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Drainage network reorganization affecting the Nene and Welland catchments of eastern England as a result of a late Middle Pleistocene glacial advance

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Abstract

Britain's latitude is critical for determining the southerly extent of western European ice sheet expansion. Palaeoclimate and palaeosea-level reconstruction in Britain, however, is complicated by spatially discontinuous glacigenic deposits and genetic and stratigraphic interpretations have relied on their lithological characteristics. This study adopted a sedimentary facies approach combined with geomorphological analyses for investigating upper Middle Pleistocene deposits in two adjacent catchments: Nene and Welland. Detailed sedimentology determined not only genesis of ice-contact (Welland) and glaciolacustrine (Nene) deposits but also provided insight on lake surface water levels. The ice-contact deposits recorded a constant lake level at the same height as alluvial remnants upstream in the Welland valley. These alluvial remnants are located where present tributaries join the Welland, indicating they were formed where influent streams entered a former lake and therefore can be interpreted as fluvial terraces resulting from local baselevel rise. The glaciolacustrine deposits in the Nene valley recorded fluctuating lake levels, indicating that altitudinally separated sand and gravel bodies coincident with these fluctuations and located where influent streams entered the lake also can be interpreted as fluvial terraces, but resulting from fluctuating baselevel. Sand and gravel bodies at the southern end of a dry valley linking the two catchments are interpreted as alluvial fan remnants, and those occurring on interfluves downstream of the alluvial fan remnants as flood deposits emanating from lake overflow. This drainage reorganization probably occurred in marine oxygen isotope stage (MIS) 8, but the ice advance footprint is different to that in MI 6.

KEYWORDS
Drainage reorganization, ice-contact fan, lacustrine deposits, marine oxygen isotope stage 8, Middle Pleistocene, River Nene, River Welland

1 | INTRODUCTION

The Quaternary Period is characterized by Milanković-driven climate cycles with stadials and interglacials as end members, represented by low and high eustatic sea level, respectively, as global ice accumulates and melts (Hays, Imbrie, & Shackleton, 1976; Lisiecki & Raymo, 2005; Past Interglacials Working Group of PAGES, 2016; Shackleton, Berger, & Peltier, 1990). At far-field sites relative to the major ice-accumulation centres of the north and south poles (Long et al., 2015), in the absence of Earth's tectonic processes, the provision of both accommodation space and preservation potential (Swift & Thorne, 1991) are largely in response to eustasy and can be considered in a straightforward manner. At intermediate to near-field sites the patterns of provision of accommodation space and preservation potential are highly complex, not least as a result of glacioisostasy. This makes determination of successive ice advance footprints very difficult across the spectrum of depositional systems in these regions. Nevertheless, such information is essential for palaeoclimate and palaeosealevel reconstruction, as well as for modelling future trends in climate change and sea-level (Long et al., 2015).

For example, glacier advance has profound as well as more subtle effects on pre-existing drainage networks (Starkel, 1991). At the extreme they can be completely overridden by large-scale ice sheets. Valleys can be dammed by advancing and retreating glaciers (Owen, 1996; Winsemann, Asprion, & Meyer, 2007), and by their outwash, forming lakes that in turn have a marked effect on drainage systems. The lakes so formed can drain catastrophically (Coxon, Owen, & Mitchell, 1996). Lakes formed at glacier margins can be huge (e.g., Lake Missoula, USA—Baker, 1973; Kuray—Chuja, Russia–Carling et al., 2011), and their flood deposits can have a major impact on land (Bretz, 1928) and on climate through their effects on oceanic circulation (Baker, 2002; Couch & Eyles, 2008). In the context of the British Isles such lakes, although not on the same scale, have been recorded for the two major glaciations (Anglian and Devensian, that is, marine oxygen isotope stages [MIS] 12 and 2, respectively) known to have affected the English Midlands and East Anglia (Figure 1a; for example, Lake Harrison—Bishop (1957), Figure 1b; Lake Humber—Lewis (1887), Figure 1c). Channels incised by floodwaters in the English Channel (Gupta et al., 2017; Smith, 1985) have been attributed to draining of a substantial proglacial lake in the southern North Sea basin (Zalasiewicz & Gibbard, 1988) by breaching of the Weald–Artois anticline to form the Strait of Dover (Figure 1b) in MIS 12 (Gibbard, 1995), although final breaching may not have occurred until MIS 6 (Busschers et al., 2008; Mellett et al., 2013). Flood deposits and large-scale incision have

been attributed to jökulhlaup draining of MIS 2 Lake Humber (Bateman, Buckland, Chase, Frederick, & Gaunt, 2008; and references therein). Major drainage reorganization has been attributed to the advance of Anglian ice (Gibbard, 1977), and Anglian ice advance is considered to have overridden preglacial drainage systems (Gallois, 1999; Horton, 1970; Kellaway & Taylor, 1953). There are few observations (Gibbard, Boreham, Roe, & Burger, 1996), however, of the response on fluvial systems draining into the respective lakes, for example, aggradation to the new baselevel forced by the rising lake level and terrace formation following lake drainage.

In contrast to the records of the Anglian and Devensian glaciations, evidence for the intervening cold stages is less reliably dated and accordingly more contentious (Clark et al., 2004). For example, the Thrussington and Oadby Tills of central England being assigned to MIS 10 (Sumbler, 1995, 2001) rather than the Anglian glaciation (Perrin, Rose, & Davies, 1979). Hamblin et al. (2005), Rose (2009) and Lee, Busschers, and Sejrup (2012) have also proposed evidence of MIS 10 glaciation in north Norfolk (Figure 1a). The Wragby, Welton (at Welton-le-Wold, Figure 2a) and Calcethorpe Tills of Lincolnshire (Figure 1a) have been assigned to MIS 8 or 6, as well as the Anglian glaciation (Lewis, 1999; Straw, 1983). Until recently the only demonstrable evidence of post-Anglian and pre-Devensian glaciation in East Anglia was a delta at Tottenhill (Figure 2) that was deposited in a lake formed by ice damming The Wash (Figure 2a; Gibbard, West, Andrew, & Pettit, 1991, 1992). This glaciation has been attributed recently to MIS 6 on the basis of OSL (optically stimulated luminescence) dating, when a small lobe of ice advanced down the eastern side of the Fen Basin (Figure 1a), as evidenced by ice-marginal sedimentation and landforms (Gibbard, Boreham, West, & Rolfe, 2012; Gibbard, West, Boreham, & Rolfe, 2012; Gibbard et al., 2009). West (2007) describes the drainage network reorganization in East Anglia in response to this MIS 6 ice advance. It should be noted, however, that full details of the OSL dating have not been published, which calls into question the stratigraphical interpretation. Corroboration of age attribution is important because archaeological sites in the same area have been reliably dated to ages older than MIS 6 (Voinchet et al., 2015). Indeed, this same event has been attributed to MIS 8 by Straw (2000, 2011), an age supported by Boreham, White, Bridgland, Howard, and White (2010) and White, Bridgland, Westaway, Howard, and White (2010), White, Bridgland, Westaway, and Straw (2017) where full details of the derivation of these views are provided (Figure 2a). These polemic positions arise mainly from two sources. The first is that British late Middle Pleistocene glacigenic deposits tend to be spatially
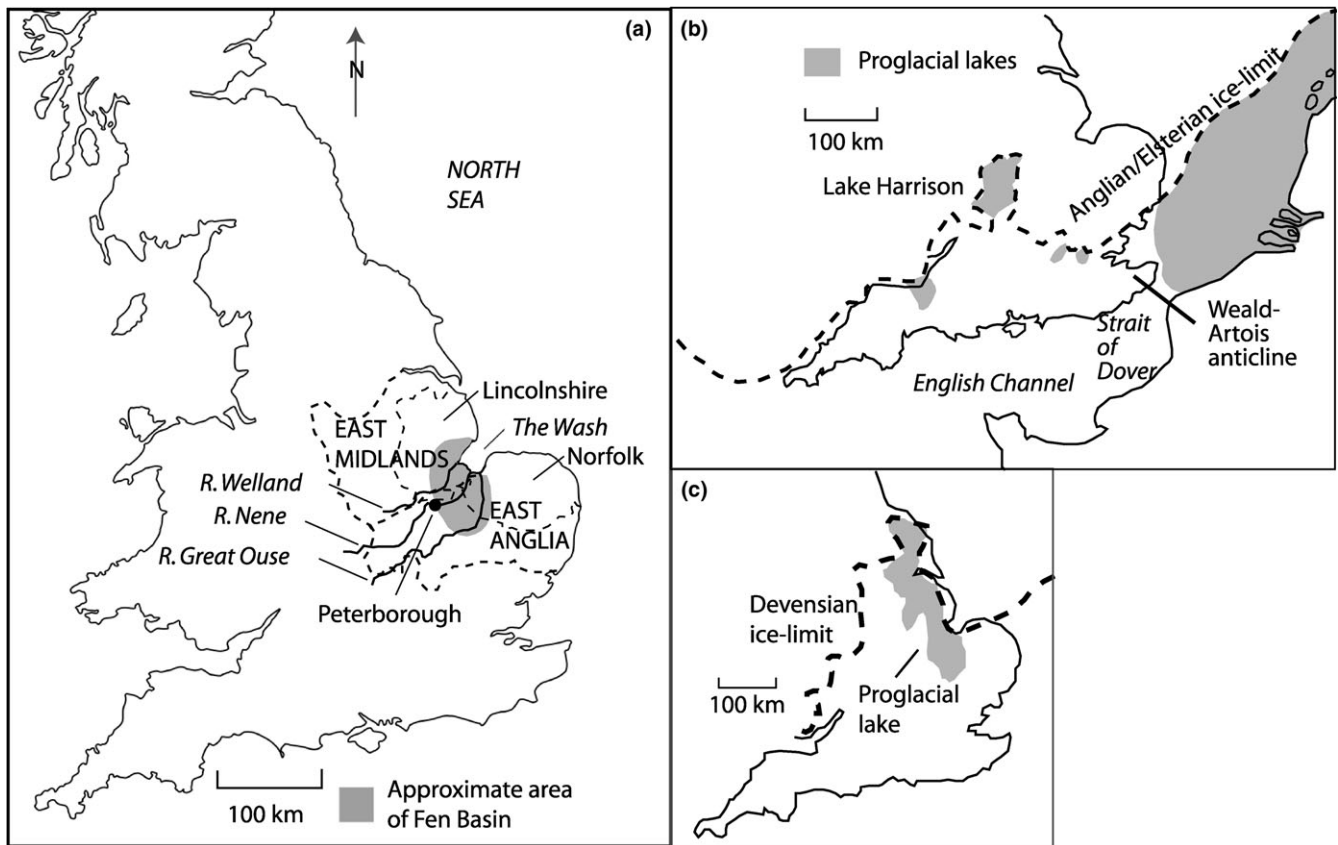
FIGURE 1 (a) Location of the English East Midlands and East Anglia regions, the Fen Basin and the rivers Welland, Nene and Great Ouse with outlets at The Wash. (b) Postulated Anglian/Elsterian (marine oxygen isotope stage (MIS) 12) ice margin with Lake Harrison and North Sea proglacial lake shown. (c) Devensian/Weichselian (MIS 2) ice margin with postulated proglacial lake occupying the Fen Basin. (b, c—based on Woodcock, 2002)

discontinuous, presenting problems for genetic and stratigraphic interpretation. The second is that different approaches are used in the study of these deposits.

This study adopts a sedimentary facies approach based on detailed sedimentology (Davis, 1983; Reading, 1986, 1996) combined with geomorphological analyses (Brown & Keough, 1992; Miall, 1985). The sediments investigated are glacial sand and gravel deposits (BGS, 1978) that occupy a present-day interfluve site to the north of Uffington (Figure 2a, National Grid Reference SK 062 090), and lacustrine deposits at Elton (Figure 2a, TL 090 927) mapped as Jurassic Oxford Clay (BGS, 1976). These deposits are considered to postdate the Anglian and predate the Devensian glaciations. Detailed sedimentology of the deposits at Uffington and Elton is presented and aspects of the sedimentology discussed before considering the palaeogeographical implications by relating the sedimentology to associated landscape elements. Age of the palaeogeographical reconstruction is then considered utilizing age determinations, biostratigraphy and stratigraphical relations from late Middle Pleistocene sites at Sutton Cross and Whittlesey (Figure 2a; Langford, 1999; Langford et al., 2007,

2017; Langford, Boreham, Coope, Fletcher, et al., 2014; Langford, Boreham, Coope, Horne, et al., 2014). The findings of this study are then discussed with regard to MIS 8 and 6 ice margins.

