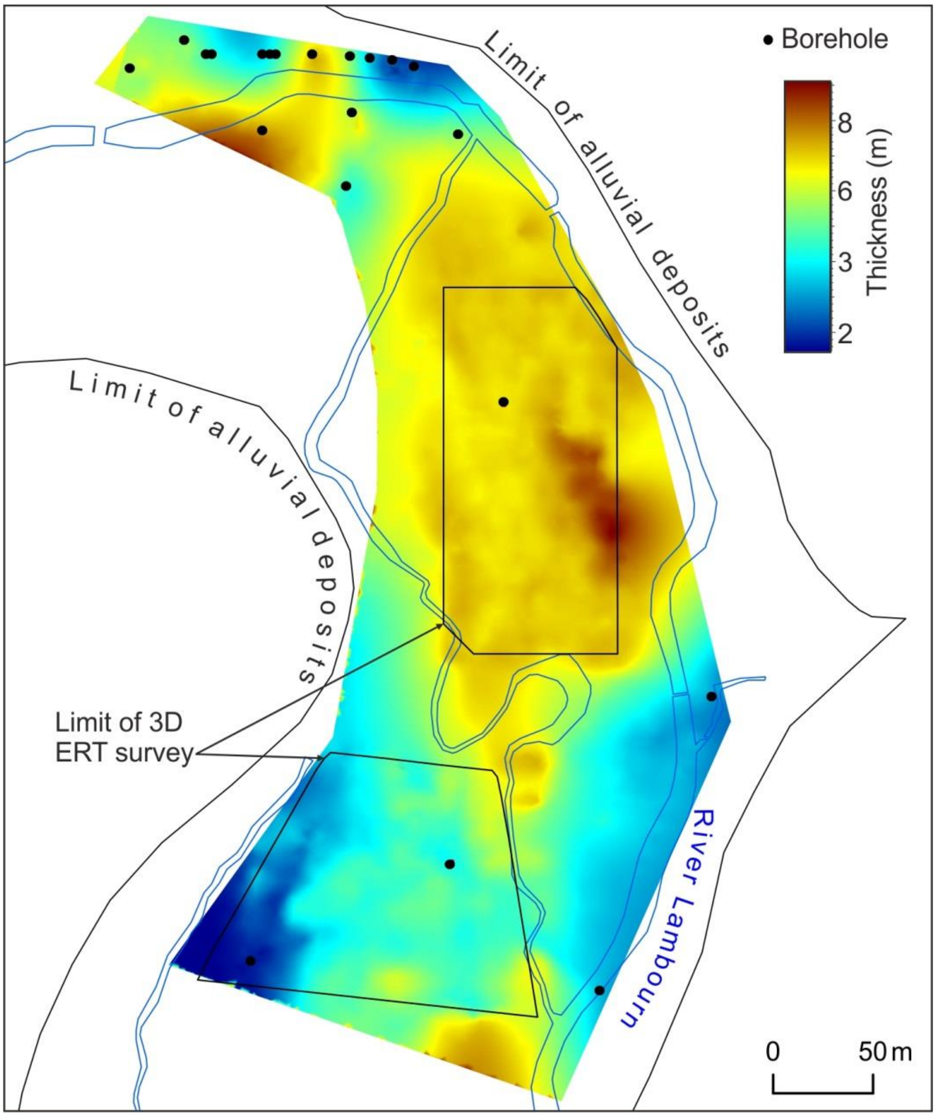

Figure 8. Thickness map of Quaternary deposits overlying Chalk based on the interpolation of data from 3D ERT (Chambers et al., 2014) and boreholes.

