Lee, J.R. 2014. Outwash sedimentation and glacitectonic deformation during accretion of the Cromer Ridge: evidence from Holt, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, 64, 3-31.

OUTWASH SEDIMENTATION AND GLACITECTONIC DEFORMATION DURING ACCRETION OF THE CROMER RIDGE: EVIDENCE FROM HOLT, NORTH NORFOLK, UK

Jonathan R. Lee
British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.

Email: jrlee@bgs.ac.uk

ABSTRACT

Sections through sand and gravel deposits exposed by aggregate extraction provide further evidence for the development of a complex proglacial / ice-marginal meltwater drainage system during the Anglian Glaciation. Their sedimentology indicates that deposition occurred within a series of anastomosing braided river channels – interpreted as background sedimentation, punctuated by episodes of elevated discharge characterised by unconstrained sheet-flow. Meltwater sediments form part of an extensive (albeit heavily-dissected) sandur that extends southwards from Cromer towards Norwich and developed during a temporary ice-marginal still-stand associated with the formation of the Cromer Ridge 'moraine complex'.

INTRODUCTION

One of the most striking reminders that much of north Norfolk's landscape was shaped by past episodes of glaciation is the Cromer Ridge - a prominent landform that extends westwards from Cromer and Trimingham to Fakenham (Figure 1) (West, 1957; Straw, 1973; Straw and Clayton, 1979; Boulton *et al*., 1984; Hart and Boulton, 1991). The Cromer Ridge forms part of a moraine complex produced at the terminus of a Middle Pleistocene ice advance that extended southwards down the current western margins of the Southern North Sea Basin into north Norfolk (Boulton *et al*., 1984; Hart, 1990; Pawley, 2006; Lee *et al*., 2013). However, rather than reflecting the maximum ice-marginal position (Hart, 1990; Hart and Boulton, 1991), current interpretations suggest that the Cromer Ridge represents a temporary still-stand produced during the retreat of the ice margin from a maximum extent located further to the south (Lee *et al*., 2013). Boreholes and field exposures through the eastern sector of the Cromer Ridge reveal that the landform possesses a complex internal architecture composed of thrust-stacked slices of pre-existing glacigenic sediment and forms part of the so-called 'Contorted Drift' (Reid, 1882; Boulton *et al*., 1984; Banham, 1988; Hart, 1990; Ehlers and Gibbard, 1991; Hart and Boulton, 1991; Pawley, 2006; Lee *et al*., 2013). Draped over the ridge and extending southwards towards Norwich is a heavily-dissected sheet of outwash sands and gravels (West, 1957; Banham, 1977; Straw, 1979; Moorlock *et al*., 2000; Pawley *et al*., 2005; Pawley *et al*., 2008). The lithology and extent of these gravels is well-established (Solomon, 1932; Straw, 1973; Straw and Clayton, 1979; Moorlock *et al*., 2002; Lee, 2003; Lee *et al*., 2004), however, their origin and precise genetic relationship to the Cromer Ridge is generally poorly constrained. Within this paper, the sedimentology of outwash sands and gravels from a site in north Norfolk is examined and placed within the wider framework of ice-marginal retreat.

GEOLOGICAL CONTEXT

The study locality is Holt Quarry (National Grid Reference: TG 073,369) situated approximately 1km to the south-southwest of Holt, north Norfolk (Figure 1). Where the original ground surface is preserved, it occurs between approximately 60 to 63 metres OD. This elevated topography forms part of the Cromer Ridge, a pronounced ridge that trends broadly west-southwest to east-northeast across north Norfolk from Thursford in the west, through Holt to Overstrand and Trimingham in the east where the landform intersects the coast (Boulton *et al*., 1984; Hart, 1990; Lee *et al*., 2013).

The Cromer Ridge has been widely interpreted as a composite push moraine formed at the maximum extent of a major southwards ice advance into the North Sea Basin (Reid, 1882; Banham, 1988; Hart, 1990; Hart and Boulton, 1991; Lunkka, 1994). The age of the landform has proven controversial (Boulton *et al*., 1984; Lee *et al*., 2011a, 2012) with opinions sharply-divided between an Anglian (MIS 12) (Banham *et al*., 2001; Preece *et al*., 2009) or later Middle Pleistocene (MIS 6) age (Clark *et al*., 2004; Hamblin *et al*., 2005; Rose, 2009). Subsequent OSL dating of gravels that cap the Cromer Ridge demonstrate deposition during the Anglian Glaciation and, by inference, the accretion of the ridge during the same glaciation. More recently, Lee *et al*. (2013) has argued that the Cromer Ridge represents the position of a temporary ice-marginal still-stand associated with a more extensive and complex pattern of ice-marginal retreat from a maximum position probably located around Aylsham.