2 | METHODS

The deposits north of Uffington were exposed during gravel extraction by the landowner, and those at Elton during road construction. As the exposures at both sites were temporary and shallow, and work was ongoing, detailed graphic logs were not recorded. Description (and construction of the two graphic logs for the Elton site) therefore relied upon overlapping sequences of photographs, field sketches and notes, and close-up photographs of important features. Lithofacies coding is adapted from Miall (1977) and Dardis (1985). The sedimentary successions are divided into facies associations (denoted in italic typeface) and their component sedimentary facies. Deposit and bed thicknesses were determined using a 1.2 m staff with 5 cm increments, and sand grain size was determined in the field
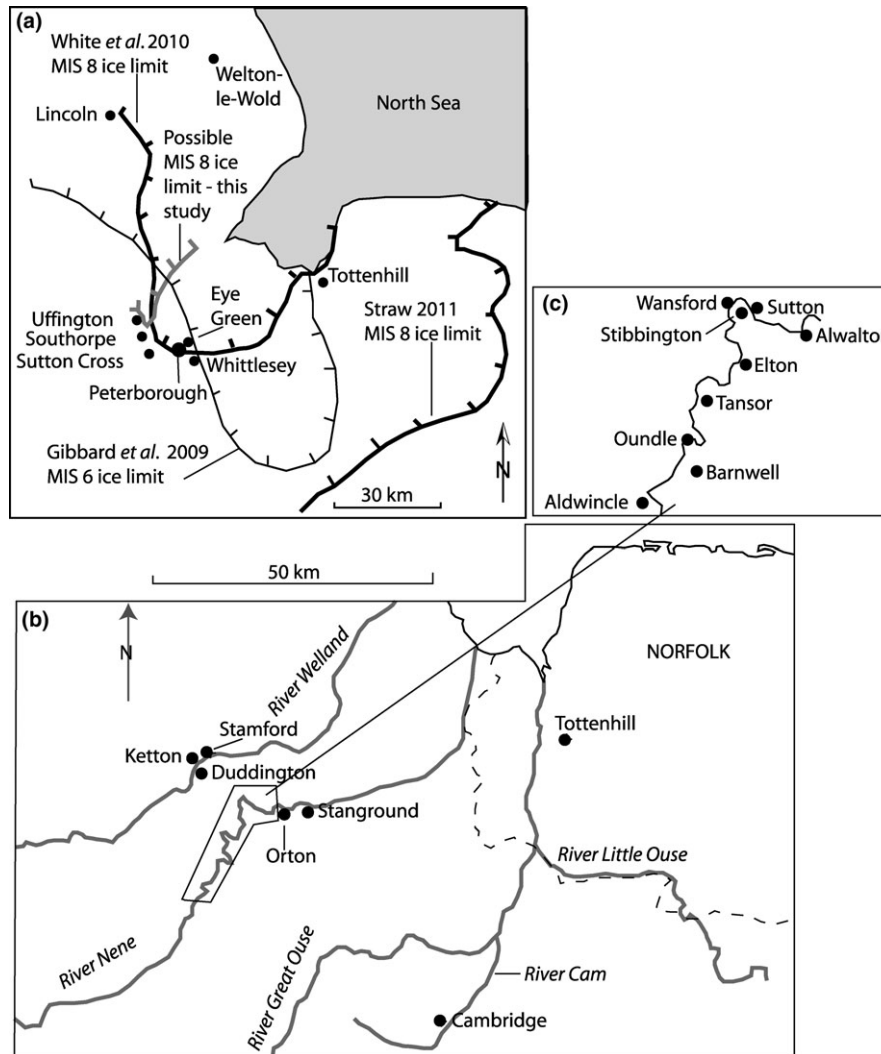
FIGURE 2 (a) Configuration of postulated MIS 8 and MIS 6 ice margins in the study area. (b, c) Locations mentioned in the text

using a comparative chart. Stratification direction and dip are all apparent values, that is, as observed in the faces exposed during investigation. Observations of pebble imbrication were not quantified but are based on the careful removal and measurement of the *ab* axis dips of between 5 and 10 clasts in individual beds where imbrication was evident. Clast-lithology samples were collected from freshly cleaned faces and sieved through 32, 16, 11.2, and 8 mm (-5, -4, -3.5, and -3 ø) mesh sieves. As the samples for Elton were small all clasts ≥ 8 mm were counted, but for Uffington those in the 11.2 and 16 mm sieves were counted separately. Clast-fabric data for Elton comprised the orientation and dip of 25 clasts with an *a* axis noticeably longer than the *b* axis. The data were fed into a computer program devised by Dr G.F. Dardis, which produces the eigenvector and S_1, S_2, and S_3 eigenvalues (degree of clustering around the eigenvectors) as output.

2.1 | Glacial sand and gravel north of Uffington

North of Uffington, the British Geological Survey (BGS, 1978; Booth, 1981) has mapped a north–south trending sequence of glacial sand and gravel (Figure 3). These occupy interfluve areas between 20 and 30 m OD at the eastern edge of the Jurassic escarpment and the western margin of the Fen Basin, between the River Welland to the south and its tributary East Glen River to the north. The glacial sands and gravels at Uffington are described as such because of their close association with "Boulder Clay" (Lowestoft Till; Booth, 1981), although these are not extensive (BGS, 1978).

Temporary sections at "A" in Figure 3, with a present-day surface height of about 30 m OD, were investigated in May 1997 (Figure 4a). A maximum thickness of 4 m was observed resting unconformably on Jurassic Oxford Clay
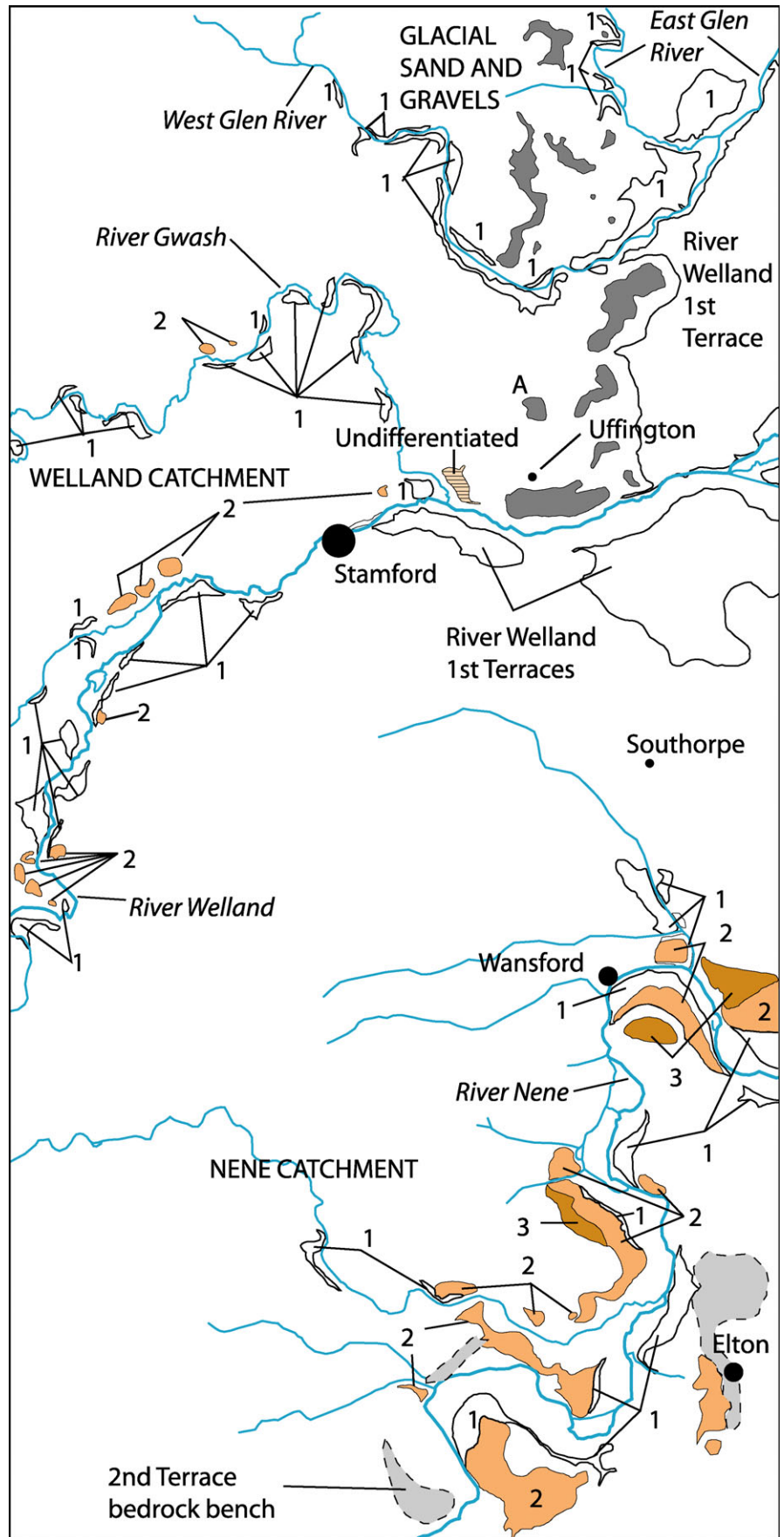
FIGURE 3 Distribution of glacial sands and gravels north of the River Welland as well as Nene and Welland fluvial terraces relevant to the sites studied (Redrawn from BGS, 1976, 1978, 1984)

(Figure 4b, c). Table 1 lists both the sedimentary facies observed and the lithofacies coding used.
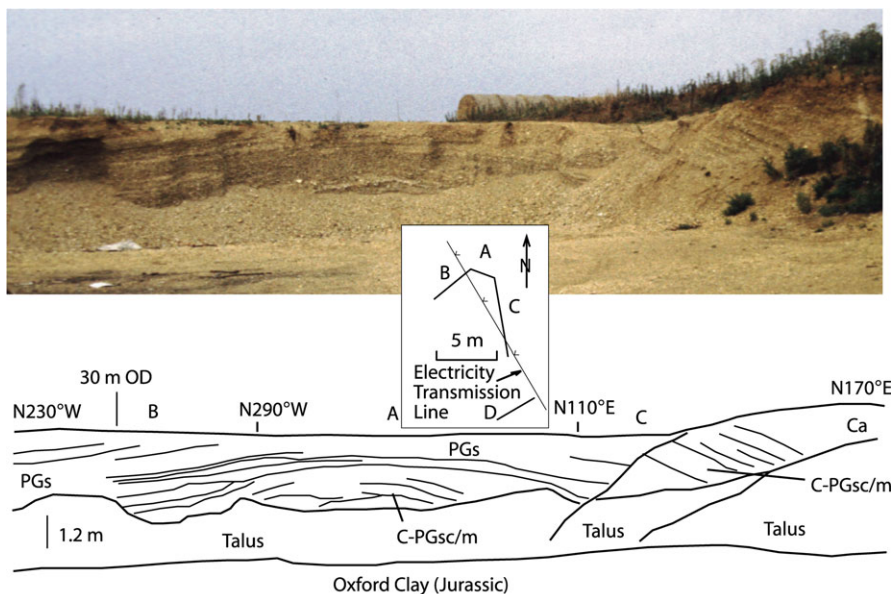
2.1.1 | Description

Facies association *C–PGmc/m* was observed in section A (Figure 4) where it comprises interbedded gravel facies of different textures (Figure 5 and Table 1), but mostly poorly sorted, that form a crude horizontal stratification. The observed maximum thickness of *C–PGmc/m* in section A is about 3 m, most of which was obscured by talus. Excavation beneath the staff in Figure 5 indicated a coarse clast-supported open-framework (OF) gravel at the base with cobble-sized clasts of reworked Oxford Clay, fining upwards to pebbly clast-supported OF gravel beneath pebbly clast-supported closed-framework (CF) gravel. The tripartite sequence of CGmc-m overlain by PGs/mcOF and then PGs/mcCF, is repeated at least three times in section C (Figure 6) where it forms crude southward-dipping foresets. Clast-lithology analysis (Table 2) indicates dominance of limestone and flint but with significant components of chalk and sandstone (the latter category also includes quartz and quartzite clasts). Of the sandstone category, 7.7% (of total clast count) is considered to have a Triassic provenance.

