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Late Middle Pleistocene glaciofluvial sedimentation in western Norfolk, England

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Abstract

Investigation of landforms on the eastern margin of the East Anglian Fenland basin has demonstrated that they represent a series of glaciofluvial delta-fan and related sediment accumulations (the Skertchly Line) deposited at the margin of an ice-lobe that entered the depression. This 'Tottenhill glaciation' dated to ca 160 ka, or the late Wolstonian (= late Saalian) Stage, is equivalent to that during the Netherlands' Drenthe Substage (Marine Isotope Stage 6). Of these landform complexes, an additional site at Shouldham Thorpe, previously nominated as the stratotype for deposits linked to a pre-Anglian Stage, Midlands'-derived Ingham/'Bytham river', has now been studied. Examination of the internal structure and form of the feature, using ground-penetrating radar (GPR), supported by section logging, borehole records, local landscape morphology and previous description, together indicate that the deposits rest on an eroded surface of Lowestoft Formation diamicton (Anglian Stage) and must therefore be of post-, rather than pre-Anglian age. The investigations indicate that the Shouldham deposits were laid down as a glacio-marginal subaerial ('terminoglacial') fan at the ice-front. In common with other sequences in the Skertchly Line complexes, deposition at Shouldham Thorpe was accompanied by minor ice-front movement, this fan potentially being deposited before retreat to the Tottenhill locality. The implications of the results are discussed.

Keywords: Wolstonian, marginal fan, Fenland, ground penetrating radar, glaciation

Introduction

In two recent articles, Gibbard et al. (2009; 2012) presented evidence for late Middle Pleistocene glaciation in the Fenland Basin of East Anglia, England (Fig. 1). Investigation of the setting, morphology and internal architecture of a line of hills adjacent to the south to eastern Fenland margin has demonstrated that they represent glacio-marginal fan-delta complexes. The accumulations mark a distinct glacial maximum limit (the Skertchly Line) and were formed where an ice-lobe, flowing from the north to north-west, dammed a series of local streams to form a proglacial lake in contact with the ice-front. The fan deltas were deposited where meltwater discharged from the ice into the lake. This 'Tottenhill advance' has been shown to be of late Wolstonian age (i.e. late Saalian, broadly early Marine Isotope Stage (MIS) 6), an age confirmed by multiple lines of evidence including numerical dating, i.e. intermediate between the Hoxnian (Holsteinian; ca MIS 11c; cf. Ashton et al., 2008) and Ipswichian (Eemian; ca MIS 5e) interglacial stages (Clark et al., 2004; Gibbard et al., 1991, 1992, 2009; 2012; Lewis & Rose, 1991; Gibbard & Clark, 2011).

The deposits mapped at Shouldham Thorpe, Norfolk, England occur 18.5 km N of the Feltwell site (Gibbard et al., 2009, 2012) and 3.6 km SSE of Tottenhill (Gibbard et al., 1992) (Figs 1, 2), both of which represent ice-marginal sediments and landforms of the Skertchly Line limit. They are exposed at the Parish pit (National Grid reference: TF 657085: 32 m OD) and consist of a series of sands and gravels that rest on Sandringham Sand/Gault Clay (Lower Cretaceous) bedrock. The sediments underlie a subdued hill-like landform, similar in scale and morphology to those described from further south, although it is subdued, gently sloping at a gradient of 0.8 m km^{-1} towards the ESE over

Fig. 1. Regional location map. The glacial limit west of Exning is based on Boreham (unpublished).

1.075 km. A potential ice-contact slope, immediately to the NW of the excavations, aligned NNE-SSW, is identified in the field (Fig. 2). Old excavations up to 6 m in depth occur in the extreme NW corner of the landform, whilst the small gravel working – the Parish pit – occurs immediately to the south (Fig. 2).

The only recent descriptions of the Parish pit sequence were published by Lewis (1989, p. 134-135; 1991, p. 127-130). However, the deposits were mentioned in the compilation of East Anglian stratigraphy by the same author (Lewis 1999, p. 19) where they were termed the Shouldham Thorpe Member of the Shouldham Formation (the Shouldham pit being designated as the stratotype of these units). They were interpreted by Lee et al. (2004) as a remnant of a NNW to SSE-aligned 'Ingham/Bytham' river spread. The sands and gravels were mapped and recorded as being ca 6 m thick in the Geological Survey memoir for South-Western Norfolk and of Northern Cambridgeshire (Whitaker et al., 1893, p.72), later surveys failing to recognise the deposits (Sheet 159 Wisbech, 1995: Fig. 3).

This paper discusses the re-examination of the Shouldham Thorpe landform and underlying sequence in the light of its occurrence intermediate occurrence between deposits recently identifed as being of glaciofluvial ice-marginal accumulations, yet its having been interpreted as a remnant fluvial deposit. The implications of the results obtained are also presented and complete a series of studies of the ice margin in the East Fenland region.

Site descriptions

The sites described are located using the British Ordnance Survey National Grid reference system (NGR) (Fig. 2). The localities are related to their topographic setting by their morphology from geological maps or aerial photographic interpretation. Exposures were examined and logged, with directional and structural features being recorded. Standard facies codes (modified from Miall 1978; Eyles et al., 1983) were used throughout. The exposure description was supported by ground penetrating radar (GPR) and available borehole records to establish the internal structure of the sediments in unexposed areas.

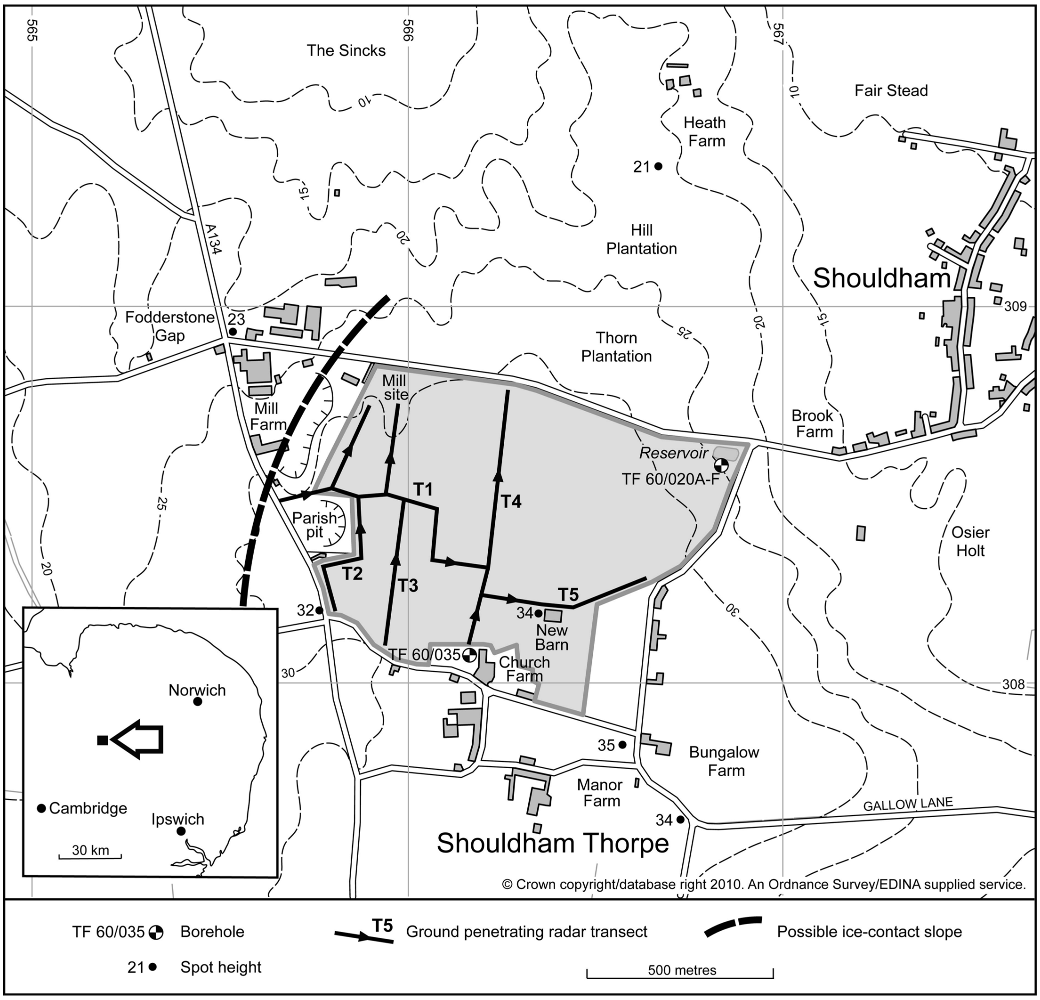


Fig. 2. Shouldham Thorpe: location map showing the ground penetrating radar transects and their relations to the Parish pit, Mill and BGS borehole localities (cf. Fig. 2). The heights are given in metres.