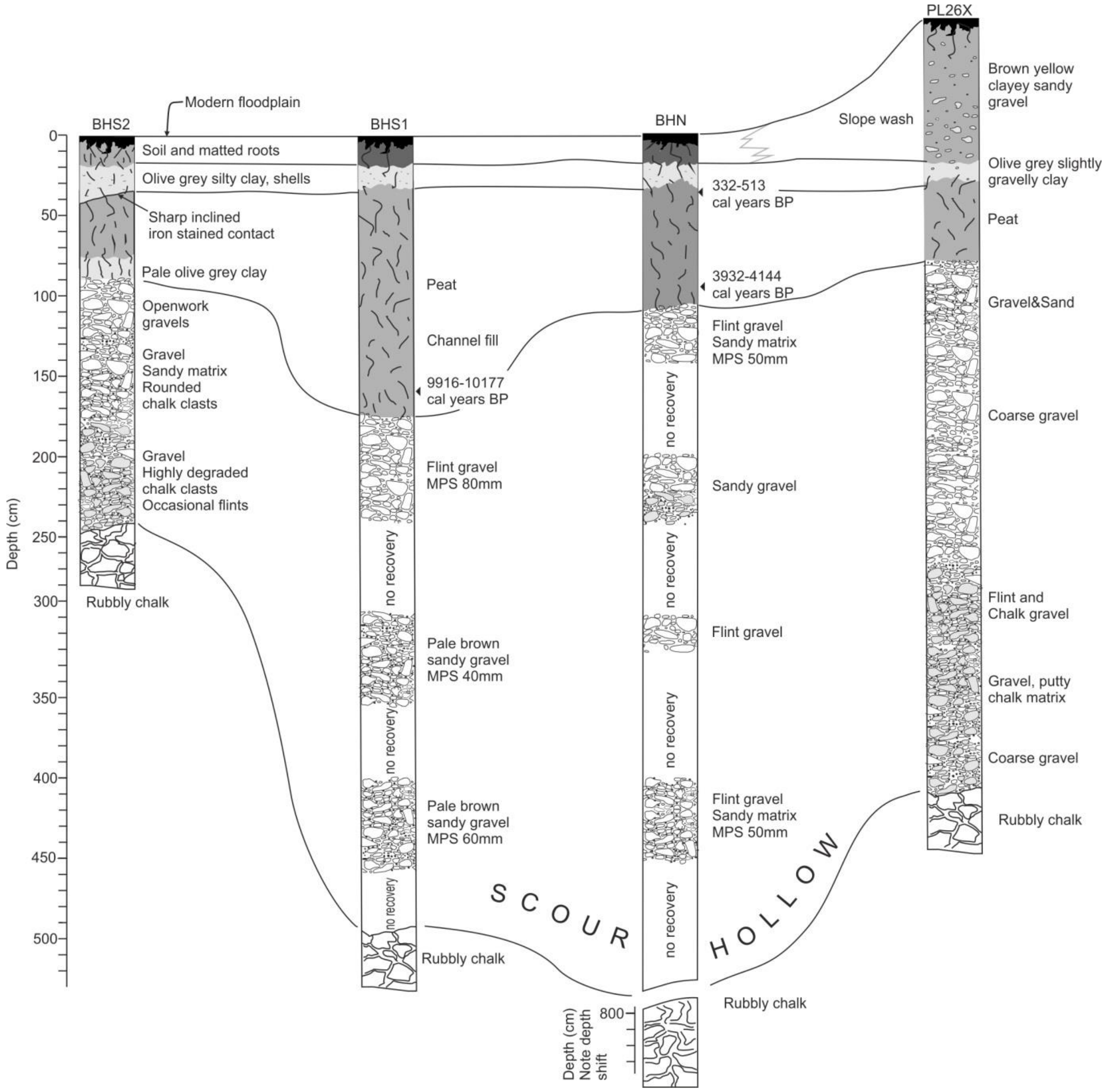

Figure 9. Correlation of selected boreholes across the Boxford site (see Figure 7 for locations).