Facies association *PGs* was observed in sections A–C (Figure 4), but was best developed in section B (Figure 7), where it formed a maximum thickness of about 2 m. In section A, the association overlies *C–PGmc/m*, but in section C it underlies a later aggradation of *C–PGmc/m*. In section B, pebbly, structureless (massive) clast-supported gravel (PGmc) passes upwardly and laterally into pebbly, stratified clast-supported gravel (PGcs) forming southward-dipping foresets coincident with increasing sand content. Locally, where sand content increases, small pockets of matrix-supported gravel occur. There is an increasing tendency for pebble *ab* axes to be aligned transverse to slope as stratification is better developed, but where stratification is poorly developed *ab* axes tend to align parallel with slope. An erosional discontinuity marks the base of an overlying PGcs with foresets dipping in the same southerly direction. In the upper part of this overlying unit, at the southern end of section B, a minor lens of planar cross-stratified sand passing laterally to structureless (massive) sand was observed, which was truncated and overlain by PGmcOF.

Facies association *B–PGmc/m* was observed in section D (Figure 4). Only the upper 1 m or so of section D was exposed; most of this poorly, with the lower parts obscured by vegetated talus slopes. The two-dimensional facies architecture observed is similar to *C–PGmc/m* (Figure 8a), with lateral aggradation of individual facies forming crude south-westward-dipping foresets. Clast-lithology analysis (Table 2) indicates an increase in *B–PGmc/m*, compared with *C–PGmc/m*, in the flint content at the expense of chalk, probably reflecting the higher energy conditions. Values for the other categories are essentially the same for both samples.

The stratigraphic succession recorded in sections A–D is shown in idealized form in Figure 8b.

FIGURE 4 Location of sections investigated and the sedimentary succession observed in the glacial sands and gravels north of Uffington, looking north-northeast (Photographed by H. E. Langford, 15 May 1997)

TABLE 1 Description of lithofacies codes used for the sedimentary succession north of Uffington

Facies association	Component facies[a]	Description[b]
B–PGsc/m Bouldery to pebbly stratified clast-supported gravel with minor matrix-supported horizons	BGmc/m	Bouldery massive clast-supported gravel with a muddy matrix and minor matrix-supported pockets
	PGmc(n)	Pebbly massive clast-supported normally graded open-framework (OF) gravel
	PGmc	Pebbly massive clast-supported gravel
PGs Pebbly stratified gravel	PGmc(n)	Pebbly massive clast-supported normally graded gravel
	Sp–Sm	Planar cross-bedded sands passing laterally to massive sands
	PGsc/m	Pebbly stratified clast-supported gravel with minor matrix-supported horizons
	PG(s)c	Pebbly weakly stratified clast-supported gravel
C–PGsc/m Cobbly to pebbly stratified clast-supported gravel with minor matrix-supported horizons	PGmc	Pebbly massive clast-supported gravel
	PGmm	Pebbly massive matrix-supported gravel
	PGsc/m	Pebbly stratified clast-supported gravel with minor matrix-supported horizons
	PGmc/m	Pebbly massive clast-supported gravel with minor matrix-supported horizons
	PGmc–m(n)	Pebbly massive clast- to matrix-supported normally graded gravel
	PGmc(n)	Pebbly massive clast-supported normally graded gravel
	CGmc(n	Cobbly massive clast-supported normally graded gravel
	CGmc–m	Cobbly massive clast- to matrix-supported gravel in muddy matrix

Note. [a]Lithofacies codes adapted from Miall (1977) and Dardis (1985). The gravel clast size prefixes denote the largest size commonly present, that is, not the average clast size. [b]Unless stated otherwise gravel facies are closed framework (CF).

2.1.2 | Interpretation

Langford (1999) determined a glaciofluvial depositional environment for this sedimentary succession, although he noted the following uncertainties in the interpretation: (i) foreset bedding and large-scale cross-bedding are rare in braided stream deposits (Miall, 1977); (ii) the absence of geomorphological evidence for flow confinement and expansion. Subsequently, in the light of compelling ground-penetrating radar evidence of foreset bedding reported by Gibbard et al. (2009) in similar deposits, the sedimentary evidence from the sand and gravel deposits north of Uffington was re-examined in 2010 (Langford, 2012a). The fundamental difference between the former interpretation and that presented below is that facies association *C–PGmc/m* represents a feeder channel of a delta and not the deposits of a fluvial bar. The rationale for the revised interpretation follows.

Facies association *PGs* has a distinct fan-lobe morphology (Figure 4b) with well-developed foresets (Figure 7) up to 2 m in height, indicating deposition in a water body at least 2 m deep (Picard & High, 1973) and a feeder channel (point-source) delivering sediment from the north-northeast, perpendicular to section A (Figure 4). Foresets, although not so well-developed, are also a dominant feature of facies associations *C–PGmc/m* and *B–PGmc/m* (Figures 5 and 8a). The foreset bedding and fan-lobe morphology indicate a deltaic depositional environment, that is, sedimentation from a feeder channel on entering a standing body of water

(Selley, 1976), with energetic jet flows from the feeder channel producing sets of avalanche faces (Leeder, 2009).

The rarity of fine-grained sediments suggests a glaciolacustrine depositional environment in which sediment bypass of finer-grained sediment occurs in the form of suspended sediment-laden plumes produced by water-density contrast (Benn & Evans, 1998; Bennett & Glasser, 1996; Cohen, 1979; Miller, 1996). Martini (1990) describes a similar situation and suggests that removal of the fine fraction occurred during highly turbulent flow within the feeder system itself. Thus, the tripartite sequence C–PGmc-m overlain by C–PGs/mc(OF) and then PGs/mc observed in facies association *C–PGmc/m*, and similarly in *B–PGmc/m*, may be explained as follows:

1. Fines are removed in the feeder channel during highly turbulent flow and the remaining sediment is delivered to the top of the slope to be deposited on the slope as slurry flows (facies PGs/mc);
2. Open-framework gravel (facies C–PGs/mc(OF)) develops in the feeder channel, the top of which is infiltrated by fines out of suspension during flow cessation (facies C–PGmc-m);
3. During flow recommencement facies C–PGmc-m in the feeder channel is mobilized, delivered to the top of the slope and deposited on the slope as a slurry flow;
4. Mobilization of the underlying facies C–PGs/mc(OF) in the feeder channel, delivery, and deposition as a grain flow;
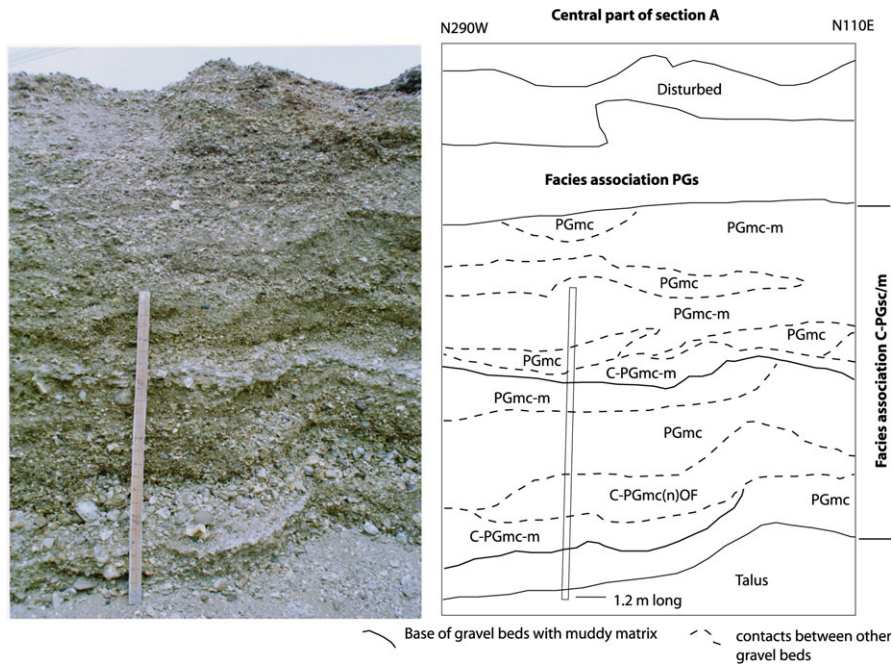
FIGURE 5 Photograph (H. E. Langford, 15 May 1997) and sketch of central part of section A at Uffington showing two-dimensional facies architecture

5. Deposition of facies PGs/mc (and PGs/mc(OF)) in higher energy turbulent flow conditions) until flow cessation.

In general, unsteady flow conditions prevailed, with facies C–PGmc-m possibly representing resumption of flow during the spring thaw. Facies association *PGs* in contrast indicates a period, or two, of sustained flow, possibly in response to more extensive spring thaws. The apparent lack of topsets and toesets indicates, respectively, direct influx from a subglacial portal to form a subaqueous meltwater fan (Benn & Evans, 1998) and a sufficiently strong turbulent plume to enable fine-sediment bypass.

2.2 | Lacustrine deposits at Elton

Temporary sections at Elton (Figure 2c) were investigated during road construction in 1990. The deposits studied crop out at between 28 and 35 m OD. They are mapped as Jurassic Oxford Clay by BGS (1976) and Harrisson (1981), but form one of the stripped terrace benches of Castleden (1980; Figure 3). Commercial site investigation data (see Langford, 1999) record up to 3 m of "boulder clay" overlying the Oxford Clay (Figure 9a). The contact between the "boulder clay" facies and the underlying Oxford Clay in Figure 9a is approximate and is interpreted from the descriptions given in commercial boreholes (BH) 2–6. Three facies associations have been identified within the "boulder clay" unit (Figure 9a and Table 3). The exact relationship of facies association *PDd* (log 1, Figure 9a) with facies association *Fm/PDm–cm* is not known, but is inferred from the presence of a structureless clay (Fm) above a very degraded outcrop of *PDd*. Brief descriptions

of the facies associations and their component facies are provided in Table 3.

2.2.1 | Description

Deformed diamicton (PDd), sand (Sd), and fines (Fd) comprise facies association *PDd* (Table 3 and Figure 9a,b), with the latter showing evidence of primary stratification: it has a maximum recorded thickness of about 1.25 m, with its base at about 25 m OD. The diamicton always forms the upper unit, but it is not known whether the lithological succession below the diamicton in log 1 is a characteristic of the sequence as a whole or whether it is a product of local deformation. Styles of deformation include compressional folding (symmetric A type folds) of substrate, that is, facies Sd and Fd prior to deformation, rotation incorporating diamicton and substrate sediments, and subhorizontal shearing of upwardly injected substrate material. The apparent direction of the shearing, as visualized in two parallel sections 1 m apart, is towards the west. Clast-fabric analysis produced an S_1 value of 0.5771 and an azimuth (V_1) of 7.3/022°. Clast-lithology analysis (Table 4) indicates predominantly flint and limestone (2.3% chalk), but with significant proportions in the ironstone and sandstone categories.

