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Luminescence dating of a late Middle Pleistocene glacial advance in eastern England

Philip L. Gibbard[1], Mark D. Bateman[2], Jane Leathard[2] and R.G. West[a]

[1]Scott Polar Research Institute, University of Cambridge, Lensfield Road, Cambridge CB2 1ER, England, UK and [2]Department of Geography, University of Sheffield, Sheffield S10 2TN, England, UK

Original Article

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Author for correspondence:
Philip L. Gibbard, Email: plg1@cam.ac.uk

[a]Deceased.

Abstract

Previous investigation of isolated landforms, on the eastern margin of the East Anglian Fenland, England, has demonstrated that they represent an ice-marginal delta and alluvial fan complex deposited at the margin of an ice lobe that entered the Fenland during the 'Tottenhill glaciation' (termed the 'Skertchly Line'). They have been attributed, based on regional correlations, to a glaciation during the Late Wolstonian (i.e. Late Saalian) Substage (Drenthe Stadial, early Marine Isotope Stage (MIS) 6). This paper aimed to test this correlation by directly optically luminescence dating, for the first time, sediments found within the Skertchly Line at Shouldham Thorpe, Norfolk, and Maidscross Hill, Suffolk, together with those in associated kame terrace deposits at Watlington, Norfolk. Ages ranged from 244 ± 10 ka to 12.8 ± 0.46 ka, all the results being younger than MIS 8 with some clearly showing the landforms have been subsequently subjected to periglacial processes, particularly during the Late Devensian Substage (~MIS 2). Most of the remainder fall within the range 169–212 ka and could be assigned to MIS 6, thus confirming the previously proposed age of the glaciation. The local and regional implications of these conclusions are discussed, the maximum ice limit being linked to that of the Amersfoort–Nijmegen glaciotectonic ridge limit in the central Netherlands.

Introduction

In a series of articles over the last two decades (Gibbard et al., 1991, 1992, 2009, 2012a, 2012b, 2018; West et al., 2014; Gibbard, 1991), evidence has emerged indicating that the Fenland region of East Anglia, England, was glaciated during the late Middle Pleistocene. The detailed investigation of the setting, morphology and internal architecture of a line of hills adjacent to the eastern Fenland margin demonstrated that they represent a series of ice-contact fan deltas, a subaerial glaciomarginal alluvial fan and in one case a subaerial kame terrace-like deposit (grouped as the Feltwell Formation: Gibbard et al., 2009, 2018). The accumulations mark a distinct maximum glacial limit termed the 'Skertchly Line'; Figs. 1a, b and 2), identified in the series studies, noted above. This complex of landforms was formed where an ice lobe, flowing from the north to north-west, dammed a series of local streams on its eastern and south-eastern flank to form a proglacial lake in contact with the ice front. The ice-contact fan deltas and a subaerial alluvial fan were deposited where meltwater discharged from tunnel portals in the ice. The ice-contact (glaciomarginal) deltas accumulated in a lake that was recognised first by Paterson (1939, 1942), termed 'Lake Paterson', that initially drained through the Little Ouse–Waveney valleys, and to the southern North Sea basin, whilst the second more northerly lake was dammed in the Nar valley (Gibbard et al., 1991; 1992) (Fig.3). This 'Tottenhill advance' (Clark et al., 2004; Lewis and Rose, 1991; Clark and Gibbard, 2011; Gibbard et al., 2018; Turner et al., 2020) was determined to be of Late Wolstonian age (i.e. Late Saalian, within Marine Isotope Stage (MIS) 6). Despite suggestions that the marginal deposits had been previously interpreted as remnants of an older fluvial terrace, they have been shown to be of ice-marginal origin (see discussion in Gibbard et al., 2009, 2012a, b; Turner et al., 2020), their age was confirmed by multiple lines of evidence, including previously determined optically stimulated luminescence (OSL) ages from individual localities (*c.* 160 ka), including from Warren Hill (Three Hills) and Tottenhill, Norfolk (cf. below) and the presence of an interglacial palaeosol developed on the deposits' surface (Gibbard et al. 1991, 1992, 2009, 2012; Gibbard, 1991; Lewis and Rose, 1991; Clark et al., 2004; Clark and Gibbard, 2011; West et al., 2014; Pawley et al., 2008, Pawley, personal communication). This evidence has demonstrated that the Skertchly Line deposits and landforms are intermediate in age between the Hoxnian (Holsteinian; *c.* ?MIS 11c; *cf.* Ashton et al., 2008) and Ipswichian (Eemian; *c.* MIS 5e) interglacial stages (Clark et al., 2004; Gibbard et al., 1991, 1992, 2009, 2018; Lewis and Rose, 1991; Clark and Gibbard, 2011; West and Gibbard, 2021). This glaciation greatly influenced the subsequent evolution of the Fenland basin and drainage systems and landscape morphology throughout the region, especially the English Midlands, glaciated during this event.

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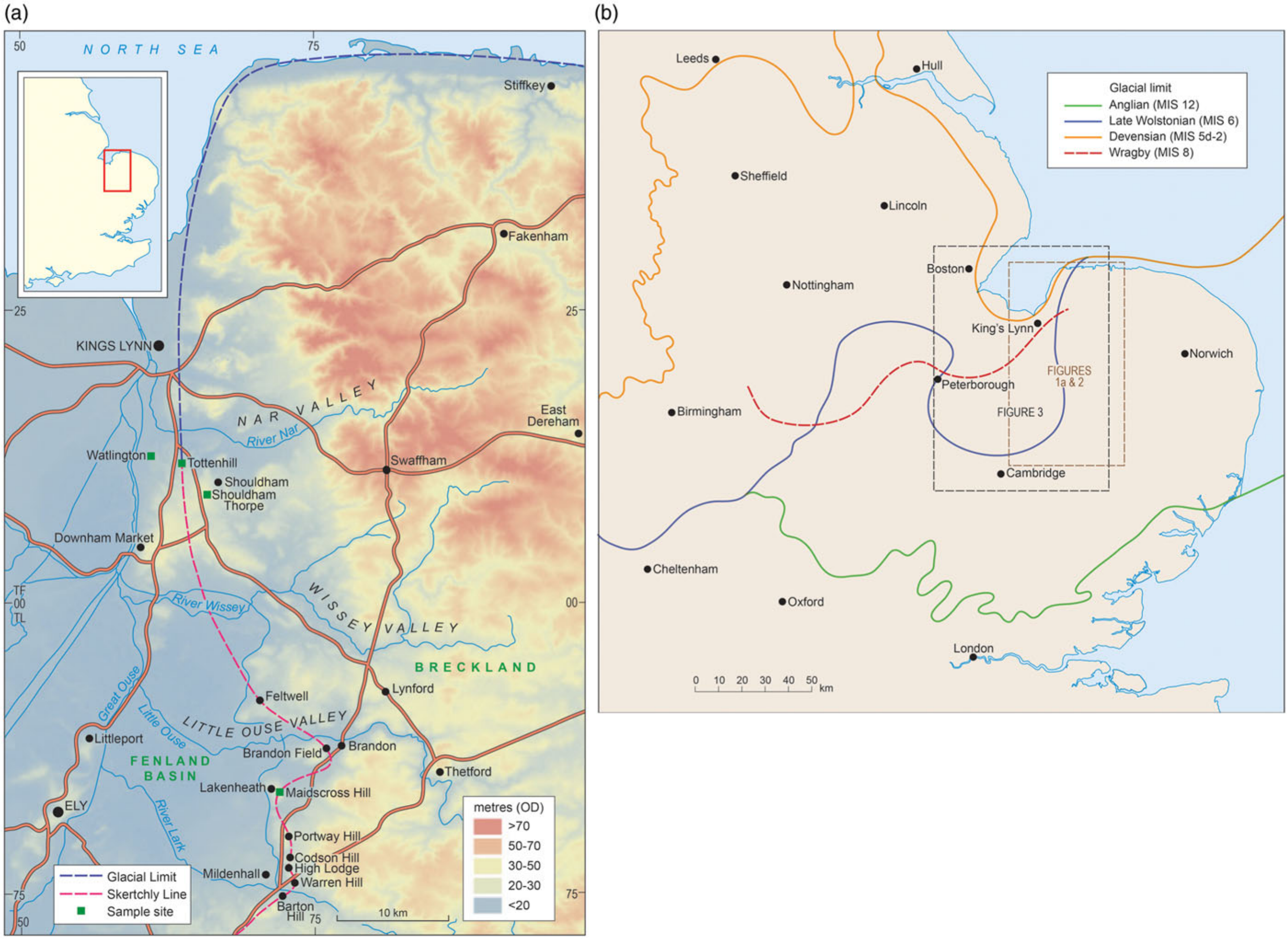

Fig. 1. a. Location map showing western East Anglia and the Fenland basin study area. 1b. The proposed glaciation limits for eastern England based on Clark and Gibbard (2011) and Gibbard et al. (2018) (solid lines), the limit for the possible Middle Wolstonian 'MIS 8' glaciation postulated by White et al. (2017) (dotted line). For site localities see Fig. 1a.

Based on extensive preserved evidence, during the Middle Pleistocene Anglian Stage (Elsterian Stage, *c.* Marine Isotope Stage 12; Table 1), ice extended across all of East Anglia as far south as the Thames Valley, as well as offshore in the southern North Sea and Irish Sea basins (Clark et al., 2004). An extensive ice sheet also existed during the Devensian Stage (MIS 2/3) when ice extended south in the North Sea as far as the Norfolk coast (Roberts et al., 2018). Intermediate between the Anglian and Devensian glacial events, a Wolstonian-age glaciation was originally identified in the English Midlands (e.g. Shotton, 1953; Rice, 1968) and subsequently recognised in Yorkshire, Lincolnshire and northern East Anglia (Clark and Gibbard, 2011). At many places, however, Wolstonian-age glacial deposits were thought by some to pre-date the stage. This was particularly the case in East Anglia where there has been considerable controversy concerning the number of glaciations, their extent and relationships of glacial sequences one to another, particularly in recent years (e.g. Clark et al., 2004; Straw, 2005, 2011; White et al., 2010, 2017; Clark and Gibbard, 2011; Turner, 2020: Fig. 1b). Resolution of these issues has been problematic because evidence of the extent and stratigraphical relationships of the Wolstonian glaciation are only poorly preserved in the eastern English Pleistocene record as a consequence of later erosion and disagreements over the age dating (Clark et al., 2004).