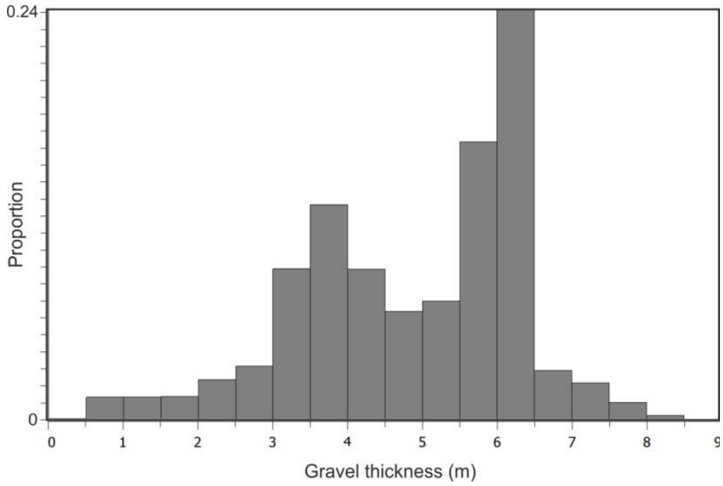

Figure 10. Histogram showing the distribution of gravel thickness based on boreholes and the interpretation of 3D ERT.