Facies association *Fm/PDm–cm* (Table 3 and Figure 9a, c) is dominated by structureless muds (facies Fm). A total thickness of >2 m was recorded at log 2, with its base at about 27 m OD, but further east the unit has aggraded up to 32 m OD. In the lower part of *Fm/PDm–cm*, facies Fm is interbedded with resedimented bands of Jurassic Oxford Clay (facies PDm–cm) and ribbons of medium to coarse sand (facies Sm). Laterally persistent bands of gypsum
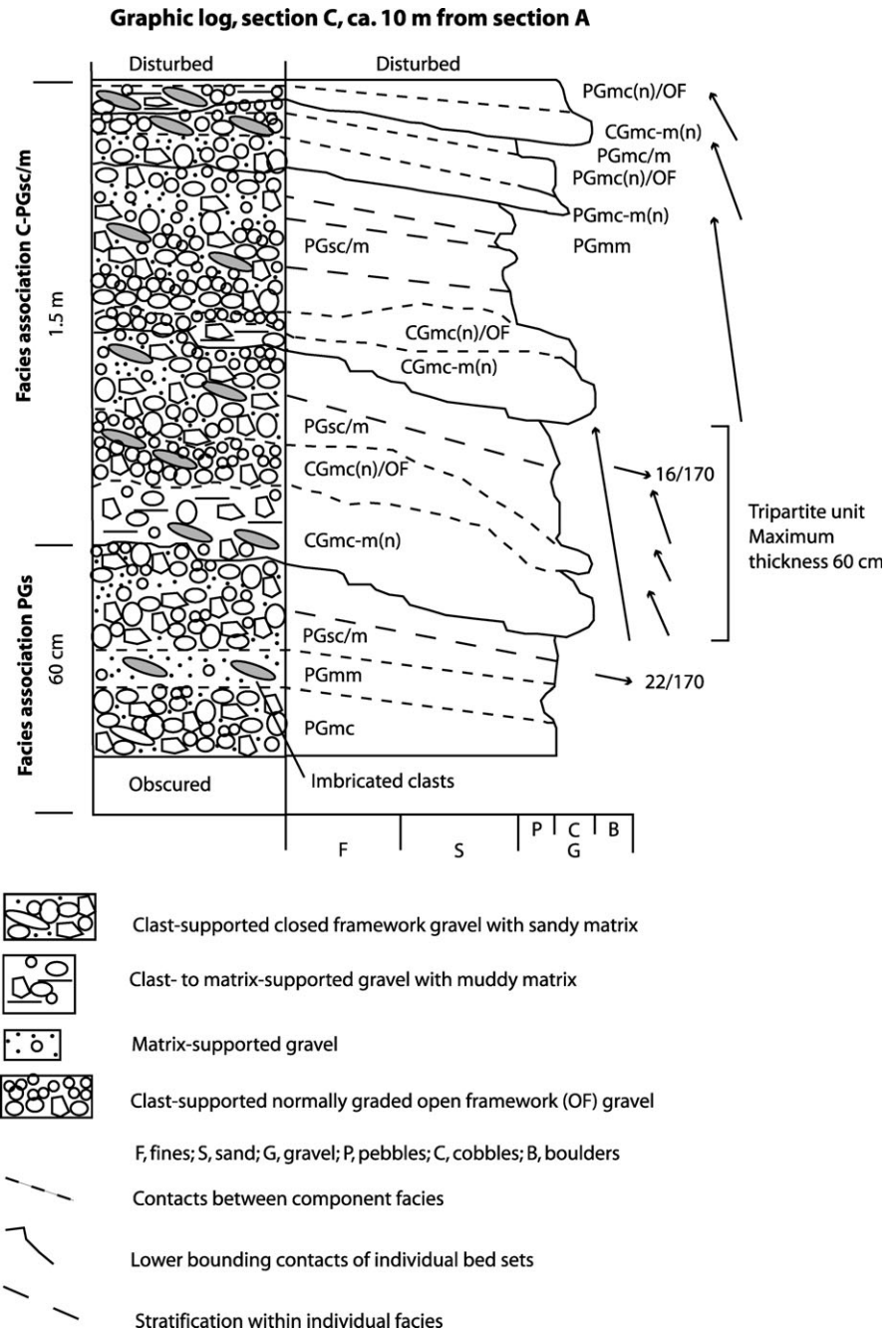
FIGURE 6 Graphic log for part of section C at Uffington based on photographs and field notes (May 1997). The dip and bearing measurements represent apparent dip, that is, as depicted in the exposed face. Note that this sequence is not a vertical succession but depicts lateral and vertical aggradation over a width of 2.1 m. Facies mostly are arranged in tripartite sequences forming crude southward-dipping foresets

occur in facies Fm. In the vicinity of BH4 (Figure 9a) facies PDm–cm and Sm were observed to dip towards the east. Locally the following sequence was recorded: gypsum in Fm, overlain sequentially by a sand ribbon, resedimented Oxford Clay and Fm with gypsum development.

Facies association *Fm/PGmm* (Table 3 and Figure 9a, d) comprises structureless muds (Fm) with lenses of matrix-supported sandy gravels (PGmm), structureless sand (Sm), and horizontally stratified sands (Sh), with the latter being restricted to lenses no more than 30 cm wide. Textural differences revealed by variations in moisture retention capacity when the section was subaerially exposed during road construction indicate deposition locally in broad (<5 m)

channels, up to 1 m deep, with incision down to about 29 m OD and the highest aggradation at about 35 m OD. The maximum recorded thickness was about 3 m. Reactivation surfaces in some PGmm lenses record discontinuous flows or fluctuations in flow energy; the separation of sandy and sandy gravel phases in some PGmm lenses record fluctuations in flow energy. Upwardly concave lower bounding surfaces of the lenses are common and some lenses preserve upwardly convex upper bounding surfaces. Within lenses, subsequent events also are marked by sharp, erosive, upwardly concave bases. Most lenses show erosion by facies Fm, with scattered pebbles in Fm at the margins of PGmm lenses, and even over distances of 10 m there is considerable

TABLE 2 Clast lithology, Uffington

Facies	Lithology	>16 <32 mm		>11.2 <16 mm		Total	
		Number	%	Number	%	Number	%
PGsc/m[a]	Chalk[b]	13	10.8	50	13.4	63	12.8
	Limestone	54	45.0	200	53.5	254	51.4
	Flint	30	25.0	78	20.9	108	21.9
	Sandstone, etc.[c]	16	13.3	28	7.5	44	8.9
	Ironstone	1	0.8	10	2.7	11	2.2
	Other	6	5.0	8	2.1	14	2.8
	Total	120		374		494	
BGmc/m	Chalk	5	1.4	22	6.3	27	3.8
	Limestone	184	51.7	183	52.3	367	52.0
	Flint	104	29.2	106	30.3	210	29.7
	Sandstone, etc.[d]	50	14.0	20	5.7	70	9.9
	Ironstone	5	1.4	11	3.1	16	2.3
	Other	8	2.2	8	2.3	16	2.3
	Total	356		350		706	

Note. [a]Some clasts were covered by a black (carbon?) coating. [b]Hard nodular (chert-like) chalk. [c]Includes quartz and quartzite. Triassic content = 7.7% of total clast count. [d]Includes quartz and quartzite. Triassic content = 6.4% of total clast count.

Middle of section B, facies association PGs

Marked stratification indicated by increased sand component

Continuation of facies PGs above discontinuity

N230W   N050E

Discontinuity

1.2 m long

Increasing sand component, especially downslope

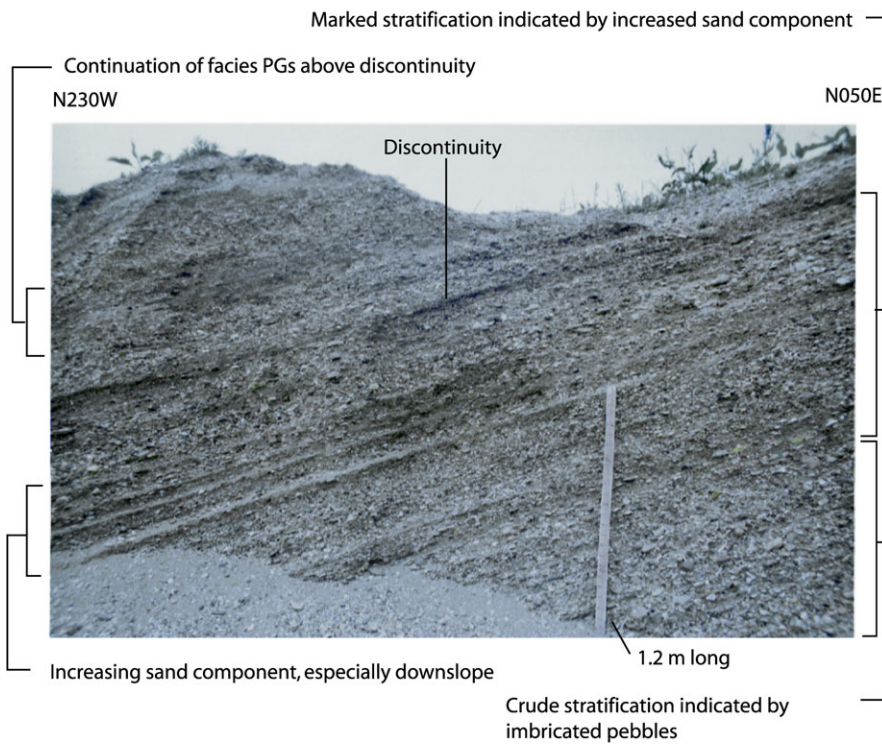Crude stratification indicated by imbricated pebbles

FIGURE 7 Sedimentary facies PGs in section B at Uffington (Photographed by H. E. Langford, 15 May 1997)

variation in the form and dimensions of individual lenses. Clast-lithology analysis (Table 4) of PGmm indicates predominantly limestone (32.9%), chalk (30.1%), and flint (25%), with minor ironstone and sandstone.

2.2.2 | Interpretation

Primary sedimentary structures in facies Sd and Fd of facies association *PDd* indicate horizontal stratification.
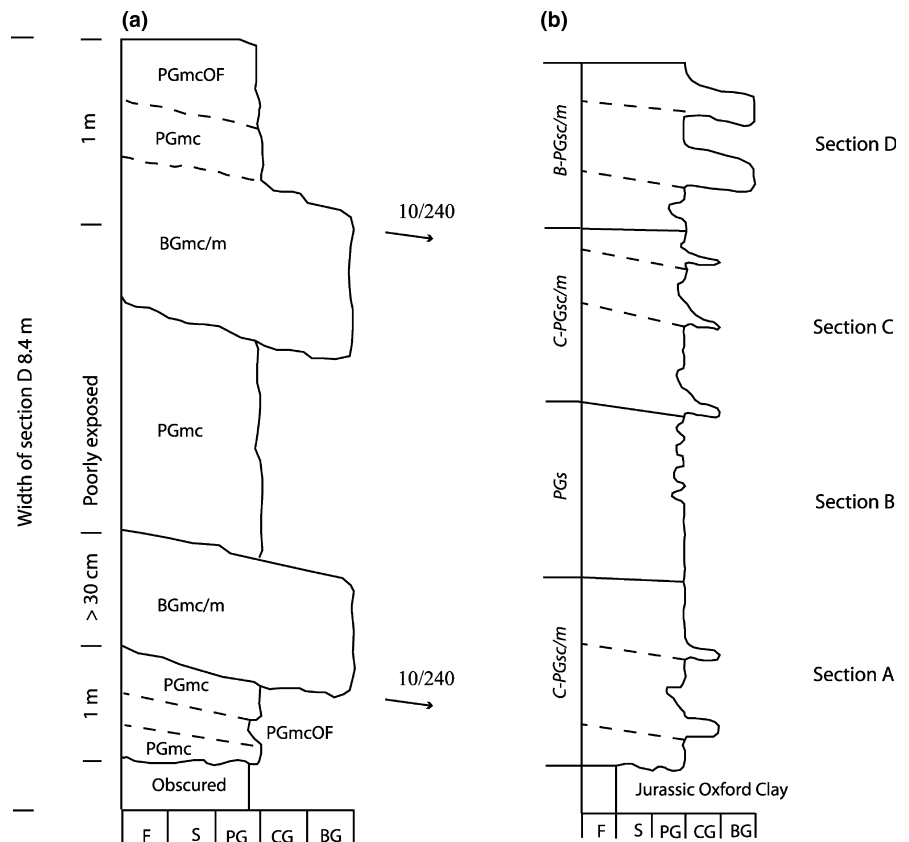
FIGURE 8 (a) Idealized lithological log for section D at Uffington. Note that this is not a vertical succession but represents lateral aggradation over about 8.4 m. Only the upper 1 m of parts of section D was clearly exposed. Only two beds of facies BGmc/m appeared to be present but their thickness could not be ascertained. (b) Simplified stratigraphical log based on observations from sections A–D

The fine-grained nature of Fd indicates deposition from suspension and the stratification indicates periodic influx of sand sheets as bedload and fines in suspension into a standing body of water. Subsequent deposition of facies PDd by cohesive flow processes resulted in deformation by loading and lateral compression while the underlying sediments were still very wet. A prominent shear zone indicates a shear direction, and hence transport direction, from the east, where the Anglian (MIS 12) chalk-rich diamicton source of PDd mantles the surrounding hills above about 40 m OD (BGS, 1976; Harrisson, 1981; Langford, 1999). Clast-fabric data indicate that the clasts were arranged predominantly transverse to the direction of shearing. The erratic/local ratio of 2.28 for the clasts corresponds to those recorded by Castleden (1980) for the River Nene Third Terrace upstream of Stibbington, and the clast-lithology assemblage is very similar to Castleden's samples 1 and 2 from Aldwincle and Barnwell (Figure 2c), respectively.

The structureless mud (facies Fm) of facies association *Fm/PDm–cm* (Figure 9a, c) is attributed to the deposition from the suspension of liberated and mobilized bedrock material, as evidenced by the periodic input of resedimented Oxford Clay (facies PDm-cm) from the submerged slopes and floor of the lake. At Stanground (Figure 2b), Oxford Clay forming the side of a MIS 12 palaeochannel that was subject to subaqueous slope processes has been altered in situ to form a tripartite sequence of fissile Oxford

Clay at the base overlain by: (a) a lower brecciated zone with upwardly curved shear planes; (b) an upper homogeneous zone with similar shear planes (Figure 10; Langford, 1999). Both facies were found transported downslope by cohesive flow processes, as resedimented Oxford Clay dominated by elements from the brecciated zone was observed in more distal locations and at deeper levels within the palaeochannel. Such a process is envisaged here, with the upper zone providing abundant material for deposition from suspension (i.e., facies Fm). Cryogenic processes (cf. Burton, 1987; West, 1991) operating on bare valley sides and dried out lake-floor sediments would have provided ample erodible material for both gravity flows and in suspension.