Two exposures were examined, first at the Parish pit (Grid reference: TF 657085) and a second near the Mill (Grid reference: TF 659087) (Figs 2, 4, 5).

The sequence at the Parish pit was recorded by Lewis (1989; 1991) but was re-examined during this project, generally confirming that author's observations. The sequence exposes over 7 m of predominantly horizontally disposed deposits beneath the modern ground surface (Fig. 4, 5). The basal sediments, resting on bedrock, comprise two units of alternating horizontally stratified matrix-supported fine to medium gravel (facies Gms) 30 cm thick and 20 cm of planar cross-bedded sand. These are overlain by 4 m of horizontal multi-storey planar cross-bedded sand units, 30-40 cm thick (facies St, Sp), with minor subunits of horizontally bedded sand (facies Sh), some units including a narrow pebbly basal contact. Horizontally stratified fine to medium, matrix-supported gravel (facies Gms) units 10-25 cm thick occur resting on erosional bases. The whole exposure (Fig. 4, 5) shows a shallow channel, 25 cm deep and 2.5 m wide, cut across the planar-bedded sands, the base at 3.5 m depth and was infilled by planar-bedded pebbly sand (facies Sh). A similar channel-like infill occurred slightly higher in the sequence at 2.75 m depth. Two high-angle normal faults pass through the middle part of the sequence giving a step-like offset of a few centimetres towards the south (Fig. 4, 5). These faults do not penetrate to the surface but terminate ca 2.0 m above the base at a silt band.

The upper ca 1 m of well-sorted medium sand with scattered pebbles, mostly of flint, blankets the sequence (facies Scr), immediately beneath the modern ground surface (Figs 4, 5). The slightly reddened character of this deposit possibly represents a disrupted relict palaeosol, comparable to that seen at Tottenhill (Lewis & Rose 1991; Gibbard et al., 1992). The sand rests on a pebbly 'armoured' surface, one clast in thickness (Gm), that resembles a buried ground surface. Immediately beneath is 10 cm of iron-oxide cemented silty gravel 5-10 cm thick, underlain by 30 cm of mottled brown massive silt (facies Fm). At the extreme N side of the exposure 20 cm below the ground surface a tongue-like wedge of brown diamicton (facies Dmm), 40 cm thick, rested on the underlying silts with a sharp basal boundary. It was overlain by the massive sand, noted above. Throughout the deposits palaeocurrent measurements indicate a consistent flow direction towards SE-SSE, as noted by Lewis (1989; 1991).

The second site, near the Mill, was found in the corner of a field in a pit dug for irrigation purposes (Fig. 2). Here 25 cm of brown weathered silty clay diamicton (facies Dmm) with quartz

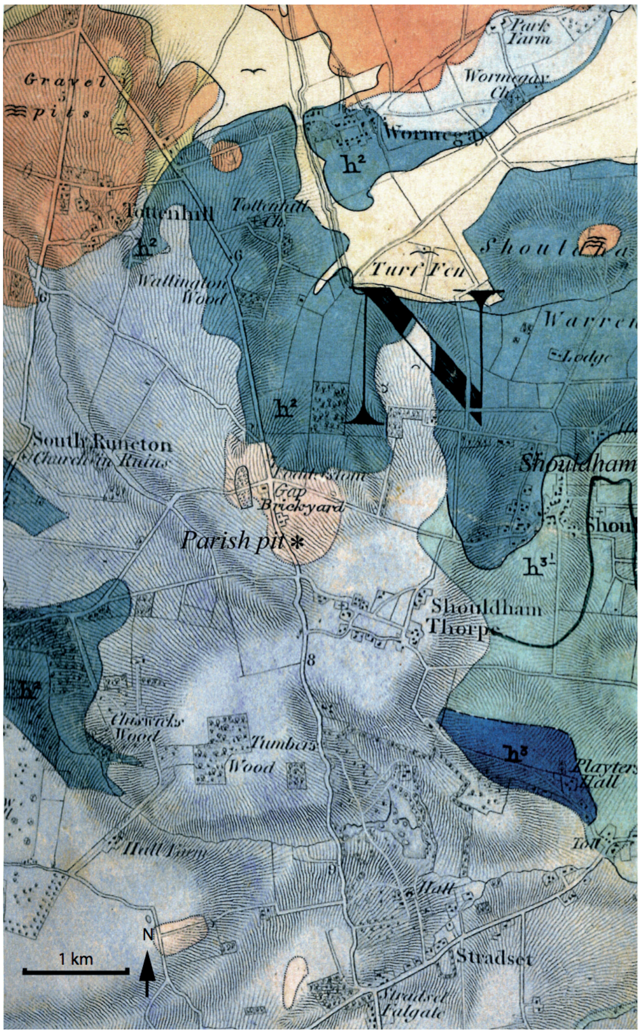


Fig. 3. First edition of the Geological Survey map of South-Western Norfolk and of Northern Cambridgeshire (Whitaker et al., 1873 sheet 65), showing the sands and gravels at Foddeston Gap (Shouldham Thorpe) mapped in pink, resting on boulder clay (diamicton: in light blue). The sites' proximity to that at Tottenhill (where the gravel spread is mapped in orange) can also be seen.

and chalk clasts was exposed. Similar material was recorded in boreholes (BGS TF 60/020A-F ca 26 m: Fig. 2) put down for water extraction adjacent to the reservoir, at a lower elevation in the east (Fig. 2). Here the diamicton was 9.0 m thick and rested directly on the Gault Clay bedrock. It was again found in a borehole at the Church Farm buildings (BGS TF 60/035 ca 32 m) where it is 19.03 m thick and underlies the sands. Indeed this diamicton is mapped in the surrounding area where it also underlies the spread of gravel and sand at Shouldham Thorpe. It is correlated with the Lowestoft Formation of the Anglian Stage. The diamicton was also formerly exposed in a brickyard NW of Fodderstone Gap cross-roads (Fig. 2, 3) where Whitaker et al. (1873, p.72) observed 15.25 m (50 ft) of fawn-coloured chalky diamicton, notably containing a massive erratic of fossiliferous Jurassic Kimmeridge Clay 4.5 m in diameter. Here again the diamicton rested directly on the Gault Clay bedrock.

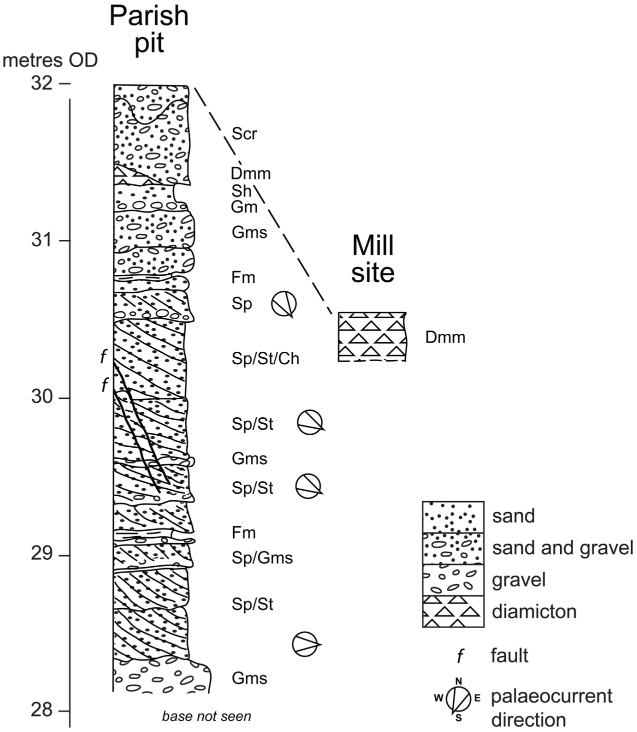


Fig. 4. Shouldham Thorpe: sediment logs from the exposures in the Parish pit and the Mill site. The standard facies codes are modified from Miall (1978) and Eyles et al. (1983). The location of the sites is shown in Fig.2.