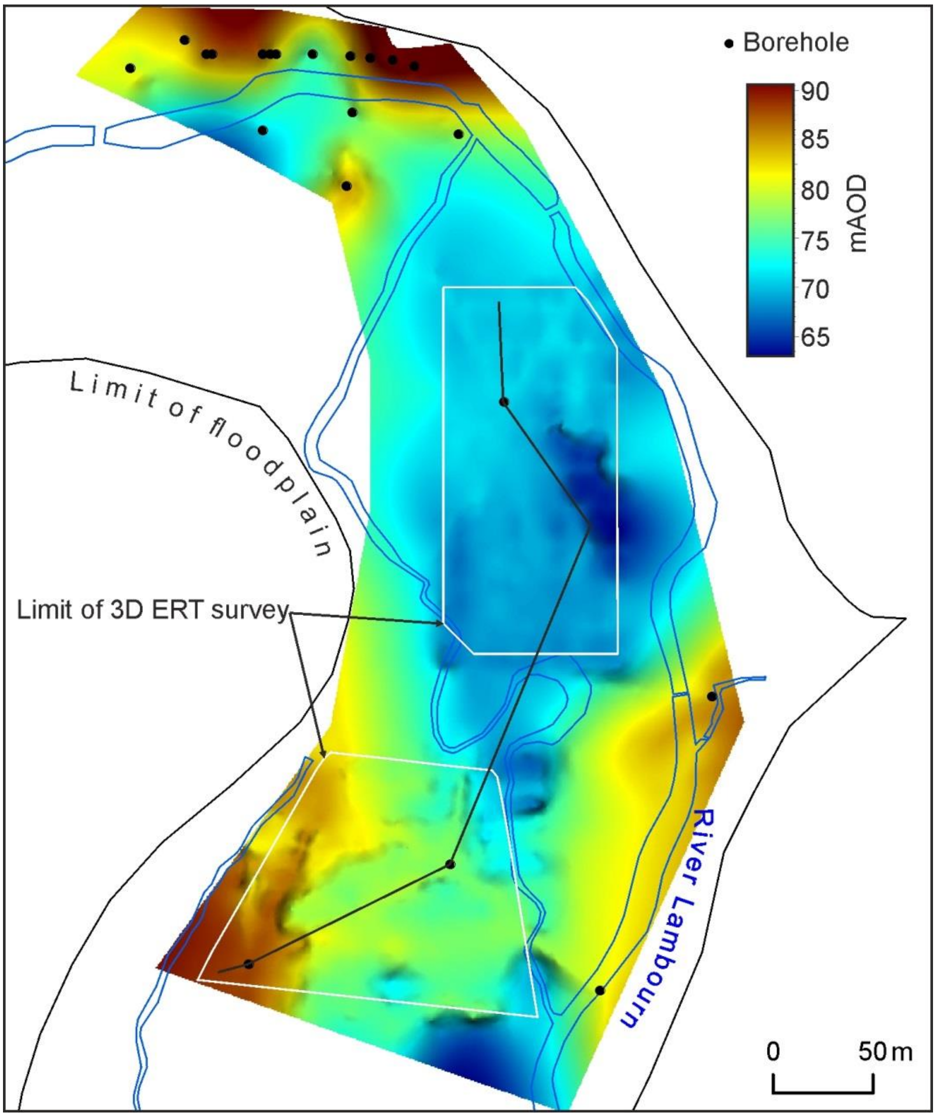

Figure 11. Interpolated surface on the Chalk rockhead (base of the gravels) based on 3D ERT surveys and boreholes.

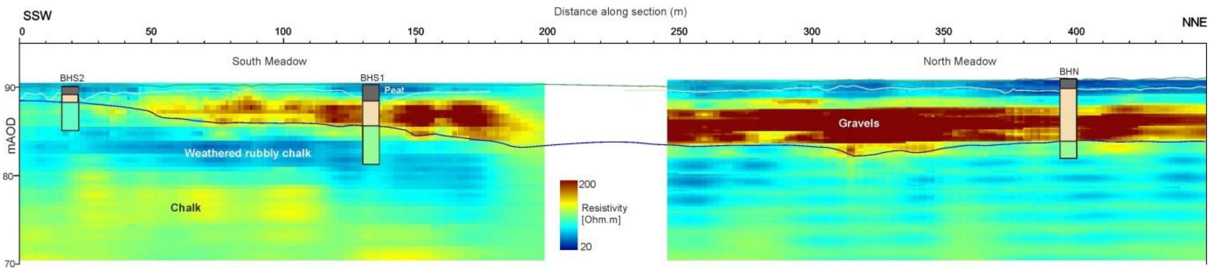

Figure 12. Slice through interpolated 3D ERT model (see Figure 14 for the location of the two separate blocks) showing the thinning of high-resistivity gravels (warm colours) toward the SSW. See Chambers et al. (2014) for additional information on the ERT survey and Figure 5 for key to simplified borehole logs.

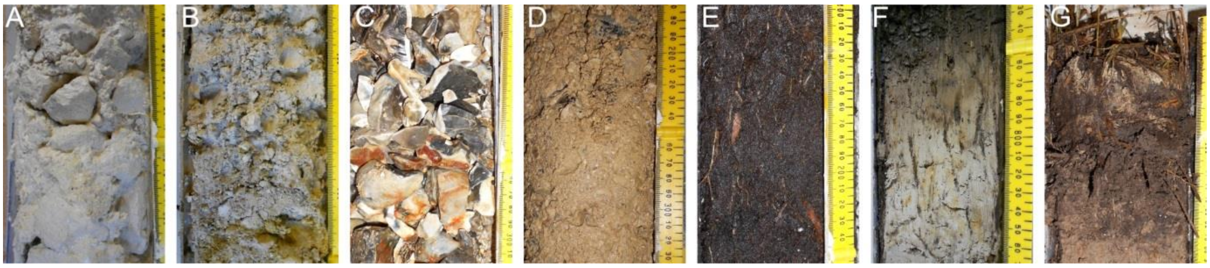

Figure 13. Core photographs showing the range of Quaternary deposits at Boxford, (A) Chalk with many closely-spaced circumgranular fractures giving a rubbly appearance; (B) admixture of highly-degraded chalk clasts and flint; (C) flint gravel; (D) sandy flint gravel; (E) fibrous woody peat with roots; (F) rooted pale grey chalky clay; (G) modern soil profile with rooted vegetation.