Periodic, perhaps seasonal, drying out of the lake periphery, at least, is suggested by the presence of the gypsum bands in the lacustrine deposits at Elton. The gypsum is envisaged to have formed as the sulphate and calcium-rich facies Fm became subaerially exposed. The substrate Oxford Clay (which can contain up to 2.4% gypsum) and deposits derived from it would have supplied the necessary sulphate and calcium (Langford, 1999; Norry, Dunham, & Hudson, 1994). Calcium and sulphate also would have been available from the Anglian chalk-rich diamictons (Langford, 1999) that mantle the surrounding hills.

The sand ribbons (Sm) probably represent periodic traction flow deposits, and their two-dimensional geometry
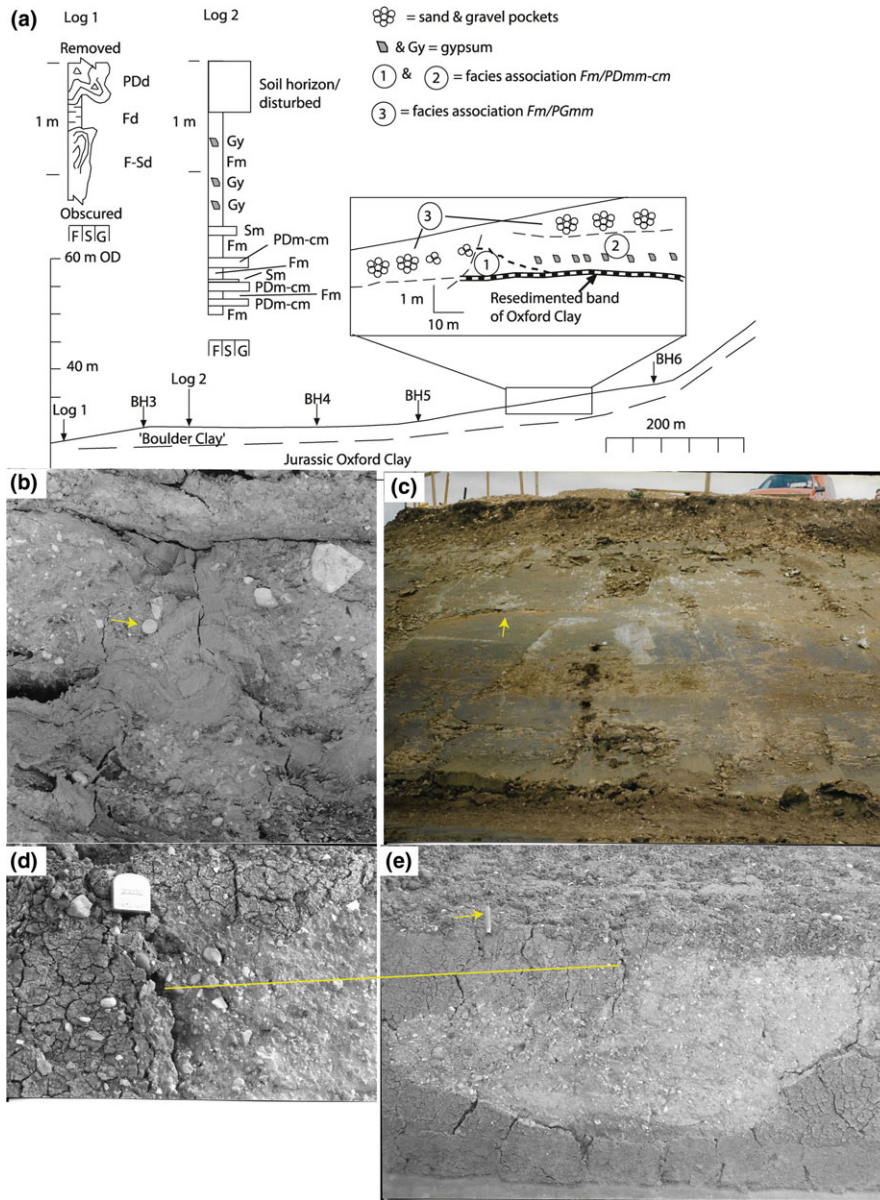
FIGURE 9 The lacustrine sedimentary succession investigated at Elton. (a) Simplified sketch of location of borehole and graphic logs and exposed section. (Adapted from Langford, 1999) (b) Facies association *PDd* at log 1; coin for scale (arrowed) is 25 mm in diameter. (c) Facies association *Fm/PDmm–cm* at log 2; the dark bands are reworked Oxford Clay and the arrow indicates a continuous sand ribbon. (d, e) Example of sand and gravel pocket in facies association *Fm/PGmm*; the tape measure is 5 cm wide and the trowel (arrowed) is 27 cm long

suggests draping of pre-existing accretion surfaces by a continuous sand sheet. Although Sm in *Fm/PDm–cm* represents sand ribbons rather than beds of massive sand, their origin may be similar to the sheet-like sandstone beds found on distal parts of alluvial fans or floodplains, which are considered to be products of sheet floods (Collinson, 1996).

The apparent eastward dip of the sand ribbons and PDmc–m beds is difficult to explain because it is towards the lake margin and there is no evidence of deepening in that direction. This sequence therefore may represent a distal depositional lobe of a subaqueous fan prograding into the lake basin from the west, that is, fed by the main channel upstream of Elton (Figure 11), during phases when the water level was high, and the gypsum formed when the lobes became exposed subaerially during low-water phases. The sedimentary succession in *Fm/PDm–cm* does not

appear to have a regular pattern, but at one location the succession indicates facies Sm draping the underlying accretion surface (below which were pockets of gypsum), deposition of facies PDm–cm, followed by facies Fm, in which gypsum subsequently formed. There is a possibility, therefore, that facies Sm represents the spring thaw flood prior to rising water level in the lake, facies PDm–cm was deposited as cohesive flows generated by slope failure during rising water level and Fm was deposited from suspension at the high water level stage. Subsequently the water level fell and gypsum formed in deposits that were subaerially exposed.

The nature of the contact between facies associations *Fm/PDm–cm* and *Fm/PGmm* indicates significant and widespread erosion associated with a change in the dominant depositional process: *Fm/PGmm* is characterized by channel cut-and-fill comprising lenses of PGmm, Sm, and

TABLE 3 Description of lithofacies codes used for the sedimentary succession at Elton

Facies association	Component facies[a]	Description[b]
Fm/PGmm	Fm	Massive (structureless) fines (mud)
	PGmm	Pebbly, matrix-supported massive gravel
	Sm	Massive sand
	Sh	Horizontally stratified sand
Fm/PDm–cm	Fm	Massive fines
	PDm–cm	Pebbly, matrix-supported to clast-supported massive diamicton
	Sm	Massive sand
PDd	PDd	Deformed pebbly diamicton
	Sd	Deformed sand
	Fd	Deformed fines

Note. [a]Lithofacies codes adapted from Miall (1977) and Dardis (1985). The gravel clast size prefixes denote the largest size commonly present, that is, not the average clast size. [b]Unless stated otherwise gravel facies are closed framework.

TABLE 4 Clast lithology, Elton

	PGd (>8 mm)		PGmm (>8 mm)	
Lithology	Number	%	Number	%
Chalk	4	2.3	65	30.1
Limestone	34	19.4	71	32.9
Flint	97[a]	55.2	54	25.0
Sandstone, etc.	21[b]	12.0	11[c]	5.1
Ironstone	19	10.9	12	5.5
Other			3	1.4
Total	175		216	

Note. [a]Several fragments appear as though they are from the same clast originally. [b]Includes quartz and quartzite. Triassic content = 12% of total. [c]Includes quartz and quartzite. Triassic content = 1.4% of total.

Sh within a matrix of Fm. The lack of vertically and sub-vertically arranged clasts and of deformed primary sedimentary structures within and without the lenses indicates that they are not the product of postdepositional deformational processes. The presence of clasts floating within the surrounding facies Fm indicates that the lenses do not represent infilling of conduits. Instead, the channelized and matrix-support nature of facies PGmm suggests cohesionless debris flows (Collinson, 1996; Nemec & Steel, 1984). The erosive base of channels within *Fm/PGmm* and the erosion of facies PGmm by facies Fm suggest turbulent flow during deposition of the latter rather than deposition from suspension.

In Figure 9a, lenses appear at two levels. At the lower level, the size of individual lenses diminishes towards the

FIGURE 10 Modification of bedrock Jurassic Oxford Clay forming a Middle Pleistocene subaqueous slope at Stanground, near Peterborough: (a) homogenized Oxford Clay; (b) brecciated Oxford Clay; (c) fissile Oxford Clay in situ. The penknife handle is 8.3 cm long and the arrows indicate shear planes (Photographed by H. E. Langford, October 1993)

steeply inclined contact with *Fm/PDm–cm*, which may reflect increased turbulence at channel margins, either as a boundary-layer effect or by flow on the outer edge of a bend (Leeder, 2009). It was noted that facies association *Fm/PDm–cm* may represent accumulation of delta lobes,

which would support the latter explanation as flows associated with the deposition of *Fm/PGmm* would have been controlled by the topography of such subaqueous landforms.

The high erratic/local ratio of 1.6 for facies PGmm reflects the high chalk content, otherwise it would be similar to the ratio recorded by Castleden (1980) for the River Nene Third Terrace at Orton (Figure 2b). Compared with facies association *PGd*, a change in source of sediment supply is indicated by the clast-lithology assemblage of facies PGmm, which is richer in chalk and limestone than facies PGd. The enrichment of chalk and limestone suggests degradation of the local land surface: Jurassic limestone crops out locally and the Anglian chalk-rich diamictons capping the hills to the east contain up to 60% chalk (Langford, 1999, 2004c, 2011). The relatively high percentage of flint and the presence of sandstone and ironstone suggest reworking of fluvial sediments, perhaps those that sourced facies PGd, which is enriched in these components.

3 | DISCUSSION

The sedimentology and three-dimensional facies architecture of the sedimentary succession north of Uffington indicates deposition as a subaqueous ice-contact fan (Gibbard et al., 2009, 2012, 2012; Winsemann et al., 2007; *contra* Langford, 1999, 2004a). Coarse-grained deltas such as the deposits described here occur in a range of depositional settings (see Colella & Prior, 1990), including alluvial deltas (sensu Nemec, 1990a) and grounding-line/subaqueous-outwash fans (Benn & Evans, 1998), in which gravitational processes such as debris, grain, and turbidite flows dominate (Cohen, 1979; Martini, 1990; Mastalerz, 1990; Miller, 1996; Nemec, 1990b; Nichols, 2009; Winsemann et al., 2007). Crude foreset-stratified poorly sorted gravels are indicative of mass-flow processes (Martini, 1990), that is, slurry and grain flows (Carter, 1975; Cohen, 1979), and open-framework gravels commonly feature in grain flow deposits produced by highly turbulent flow (Leeder, 2009; Martini, 1990).

In the context of the deposits mapped as glacial sands and gravels in Figure 3, and the interpretation of the sedimentary succession observed as an ice-contact subaqueous fan, it is difficult to demonstrate the depositional environment with any certainty without geomorphological evidence to establish the cause of flow confinement or expansion. As diamictons that could represent till are present only sporadically (BGS, 1978), and subglacial landforms absent, a glacial depositional environment may be difficult to envisage. In a study of Pleistocene glacial fan deltas, however, Martini (1990) noted that till was rarely present. In a glacial environment the glacier or ice sheet and associated landforms may form the geomorphological conditions that constrain and promote depositional processes and environments, but the preservation potential of the geomorphological framework thus formed may be low, whereas that for the depositional products may be high (Martini, 1990). A similar situation has been described recently by Gibbard et al. (2009, 2012, 2012), who investigated a group of positive landforms on the eastern side of the Fen Basin (Figures 1a and 2a).

As noted by Winsemann et al. (2007), glacial-lake deposits are most likely to be a record of deglaciation or maximum ice limit, because during ice advance such deposits would be incorporated into the base of the ice. The deposits mapped as glacial sands and gravels in Figure 3 are therefore likely to represent the maximum ice advance. Lake confinement by high ground to the west and south (Figure 11), and ice to the north therefore can be envisaged, but establishing confinement to the east is problematic, although in the scenario depicted here, the confinement is likely to have been by ice or by glaciofluvial discharge.