Dating of the Tottenhill glacial advance to the Skertchly Line complex in Fenland to the Late Wolstonian Substage (i.e. Late Saalian Substage, ~MIS 6) was based primarily on litho- and morphostratigraphical relationships in the region, bracketing ages and the presence of an interglacial palaeosol developed on the deposits' surface (Gibbard et al., 2018 and the references therein). This clearly marks it as distinct from the earlier Anglian glaciation. However, published numerical ages on Tottenhill glacial deposits are absent apart from a preliminary assay (without uncertainties) of *c.* 160 ka reported in Gibbard et al. (2009). Nearby on the Norfolk coast at Stiffkey, recent work on the moraine landform deposits there reported ages of 141 ± 9.4 and 165 ± 11 ka (Evans et al., 2019) indicating at least regional presence of ice within MIS6, although this may not necessarily be the same event as the Tottenhill glacial advance.

Based on quarry exposures at Maidscross Hill, Suffolk, and Shouldham Thorpe and Watlington, near Tottenhill, Norfolk, this article presents the results of numerical luminescence age determinations of the series of gravel and sand accumulations that underlie the characteristic 'Skertchly Line' landforms. Previous detailed geological and geomorphological investigation of landforms, supported by a ground-penetrating radar (GPR) investigation of unexposed areas, demonstrated their origin as glaciomarginal

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Fig. 2. Quaternary geological map of the study region, showing the glacial deposits, gravel spreads and the Fenland Holocene deposits. The approximate 'Skertchly Line' glacial maximum limit is also shown. Map source: EDINA.

accumulations. The aim was to determine whether the attribution of the Tottenhill glacial advance to MIS 6 could be geochronologically substantiated. The regional implications of the findings are presented herein.

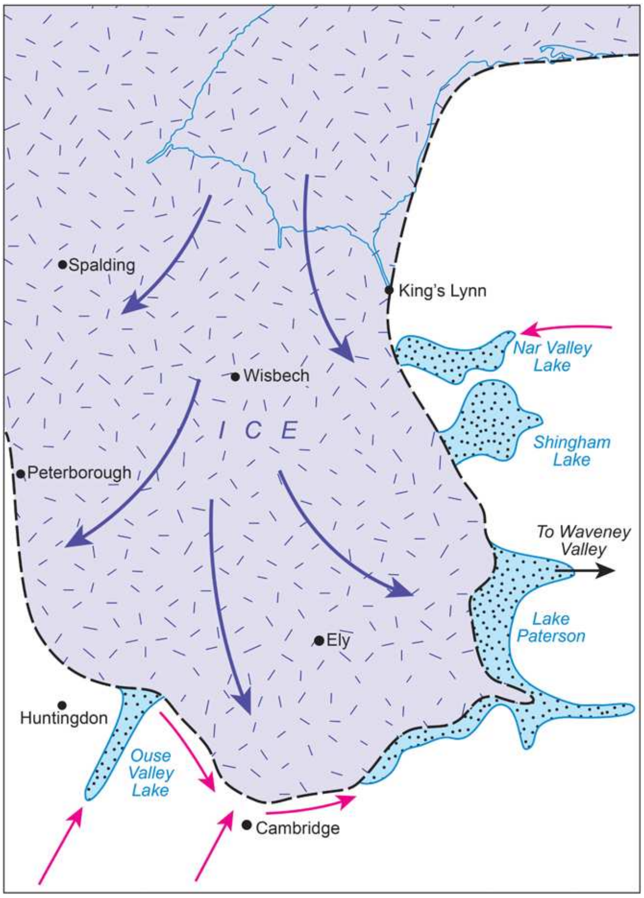

Fig. 3. Schematic palaeogeography showing the maximum extent of the Tottenhill glacial lobe in Fenland (Late Wolstonian Substage) and associated drainage alignments and glacial lakes (modified from Gibbard et al. 2018). The blue arrows indicate the direction of ice advance. For site localities see Fig. 1a.

Sample site successions

The investigation of the sites undertaken during this study is summarised below. The descriptions include standard facies codes (modified from Miall, 1978; Eyles et al., 1983). Summary site descriptions only are presented. For full details, reference should be made to Gibbard et al. (2009; 2012a, b).

Maidscross Hill (Lakenheath), Suffolk

Maidscross Hill (The Broom), east of Lakenheath (National Grid Reference – TL 725826), reaches an altitude of 31 m OD (Fig. 4). The deposits were exposed in a large pit on the SE side of the hill adjacent to the RAF Lakenheath NW boundary. Here, vertical test pits were dug and sections revealed and cleaned. A composite log is given in Fig. 4. The artefact-bearing sediments here have been investigated since the mid-nineteenth century (cf. Gibbard et al., 2009 for details).

The sedimentary succession at Maidscross Hill rests on bedrock Chalk, the basal sediments comprising laminated granular fine sands with chalk fragments (facies Sh) at least 20 cm in thickness (in borehole at the base). They are conformably overlain by horizontally stratified medium sand with silt laminae and coarsening upwards to pebbly cross-bedded medium to coarse sand with increasing pebble clasts up to 1.20 m thick (facies Sh). Faintly ripple-laminated medium sand, rich in chalk granules, interbedded with grey silt drapes 2–3 cm thick, the overall unit being 1.35 m thick (facies Sr) overlies the previous sediments. This bed is truncated by a marked horizontal erosional surface overlain by fine to medium matrix-supported gravel. The gravels are not only dominated by chalk clasts of up to 15 cm in diameter, but also include flint, quartz, quartzite and occasional other lithologies (facies Gms). Gently dipping medium to coarse gravel foreset-bedded units of *c.* 0.40–1.20 m in thickness occurs at neighbouring sites. The large-scale foreset beds are divided by buff medium sand and interbedded silt laminae 1.5–2 cm thick. Palaeocurrent measurements indicate variable flow towards 105–180°, that is, towards the SE. Coarse gravel can only be seen close to the surface, 50 m N and NW of the exposure described. This

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Table 1. Geological timetable of events in the Fenland region, eastern England, and their correlation to the near Continent during the Middle to Late Pleistocene subseries (modified from Gibbard et al., 2018). The NW European chronostratigraphy/climatostratigraphy is modified from Litt et al. (2007, 2008) and Roskosch et al. (2015). For further explanation see the text.

British chronostratigraphy/climatostratigraphy		Fluvial events	Glacial events	Climate/ environment	Human occupation	Continental chronostratigraphy/ climatostratigraphy			Approx. Marine Isotope (Sub-) Stage (MIS)
Ipswichian		Aggradation of temperate floodplain and channel sediments		Temperate		Eemian			~5e
Wolstonian	Late	Downcutting and aggradation of gravel and sand in river valleys		Periglacial		Warthe Stadial	Saalian	Late	6
		Non-deposition							
		Downcutting and aggradation of gravel and sand in river valleys, e.g. Balderton Member (Trent system)							
		Watlington Gravel deposition	Wolstonian Tottenhill glaciation *s.s.* lacustrine ponding of river valleys	Periglacial/ glacial		Drenthe Stadial			
		Downcutting and aggradation of gravel and sand in river valleys and lacustrine sedimentation							
		Deposition of Waverley Wood, and associated deposits. Brooksby, High Lodge, ?Frog Hall deposits silt deposits. Complex 'interglacial' channel fills.		Boreal/ Temperate	*	?Schöningen Interstadial/ Interglacial			~7
	Early/ Middle	Downcutting and aggradation of gravel and sand in river valleys		Periglacial	*			Early/ Middle	8-~11b
		Non-deposition		Periglacial					
		lake basin infill with fine-grained sedimentation in river valleys, etc. during interglacial event.	?	Periglacial	?	?Fuhne Stadial			
Hoxnian		Infill of lake basins, incoherent river system.		Temperate	*	Holsteinian			~11c