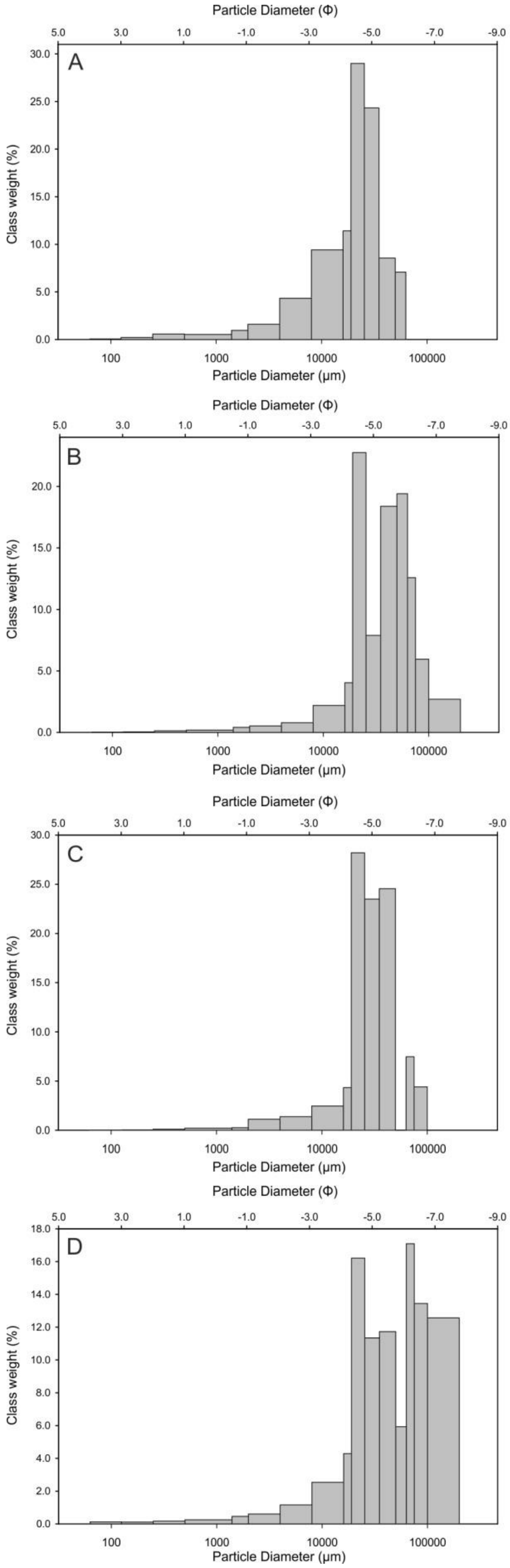

Figure 14. Histograms showing grain-size distribution based on sieving of bulk (average sample weight=21 kg) gravel samples recovered from four downhole depth intervals in Borehole PL26X at Westbrook Farm. (A=2.0-

2.5 m; B=2.5-3.0 m; C=3.0-3.5 m; D=4.0-4.5 m). Histograms were generated using GRADISTAT (Blott and Pye, 2001).