Ground Penetrating Radar investigations

Ground Penetrating Radar (GPR) is a powerful, non-intrusive electromagnetic profiling technique for revealing sedimentary structures in the shallow subsurface. The analogous propagation and reflection between the electromagnetic and acoustic waves allows the principles of seismic stratigraphy (Roksandic 1978; Sangree & Widmier 1979) to be used in the interpretation of the GPR data, known as radar stratigraphy (Gawthorpe et al., 1993; Neal 2004). Stratified sediments usually have a greater lateral lithological continuity, as well as physical properties, parallel to the depositional surfaces than across them (Sangree & Widmier 1979). This concept of parallelism allows the recognition of the sedimentary structures from the GPR images and through this the interpretation of the depositional environment. The physical basis for the GPR method is given by Annan & Davis (1976) and Davis & Annan (1989). GPR has been widely used in sedimentological studies (cf. Neal 2004) and especially in deltaic sediments, for example by Jol & Smith (1991), Smith & Jol (1992, 1997) and Roberts et al. (2003). Glaciotectonic structures have also been studied using GPR by Lønne & Lauritsen (1996), Overgaard & Jakobsen (2001), Bakker & Van Der Meer (2003) and Bakker (2004), among others.

In this study the GPR data was collected using a GSSI 200 MHz shielded antennae in common offset mode using a clicker-wheel as a trigger. The 200 MHz antenna offers acceptable depth penetration and excellent acuity. The location and altitude of

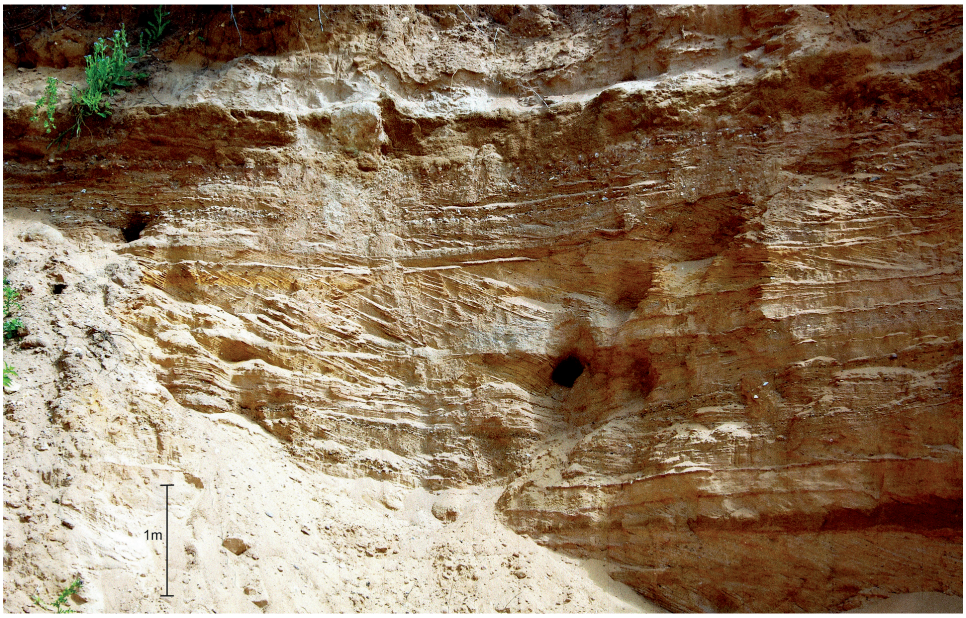


Fig. 5. Shouldham Thorpe: detail of the Parish pit section showing the sand and gravel sequence and the two high-angle normal faults mentioned in the text (cf. Fig. 4). For location see Fig. 2. (Photograph: P.L. Gibbard, 2009).

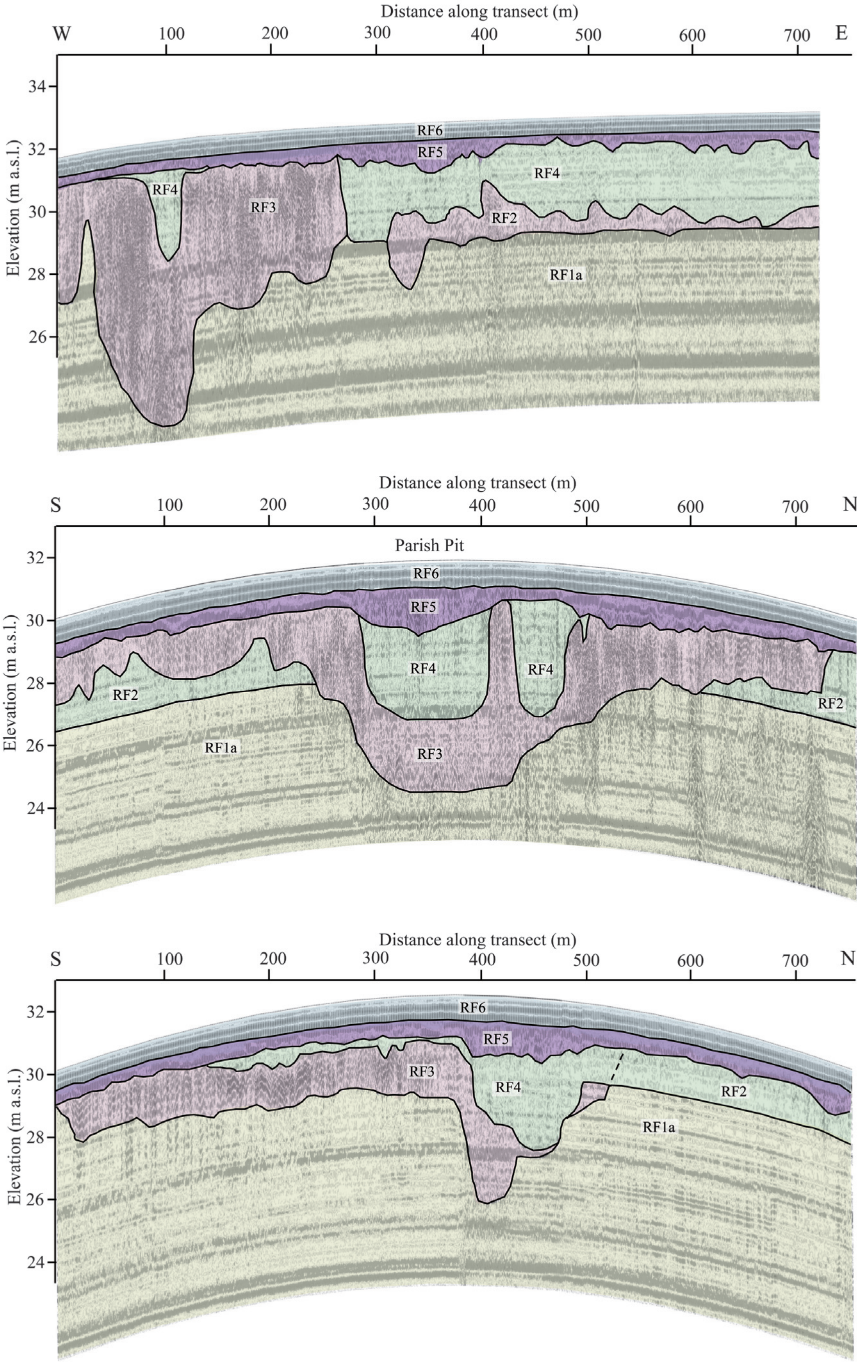
GPR transects was determined using a Leica GPS1200 system. In addition, the topography was surveyed using mapped altitude contours, markers of the highest and lowest points of the survey lines and using horizontal subsurface reflectors.