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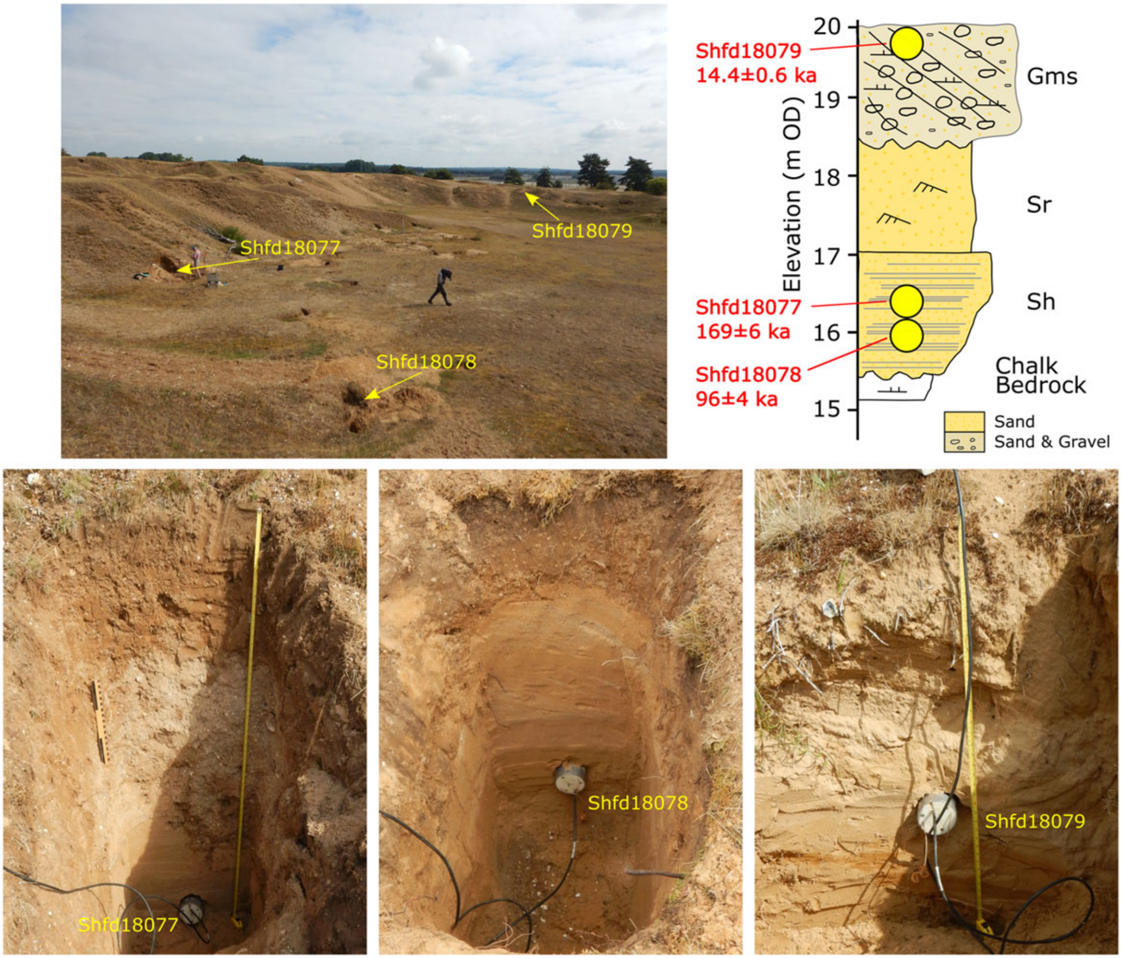

Figure 4. Luminescence sample localities for the Maidscross Hill site with the approximate positions of IRSL samples and pIRIR_{225} ages shown on the stratigraphic log of Gibbard *et al* (2009).

sediment facies distribution parallels that found at other nearby sites, for example, Three Hills (Gibbard et al., 2009). To the SE of Maidscross Hill, the succession comprises laminated sands and silts at the base, resting on highly fragmented Chalk. Horizontally and ripple-cross-laminated sands are truncated by planar cross-stratified medium to fine gravel. The succession coarsens upwards again implying derivation from a source to the NW of the sample site.

Comparison of the facies successions recorded from the limited exposure conforms to the facies typical of mid- to distal slope facies (cf. Lang et al., 2021) with the sand-silt-dominated units reflecting cyclic step deposits, whilst the gravel units represent a higher energy proximal facies.

Three samples were collected for luminescence dating (Fig. 4). Two samples (Shfd18077 and Shfd18078) were taken from low in the stratigraphy from the horizontally stratified medium sand (Sh) unit. One sample (Shfd18079) was collected from a sand facies in the upper part of the fine to medium matrix-supported gravel.

Shouldham Thorpe, Norfolk

An exposure was cleaned and re-examined at the Parish pit located ~1.5 km west of the village of Shouldham (National Grid Reference: TF 657085). This succession was first described by Lewis (1989, 1991) and was re-examined by Gibbard et al. (2012b). The profile comprises over 7 m of predominantly horizontally stratified deposits underlying the modern ground surface (Fig. 5). The basal sediments rest on bedrock, comprise matrix-supported fine to medium gravel (facies Gms) 30 cm thick and 20 cm of planar-parallel-bedded sand and are overlain by 4 m of horizontal multi-storey planar-parallel-bedded sand units, 30–40 cm thick (facies St, Sp), some units including a thin basal gravel lag. Horizontally stratified fine to medium, matrix-supported gravel (facies Gms) units of 10–25 cm thick occur resting on erosional bases. A shallow channel, 25 cm deep and 2.5 m wide, cut across the planar-parallel bedded sands, the base at 3.5 m depth, and was infilled by planar-parallel-bedded pebbly sand (facies Sh). A similar channel-like infill occurred slightly higher in the succession at 2.75 m depth.

The upper *c.* 1m of well-sorted medium sand with scattered pebbles, mostly of flint, blankets the succession (facies Scr), immediately beneath the modern ground surface (Fig. 5). The slightly reddened character of this deposit possibly represents a disrupted relict palaeosol, comparable to that seen at Tottenhill (Lewis and Rose, 1991; Gibbard et al., 1992). At the extreme N side of the exposure 20 cm below the ground surface, a tongue-like wedge of brown glacial diamicton (facies Dmm), 40 cm thick,

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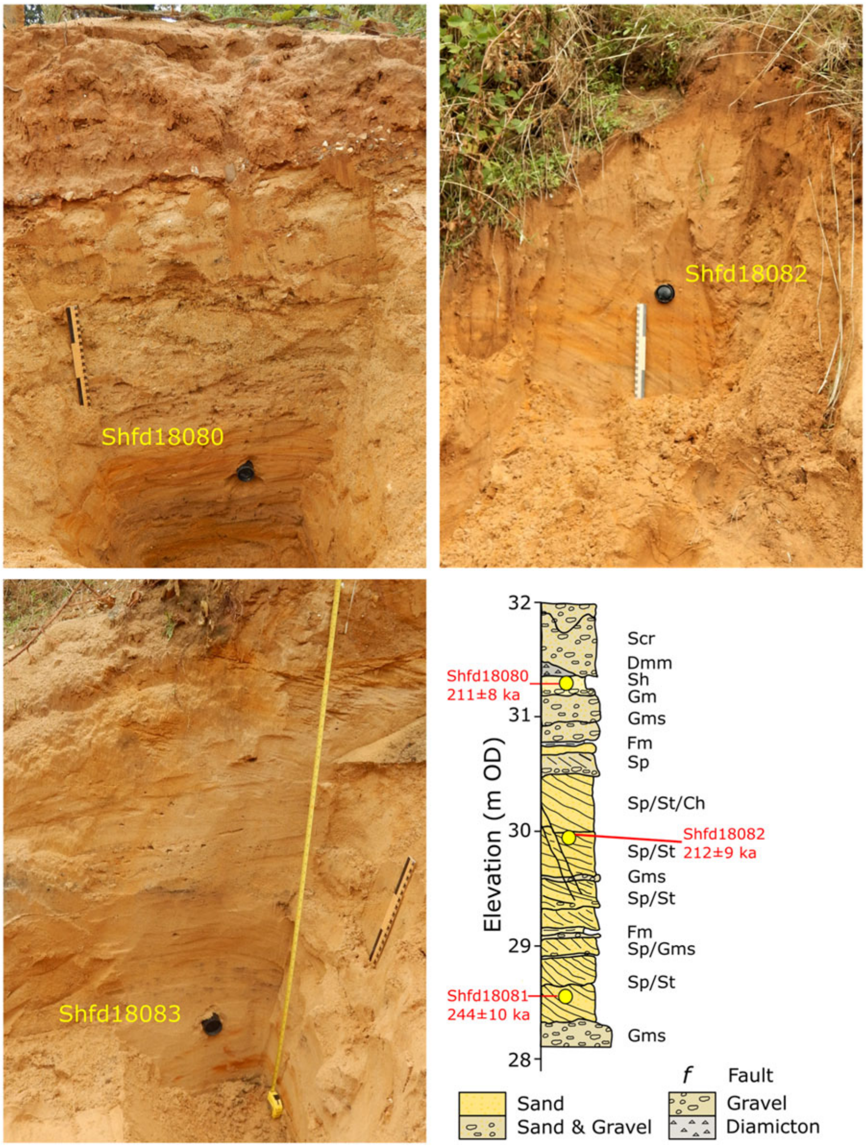

Figure 5. Luminescence sample localities for the Shouldham Thorpe site with the approximate positions of IRSL samples and pIRIR$_{225}$ ages shown on the composite stratigraphic log of Gibbard *et al* (2012b).

rested on the underlying silts with a sharp basal boundary. Throughout the deposits, palaeocurrent measurements indicate a consistent flow direction towards SE-SSE, as noted by Lewis (1989; 1991).

Examination of the internal structure and form of the feature, including 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 are therefore of post-Anglian age (Gibbard et al., 2012b). The investigations indicate that the Shouldham deposits were laid down as a subaerial glaciomarginal fan directly in contact with the ice front.

Three samples were collected for luminescence dating (Fig. 5). One (Shfd18081) was from low in the stratigraphy in the planar-parallel-bedded sand (Sp) unit. The second (Shfd18082) was collected from mid-way up the stratigraphic profile in planar cross-bedded sand (Sp). The third (Shfd18080) was from the upper part of the succession in horizontally bedded sand immediately below the diamicton.

Watlington Quarry

Present-day quarrying provided an opportunity to view sediments between the villages of Watlington and Tottenhill (National Grid Reference: TF 625109). A recently exposed working quarry face revealed a ~60 m long, 4 m high vertical face approximately 7 m OD in elevation (Fig. 6).