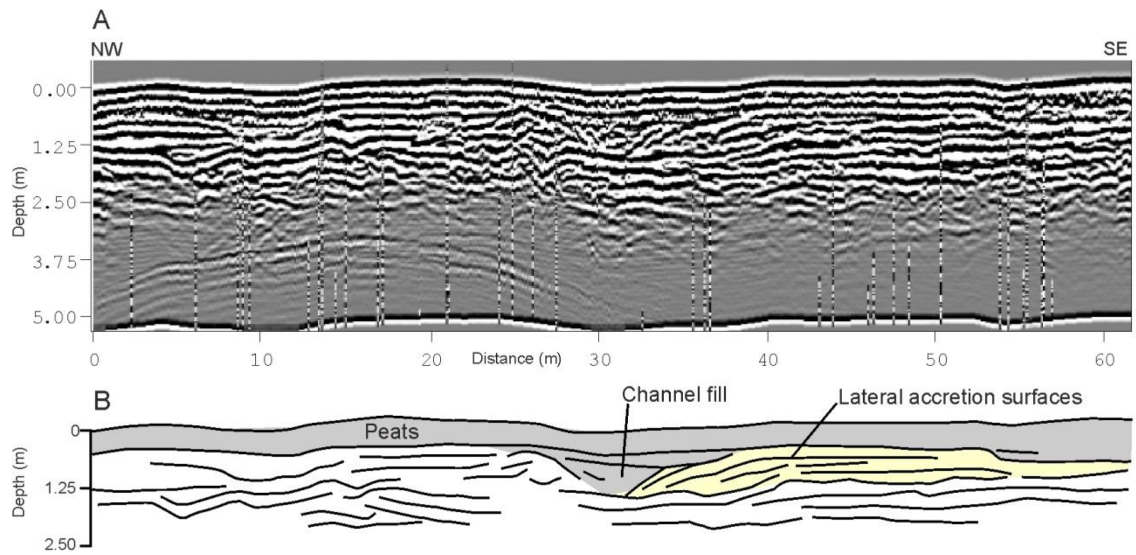

Figure 15. (A) GPR profile from Musgrave (2006) (see Figure 7 for location). (B) Interpretation of GPR profile showing the unconformity between the gravels and overlying peats and the well-defined set of inclined reflectors passing laterally into a concave-up channel-form feature.

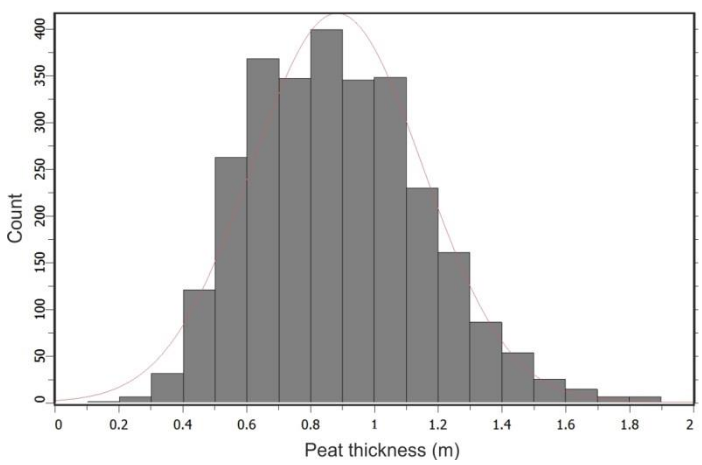

Figure 16. Histogram showing distribution of peat thickness from 2815 probe measurements (see Figure 7 for sample locations).