Investigations were undertaken at Church Farm, Shouldham Thorpe, to the east of the Parish pit, which exposed sections in largely sand-dominated sediments (cf. above; Figs 2, 4, 5). The survey comprised twelve GPR (five of which are illustrated in Fig. 2) profiles with a total length of over 5000 metres. The locations of the GPR transects are shown in Figure 2. Post-processing of raw data comprised data editing, depth conversion, topography correction, adjustment of the time-zero, amplitude zero-level correction, background removal, filtering and gain control using Radan software. The average relative dielectricity value (er) of 6, used for depth conversion, was estimated from the literature (Davis & Annan 1989; Hänninen 1991; Neal 2004) and from observations of stratigraphy in the Parish pit and BGS boreholes from various localities at Church Farm ('ground truthing'). The radar stratigraphy presented is based on the recognition and interpretation of radar surfaces (bounding surfaces), radar facies (bed assemblages) and radar packages (geometry of the deposits) (Neal et al., 2002). Here six radar facies (RF1-RF6) and five radar surfaces are identified (RS1-RS5). The radar facies are summarised in Table 1.

Table 1. Radar facies and radar surfaces identified in this study.

	Description	Geological interpretation
Radar facies RF1a	Moderate to high amplitude, planar, subparallel, mostly continuous reflectors, truncated by RS1 & RS2	Bedrock
Radar facies RF1b	Low to moderate amplitude, planar, sub-parallel, sometimes discontinuous reflectors, truncated by RS1 & RS2. Probably stratigraphically above RF1a	Diamicton
Radar surface RS1	Sub-horizontal, occasionally discontinuous, wavy surface	Erosional unconformity
Radar facies RF2	Low to moderate amplitude, planar, subparallel, sometimes discontinuous reflectors, truncated by RS2 & RS3	Basal sand sheet
Radar surface RS2	Sub-horizontal planar or sinuous, undulating surface, sometimes creating channel-forms.	Erosional boundary
Radar facies RF3	Moderate to high amplitude, dipping, oblique or concave continuous and discontinuous reflectors, truncated by RS3	Gravel and sand filling channel-forms
Radar surface RS3	Sub-horizontal planar or sinuous, wavy, undulating surface, sometimes creating channel-forms	Erosional unconformity
Radar facies RF4	Medium to low amplitude, planar, sinuous, sub-parallel, sometimes discontinuous reflectors, truncated by RS4	Sand filling channel-forms
Radar surface RS4	Sub-horizontal, sinuous, wavy, undulating surface	Erosional unconformity
Radar facies RF5	Moderate to high amplitude, planar, subparallel, sometimes sinuous, mostly continuous reflectors, truncated by RS5	Sheets of outwash deposits in places periglacially disturbed
Radar surface RS5	Sub-horizontal, planar complex wavy surface	Partly erosional boundary
Radar facies RF6	Moderate to high amplitude, planar, subparallel, mostly continuous reflectors	Cover sand and regolith

The ca 700 m long GPR transect T1 (Fig 6A) west-east across the study area shows a ca 7 m deep gravel-filled channel-form (RF3) ca 250 m wide cut into bedrock (RF1a) in the western part of the site. A further sand-filled channel-form (RF4) appears to be cut into the top of the gravel unit. A unit of gravelly deposits (RF5), including small channel-forms, cuts across the lower units. The eastern end of this transect encountered a body of sand (RF4) lying above a basal gravel unit (RF2). The south-north aligned transect T2 (Fig. 6b) crosses T1 at approximately 90° and reveals a similar large gravel-filled channel-form (RF3) with two discrete sand-filled channel-forms (RF4) incised into it. Small channel-forms filled by gravelly outwash deposits (RF5) cut into the underlying sediments. To the south and north the gravel appears to overlie a unit of basal sand (RF2). The largest of the sand-filled channels is adjacent to the Parish pit (Figs 2, 4) itself, where ca 4 m of planar and horizontally cross-bedded sand (facies Sh, Sp) is exposed in the section. It appears that the sand unit overlying basal gravel in the eastern part of T1 represents a section aligned along the centre-line of this channel. This view is substantiated by the arrangement of deposits in transect T3 (Fig. 6c), which provides a south-north aligned section showing a shallow spread of gravel (RF3) to the south, and a ca 6 m deep gravel-filled channel-form cut into bedrock (RF1a) to the north, with a sand-filled channel- form (RF4) cut into the top of the gravel. Gravelly deposits (RF5) occupy a small channel-form incised into the sandy sediments.



a. T1.

b. T2.

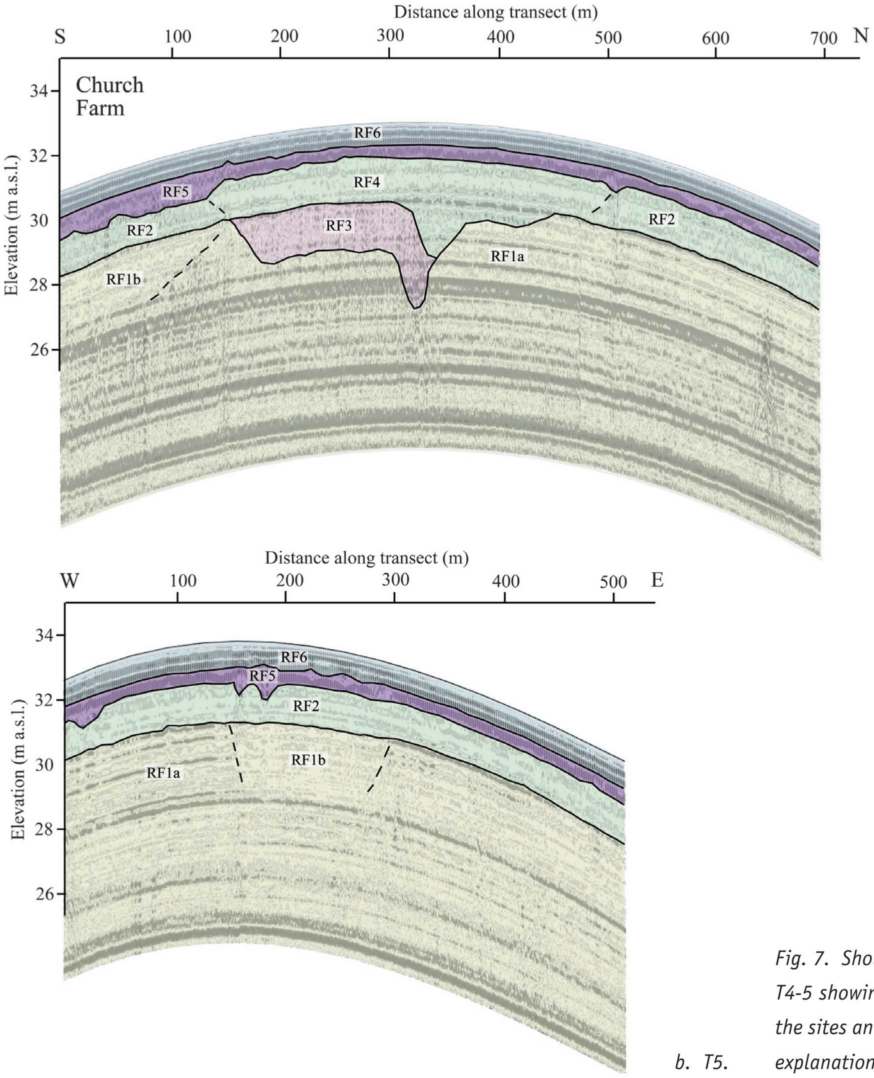
c. T3.

Fig. 6. Shouldham Thorpe: ground penetrating radar transects T1-3 showing the radar facies (RF) identified. The location of the sites and individual transects is given in Fig. 2. See text for explanation.

At the northern end of T3 it appears that a sheet of basal sand (RF2) overlies bedrock. The reflector boundary between the basal sand (RF2) and the sand-filled channel (RF4) is very difficult to determine, largely because both units have similar dialectric values.

Transect T4 (Fig. 7a) runs south-north across the site and provides a more easterly section through the channel complex. The BGS borehole TF 60/035 at Church Farm indicates diamicton close to the southern end of this transect where radar facies RF1b appears to lie above bedrock (RF1a). In the centre of the transect there is a ca 4 m deep gravel-filled channel-form (RF3) cut into bedrock (RF1a) with a sand-filled channel-form (RF4) cut into the top of the gravel. Above this, gravel-dominated sediment (RF5) fills occasional channel forms cut into the sands. To the south and north there appears to be a unit of basal sand (RF2), although as noted above, the exact boundaries with RF4 can only be conjectural because of the poor reflectors produced by two units with the same dialectric value. Transect T5 (Fig. 7b) provides a ca 500 m west-east section through the eastern part of the site. In the centre of the transect there appears to be a body of diamicton (RF1b) apparently occupying a poorly-defined channel-form cut into bedrock (RF1a). Above this is a sheet of sand that may belong to both RS2 (basal sand) and RS4 (channel-fill sand), although the reflector boundary between them is hard to detect. Overlying this is a sheet of gravelly deposits (RF5).