Logging revealed the exposure to be mostly poorly bedded to massive matrix-supported fine to medium gravel (Gms). The gravel comprised almost entirely of flint (97%) and the matrix was a medium to coarse sand. In places it was noted *in situ* clasts had been split. Borehole logs indicate a further 18 m of gravel beneath the exposure sitting on Jurassic Kimmeridge Formation clay. Within the gravel were large teardrop shaped periglacial cryoturbation structures ranging from 1.4 to 2.5 m in width and 1.6 to 2.7 m in depth (Fig. 7). These clearly had developed after gravel deposition as the boundaries were sharp and clast orientation in gravel directly adjacent to the structures showed preferential vertical alignment. The cryoturbation structures were filled with sand (Ss) and occasional clasts with some evidence of fining away from the centre of the feature as the margins were more clayey. In places,

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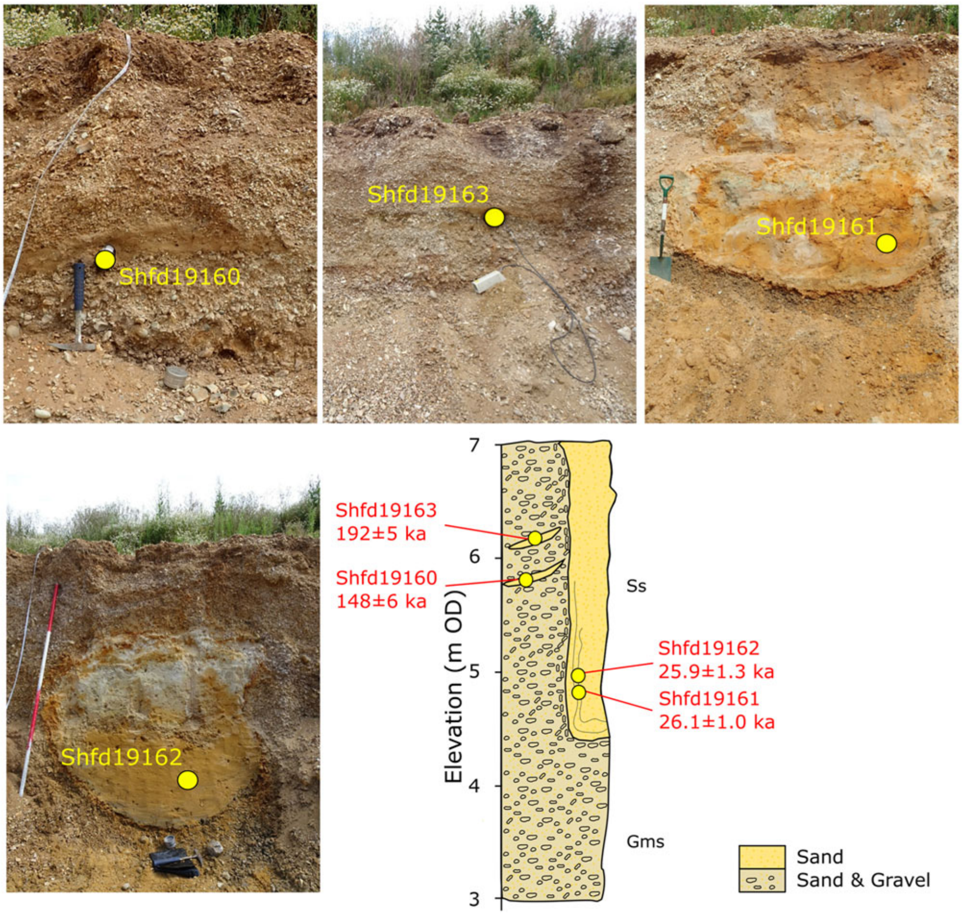

Figure 6. Composite log with Luminescence sample localities and pIRIR_{225} ages for the Watlington Site. Note vertically aligned clasts adjacent to sand filled cryoturbation feature.

the sand was indurated and there was clear evidence for post-depositional iron staining with a well-developed iron pan at the base of each feature. Planform excavations during quarrying revealed these features are irregularly spaced and not forming a network (Fig. 7d and e).

The gravels revealed at Watlington are thought to form part of a gravel train (the Watlington Member) which was identified by Gibbard et al. (2018). This extends along the eastern Fenland margin northwards from north of Downham Market to Watlington, immediately west of Tottenhill, at the mouth of the Nar Valley (Figs. 1 and 2). The deposits' surface forms a distinct terrace-like feature declining in the same direction from *c.* 9 m O.D. to 5 m O.D. at Watlington, its present form including a steep west-facing margin, whilst its eastern limit forms a gentle gradient with local topography. At its northern end, the spread abuts the Tottenhill deposits described by Gibbard et al. (1991; 1992), the uppermost surface of which occurs at 12 m O.D. However, since the terraciform surface of the Watlington Gravel deposits occurs at a distinctly lower elevation (c. 5–6 m O.D.), Gibbard et al. (2018) concluded that it was incised into the deltaic accumulation subsequent to deposition of the latter.

Gallois (1978) interpreted this spread as a fan deposited into a lake filling the Fenland basin. However, the form and occurrence of these deposits imply that they represent abraided stream, kame terrace accumulation laid down by meltwater flowing northwards marginal to the ice lobe during its occupation of the basin immediately to the west (Gibbard et al., 2018). The altitudinal relationship of this landform to the Tottenhill sequence demonstrates that the Watlington Gravel post-dates the former implying that it accumulated during a stillstand of the Fenland ice lobe when the meltwater drainage was aligned northwards towards the North Sea. This contrasts with the eastwards drainage that occurred during the phase represented by the glacial lacustrine deposits at Tottenhill itself.

A total for four samples were collected for luminescence dating from the Watlington Quarry. Two samples (Shfd19160 and Shfd19163) were collected from rare small (~10 cm thick, ~30 cm in length) sand lenses within the gravel (Fig 6). A further two samples (Shfd19161 and Shfd19162) were collected from the sand contained within two different cryoturbation features (Fig 6).

Sediment sampling and investigation

Field Methods

Locations for luminescence dating were selected in sand units devoid of organic material at least below 50 cm from the present-day surface to avoid recent pedoturbation or soil formation. At freshly cleaned locations, sand samples were obtained by driving 50 mm diameter opaque PVC tubes into the selected sediment. *In situ* dose rate measurements were also undertaken using an EG and G micronomad. Additional large (>20 kg) samples were taken at the Watlington Quarry site of the gravel and finer grained units for particle size, shape and roundness characterisation to aid interpretation of their transportation and depositional environment.

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Figure 7. Cryoturbation structures found at Watlington Quarry. (A) vertical profile through structures which repeat and Irregular Intervals with (B) annotated version showing feature boundaries. (C) planform of cryoturbation structure with (D) vertical profile through same structure. (E) cleared quarry floor showing frequency of structures within a ~50 m^2 area (photograph courtesy of Vince Spall) with (F) annotated version showing feature boundaries.

Sediment characterisation

The gravel and sand samples were dried and sieved through a nest of sieves using a mechanical agitator as Gale and Hoare (2012). Particles <1 mm were measured using a Horiba LA-950 laser diffraction particle size distribution analyser. Prior to measurement, subsamples were riffled down and treated with 0.1% hexametaphosphate, before dispersal in de-ionised water within the instrument using ultrasound and pumping. Resultant data were used in GRADISTAv8 to calculate the mean grain size of each sample, sorting, skewness and kurtosis. Clasts >16 mm were also analysed for form and sphericity (ψ_P) per Gale and Hoare (2012) and roundness/angularity as per Powers (1952).

Luminescence dating

Luminescence dating using OSL on extracted quartz minerals has been successfully applied to East Anglian sediments as old as MIS 12 (e.g. Pawley et al., 2008 who measured ages back to 494 ± 42 ka). However, OSL dating as early as this is only possible where background dose rates are extremely low as they are on the Cretaceous Chalk. In areas with average background radioactivity, the quartz OSL signal saturates after 150,000 years of burial or younger (Mahan and DeWitt, 2019). An alternative approach is to measure feldspars using infrared stimulated luminescence (IRSL) for which under average dose rate conditions an upper dating limit of 200,000–300,000 years or even more has been reported (Mahan and DeWitt, 2019). Unfortunately, IRSL signal measured at 50°C (IRSL$_{50}$) has been shown to sometime underestimate ages due to anomalous fading (Spooner, 1994; Mahan and DeWitt, 2019) leading the necessity for complex and very precise fading corrections being needed (e.g. Lamothe et al., 2003). However, more recently it has been found that fading problems can be eliminated or significantly reduced by measuring the IRSL signal at an elevated temperature after the IRSL$_{50}$ signal has been measured (e.g. Buylaert et al., 2009).

As outlined by Bateman (2019), the other significant challenge for the successful application of luminescence dating to glacial, periglacial and fluvial sediments is that prior to burial sediments

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were exposed to sufficient sunlight (bleached) at some point during erosion, transportation and at deposition. From this perspective, OSL signal resets quicker than $IRSL_{50}$ and IRSL signal measured at 225°C ($IRSL_{225}$) is even slower to reset (Bateman, 2019, Fig 8.2). A strategy employed to help with this is making multiple replicate measurements of palaeodoses (D_e). A well-bleached sediment should have a tight normally distributed D_e distribution centred on the true burial age and a low over-dispersion (OD). In contrast where only some grains were bleached, a skewed or multimodal D_e distribution would be expected with high OD (Bateman, 2019, Fig 8.5).

Given the potential antiquity of the collected samples and the discussion above, both $IRSL_{50}$ and IRSL at 225°C ($IRSL_{225}$) measurements from extracted feldspars were employed in this study as per Bickel et al. (2015). Samples were prepared following the procedure outlined in Bateman and Catt (1996) using a grain size range of 180–212μm. Prepared feldspar grains were mounted as a ~5-mm diameter monolayer on 9.6-mm diameter stainless steel discs. Each aliquot therefore comprised ~650 grains. All measurements were undertaken following a preheat of 260°C for 300 seconds in a Risø luminescence reader with stimulation from IR LEDs. Palaeodoses (D_e) were measured using the single aliquot regenerative (SAR) approach of Murray and Wintle (2003) with five regeneration points. As per Rhodes (2015) following IRSL measurement at 50°C ($IRSL_{50}$), the IRSL signal was measured a second time with the sample held to 225°C. This is referred to as the post-IRSL IRSL signal ($pIRIR_{225}$). Sensitivity corrections were made from repeat measurement of an experimentally derived 50 Gy test dose, and a thermal bleach at 290ºc was employed at the end of each SAR cycle to ensure that all traps were emptied before the next SAR cycle. At least 24 replicates of each sample were measured.