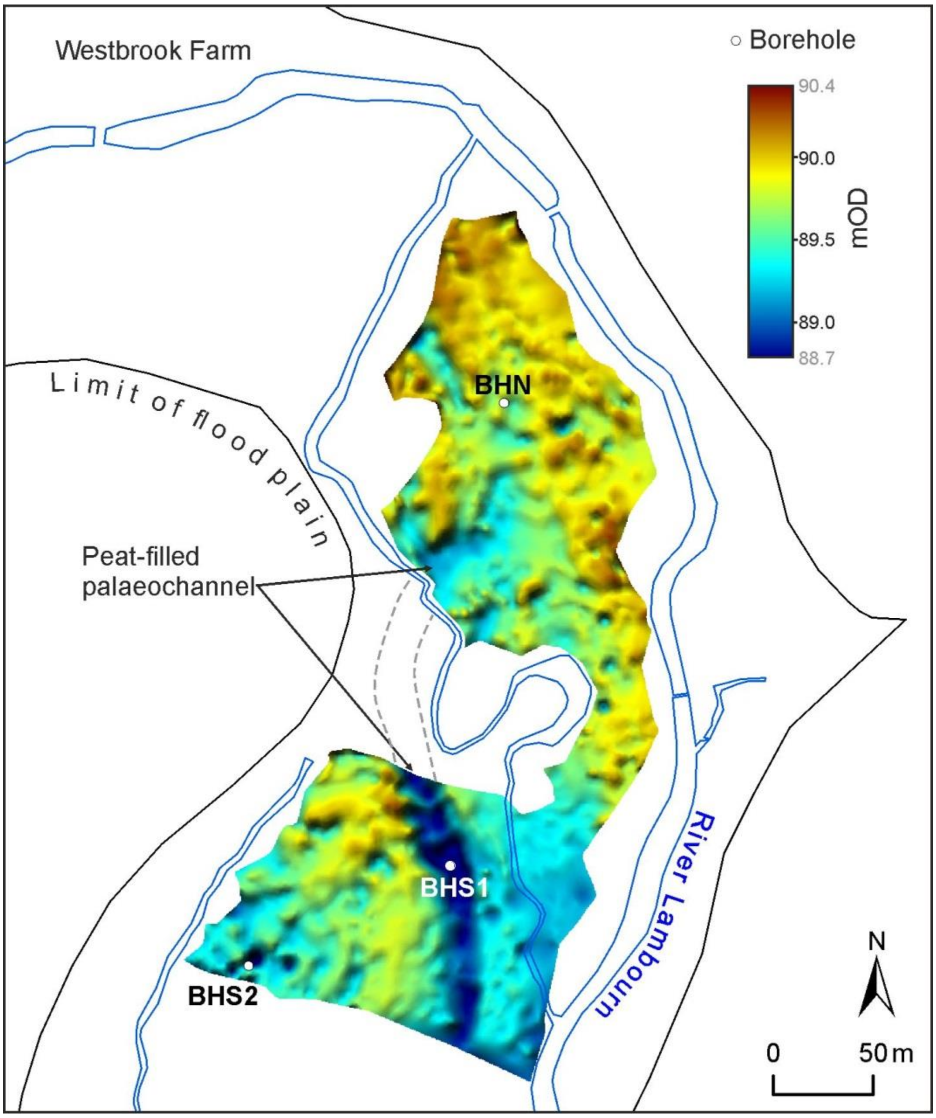

Figure 17. Interpolated surface on the top of the gravels (base of the peats) based on intrusive probe survey (see Figure 7 for location of sample points). Note the peat-filled palaeochannel which is particularly prominent in the South Meadow at borehole BHS1.

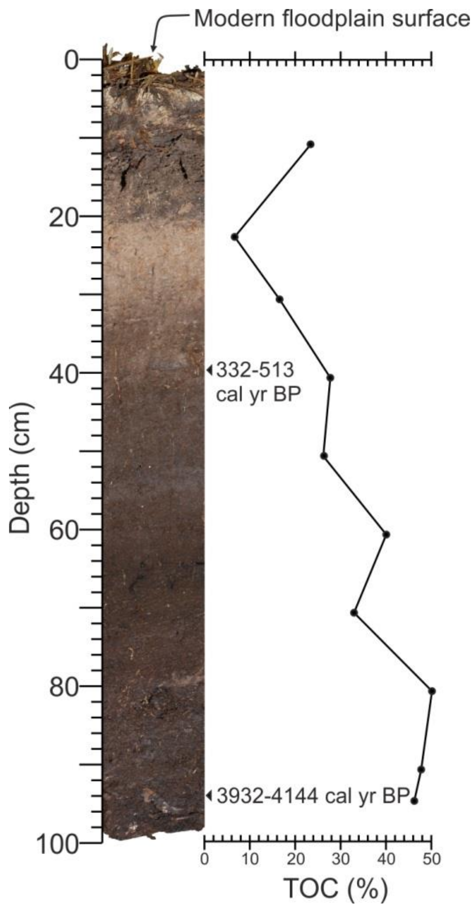

Figure 18. Peat stratigraphy in borehole BHN in the North Meadow (see Figure 7 for location). Calibrated radiocarbon dates (Table 1) are shown together with the vertical distribution of total organic carbon (TOC).