Figure 8 shows a three-dimensional fence diagram indicating the spatial relationship of the reflectors identified in transects T1-5. A thin basal sand unit (RF2) overlies bedrock across much of the area. It is clear that the deep gravel-filled channel-forms (RF3) are confined to the west of the site, and that these rapidly shallow to the east to form a gravel sheet (RF3) that quickly narrows and thins. In contrast the sand-filled channel-forms (RF4) cut into the surface of the gravel converge and then spread to form a wide sheet-like fan of sandy deposits (RF2/4) in the eastern part of the site. The architecture of these three sediment bodies is shown in Fig. 9. It is possible that there is considerable facies change from west to east across the landform, for example from gravel to sand, which could mean that the two sediment bodies discussed above are in fact lateral equivalents and therefore coeval.



a. T4.

b. T5.

Fig. 7. Shouldham Thorpe: ground penetrating radar transects T4-5 showing the radar facies (RF) identified. The location of the sites and individual transects is given in Fig. 2. See text for explanation.

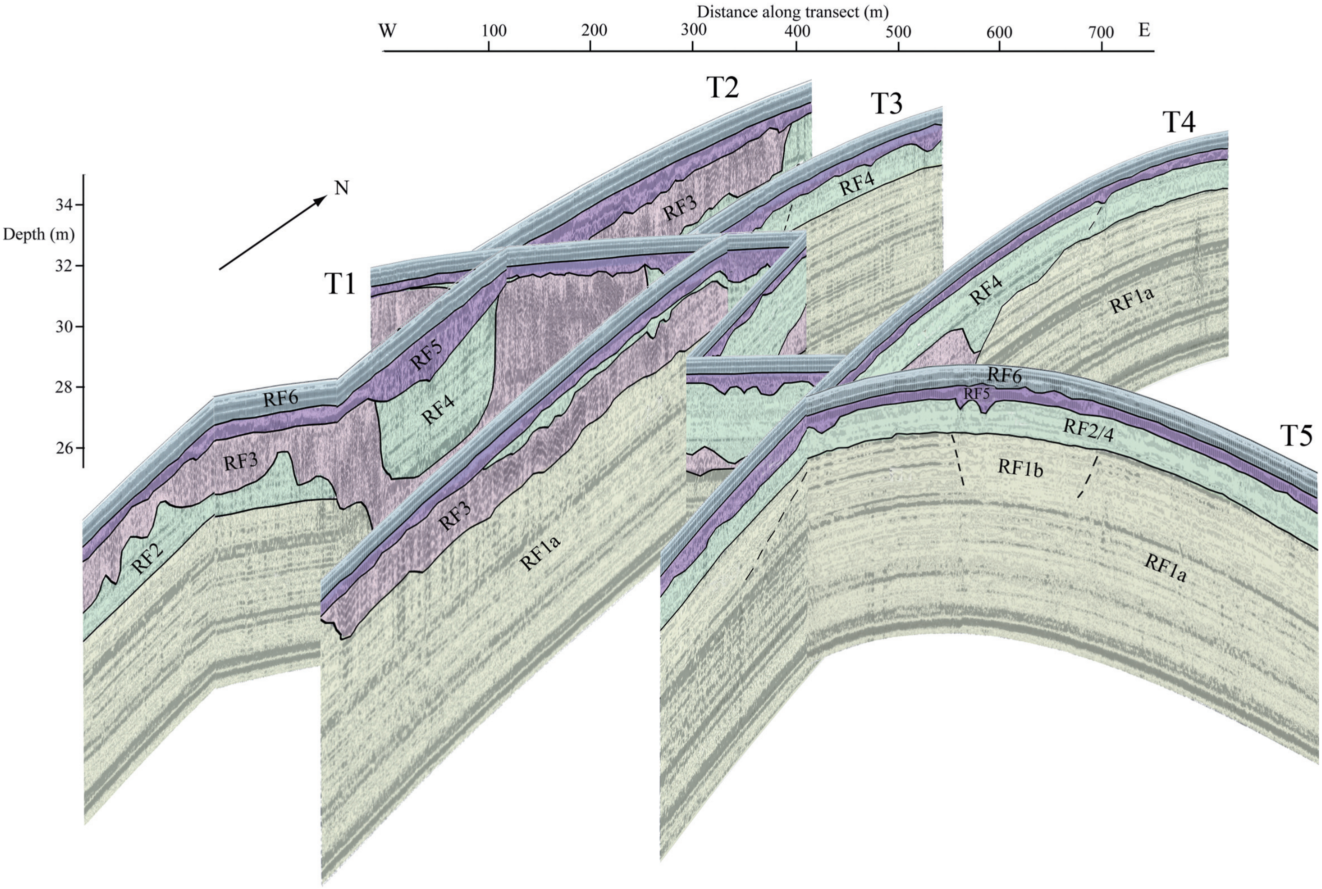


Fig. 8. Shouldham Thorpe: fence diagram showing ground penetrating radar transects T1-5 combined. The location of the sites and individual transects is given in Fig. 2. See text for explanation.

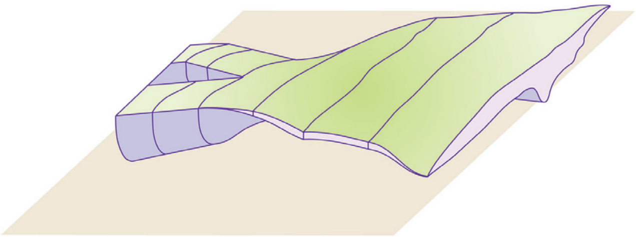
Gravel lithology

Lewis (1991, p. 128) made five clast-lithological counts from the Parish pit section. His analyses (based on the 11.2 to 16.0 mm fraction) are not directly comparable to those previously undertaken by the authors from other Skertchly Line sites (cf. Gibbard 2009; 2012) for which the 8-16 mm fraction was used. Therefore Lewis (op. cit.) published counts have been simplified here into four lithological groups (flint, quartz and quartzite, chert and ironstone). The assemblages predominantly comprise quartz and quartzite pebbles (60%), and chert (12%) of non-local origin. Both these lithologies probably originate from the Midlands where source rocks include respectively Triassic pebble-beds and Carboniferous or post-Carboniferous conglomerates. Local materials are represented by flint (19%) and ironstone (7%).

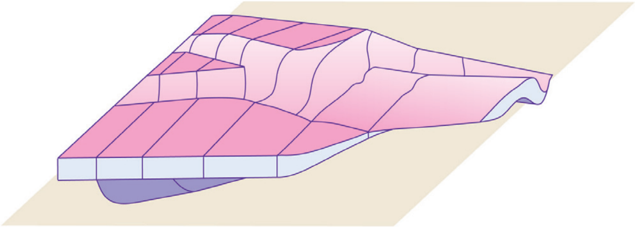
Gravels in the area are usually flint-dominated, interpreted as being sourced locally, either from pre-existing fluvial accumulations or from the underlying Lowestoft Formation diamicton sediment. A mixture of flint and a minor far-travelled component could have been, in part, derived from Lower Greensand (Lower Cretaceous) bedrock which is a potential source of erratic pebbles (Nicholls 1947; Wells et al., 1947; Hawkes 1951; Chatwin 1961). Lower Cretaceous and Jurassic strata within 20 km of Shouldham Thorpe contribute the material grouped as 'other' lithologies, such as ironstone. However, the occurrence of quartz and quartzite pebbles in the assemblages has been particularly associated with eastwards transport of East Midlands material by an Ingham (e.g. Clarke & Auton 1984; Hey & Auton 1988) or Bytham river system (Rose 1987; Lewis & Bridgland 1991; Rose & Wymer 1994). Indeed Lewis (1991) considered these deposits to be the type representative of these 'fluvial' sediments in eastern England, as already noted (Appendix). However, the reinterpretation of these deposits as of glacio-marginal origin implies that the quartzitic and other distantly-derived component lithologies must have been derived either directly from the Midlands' source Triassic and Carboniferous rocks, or more probably reworked locally, together with the other component lithologies in these assemblages.