All IRSL measurements showed a strong rapidly decreasing signal (Fig. 8A and B) and growth curves which grew well with laboratory doses (Fig. 8C and D). For samples from Watlington and Maidscross Hill, SAR regeneration dose points showed a good fit with a single saturating exponential curve. Importantly, all aliquots from these samples had growth curves that showed no signs of saturation (as exemplified in Fig. 8E). SAR growth curve data from the Shouldham samples were best fitted with expontential + linear curves as the D_e values for this site were much higher (>375 Gy). Two samples (Shfd18080 and Shfd18081) from this site had 20% and 8%, respectively, of saturated aliquots. When replicates were examined for each sample, all had normal distributions with low OD and limited skewness with no indication of incomplete bleaching.

External dose rates for the samples were based on the field gamma spectrometry measurements for the gamma dose. External beta dose rates were based on Inductively coupled plasma - optical emission spectrometry (ICP-OES) and Inductively coupled plasma mass spectrometry (ICP-MS) elemental measurements converted dose rates using data from Guerin et al. (2011). Both beta and gamma doses were appropriately attenuated for grain size, density and a palaeomoisture value based on present-day moisture levels (Table 2). The latter was assumed as whilst the sediments would have been saturated at deposition and during the establishment of permafrost during MIS 2, the present-day values are thought to represent the majority of time as the sampled sediments are free draining sands and gravels. The exception to this was the Watlington quarry which is at a lower elevation, overlying clay and which currently has to be pumped. Sediment here may have been saturated for longer. For this site, a partially saturated palaeomoisture value of 15% (as per Evans et al., 2021) was applied. A 5% error was applied to this term to incorporate fluctuations through time. An internal dose rate was based on an assumed internal potassium content of 12% (as Huntley and Baril, 1997) and Rb of 400 ppm (as per Huntley and Hancock, 2001). The Prescott and Hutton (1994) algorithm was used to calculate the cosmogenic-derived dose rate. Ages were calculated from 2020. Given the good replicate reproducibility, limited D_e replicate skew and low OD values, D_e values for each sample were extracted using the Common Age Model of Galbriath and Green (1990). D_e values for measurements at $pIRIR_{225}$ also include a subtraction of a residual of 10.73 Gy as determined on Shfd18077 by prolonged daylight bleaching (7 days) in the University of Sheffield, followed by measurement as above.

Results

Sediment characterisation

Results from Watlington show that 69% of clasts are sub-angular to very angular (Fig. 9). Whilst flints tend to be angular and are resistant to wear having as they do a low abrasional response (Sneed and Folk, 1958), it may also indicate the majority of clasts were only transported a relatively short distance. The small percentage of 'rounded' flint are interpreted as reworked clasts (Eyles et al., 1983). Particle size analysis of the gravel unit showed it to have a 78:22 ratio of gravel to sand and a mean size of 11–16 mm being best described as a very poorly sorted sandy medium gravel (Fig. 10). Bladed- and platy-shaped clasts make up to 69% of the gravel with sphericity analysis showing no dominant categories. Based on the covariance of C_{40} and RA indices and RA and RWS indices (cf. Benn and Ballantyne, 1994 for details), the gravels fall into the subglacial envelopes (Table 2; Lukas et al., 2013). In summary, it would appear that the majority of the clasts were only transported a relatively short distance by ice.

The cryoturbation structures are interpreted as either thermokarst or flat-bottomed involutions, the bases of which indicate an active layer of at least 2.5 m when they were forming resulting from liquefaction (load casting) of sediments in a very wet environment. They are similar in size, shape and connectivity to those described from Belgium by Gullentops and Paulissen (1978). The numerous *in situ* broken clasts that found throughout the gravel unit are interpreted as indicating intense freeze/thaw processes either just after gravel deposition or during subsequent periglacial phases. The involution fill is unimodal and best described as a moderately sorted gravelly sand, dominated by sand in the 250–350 μm size range.

Luminescence ages

As can be seen in Table 2, whilst the IR_{50} D_e measurements are consistent with each other, they are much smaller than their equivalent $pIRIR_{225}$ D_e values even when the residual has been subtracted from the latter. Given both the IR_{50} and $pIRIR_{225}$ D_e distributions are broadly similar in shape (Fig. 9), it is thought less likely that the younger IR_{50} ages represent better resetting prior to burial. Instead it is thought the lower ages represent the impacts of uncorrected for anomalous fading. No fading correction was made on the $pIRIR_{225}$ measurements as studies have shown natural (as opposed to laboratory-induced) fading at elevated temperatures is reduced or not observable (e.g. Rhodes 2015). On this basis, the $pIRIR_{225}$ ages are preferred and used in the discussion that follows.

The uppermost sample (Shfd18079) at Maidcross Hill has an age of 14.4 ± 0.6 ka indicating MIS 2 deposition at the site, associated with periglacial cryoturbation and aeolian activity as seen

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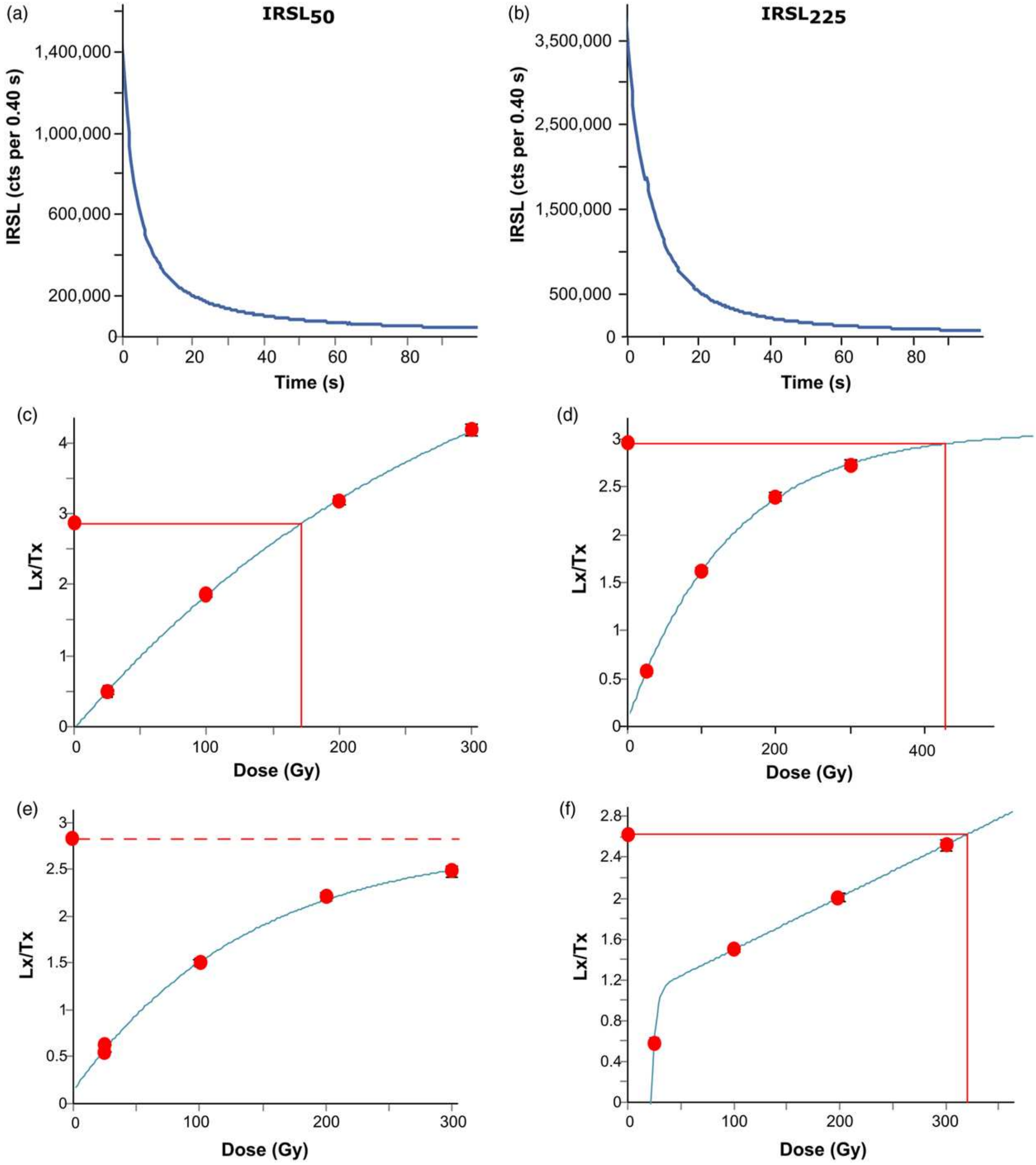

Figure 8. Example IRSL data from sample Shfd18077. (A) and (B) Shine down curves showing rapid trap emptying with IRSL_{50} and IRSL_{225} stimulation. (C) and (D) SAR growth curves of the same aliquot measured with IRSL_{50} (C) and IRSL_{225} (D). Note where red line intersects the X axis showing a higher recovered Dose for the IRSL_{225} measurement. (E) SAR growth curve measured with IRSL_{50} showing a saturated aliquot where the natural dose plotted on the Y axis does not intersect the SAR growth curve. (F) SAR growth curve measured with IRSL_{50} showing an aliquot best fitted by a single saturating exponential + linear curve to obtain a D_e value.

nearby (Bateman et al. 2014). The other samples from low down in the stratigraphy are much older at 96 ± 4 ka (Shfd18078) and 169 ± 6 ka (Shfd18077). The former is disregarded as despite being lower in the succession, it returns a younger age. As the sample was collected in a test pit dug in the quarry floor, it is presumed to have suffered from anthropogenic disturbance during past quarrying of the site. The best age estimate for the Maidscross Hill deltaic gravels is therefore ~163–175 ka (MIS 6c).