The dominance of facies Fm rather than well-stratified fine-grained deposits in the sedimentary succession recorded at Elton, interpreted to have accumulated in a cold-stage lacustrine environment affected by marked seasonal discharges, may seem unusual. Structureless muds are not uncommon in such situations, however, and their origin may be attributable to one of several processes (Collinson, 1996; Hart, 1992; Lunkka, 1994; Nemec & Steel, 1984; Owen, 1996; Stow, Reading, & Collinson, 1996). In the context reported here, shallow water bodies are prone to wind mixing and current movement, which prevents stratification in the water body (Smith & Ashley, 1985). In addition, the size-range of the sediment supply available (i.e., the Oxford Clay) may have limited the opportunity for more obvious stratification to develop.

An alternative origin for facies PGmm and elements of facies Fm in facies association *Fm/PGmm* may be generation by turbidity currents, with the former being deposited by high-density turbidity currents (Stow et al., 1996) in a confined high-density flow (Prior & Bornhold, 1989) and the latter by low-density turbidity currents (i.e., late stage of high-density turbidity current) by concentration of the dilute suspension as a result of flow deceleration to form a slow-moving hyperconcentrated flow (see Stow et al., 1996), which would explain the presence of pebble-sized clasts derived from facies PGmm floating in facies Fm. Turbidity currents in freshwater lakes may be generated directly when highly turbid river water enters a freshwater lake and forms a hyperpycnal flow (Cohen, 1979; Stow et al., 1996). As noted by Nemec (1990b) they also may be associated with subaqueous debris flows on a delta front or with intense sediment fallout from the suspension plume
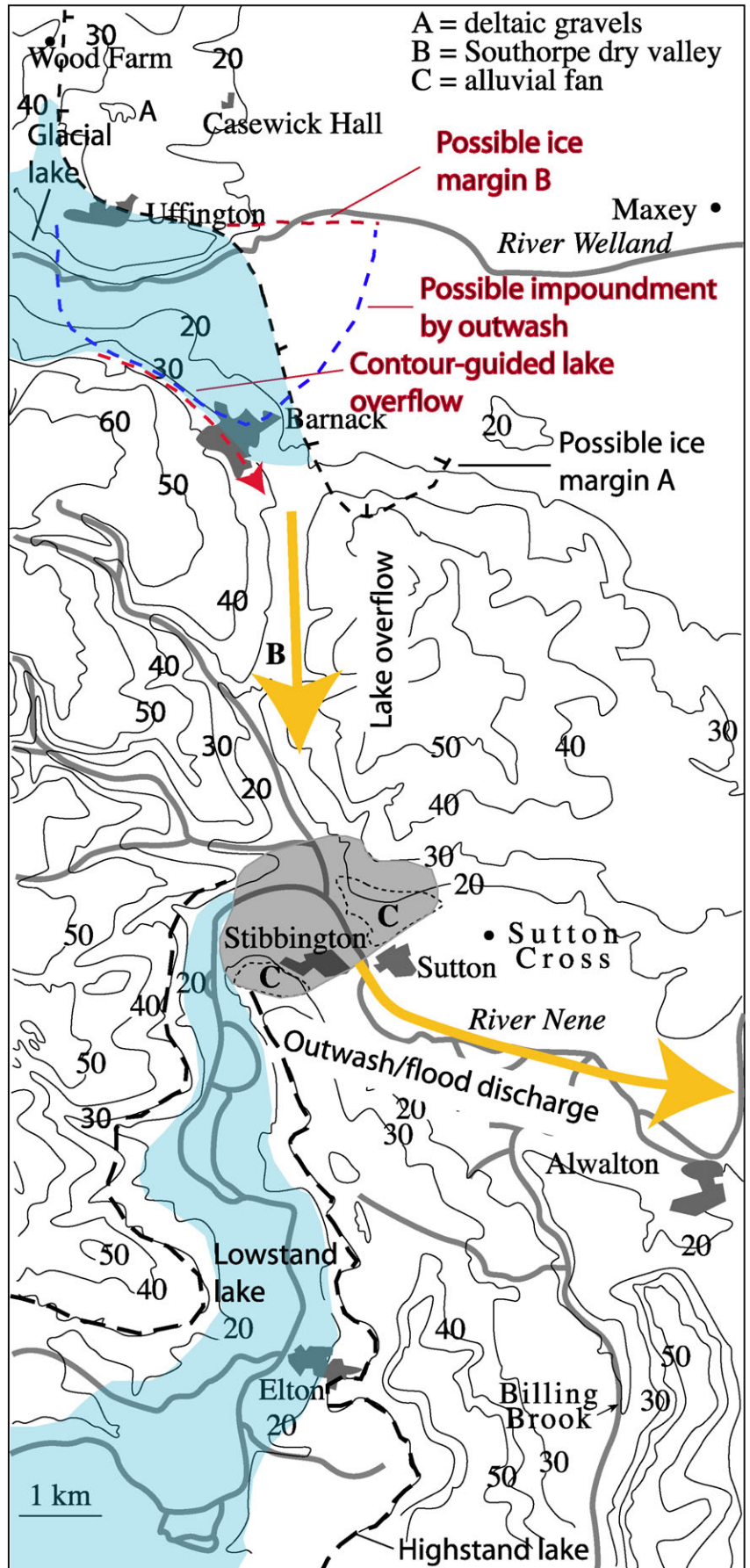
FIGURE 11 Reconstructed conditions envisaged for impoundment of the proto-Welland, and for highstand and lowstand lakes and breaching of the alluvial fan in the proto-Nene during high-magnitude events

of a stream outflow jet during flood-stage. Talbot and Allen (1996) point out that deposition of sand and gravel by turbidity currents in a freshwater lake setting requires steep basins in order to limit development of a subaerial delta plain. At Elton this requirement may have been satisfied during the late highstand phase and destabilization of former subaerial deposits as the water-table rose.

3.1 | Implications for palaeogeographical reconstruction

In the present context three alternative scenarios can be considered.

1. Prior to the existence of the River Welland a small lobe of ice could have advanced against the high ground to the east of Barnack (Figure 11) thereby forming a small ice-contact lake (cf. Syverson, 1998) in the vicinity of a subglacial outlet.
2. As above but with the ice impounding the proto-Welland and forming a lake upstream.
3. The outwash itself could have impounded the proto-Welland and formed a lake upstream.

The two and three-dimensional facies architecture of the ice-contact fan deposits north of Uffington indicates flow towards the Southorpe dry valley (Figure 11). Langford (1999, 2004a) envisaged something similar to the first of these scenarios and that the Southorpe dry valley originated as a subaerial glacial meltwater channel (cf. Martini, 1990), as suggested by Kellaway and Taylor (1953); consequently the River Welland could not have existed at this time. The above reinterpretation of these deposits as an ice-contact fan and further examination of the disposition of River Welland Second Terrace deposits (see below), however, suggest that the River Welland was in existence. The deposits immediately north of Uffington (Figure 3) therefore could be remnants of the infilling of the proto-Welland, and the ice-contact fan could represent the local maximum ice extent. The Southorpe dry valley, therefore, could have been created by overspill of the ice-contact lake formed by impounding the proto-Welland in scenarios 2 or 3. Either of these scenarios could be adopted in the palaeogeographical reconstruction outlined below (Figures 11 and 12).

For both scenarios, the sedimentary data for the ice-contact fan indicate, for the proto-Welland lake:

1. A minimum lake-level height of about 30 m OD;
2. A minimum height above 30 m OD for the outwash barrier;
3. A minimum height of 30 m for the spillover into the Southorpe dry valley;

4. A constant lake-level height.

During high-magnitude events (e.g., annual spring thaw) the proto-Welland lake waters would have spilled over into the Southorpe dry valley. The overflow may not have been carrying much in the way of sediment load, in which case the potential for erosion would be high (Kearey, 1993, p. 109). The flow would become unconfined as it entered the proto-Nene valley and the eroded material would have formed an alluvial fan (Bloom, 1998; Nichols, 2009; Summerfield, 1991), represented by the River Nene Third Terraces at Stibbington and Sutton (Figures 11 and 12) with present surface heights of >21 m OD and >17 m OD, respectively (Castleden, 1980; Harrisson, 1981). The alluvial fan would have impounded the flow of the proto-Nene, thereby forming a lake upstream (Figure 11).

The lacustrine sedimentary data from Elton (Figure 9) indicate, for the proto-Nene lake (Figures 11 and 12):

1. A maximum lake-level height of 35 m;
2. The height of the alluvial fan upstream was periodically at 30 m OD or below and periodically above 32 m OD;
3. Fluctuating lake levels of <27 m OD up to 32 m OD gave way to a late lake-deepening phase up to 35 m OD;
4. Two major incisions during the late phase.

Although lake level in the proto-Nene would have been controlled by the height of the Stibbington–Sutton alluvial fan independently of the lake level in the proto-Welland, high-magnitude floodwaters from the latter would have supplied sediment to the alluvial fan thereby temporarily determining its height. As sediment supply to the proto-Nene lake was largely determined by catchment runoff (the Southorpe overflow channel only being active during high-magnitude floods), the high-magnitude events recorded late in the lacustrine succession at Elton could indicate regional large-scale (spring?) thaw, possibly coincident with the higher energy flows recorded late in the ice-contact fan succession north of Uffington. It is envisaged that during these high-magnitude events the proto-Nene alluvial fan was breached and that the ensuing flood deposits (Figures 11 and 12):

1. Choked the pre-existing valley with sediment as ironstone-rich, coalescing gravel bars (cf. Bluck, 1982) moved downstream (Figure 13a; Langford, 1999; Langford, Keen, & Griffiths, 2004);
2. Delivered limestone-rich gravels as far east as Whittlesey (Figure 13b, c; Langford, 1999, 2012a; Langford, Bateman, et al., 2004; Langford et al., 2007);
3. Deposited extensive River Nene Third Terrace sands and gravels on interfluve sites as far downstream as Peterborough (Figure 13d) once flow expansion occurred.

It may be the deposits of this event that overlie the Woodston Beds at Peterborough (TL 18 96). Horton et al. (1992) attribute the Woodston Beds to MIS 9, but more recently Penkman (2005) has determined an AAR age estimate of MIS 11.

The above palaeogeographical reconstruction goes some way to reconciling the following observations of Castleden (1980):

1. The River Nene Third Terrace is present only downstream of Aldwincle;
2. River Nene Third Terraces between Aldwincle and Alwalton (Figure 2d) occur along the valley sides but those downstream of Alwalton occur on interfluve areas;
3. "Stripped bedrock benches" (cf. strath terraces; Summerfield, 1991; Bloom, 1998; Hancock & Anderson, 2002) occur between Elton and Aldwincle coincident in altitude with River Nene Second and Third Terraces (Figure 3);
4. Younger terraces (First and Second) of the River Nene occur within a meander belt, whereas Third Terraces occur outside the meander belt;
5. Unlike the River Nene the Welland does not have a third terrace system.

First Terraces (of both the Nene and the Welland) are generally contiguous with the present floodplain, but River Welland Second Terraces upstream of Stamford are stepped back from the floodplain and invariably not contiguous with First Terraces (Figure 3; BGS, 1978). This pattern is consistent with aggradation at a new level imposed by the presence of a lake with a constant surface level within the catchment, prior to restoration to the former fluvial condition; or with response to allocyclic rather than autocyclic processes (Reading & Levell, 1996). Upstream, River Welland Second Terrace deposits at Duddington (Figure 2b) with a surface height of no more than 35 m OD are likely to indicate the influent main stream and maximum extent of the lake, whereas those east of Ketton (Figure 2b) 3 km downstream, with a similar surface height, are likely to indicate an influent tributary.