Depositional sequence

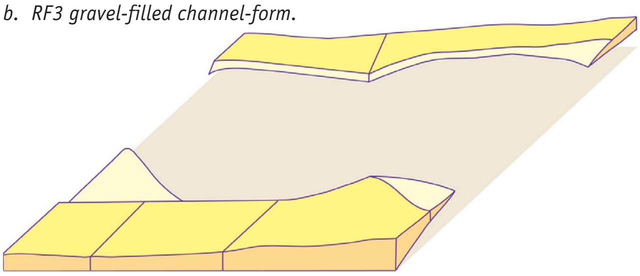
The sand and gravel spread at Shouldham Thorpe clearly rests directly on an eroded surface underlain by Lower Cretaceous bedrock and Anglian/Elsterian-age Lowestoft Formation diamicton (till). The disposition of deposits from the radar plots and the mapped localities indicates that the deposits



a. RF4 sand-filled channel-form.



b. RF3 gravel-filled channel-form.



c. RF2 basal sand.

Fig. 9. Shouldham Thorpe: schematic block diagrams showing the distribution of units RF2 (basal sand), RF3 (gravel filled channels) & RF4 (sand filled channels) identified in the ground penetrating radar transects. The location of the sites and individual transects is given in Fig. 2. See text for explanation.

occupy a broad valley-like trench (ca 600 m wide) incised into, and in the west through, the diamicton. This valley form is apparently absent further eastwards where finer-grained sediment facies occur, presumably where erosion was less effective. These observations suggest that the valley form was excavated either during or immediately before deposition of the sorted sediments, the the meltwater possibly discharging via a pre-existing stream valley.

The sand and gravel sediments at Shouldham Thorpe were interpreted by Lewis (1989, 1991) as being of fluvial origin, representing deposition by a braided stream. Whilst this interpretation is logical, given that it was based solely on the evidence observed in the Parish pit section, when the sequence is viewed in the light of both the detailed structure and the horizontal and vertical facies changes revealed by the GPR, and the occurrence beneath the fan-like landform already noted above, a more complex picture emerges.

The morphology of the landform, with a steep, ice-contact-like slope on the NW side (Fig. 2), and a gently dipping surface towards the SE (ca 3-4 degrees), the feature appears to be a fan comparable to those already described from Tottenhill, Feltwell and sites further south (cf. above). However, the very shallow gradient on the 'distal' surface suggests that the fan might be a sub-aerial rather than a sub-aquatic accumulation, unlike the others described from the Fenland margin (cf. Gibbard et al., 1992; 2009).

The sedimentary and topographic characteristics of sub-aerial ice-margin meltwater fans have most recently been thoroughly reviewed by Zielinski & Van Loon (2000). These authors recognise three subenvironments that characterise sub-aerial glacial fans: 1) the ice-proximal (ice-contact); 2) the middle; and 3) the distal subenvironments.

The basal gravels and sands (facies Gms: Fig. 4) rest on an eroded bedrock surface which the GPR shows filling substantial crossing channels (RF3) incised into the substrate invite classification into Zielinski & Van Loon's (2000) ice-proximal subenvironment. This setting is dominated by gravel-bed stream sequences, the steep slopes, combined with frequent meltwater floods with hyperconcentrated flows, result in unchannelised gravel, and in some cases boulder transport. Meltwater discharges can result in deep incision of channels. During quieter periods braided streams processes predominate. Here mass-flow processes can also play a significant role, with debris-flow diamicton (cf. Benn & Evans 1998) represented by the narrow tongue of sandy diamicton in the uppermost part of the Parish pit (Fig. 4), derived from a nearby source, either the ice front or an elevated area adjacent to the accumulations. The minor normal faulting present in the underlying sediments might be related to minor sediment collapse associated with sediment accumulation on local dead-ice blocks buried during deposition.

However, the major part of the sequence is dominated by horizontal multi-storey planar cross-bedded sand units (facies St, Sp: Fig. 4, 5), together with horizontally stratified, matrix-supported gravel (facies Gms), and shallow cross-cutting channels suggests that the bulk of the exposed sequence and underlying the east of Church Farm was deposited in sand-bed braided channels, whilst the horizontally bedded sands represent sand-bed sheetflow in the middle subenvironment.

The deposition of fines and fine sand is poorly represented in the Parish pit exposure (Figs 4, 5), whereas they are more dominant beneath the distal, eastern area of the landform, as shown in the GPR plots (cf. above). Such facies characterise Zielinski & Van Loon's (2000), third or distal subenvironment where deposition from shallow, distal sheet flows are common during high-discharge events, whilst during quiet periods suspension-load fines settle in standing water, generally forming thin sheets that cap fan sequences, as well as thicker accumulations that infill surface depressions or pools.

Taking all the observations at the Parish pit and in the GPR plots together, the rapid facies changes, both laterally and longitudinally beneath the landform, the occurrence of an ice-contact slope and the interdigitation of glacial diamicton reinforce the view that the sequence is indeed not a fan-delta, like other sites in the Skertchly Line limit. Instead, the Shouldham Thorpe sequences and landform represent a fan-like accumulation showing the facies and architectural structure typically found in subaerial terminoglacial fans (cf. Zielinski & Van Loon, 2000). The apex of the fan appears to have occurred immediately SE of the Fodderstone Gap cross-roads (Fig. 2). A schematic enviromental reconstruction illustrating the overall sedimentary system envisaged for this sequence is shown in Fig. 10.

Regional Implications

As already stated, Lewis (1991, p.130) interpreted the Shouldham Thorpe sequence as representing the 'deposits of fluvial environment, the materials having been transported from the west of the Fenland Basin in a NNW-SSE direction across the site'. On this basis he argued that it represented a river system which crossed the Fenland basin region. This interpretation was reinforced by the gravel composition, characteristically enriched in non-local lithologies, in particular quartz and quartzite, originally derived from the English Midlands. He correlated the deposits with those in south Lincolnshire at Castle Bytham which had been related to a Bytham river from the West Midlands', proposed by Rose (1994), Lewis (1989, 1991, 1993) and Lee et al. (2004) principally on the basis of altitudinal gradient projection. In addition, Lewis (1991) recognised that they could be linked with the quartz and quartzite-bearing gravels along the Fenland margin, interpreting the latter as a fragmented terrace-staircase and correlating the sediments to the Ingham (Bytham) Formation gravels and sands of the Bury St. Edmunds area of Suffolk to the south-east (Clarke & Auton 1984; Hey & Auton 1988; Lewis & Bridgland 1991). However, the recent re-evaluation of the spreads by Gibbard et al. (2009, 2012) has demonstrated unequivocally that the eastern Fenland margin sequences represent glacio-marginal accumulations along the Skertchly Line limit of the Tottenhill glaciation, and not therefore fluvial ('terrace') sediments. They are also significantly younger than the Early to early Middle Pleistocene Ingham (Bytham) Formation deposits, since they are of post-Anglian age. Suggestions (e.g. Hosfield 2011) that older (pre-Anglian-age) fluvial sediments could occur at the Skertchly Line localities are untenable, being consistently contradicted by the evidence, with the possible exception of the basal, glaciotectonically dislocated sediments in the High Lodge area (cf. Gibbard et al., 2009).

The Shouldham Thorpe landform is the last remaining locality where possible pre-Anglian fluvial sediments might have been preserved on the Fenland margin as a representative of an Ingham (Bytham) river. However, its recognition as an ice-marginal fan, the position and glacial character of which implies that it was also formed on the Skertchly Line, means that no direct evidence remains to support the river's alignment across this area. Instead the Shouldham Thorpe site occurs intermediate between that at Tottenhill to the NNW, and Feltwell to the south (Figs 1, 2). However, unlike the other complexes identified, it does not appear to represent a sub-aquatic fan-delta but a sub-aerial accumulation. This is explained by the fact that the Shouldham Thorpe landform occurs higher in the topography than the delta-fan landforms, its upper surface reaching over 32 m OD, i.e. at least 12 m higher than the maximum water level in the contemporaneous ice-dammed 'Shingham lake' to the south-east (identified by West, in preparation) and at least 20 m above the lake level in the neighbouring Nar valley to the north during the Tottenhill event. The recognition that the Shouldham Thorpe fan is a sub-aerial, rather than a sub-aquatic accumulation implies that the water must have drained towards one of these two valleys.