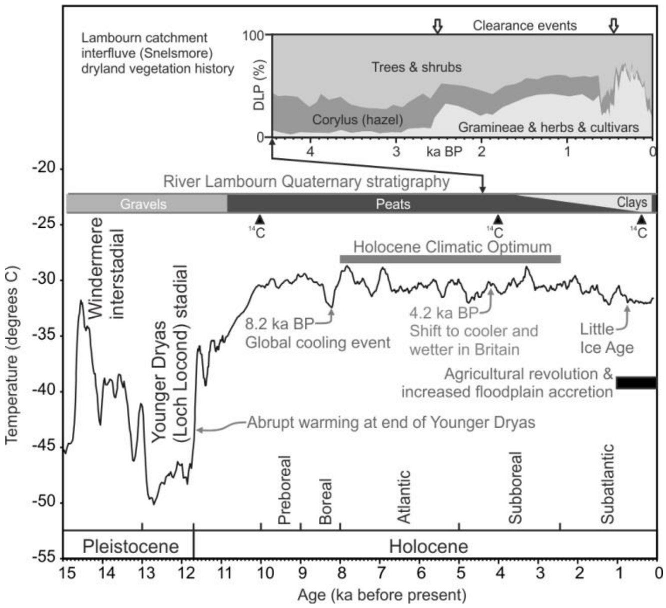

Figure 19. Selected Late Pleistocene and Holocene events plotted against part of the temperature curve deduced from the GISP2 Greenland ice-core (Walker et al., 2009). The standard chronology and pollen zonation for the Holocene is shown (Anderson et al., 2007) together with the generalised stratigraphy of sub-floodplain Quaternary deposits at Boxford on the River Lambourn. The changing proportion of dry land pollen (DLP) at Snelsmore in the Lambourn catchment is modified and simplified from Waton (1982).

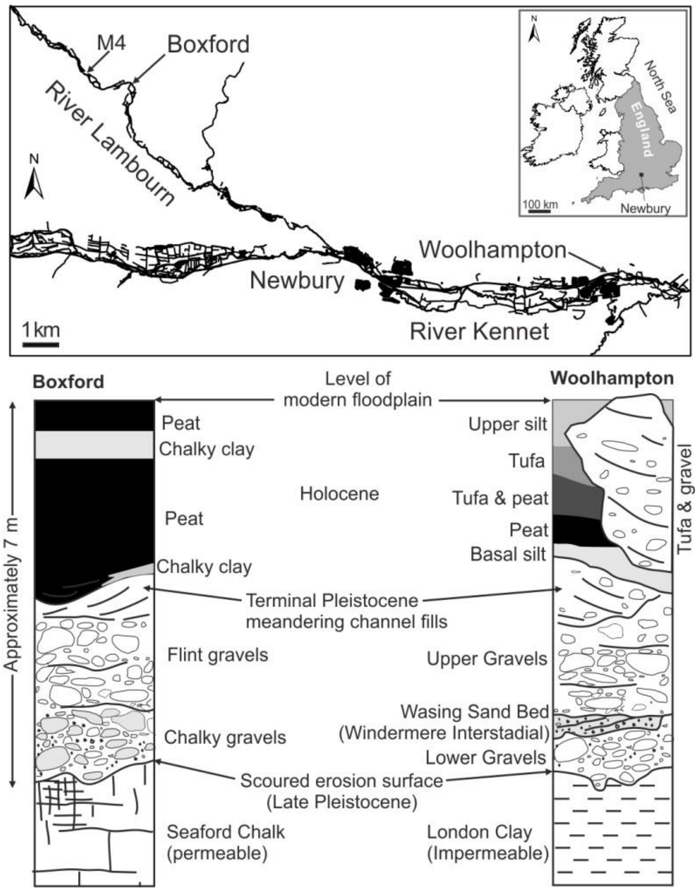

Figure 20. Comparison of generalised Late Pleistocene to Holocene successions at Boxford on the River Lambourn and Woolhampton on the River Kennet, approximately 16 km downstream. The Woolhampton succession is based on Collins et al. (1996, 2006). Contains Ordnance Survey data © Crown copyright and database right (2010).