Ages from Shouldham Thorpe conform to stratigraphic depth and are 211 ± 8 ka (Shfd18080), 212 ± 9 ka (Shfd18082) and 244 ± 10 ka (Shfd18081). Taken at face value, the sediments at this site appear to have been emplaced during MIS 7 or the very start of MIS 6 (i.e. Late Wolstonian Substage) at the latest. However, whilst closer examination of the pIRIR data showed no indication of partial bleaching of the aliquot D_e replicates, it did reveal samples Shfd18080 and Shf18081 had saturated aliquots and all samples had large D_e values and required fitting with expontential + linear growth curves. Therefore, it cannot be completely ruled out that these may be saturated ages as the samples appear to be at the limit of the luminescence measurements employed.

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Table 2. Luminescence related data for sampled sites.

								$IRSL_{50}$				$IRSL_{225}$			
Sample Site/Code	Depth from surface (m)	Moisture (%)	Alpha dose rate (μGy a^{-1})	Beta dose rate[a] (μGy a^{-1})	Gamma dose rate[b] (μGy a^{-1})	Cosmic dose rate (μGy a^{-1})	Total dose rate (μGy a^{-1})	n[c]	De (Gy)	OD (%)	Age (ka)[d]	n	De (Gy)[e]	OD (%)	Age (ka)[d]
Shouldham ((52° 38’ 56” N, 0° 26’ 57” E)															
Shfd18080	2.80	4 ± 5	15 ± 2	518 ± 43	325 ± 16	144 ± 7	1795 ± 55	25	315 ± 2.5	9	175 ± 7	17	379 ± 4.7	13	211 ± 8
Shfd18081	6.30	4 ± 5	15 ± 2	583 ± 49	339 ± 17	94 ± 5	1877 ± 72	19	278 ± 2.3	11	148 ± 6	26	458 ± 4.5	6	244 ± 10
Shfd18082	4.55	6 ± 5	15 ± 2	715 ± 61	355 ± 18	116 ± 6	2047 ± 81	28	317 ± ± 2.8	8	155 ± 6	28	433 ± 4.1	6	212 ± 9
Maid Cross (52° 24’ 47” N, 0° 32’ 33” E)															
Shfd18077	7.20	3 ± 5	16 ± 3	534 ± 44	318 ± 16	85 ± 4	1684 ± 64	20	178 ± 1.4	15	106 ± 4.1	17	284 ± 2.7	9	169 ± 6
Shfd18078	7.60	5 ± 5	19 ± 3	719 ± 58	467 ± 24	82 ± 4	2017 ± 77	25	204 ± 1.3	16	101 ± 3.9	25	194 ± 1.4	16	96 ± 4
Shfd18079	0.70	3 ± 5	15 ± 3	530 ± 44	336 ± 16	192 ± 10	1867 ± 67	21	23.7 ± 0.14	8	12.8 ± 0.46	21	26.8 ± 0.51	5	14.4 ± 0.6
Watlington (52° 40’ 32” N, 0° 24’ 28” E)															
Shfd19160	1.20	15 ± 5	14 ± 2	243 ± 20	155 ± 8	178 ± 9	1382 ± 52	24	151 ± 1.0	7	109 ± 4.1	24	204 ± 2.1	10	148 ± 6
Shfd19161	2.10	15 ± 5	17 ± 3	541 ± 44	428 ± 24	158 ± 8	1937 ± 69	14	45.0 ± 0.28	12	23.2 ± 0.84	18	50.6 ± 0.59	12	26.1 ± 1.0
Shfd19162	2.00	15 ± 5	22 ± 4	743 ± 59	234 ± 13	160 ± 8	1951 ± 77	22	40.3 ± 0.21	14	20.7 ± 0.82	24	50.5 ± 1.6	13	25.9 ± 1.3
Shfd19163	0.95	15 ± 5	16 ± 3	462 ± 38	144 ± 8	185 ± 9	1599 ± 40	23	208 ± 1.4	10	130 ± 5.1	22	307 ± 2.6	13	192 ± 5

[a] Dose rate determined from ICP-MS elemental concentrations with an assumed internal K concentration of 12%.

[b] Dose rate determined by in situ gamma spectroscopy.

[c] Number of accepted aliquots.

[d] Ages presented in years from the year 2020 with 1 sigma uncertainties.

[e] An experimentally determined residual of 10.73 Gy was subtracted from the measured D_e to obtain the value presented.

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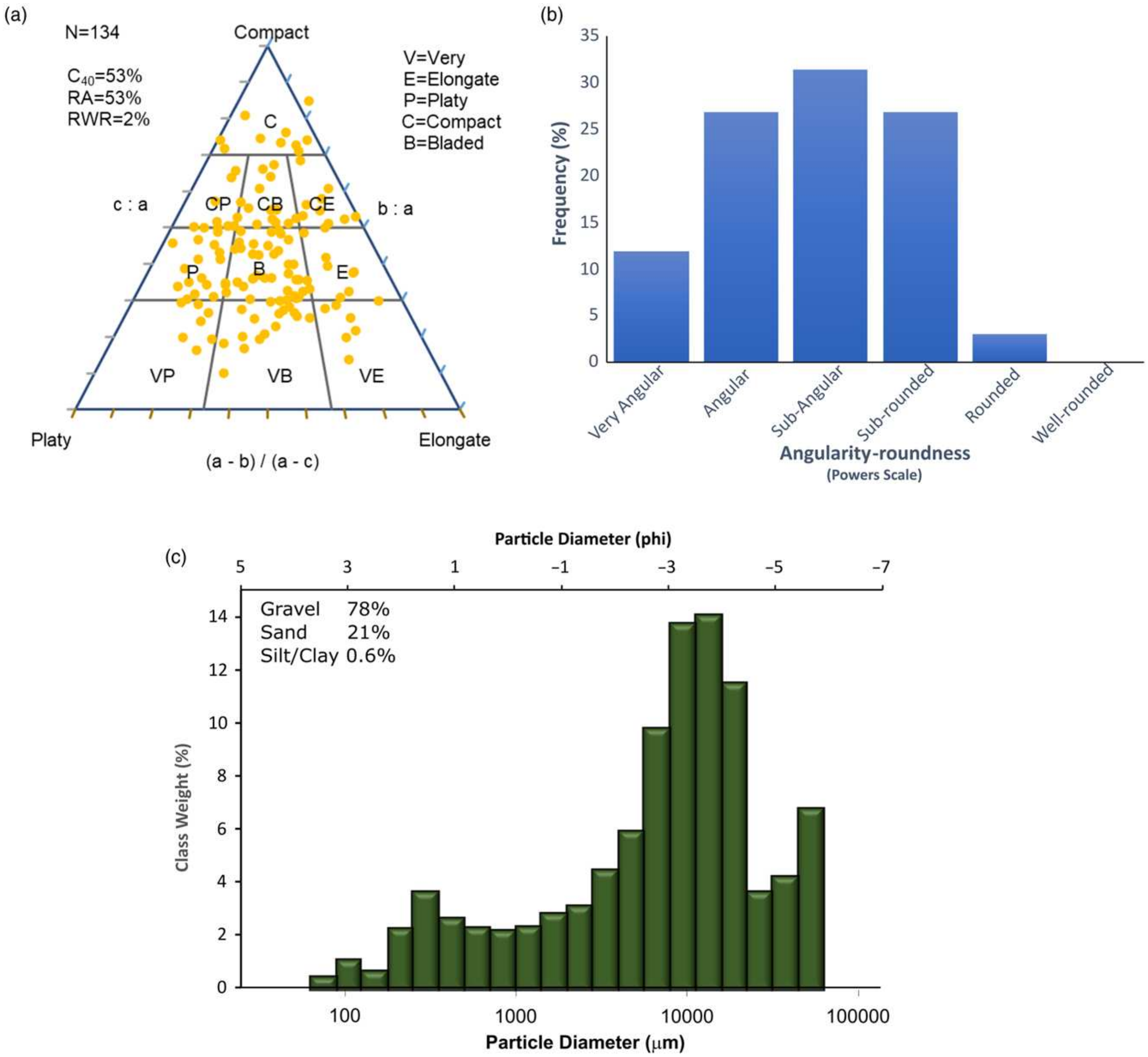

Figure 9. Sediment characterisation of the Watlington Gravels (A) Shape (B) Roundness/Angularity (C) Particle size distribution of Watlington Gravels.

At Watlington, the extensive gravel unit yielded ages of 148 ± 6 ka and 192 ± 5 ka (Shfd19160 and Shfd19163). Subsequent to this intense and severe periglacial activity took place during MIS 2 (i.e. the Late Devensian Substage) based on the ages from the involutions which were 26.1 ± 1.0 ka and 25.9 ± 1.3 ka. These coincide with a time when the last British and Irish Ice sheet was approaching the present Norfolk coast ~30 km to the north (Evans *et al* 2019). The best age estimate for the Watlington Member gravels is therefore ~148–192 ka (i.e. MIS 6, Late Wolstonian Substage).

Synthesis

Numerical age dating

As already stated, the aim of this project was to examine whether previously published attributions of the Tottenhill glacial advance and the Skertchly Line to MIS 6 (~160 ka, i.e. Late Wolstonian Substage) could be geochronologically substantiated. Ages from Shouldham are older than MIS 6. Whilst no evidence was seen in the luminescence data of partial bleaching, the sediments sampled are thought to have only been a maximum of 30–50 m from the Tottenhill glacial ice front and were deposited in a shallow channel eroded into the Lowestoft diamicton. This raises the possibility that the sediments were moved subglacially (possibly not very far) and laid down under turbid water thereby precluding *any* bleaching of the pIRIR signal (e.g. Livingstone et al., 2015; Bateman et al., 2018). If this was the case, then the ages from Shouldham are maximum ages for the Tottenhill glacial advance and possibly provide numerical ages of the pre-existing sediment from which they were reworked. Future work using pIRIR at multiple elevated temperatures (e.g. Bateman et al., 2021) to access signal of varying bleachability and at the single grain level would be able to better understand whether partial bleaching or no bleaching is an issue in such ice-proximal settings. In doing this, careful evaluation of saturation limits may be required for some samples. In contrast, the new dating results from both Maidcross Hill and Watlington are coincident with each other, show no problems with

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saturating signal and clearly support a MIS 6 age for the Tottenhill glacial advance.