The correspondence of the alignment of the palaeocurrent directions towards the south-east, and of the apparent ice-movement direction with those at the Tottenhill site itself (cf.

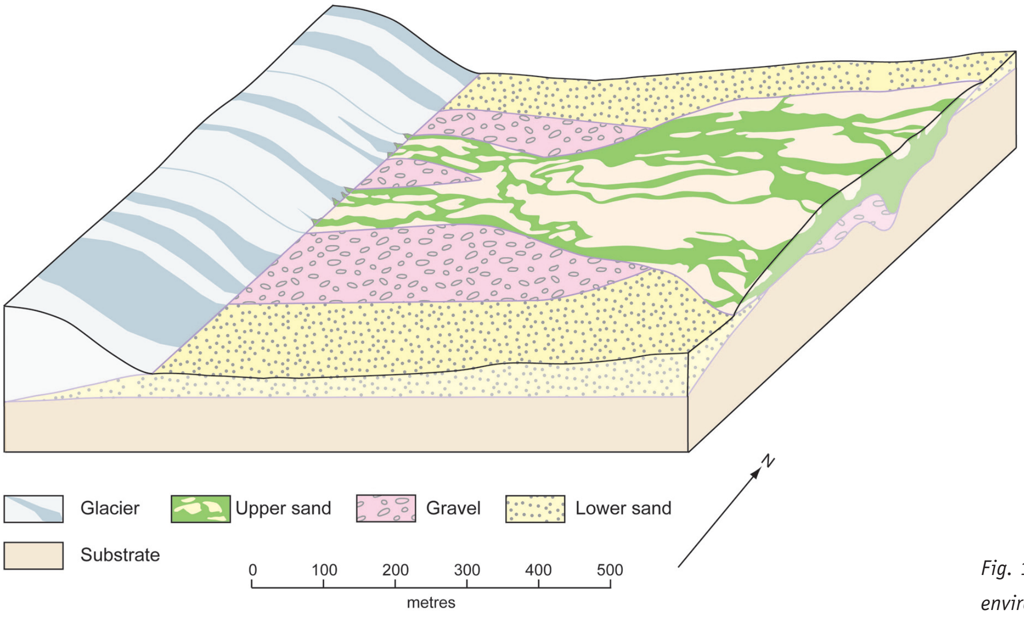


Fig. 10. Shouldham Thorpe: schematic environmental reconstruction.

Gibbard et al., 1992), suggests that the latter could represent an accumulation that slightly post-dates that at Shouldham Thorpe, i.e. the Tottenhill delta was laid down during a recessional still-stand of the same ice lobe. If this is correct, it matches closely the lines of ice-marginal sequences, interpreted as representing ice-marginal retreat (Gibbard et al., 2009, 2012). Moreover, this interpretation further implies that the Nar Valley lake, into which the Tottenhill fan-delta accumulated, post-dates that at Shingham since the surface level of the former, at 12 m OD, lies ca 8 m below that in the Wissey tributary valley. The two valleys are separated by an elongate, interfluve ridge that separates them at an altitude of ca 20 m but which is breached at Gallow Lane, south of Shouldham village. This implies that when the water-level stood at or above at 20 m OD the lakes in the two valleys would have merged into one body, but as the water level fell to 12 m, as the ice withdrew to the Tottenhill stillstand, the lakes once more became separated.

These interpretations complement the already established evidence that the Skertchly Line chain of isolated hilltop gravel and sand spreads on the eastern Fenland margin represent glacio-marginal deltaic and associated sediments. The frequent inclusion of quartz and quartzite clasts in these sediments, does not indicate they were deposited directly by a river, instead it implies that the source of the clasts could have included a pre-existing quartz-bearing gravel spread that occurred in the central Fenland that was destroyed by the glaciation and subsequent erosional processes (Gibbard et al., 2009). The occurrence of these materials, present at Shouldham Thorpe, yet absent at Tottenhill only 3.6 km to the north, implies that the quartz-bearing deposits capped a west-north-west to westward extension of the ridge that today forms the interfluve between the Nar and Wissey Valleys. Judging from the distribution of the marine, Hoxnian interglacial-age Nar Valley Clays, that infill the Nar Valley and which reach a maximum altitude of ca 23.5 m OD (Ventris 1996), their absence from areas south of this line implies that the ridge must have exceeded this height, i.e. at least 25-6 m OD. Moreover, it would have had to extend across the entire Fenland basin to link with that in the Peterborough area, where equivalent Hoxnian-age marine sediments (the Woodston Beds: Phillips 1981) occur in the Nene Valley, the high ground forming the Hoxnian North Sea coast. Furthermore, the presence of this quartz-bearing gravel-capped ridge until the glaciation, implies that much, if not all of the southern part of the Fenland basin was initially excavated by the same ice advance responsible for the deposition of both the sorted sediments and associated diamictons of the Tottenhill glaciation to the Skertchly Line. This conclusion is reinforced by the extensive occurrence of both Ipswichian (= Eemian, ~MIS 5e) Stage interglacial fluvial and littoral marine sediments, as well as underlying latest Wolstonian fluvial deposits, that occupy valley systems closely related to the modern drainage throughout the Fenland region (West et al., 1999).

Lithostratigraphy

In recognition of the apparent significance of the Shouldham Thorpe deposits as a representative of the Bytham river system, noted above, they were classified as the Shouldham Thorpe Member of a Shouldham Formation (the Shouldham Thorpe Parish pit being designated as the stratotype of both units: Lewis 1999, p.19). The reinterpretation of these formal units is discussed in the Appendix.

Discussion

The Tottenhill advance to the Skertchly Line complex has been repeatedly shown to be of late Wolstonian age (i.e. late Saalian Stage, MIS 6). This age is dependent upon the independently established litho- and morphostratigraphical relationships in the region, numerical dates from individual localities, especially from Warren Hill (Three Hills), Suffolk and Tottenhill, Norfolk and the presence of an interglacial palaeosol developed on the deposits' surface (Gibbard et al., 1991, 1992, 2009, 2012; Gibbard 1991; Lewis & Rose 1991; Clark et al., 2004; Gibbard & Clark 2011).

In spite of scepticism in the 1970-80s, substantial glaciation in eastern England during the Wolstonian Stage has been established by various authors, including Gibbard et al. (1992, 2009, 2012), but especially by Straw (2000, 2005). The latter, through his painstaking investigations in Lincolnshire, identified glacial deposits which in both their stratigraphical position and lithology closely compare with those identified on the eastern Fenland margin. Recently White et al. (2010) noted a potentially equivalent glaciation during investigations of River Trent terrace deposits in adjacent western Lincolnshire. These authors followed Straw (2000, 2005, 2011) in favouring an older age for the glaciation, which he equated to MIS 8 (i.e. middle Wolstonian) rather than MIS 6. He based this attribution on the landscape relationships in his area. He also based his correlation of the glaciation with MIS 8 by comparison with the near Continent, where he considered the substantial glacial event, the Saalian Glaciation, also occurred during that stage. Unfortunately, Straw's (2000, 2005, 2011) assumption is not supported by continental workers, the Saalian (Drenthe Substage) Glaciation having been repeatedly equated with MIS 6 throughout Europe (e.g. Busschers et al., 2008; Toucanne et al., 2009; Ehlers 2011). Nevertheless, Straw (2005, p. 34) was aware of the weakness of his case, conceding that his Lincolnshire, Welton glaciation 'could fall into any of the (MIS) Stages 6, 8 or 10'. The dating evidence in the Trent sequences is also equivocal. Therefore while it remains possible that an earlier glaciation could conceivably have occurred in Lincolnshire within the Wolstonian Stage, there is a greater probability that the event identified by these authors is the northern equivalent of the Tottenhill glaciation, described here, the dating of which is rather more reliably established.