Terrace deposits of the reaches of the River Nene considered here (Figure 3) tend to be contiguous, consistent with a fluctuating lake level and fluctuating discharge magnitudes prior to restoration to the former fluvial condition; or with response to autocyclic rather than allocyclic processes. A River Nene Third Terrace fragment at Tansor (Figure 2c; Castleden, 1980) suggests a maximum lake
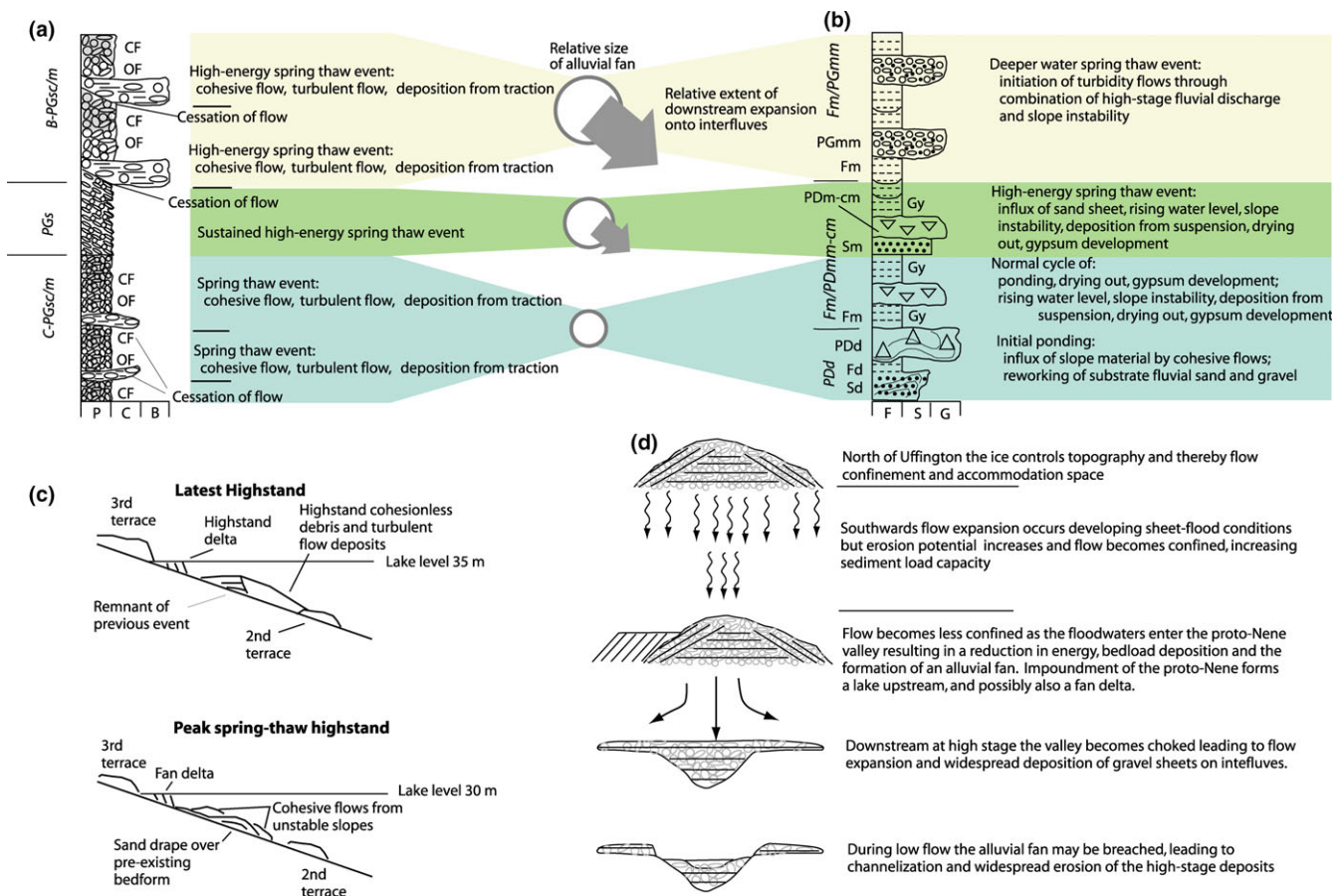

FIGURE 12 Depositional processes and environments envisaged as a result of impounding the proto-Welland, and possible correlation of events recorded in the sedimentary successions at (a) Uffington and (b) Elton. (c) Highstand scenarios at Elton. (d) Implications for accommodation space, sedimentary controls and flow conditions in the proto-Nene
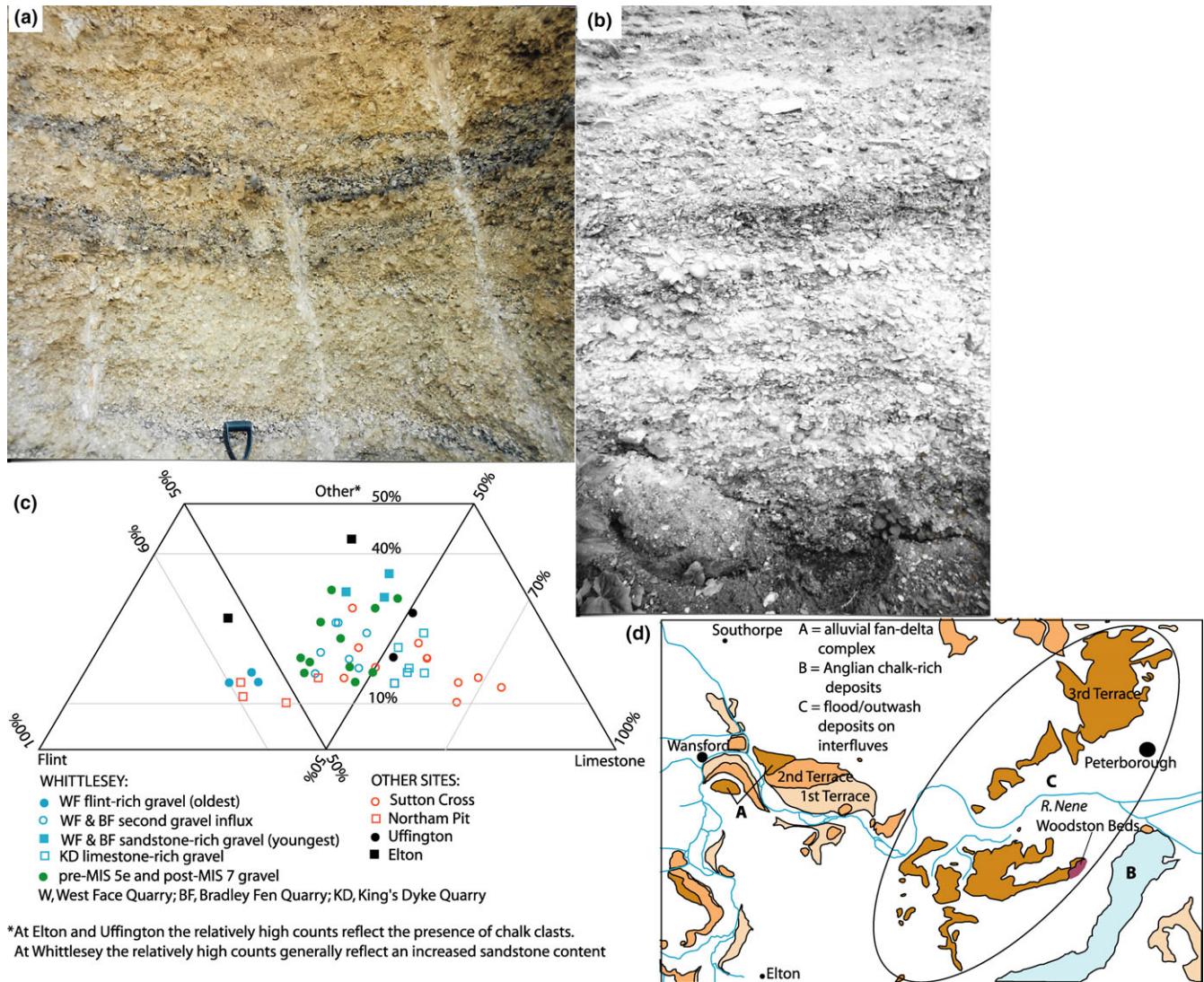
FIGURE 13 (a) Pockets of ironstone and carbon-coated clasts in weakly stratified gravel near the base of the sedimentary succession at Sutton Cross (spade handle is 11.3 cm wide). (Photograph by H. E. Langford) (b) Structureless to weakly stratified limestone-rich gravel (beneath penknife; 8.3 cm long) at King's Dyke Quarry, Whittlesey. Palaeoflow is towards the left (east). (Photograph by H. E. Langford.) (c) Clast-lithology groupings according to limestone and flint content for sedimentary facies in the Whittlesey sedimentary succession (BF, Bradley Fen; KD, King's Dyke; WF, West Face), as well as for Sutton Cross, Northam Pit (Eye Green; Figure 2a; data from Keen et al., 1990; Langford, 2004d), Uffington and Elton (Langford, 1999; Langford, Bateman, et al., 2004; Langford, Boreham, et al., 2004; Langford, Keen, et al., 2004; Langford et al., 2007). (d) Distribution of River Nene Third Terraces on interfluves downstream of Alwalton (Redrawn from BGS 1984, 1995)

level of at least 30 m. A maximum water depth of about 15 m is estimated from the base of a Second Terrace at Tansor (Harrisson, 1981). River Nene Third Terraces associated with the influent main stream and tributaries appear to have been formed between minimum heights of 25 and 30 m OD, and Second Terrace deposits below 25 m OD (Castleden, 1980; Harrisson, 1981). The Third Terraces and associated bedrock benches north of Barnwell probably mark the maximum extent of the lake. As the lacustrine deposits at Elton occur above 25 m they are likely to record only the high lake-level phases associated with the Third Terrace deposits. Much of the lacustrine succession

records shallow water lake margin deposition but late in the sequence at least two high-magnitude events are indicated.

3.2 | Stratigraphical interpretation

The sedimentary successions north of Uffington and at Elton have not been dated directly, but the age of the drainage network reorganization event discussed here can be inferred from late Middle Pleistocene sedimentary successions at Whittlesey and Sutton Cross (Figure 14). At Whittlesey a fossiliferous, fully temperate channel fill (channel B) crops

out in West Face and Bradley Fen quarries and is robustly dated by AAR analysis of 34 *Bithynia tentaculata* opercula to the penultimate interglacial (MIS 7; Penkman, 2005; Langford et al., 2007; Langford, Boreham, Coope, Fletcher, et al., 2014; Penkman et al., 2011). Channel B overlies three gravel facies deposited by streams flowing to the north to east quadrant, that is, towards The Wash, each with evidence for aggradation under cool/cold conditions (Langford et al., 2007; Langford, Boreham, Coope, Fletcher, et al., 2014; Langford, Boreham, Coope, Horne, et al., 2014). A minimum age of MIS 8 is therefore suggested for these three gravel facies. The oldest gravel aggradation is rich in flint (Figure 13c), suggesting erosion of Anglian chalk-rich diamicton to the west (Figure 13d). This gravel crops out in West Face Quarry and contains organic muds with a fossil assemblage indicative of accumulation under a cold climate (Langford, Boreham, Coope, Horne, et al., 2014). The presence of flint implies a maximum age of MIS 12, as the first significant introduction of Cretaceous material to the Peterborough area is considered to be associated with the Anglian cold stage (Horton, 1989; Langford, 1999, 2004b,c, 2011); the presence of flint at the base of the Woodston Beds confirms a minimum MIS 12 age for this introduction (Horton et al., 1992; Penkman et al., 2011).

Increased influx of limestone from upstream started in the second gravel aggradation phase (Figure 13c). The youngest of these three gravel facies is limestone-and-sandstone rich when compared with the earlier two gravel facies (Figure 13c), and the increase in sandstone is probably sourced from the infill of a SW–NE-trending channel beneath the Anglian chalk-rich diamicton (Langford, 2004b, 2011) to the south of Peterborough (Figure 13d).

A limestone-rich gravel (Figure 13b, c) deposited by a substantial stream flowing to the north to east quadrant crops out in King's Dyke Quarry (Langford, 1999, 2012a; Langford, Bateman, et al., 2004), adjacent to West Face Quarry (Langford, Boreham, Coope, Fletcher, et al., 2014; Langford, Boreham, Coope, Horne, et al., 2014), but its relationship with the above three prechannel-B cool/cold-stage gravel facies is unknown. It should be noted that the term "limestone rich" is used only in the context of the Whittlesey sedimentary succession, which lies 5 km downstream of the nearest Jurassic limestone outcrop at Peterborough. At Peterborough and upstream the gravels would be expected to be limestone rich (Langford, 2012b) because the Nene catchment is formed on Middle–Upper Jurassic limestones. In King's Dyke Quarry a MIS 6 OSL age estimate (158 ± 14 ka; Figure 14a) was determined on sands that postdate the limestone-rich gravel but predate extensive cryoturbation that is argued to predate the last interglacial (MIS 5e), that is, dates to MIS 6 (Langford, 1999; Langford, Bateman, et al., 2004; Langford et al., 2007). In composition the limestone-rich gravel is similar to the River Nene Second

Terrace gravels at Sutton Cross and the ice-contact fan deposits north of Uffington (Figure 13c; Langford, 1999; Langford, Bateman, et al., 2004). This limestone-rich gravel is interpreted as being deposited as large-scale longitudinal bars in a braided stream and is considered to be the product of a high-magnitude flood event (Langford, 1999; Langford, Bateman, et al., 2004). D-alloisoleucine/L-isoleucine (A/I) ratios of 0.191–0.291 on a *Littorina* sp. shell from the limestone-rich gravel facies suggest a maximum age of MIS 9, although a MIS 11 age is possible. A MIS 7 age is unlikely on the basis of recent data in Meijer and Cleveringa (2009) that indicate a much lower *Littorina* sp. D/L ratio for MIS 7 (0.152) than those recorded for the limestone-rich gravel facies. On balance, the age-estimate data suggest that the limestone-rich gravel dates to MIS 8, but an age in MIS 10 cannot be ruled out.