In light of these new ages, a re-examination is needed of previously reported evidence relevant to the Tottenhill glaciation and why, in some instances, a MIS 8 or older age has been ascribed to it. In support of an MIS 6 attribution, a sample from the Tottenhill Sands and Gravels Member gave an OSL quartz age of c. 160 ka (S. Pawley, 2006; personal communication) as did a preliminary determination by E. Rhodes (personal communication) from the sands at the Warren Hill (Three Hills). Looking further afield at other glacially related sediments, two OSL dates from the glaciolacustrine Plantation Sands (Lewis, 2012; Gibbard et al., 2018) at Lynford, Suffolk, in the Wissey valley gave ages of 169 ± 26.9 ka and 176 ± 27.7 ka (Schwenninger and Rhodes, 2012, pp. 30, 68). Additionally, the ages from the Stiffkey moraine on the north Norfolk coast dated this to 141 ± 9.4 and 165 ± 11 ka by Evans et al. (2019). Taken together, these ages strongly suggest the Tottenhill ice advance was of MIS 6 in age.

Although some authors suggested that the Tottenhill glaciation might be of Middle Wolstonian (c. MIS 8 or 10) age, such a correlation was, however, based on OSL ages reported by Straw (2000, 2005, 2011) and White et al. (2010, 2017) from Lincolnshire and the Trent valley system ~90 km further north-west. This association has been previously rejected by Schwenninger et al. (2007a/b, p.65) who described these OSL ages as 'inaccurately determined' and that 'only dates from deposits younger than the Ipswichian are credible'. Elsewhere, glaciations that may have occurred early during the Wolstonian Stage (?MIS 8–10) have been previously suggested (cf. Clark et al. 2004). These were based principally on geochronometry of overlying or underlying non-glacial deposits and long-distance comparison with the Thames' system deposits in the south English Midlands. The evidence central to the interpretation was that obtained from U-series determinations from the Nar Valley, near Kings Lynn in Norfolk. Here, the glaciolacustrine Setch Clays (part of the Nar Valley Clays) overlie Lowestoft Formation till and are, in turn, overlain by ice-contact glaciodeltaic Tottenhill Member sands and gravels. A freshwater peat underlying the Setch Clay yielded an age of 317 ± 14 ka (Rowe et al., 1997), which Rose (in Clark et al., 2004), following Scourse et al. (1999), interpreted as implying that the underlying till was deposited during MIS 10. The most frequently quoted example of pre-MIS 6 late Middle Pleistocene glaciation is that reported by Beets et al. (2005) suggesting that pre-Late Saalian (i.e. Middle Saalian; MIS 8) till occurs in the North Sea basin based on geophysical, micropalaeontological and amino-acid age evidence. While there is no question that till occurs at the site, there remains scepticism about the age attribution among Dutch workers who generally attribute these deposits to the Late Saalian (MIS 6; Cohen, K.M., personal communication, 2017). Despite other possible MIS 8 records from other circum – North Sea localities (e.g. White et al., 2010, 2017; Davies et al., 2012; Bridgland et al., 2015; Roskosch et al., 2015), all of these remain equally equivocal. Nowhere else in eastern England, nor the adjacent North Sea basin, has a diamicton of this age been identified and it this conflicts with both the litho- and biostratigraphy at Tottenhill (cf. Ventris, 1985, 1986, 1996), as well as with the regional stratigraphy (Gibbard et al., 1992; Gibbard, in Clark et al., 2004). Recent, amino-acid racemisation results from shells found in the Nar Valley Freshwater Beds indicate a MIS 9 and MIS 11 deposition (Barlow et al., 2017), making the underlying till more likely to relate to MIS 12. The unconformably overlying Tottenhill sands and gravels by implication therefore must post-date MIS 9, so they do not contradict the above new chronological attribution of them to MIS 6.

Elsewhere in East Anglia dating of samples collected from what are presumed to be the ice-contact (glaciomarginal) deltaic deposits at Warren Hill (i.e. Three Hills) and Maidscross Hill, that is, the Three Hills and Maidscross member, have been reported by Voinchet et al. (2015). These samples were dated by the electron spin resonance (ESR) method and produced ages of 544 ± 53 ka and 539 ± 38 ka, and 529 ± 55 and 631 ± 56 ka, respectively, which these authors conclude indicates the sediments being deposited during the early Middle Pleistocene. The deposits they dated, however, include significant quantities of chalk clasts (unlike those in the present study), which have demonstrably undergone post-depositional solution, thereby making it likely that the dose rate used for the ESR ages through time has changed. Additionally, since these sediments were deposited in an immediate ice-contact position with the Tottenhill ice lobe (as at Shouldham in this study) and the ESR signals used are harder to reset than those of OSL or IRSL, age over-estimation is possible due to the presence of an unreset antecedent signal at burial. It may be therefore that the dates obtained, rather than reflecting the ice-contact deltaic depositional event represented by the Skertchly Line sequences, instead indicate the age of the source deposits from which the materials were reworked by the Tottenhill ice lobe.

Regional implications

A MIS 6 (~160 ka) Tottenhill glacial advance reinforces the view previously presented that during the Late Wolstonian Substage (the Drenthe Stadial: Table 1), a substantial ice lobe advanced down the eastern side of Britain entered the Fenland and fanned outwards broadly towards the east, south-east, south and west (Figs. 3, 11). The advancing ice apparently stalling against the rising ground was underlain by the more resistant bedrock and was halted by the rising ground of the chalk hills to the east and south Chalk on the East Fenland margin. Deposition of these ice-contact delta fans (the Skertchly Line), which prograded into ice-dammed lake or lakes in direct contact with the ice lobe (Gibbard et al., 2009; 2018), arose from damming of the local streams, such as the Lark and Little Ouse. Initially, the lakes formed in each valley, but subsequently coalesced as the water level rose to form the extensive Lake Paterson in the south and south-eastern Fenland marginal zone. Similar lakes formed in the Nar and Wissey valleys. At Shouldham Thorpe above the lake level, a subaerial ice-contact fan was formed.

As Gibbard et al. (2009; 2018) have demonstrated, after reaching its maximum extent, the ice began to retreat in an oscillatory fashion, the dynamic ice front alternating stillstands or minor re-advances that punctuated the general ice lobe retreat. During this period the Watlington Member gravel spread, on the north-eastern Fenland margin, northwards flowing meltwater marginal to the Tottenhill ice lobe apparently formed as a kame terrace-like deposit. This glaciofluvial unit, abutting the Tottenhill delta, demonstrably post-dates the latter. This indicates the kame terrace almost certainly accumulated during a stillstand phase in the local ice recession when drainage was aligned northwards towards the North Sea via the Wash gap, contrasting with the eastwards drainage that occurred during the maximum phase represented by the glacio-lacustrine deposits at Tottenhill and other Skertchly Line localities.

Severe periglaciation during the latest Wolstonian time and through the Devensian Stage is represented by the substantial

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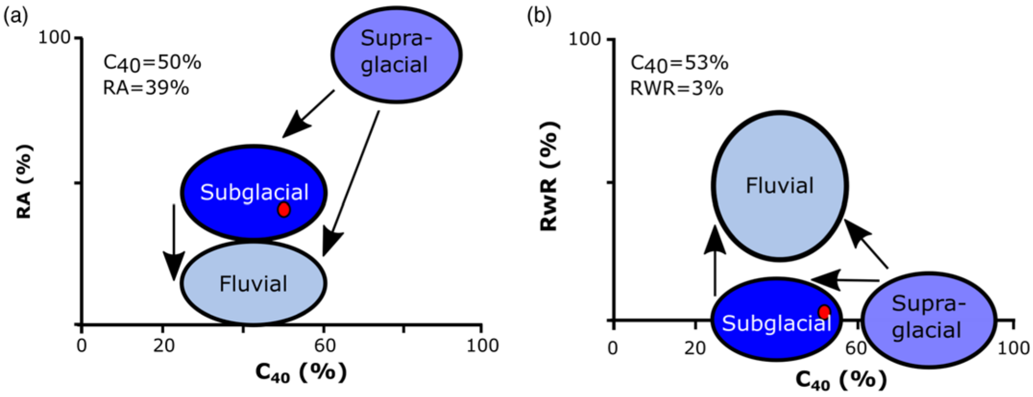

Figure 10. Roundness indices applied to the Watlington Gravels indicating (as per Lukas *et al* 2013) a sub-glacial origin. **(A)** the C_{40}/RA covariance where the RA index for roundness is calculated as the percentage of angular and very angular clast in a sample **(B)** the C_{40}/RWR covariance where RWR index is calculated as the percentage of rounded and well-rounded clast in the same sample.