As Gibbard et al. (2009, 2012) and Gibbard & Clark (2011) demonstrate, this age attribution is further reinforced in the southern North Sea basin. Here detailed analysis of offshore seismic data has indicated a distinct continuation of the Skertchly Line glacial limit north of East Anglia (the Norfolk High), based on the extent of tunnel valleys, marginal fan accumulations closely similar to those on-land and push-moraine ridge structures. Where this limit reaches the North Sea geographical Centre Line it continues as the Netherlands' Drenthe glaciation maximum (Moreau et al., 2009; Moreau 2010; Gibbard & Clark 2011, Gibbard et al., 2009, 2012). The detailed seismic analysis clearly differentiates this strongly defined feature from those of the earlier Anglian/Elsterian and later glaciations. The identification of the Tottenhill/Drenthe limit confirms that the glacial maximum identified in the Fenland region by Gibbard et al. (1992, 2009, 2012) is indeed the continuation of the Drenthe Amersfoort Ice-Push Ridge Complex limit in the Netherlands (Laban & Van der Meer 2004; Busschers et al., 2007, 2008). It must therefore be of the same age, i.e. ca 180-160 ka, as Gibbard et al. (1992; 2009) and Gibbard & Clark (2011) concluded. Moreover, it demonstrates that the British and Scandinavian ice sheets were confluent at the time, as predicted by previous workers (Rappol 1987; Van den Berg & Beets 1987), implying that a substantial glacial lake was formed in the southern North Sea basin immediately to the south of the ice margin (cf. Busschers et al., 2007, 2008; Gibbard 2007; Cohen et al., 2011; Ehlers 2011), the overflow discharge from which is recorded off the English Channel in the Bay of Biscay ocean-floor sediments (Toucanne et al., 2009).

Conclusions

The evidence presented confirms that deposits preserved at Shouldham Thorpe represent a sub-aerial glacio-marginal ('terminoglacial') outwash fan. These deposits accumulated at the margin of a Wolstonian/Saalian-age ice tongue that entered the Fenland region from the north and radiated towards the east until it encountered the rising bedrock, overlain by Anglian/Elsterian Lowestoft Formation till (diamicton) (Gibbard et al., 2009, 2012). Although a series of shallow proglacial lakes were formed against the ice-front where westward-flowing streams were dammed, the lakes eventually merging into a single water body, no lake was apparently formed at Shouldham Thorpe. This must reflect the topographic position of the site, on a relatively elevated area ca 35 m OD. At this site, where the meltwater discharged from the ice, outwash fans were rapidly formed. The delta-fans to the south consistently indicate a maximum lake-water level of ca 30 m OD in Lake Paterson of Gibbard et al. (2009). However, the water level was falling throughout the period represented, interpreted as indicating progressive incision of the col as lake drainage occurred through the Little Ouse – Waveney valleys to the North Sea basin (West 2007, 2009). The meltwater from the Shouldham Thorpe fan presumably drained into the ice-marginal lake in the Nar Valley to the north at 12 m OD.

Together with the sites described by Gibbard et al. (1992, 2009, 2012), the Shouldham Thorpe sequence marks a distinct glaciation limit complex (the Skertchly Line) that extends from Tottenhill, near Kings Lynn, Norfolk to Newmarket in Suffolk and beyond along the Fenland margin.

Implicit in the recognition of the Shouldham Thorpe landform and underlying sequence as an ice-marginal fan, the position and glacial character indicating that it formed on the Skertchly Line, is that no evidence remains to support the postulated north-south alignment of a pre-Anglian Ingham (Bytham) river on the East Fenland margin. However, the occurrence of a significant quartzose component in the Fenland margin pebble assemblages implies that the source of the clasts could be related to a pre-existing north-west to south-easterly aligned quartz-bearing gravel spread across the central Fenland.

The Appendix describes a new lithostratigraphical division, the Feltwell Formation, proposed here to include all the gravel and sand, and associated accumulations forming the Skertchly Line on the Eastern Fenland margin.

The Wolstonian Stage (equivalent to MIS ?11b-6) has been repeatedly noted to be a critical interval in the landscape evolution of eastern England during which the modern drainage system was established following both the Anglian Stage glaciation and the immediately following the Hoxnian Stage interglacial (West 1963, 1968; Gibbard 1991). Since there is now a substantial consensus, throughout northern Europe, that the major glaciation was restricted to the latter part of the period (i.e. late Wolstonian/Saalian, early in MIS 6: Gibbard & Clark 2011; Ehlers et al., 2011), on balance it appears that the earlier cold intervals (i.e. MIS 10, 8) within the Wolstonian/Saalian Stage were dominated by severe cold, non-glacial conditions in lowland Britain and on the adjacent mid-Continent. The occurrence of subsequent last (i.e. Ipswichian/Eemian Stage) interglacial fluvial sequences, at or close to modern floodplain valley level throughout the region, confirms that the present drainage system was established by this time.

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Appendix 1 – Definition of the Feltwell Formation

As noted above, the gravels and sands at the Shouldham Parish pit were classified as the Shouldham Thorpe Member of a Shouldham Formation by Lewis (1999, p.19), the section being designated as the stratotype locality. The basis for the definition of these lithostratigraphical units was the occurrence of quartz- and quartzite-rich gravel and sand noted above. Leaving aside the palaeogeographical implications of these units, their recognition as the reference sequence for the series of quartz-bearing gravels across the region requires consideration in the light of the reinterpretation of their genesis and significance.

The subdivision of geological sequences based on the physical properties of the sediments is lithostratigraphy. This division should be hierarchical. The principal intention of this approach is that the division reflects reality whilst also facilitating efficient communication. Implicit in this division is that the hierarchical level at which any individual unit is defined has no bearing on its perceived importance, rather it should recognise the unit's scale and extent within the regional sequence. The guiding principle in lithostratigraphical subdivision should be practicality and consistency, as in all classificatory schemes (Salvador, 1994; Räsänen et al., 2009; Hughes 2010; Gibbard 2012). A balance should be sought to ensure that, when divisions are proposed, they are defined at the appropriate scale and are consistently applied to enhance and clarify communication, while respecting historical precedence.

In this context the reinterpretation of the Shouldham Thorpe spread as of glaciofluvial origin results in a dilemma arising from its existing role as a stratotype for the quartz-bearing fluvial deposits.

Whilst hypothetically this reinterpretation should not change the essential validity of the deposits' identity, the question arises as to whether the Shouldham Thorpe sequence is in fact, the most appropriate candidate for a formation stratotype. Given that, by analogy with the glacial, Lowestoft or North Sea Drift Formations of eastern England, it is appropriate, both from hypothetical and indeed practical standpoints, to define a formation that not only includes all the glaciofluvial deposits of the Fenland margin, but also the associated diamicton and other related sediments in the area arising from the same glacial event and therefore possessing the same basic lithological elements.

In this sense it would be preferable to select a locality that includes a greater range of elements comprising the sequence and ideally one where the sediments are better exposed. Such a site is Feltwell in Norfolk, which has been described in detail by Gibbard et al. (2012) (Table 2). Here the sequence comprised a complex of coarse to fine stratified sediments associated with diamicton units, mass flow deposits and solutional collapse features resting on Chalk bedrock. The fan-like form of the sediments represents a delta and related feeder channel deposited at the ice-front.

The sequence at Feltwell including this range of elements, is more representative of the glacial sequence of the eastern Fenland margin as a whole. This exposure is therefore proposed here as the stratotype of a new Feltwell Formation, which includes not only the individual gravel and sand accumulations identified along the Skertchly Line but also the associated diamicton and fine-grained, glaciolacustrine accumulations resting on bedrock. At present these units are not assigned formal names but it is recommended that when this becomes possible they are considered as member- or bed-status units, as appropriate. For example, the already-defined term Shouldham Thorpe Member (a division of the new Feltwell Formation) could be retained to identify the accumulation at Shouldham Thorpe discussed herein.

Table 2. Lithostratigraphical definition of the Feltwell Formation.

Stratotype	Feltwell gravel pit, Norfolk (NGR TL 740922), sequence described in Gibbard et al., 2012)
Constituent members	Potentially includes previously defined informal members, e.g. Shouldham Thorpe Member (Lewis 1999)
Upper boundary	Surface of landforms, but locally overlain by periglacial slope materials (in part, diamicton) and aeolian sand
Lower boundary	Base erosional
Total thickness	Maximum proved thickness exceeds 10 m, but locally highly variable
Lithological characteristics	Complex sequence of stratified and sorted gravel, sand and fine sediments, intimately associated with diamicton and locally disturbed by localised collapse and glaciotectonic structures
Distribution	Includes isolated 'hilltop' and associated deposits from Exning, Newmarket, Suffolk, to Hockwold cum Wilton, and Feltwell, Norfolk (for details see Gibbard et al., 2009)

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