A later, fossiliferous, fully temperate channel fill (channel C) occurs in Bradley Fen Quarry, which is dated by AAR to MIS 5e (Langford et al., 2017). The underlying gravel facies has cut out channel B deposits, thereby strongly indicating a MIS 6 age for this later gravel aggradation. Flint enrichment is associated with the later gravel aggradation, except where it overlies pre-existing limestone-and-sandstone-rich and limestone-rich gravels (Figure 13c). Of particular significance is that the sedimentology of this later gravel facies indicates a substantial gravel-bed river flowing initially towards the south and then southwest (Langford, 2012a; Langford et al., 2017).

There is also some support for a minimum MIS 8 age from the sedimentary succession recorded at Sutton Cross (Figure 14b; Langford, 2012a; Langford, 2012b). If the cryogenic deformation at the top of the succession is assumed to be Devensian/Weichselian (MIS 5d–2) in age, and the preceding intense decalcification event Ipswichian/Eemian (MIS 5e), the fully temperate fauna present in the underlying sedimentary facies has a minimum age of MIS 7. A minimum age of MIS 7 could be reinforced by the presence of *Corbicula fluminalis* in the molluscan faunas, a species thought not to have been present in this country during the last interglacial (Keen, 1990; Meijer & Preece, 2000), however, this argument should be applied with caution (Langford et al., 2017). Underlying sedimentary facies, at the base of the succession, therefore would have a minimum age of MIS 8. The lowest of these is interpreted as cohesive flows into standing water (Langford, 1999), perhaps generated as slopes became unstable as a result of freeze–thaw phases during the glacial advance associated with the ice-contact fan deposits north of Uffington. The overlying facies was formed from coalescing gravel bars (Langford, 1999) and includes concentrations of Jurassic ironstone lenses and carbon-coated clasts (Figure 13a). The latter were also found in the ice-contact fan deposits north of Uffington, and the former may be associated with
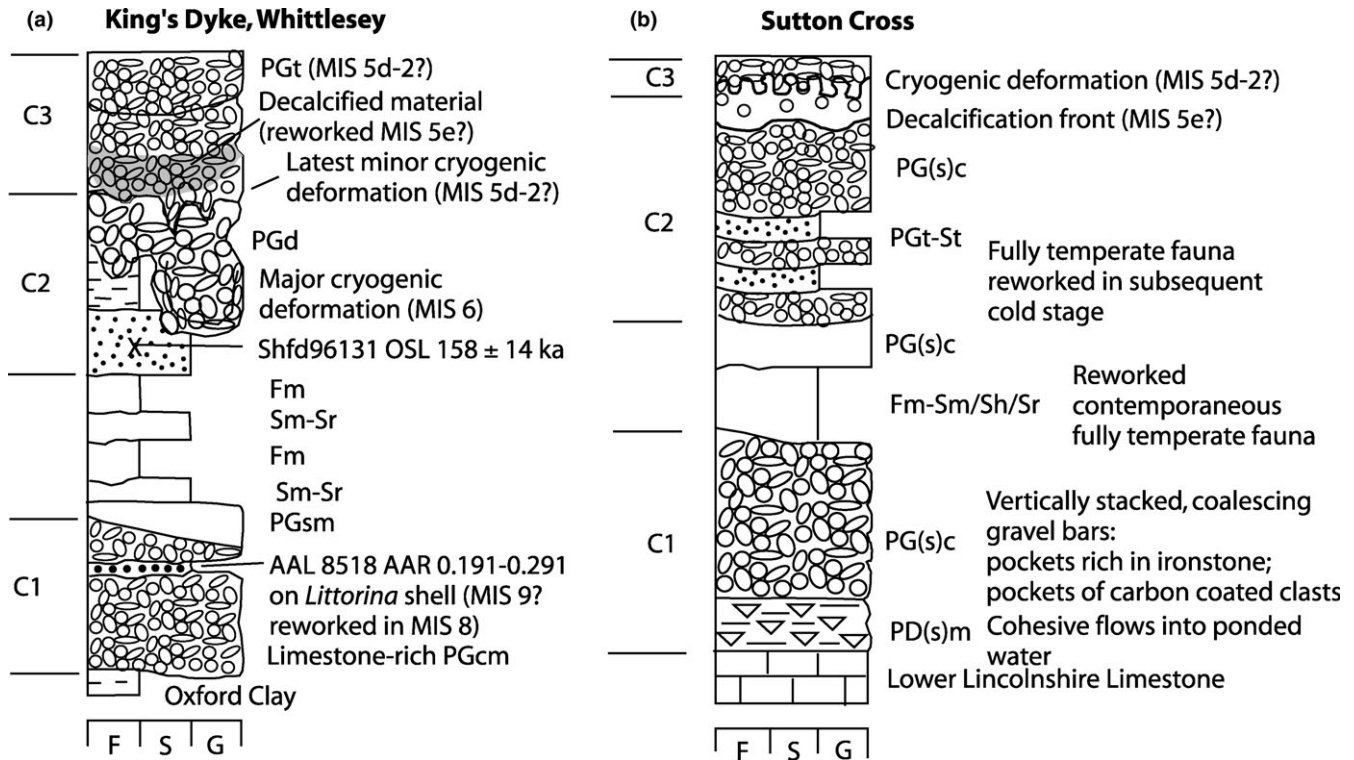
FIGURE 14 (a) Schematic stratigraphical log of the sedimentary successions at King's Dyke Quarry (Whittlesey) and (b) Sutton Cross (Langford, 1999; Langford, Bateman, et al., 2004; Langford, Keen, et al., 2004). The cold-stage deposits (C1–C3) are ornamented. The interglacial status of deposits between C1 and C2 at King's Dyke is uncertain as the temperate elements of the microfauna could be reworked from previous interglacial deposits. The interglacial between C1 and C2 at both locations is represented by weathering products

increased bedload pulses (Ashmore, 1991; Hoey & Sutheriand, 1991; Russell & Marren, 2008) from upstream of Wansford (Figure 2a) once the alluvial fan had been breached substantially.

3.3 | Implications for MIS 10, 8, and 6 ice margins in eastern England

There is no evidence for glacial overriding within the Whittlesey and Sutton Cross sedimentary successions. Combined with preservation of the MIS 11 Woodston Beds (Figure 13d), these observations suggest no glacial overriding of the Peterborough area during the last four glacial–interglacial cycles, which places important constraints on postulated ice margins and ice advance reconstructions during this period. There is therefore no support for the MIS 10 ice advance reconstruction proposed by Hamblin et al. (2005), Rose (2009) and Lee et al. (2012), and this accords with the recent proposition of Lee, Bateman, and Hitchens (2015), who for this period depict not only a MIS 6 ice margin around Tottenhill but also note that it could correspond to MIS 8.

In the Whittlesey sedimentary succession there are three gravel facies that predate MIS 7 channel B in the West Face and Bradley Fen Quarries, and a limestone-rich gravel in King's Dyke Quarry that predates MIS 6. The cool/cold climate aspect of these four gravel facies indicated by the fossil assemblages and sedimentology suggest a maximum age of MIS 12 and a minimum age of MIS 8, with the AAR age estimates for the limestone-rich gravel facies suggesting a MIS 8 age. Each of these gravel facies was deposited by a stream that flowed to the north to east quadrant, implying that The Wash was not impounded by ice advance at this time. Evidence from the sedimentary succession at Elton and that north of Uffington, however, does imply that ice may have advanced to within 15 km north of Peterborough during MIS 8, but the configuration of the ice margin would appear not to match those depicted by Straw (1983, 2011), White et al. (2010, 2017) and Westaway (2010).

The Tottenhill delta (Gibbard et al., 1991, 1992) provides unequivocal evidence for post-MIS 12 and pre-MIS 5e impoundment of The Wash, and this may correlate with sedimentary evidence for southward and south-westerly flow of a major gravel-bed river in the Bradley Fen Quarry that also suggests impoundment of The Wash. The latter is securely dated to MIS 6. Both deposits therefore may provide support for the ice advance on the eastern side of the Fen Basin proposed by Gibbard et al. (2009, 2012, 2012) and West, Gibbard, Boreham, and Rolfe (2014). The temporal and spatial grouping of the deposits investigated by

Gibbard and co-workers must remain tentative, however, as the OSL dates provided lack the essential processing data required for robust chronostratigraphic interpretation, and this remains the case for their most recent publication (Gibbard, West, & Hughes, 2018).

From the foregoing it would appear that drainage reorganization associated with the proto-Nene and proto-Welland occurred in both MIS 8 and MIS 6 due to ice advance. The regional configuration of the MIS 8 ice margin differed to that of the MIS 6 ice margin, as well as the MIS 12 and MIS 2 ice margins. In contrast to the MIS 6 and 2 ice margins, that of MIS 8 does not appear to have blocked The Wash, thus drainage of the Fenland rivers to the North Sea seems not to have been interrupted at this time.

4 | CONCLUSIONS

A combined sedimentological and geomorphological approach has been applied to the study of late Middle Pleistocene glacial sands and gravels north of Uffington and lacustrine deposits at Elton, and their related landscape elements. This approach provided plausible explanations for the deposits and associated landscape elements, and thereby has increased our understanding of drainage reorganization associated with the Nene and Welland catchments.

It is proposed here that a lobe of ice or meltwater sediments impounded the proto-Welland and formed a lake upstream with a surface height of about 30 m OD. Second Terrace deposits upstream of Uffington formed at this altitude where influent streams entered the lake. Overspill from the lake created a north-to-south-flowing channel between the present Welland and Nene rivers. An alluvial fan formed at the southern end of the overspill channel, which obstructed the proto-Nene. A lake formed in the proto-Nene upstream of the alluvial fan, and fluctuating lake levels led to fluvial deposition at varying altitudes where streams discharged into the lake. It is this mechanism that provided the accommodation space and preservation potential of sediment bodies classified as Second and Third Terraces in this part of the Nene valley. During high-magnitude flood events, flow expansion downstream of the alluvial fan resulted in deposition of sand and gravel on the interfluve areas of the lower proto-Nene, presently preserved as Third Terrace deposits.

Indirectly, a MIS 8 age for the above sequence of events is indicated by AAR and OSL data from Middle Pleistocene deposits at Whittlesey in the lower Nene catchment (Langford, 1999; Langford, Boreham, Coope, Fletcher, et al., 2014; Langford, Boreham, Coope, Horne, et al., 2014; Langford et al., 2017). In addition, the sedimentary succession at Sutton Cross downstream of the alluvial fan and 15 km upstream of Whittlesey, records aggradation during at least three glacial stages, which implies a minimum age of MIS 8 for the earliest cold-stage deposits (Langford, 1999, 2012a; Langford, Keen, et al., 2004). This supports the proposition of MIS 8 glaciation proposed by Straw (1983, 2011), White et al. (2010, 2017) and Westaway (2010) but places important constraints on their postulated ice margins.

A later gravel aggradation at Whittlesey, deposited by a major south to south-westerly flowing gravel-bed river, is securely dated to MIS 6 (Langford et al., 2017) and implies that The Wash was impounded at this time, perhaps correlative with the Tottenhill delta (Gibbard et al., 1991, 1992). From the foregoing it therefore would appear that the regional configuration of the MIS 8 ice margin differed to that of the MIS 6 ice margin. In common with MIS 6, the MIS 8 ice margin lay largely to the north of the north Norfolk coast. In contrast, however, MIS 8 ice does not appear to have blocked The Wash, thus drainage of the Fenland rivers to the North Sea seems not to have been interrupted.

Corroboration of a MIS 8 age for the drainage reorganization envisaged above is important because it would provide evidence for the extent of ice advance during a glacial stage for which there is very little information from terrestrial settings in the UK and mainland Europe; a MIS 8 glacial advance in the Dutch sector of the North Sea basin, however, has been recorded by Beets et al. (2005).

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