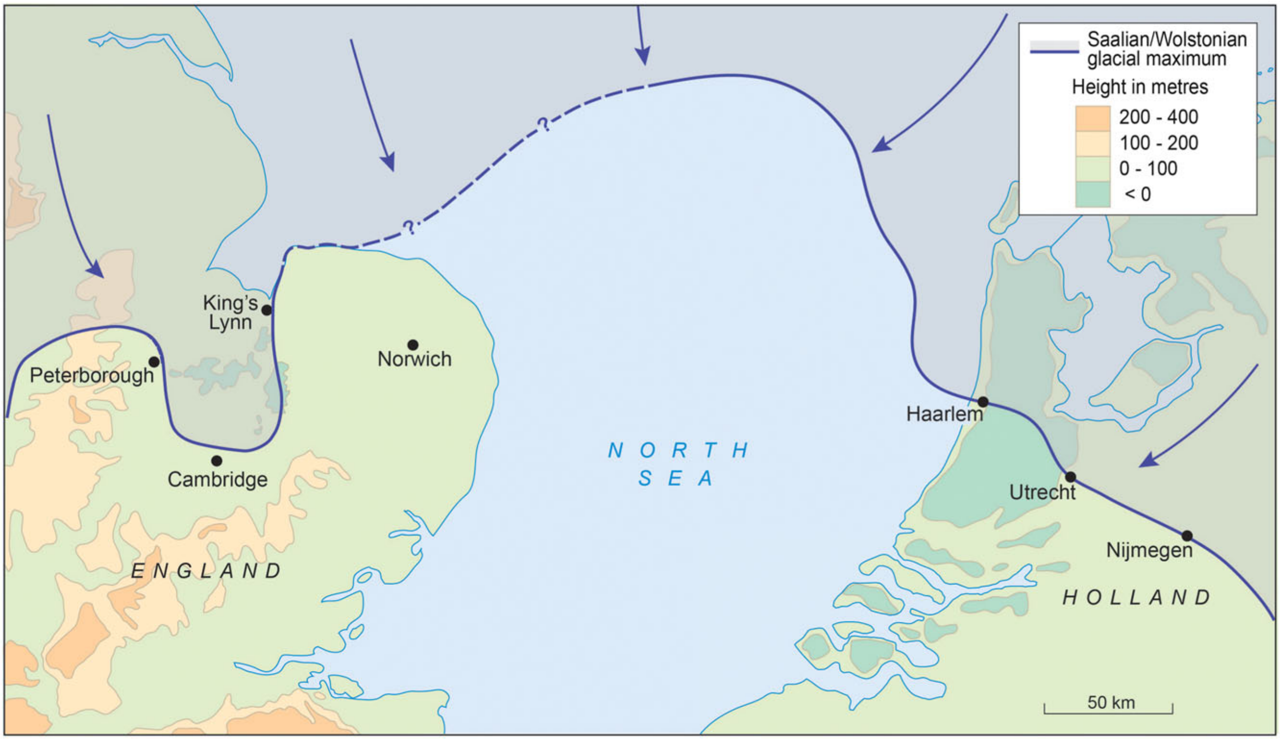

Figure 11. Postulated maximum limit of the Wolstonian Tottenhill and equivalent Drenthe glacial lobes in the southern North Sea basin. Modified from Gibson (2018) and Gibbard et al 2009).

ice wedge casts and associated cryogenic structures at Watlington. A further significant development during the Devensian was the wide dispersal and deposition of aeolian coversand, most recently during the Late Devensian Substage (~MIS 2), largely originating from recycling of the distal-deltaic sand beds of the Wolstonian glacial lake deposits over the landscape, giving the character of the Breckland of East Anglia (Bateman et al., 2014), and represented in the uppermost deposits at Watlington, Shouldham Thorpe and Three Hills (Warren Hill).

An equivalent to the substantial glaciation in eastern England during the Wolstonian Stage has been recognised by Shotton (1953, etc.) and Rice (1968, etc.) in the adjacent English Midlands. Bridgland et al. (2015) and White et al. (2010) noted a potentially equivalent glaciation during investigations of River Trent terrace deposits in adjacent western Lincolnshire and Nottinghamshire. However, these authors followed Straw (2000, 2005, 2011) in favouring an older age for the glaciation, which they equated to MIS 8 (i.e. Middle Wolstonian Substage: Fig. 1b) rather than MIS 6, an attribution based on the landscape relationships in the Lincolnshire district. Straw (2000, 2005, 2011) also based his correlation of the glaciation with MIS 8 by comparison with the near Continent, where he considered the substantial glacial event, the classical Saalian Glaciation, also occurred during that stage. Unfortunately, Straw's (2000, 2005, 2011) assumption is not supported by continental workers, the Late Saalian (Drenthe Stadial) Glaciation having been repeatedly equated with MIS 6 throughout northern Europe (e.g. Zagwijn, 1973; Busschers et al., 2008; Toucanne et al., 2009; Ehlers, 2011; Roskosch et al., 2015; Lang et al., 2018). 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' (e.g. White et al., 2017). The dating evidence in the River Trent successions is

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also disputed (cf. Gibbard et al., 2021). 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 was tested during the current studies.

As Gibbard et al. (2009, 2011) and Clark and Gibbard (2011) demonstrate, the age attribution to MIS 6 is further reinforced in the southern North Sea basin (Fig. 11). Here detailed analysis of offshore geophysical evidence indicates that the 'Skertchly Line' glacial limit can be traced north of East Anglia (the Norfolk High), based on the extent of tunnel valleys, marginal ice-contact delta-fan accumulations closely similar to those on-land and push moraine ridge structures. Where this limit reaches the North Sea Centre Line, it continues directly as the Netherlands' Drenthe Stadial glaciation maximum (Moreau et al., 2009; Moreau, 2010; Clark and Gibbard, 2011, Gibbard et al., 2009, 2012a, b). The detailed seismic analysis clearly differentiates this strongly defined feature from those of the earlier and later glaciation limits. The identification of the Tottenhill/Drenthe line confirms that the glacial maximum identified in the Fenland region by Gibbard et al. (1992, 2009, 2011, 2018) is indeed the continuation of the southernmost limit of the Drenthe Stadial glaciation in the Netherlands (Amersfoort–Nijmegen glaciotectonic ridge) (Laban and van der Meer, 2004; Busschers et al., 2007, 2008; Kars et al., 2012), the British and Scandinavian ice lobes being confluent, and further east in western Germany (e.g. Lang et al., 2018). It must therefore represent the same interval, that is, c. 180–160 ka, as Gibbard et al. (1992; 2009; 2018) and Clark and Gibbard (2011) concluded. Beyond the confluent British and Scandinavian ice sheets, a glacial lake was formed in the southern North Sea basin (cf. Busschers et al., 2007, 2008; Gibbard, 2007; Cohen et al., 2014; Ehlers, 2011; Gibbard and Cohen, 2015), the overflow discharge from which it is recorded off the English Channel in the Bay of Biscay ocean floor sediments (Toucanne et al., 2009). This evidence confirms the correlations shown in Table 1.

Conclusions

In order to test the previously established conclusions that the east Fenland margin glacial complexes and associated kame terrace-like deposits (Feltwell Formation) dated from the late Middle Pleistocene, a series of luminescence samples were collected from three significant localities in the Tottenhill glaciation Skertchly Line limit. The samples from Shouldham Thorpe and Maidscross Hill, Suffolk, were taken respectively from a subaerial glaciomarginal (ice-contact) alluvial fan and fan delta deposits, whilst those from Watlington, Norfolk, were collected from ice-marginal, subaerial kame terrace deposits.

Results firmly support the correlation of the Tottenhill glaciation with the Late Wolstonian Substage (MIS 6). The dates obtained correspond closely to those obtained from glaciofluvial deposits at Stiffkey on the Northwest Norfolk coast, those determined from the glaciolacustrine Plantation Sands (representing Lake Paterson) at Lynford, Suffolk, in the Wissey valley, together with unpublished determinations from Tottenhill and Three Hills (Warren Hill) previously noted by Gibbard et al. (2009, etc.). These ages conflict with the considerably older age determined from samples collected from deposits at Warren Hill (i.e. Three Hills) and Maidscross Hill, that is, the Three Hills and Maidscross members obtained by Voinchet et al. (2015) which are rejected as age over-estimates (see text for discussion). Likewise, U-series determinations from the late-Anglian age glaciolacustrine Setch Clays at Tottenhill, Norfolk, underlying the glaciodeltaic Tottenhill Member sands and gravels, which gave an MIS 9 age, have also been rejected.

Later formation of substantial permafrost structures, in particular ice wedge casts and cryoturbations at Watlington, together with widespread aeolian deposition of reworked glaciolacustrine sands, occurred under periglacial conditions, most recently during the Late Devensian Substage (~MIS 2).

The new ages support the previous conclusions regarding the age of the maximum extent of the Late Wolstonian ice lobe in East Anglia (Table 1) and correspond closely to dating of the glacial maximum in the West Midlands type area (Gibson, 2018).

Comparison with the sequences and geochronology on the eastern side of the North Sea indicates that they correspond closely both in terms of the geology and their geochronology with the Tottenhill glaciation and indeed confirms that it is the direct equivalent of the Late Saalian Drenthe Stadial in the southern North Sea basin and on the adjacent Continent. Indeed the Skertchly Line glacial maximum limit appears to represent the direct continuation of the Amersfoort–Nijmegen glaciotectonic ridge limit in the central Netherlands. This conclusion demonstrates the nature and behaviour of the Late Wolstonian/Late Saalian ice margin across the southern North Sea region, the ice margin being characterised by multiple lobate oscillations giving rise to glaciotectonically ice-pushed ridge landforms and associated localised meltwater discharge landforms. In total, the nature of these landforms, together with their localised distribution suggest that the ice margin, at its maximum extent, was dynamically active and potentially unstable.

Future work should concentrate on carefully controlled numerical age dating of other localities in the region as they become available. Given the ice-proximal (glaciomarginal) nature of many of the sediments associated with the Skertchly Line and the apparent antiquity, future application of luminescence dating to them would benefit from avoiding chalk-rich deposits whose dose rate may have changed through burial due to dissolution. Also careful evaluation of how well the sediments are bleached should be undertaken both through measurement at the single grain level and using measurements made at multiple elevated temperatures to access signals with a range of bleachability (cf. Bateman et al. 2021). However, needless to say, the samples should be determined from profiles that are fully understood in regard to their genesis and relationship to local and regional sequences.

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