One of the critical themes highlighted by Lee *et al*. (2013) is that a glacier advance does not always result in the deposition of a till unit – often the only record of glaciation may be a range of glacitectonic structures (folds and faults) produced as the ice overrides or pushes into and deforms adjacent substrate (Slater, 1926; Banham, 1977; Evans *et al*., 2006; Lee and Phillips, 2013). Extensive glacitectonic evidence exists in north Norfolk for several major ice advances across the region which deposited either no till, or thin till units of very-limited spatial extent (Banham and Ranson, 1965; Banham, 1966, 1975; Lee and Phillips, 2008; Phillips *et al*., 2008; Waller *et al*., 2011; Fleming *et al*., 2013; Lee *et al*., 2013; Phillips and Lee, 2013). Therefore, the preserved lithostratigraphic record of glaciation in north Norfolk, which has been extensively described by Banham (1968), Lunkka (1994) and Lee *et al*. (2004), provides an incomplete and minimum record of the glacial history of the region (Lee *et al*., 2008). This was recognised by Banham (1988) who developed a hybrid tectonostratigraphic scheme for the region encompassing both the major lithostratigraphic sub-divisions coupled with major glaciotectonic elements. Subsequent evolution of this scheme encompassing more recent lithostratigraphic and glacitectonic interpretations has recognised six major tectonostratigraphic elements (A1-A6) each associated with a major Middle Pleistocene advance of ice across the region (Table 1) (Lee *et al*., 2011b, 2013).

Of relevance to this study are the three younger tectonostratigraphic elements (A4-A6). Advance 4 (A4) was produced by a north to south advance of British North Sea ice into north Norfolk. It deposited the Bacton Green Till Member (Third Cromer Till) and associated glaciolacustrine and outwash deposits belonging to the Sheringham Cliffs Formation (Lee *et al*., 2004). Subsequent retreat of British North Sea ice led to the expansion (A5 – Advance 5) of Pennine ice across East Anglia (West and Donner, 1956; Perrin *et al*., 1979; Rose, 2009; Scheib *et al*., 2011). Deformation of the underlying sediment pile as ice advanced across north Norfolk led to the development of a pervasive glacitectonic melange (Hart, 2007; Lee and Phillips, 2008; Phillips *et al*., 2008; Fleming *et al*., 2013; Phillips and Lee, 2013) and a highly-localised chalky till (Perrin *et al*., 1979; Ehlers *et al*., 1987; Ehlers *et al*., 1991; Fish *et al*., 2000; Fish and Whiteman, 2001). A final readvance (Advance 6 – A6) of North Sea ice extended southwards across north Norfolk overriding and tectonising underlying sediments. The ice margin retreated from its maximum extent, producing a series of small 'active-retreat' terminal moraines before reaching a temporary still-stand position whereupon the Cromer Ridge was formed (Lee *et al*., 2013).

METHODOLOGY

Exposures at Holt Quarry were examined during several visits to the site between 2002 and 2006. The locations of exposures were recorded using a GPS with elevation datum surveyed relative to a local datum point using standard levelling equipment. Individual exposures were logged with a particular emphasis placed upon describing sediment texture, structure (sedimentary and tectonic) and the nature and geometry of major bounding surfaces. For the purposes of communication, figures displaying the examined exposures show lithofacies codes which summarise the main sedimentary features (Table 2). Palaeocurrent measurements were collected from bedding foresets and plotted (frequency) within rose diagrams. The dip angle and dip azimuth of fault planes were also collected using a compass clinometer, with their relative ordering denoted using standard structural nomenclature (F1, F2, F3....Fn). Fault measurements were plotted within an equal-area lower hemisphere stereographic projection (Schmidt net) as pole to planes, great circles and contours.

Lithological analysis was also undertaken on bulk gravel samples to quantitatively characterise their composition, aid provenance and correlation. Bulk samples were sieved using a combination of wet and dry sieving (Gale and Hoare, 1991) to extract the gravel fraction with counts performed on the 8-16mm and 16-32mm to enable comparison with regional data sets (Lee, 2003).

DESCRIPTION AND INTERPRETATION OF EXPOSURES

Three sections from Holt Quarry are described below (Exposures A-C) with Exposures A and B located within a lower excavation-bench and Exposure C within a higher excavation-bench.

Exposure A

Exposure A comprises a 5m thick sequence of sand and gravel capped by artificial ground (Figure 2). Basal horizons within the section are largely obscured by talus but reveal a 50cm thick sequence of horizontally-bedded fine to medium sand. Resting conformably upon these sands are a thick (33-52cm) bed of massive, clast-supported well-sorted cobble-gravel with occasional lenses of coarse sand. Cobbles possess long-axis lengths ranging from 6-14cm with flint clasts typically well-rounded and spherical (i.e. 'cannon-shot'). They are overlain conformably by a 30cm thick unit of massive to horizontally-bedded sand, truncated in-turn, by a series of shallow (upto 0.45m depth) cross-cutting sand-filled channels. Channels exhibit slightly irregular bases and contain horizontal-bedded, planar- and trough cross-bedded sets of fine to medium sand with foresets dipping towards the south and south-southwest (Figure 3a) Resting conformably upon the channel sediments are a 1.2 to 1.4m thick unit of matrix- to clast-supported cobbles and gravel. Overall, the unit fines-upwards into medium-coarse sandy gravel and is gently-inclined towards the southwest. Gravels are largely massive in structure with faint bedding discernible by sharp changes in clast size and sorting.

Gravels are truncated by early phase (F1) faulting that comprises three moderately to steeply-inclined reverse faults. Throws of between 15-25cm were recorded with fault planes dipping northwards (Figure 4). A second stage (F2) of low-angle thrust faulting truncates F1 faults with the fault plane also dipping northwards. F2 faulting is truncated in-turn by sands that cap the sequence. The shape of the contact between the gravels and overlying sand unit (upto 2.3m thick) varies along the length of the exposure. At the northeast end, sands occupy a deep (1.3m) irregular-shaped channel incised into the underlying gravels, whereas to the southwest, the contact exhibits smaller-scale irregularity comprising localised small scours, flame-like contortions and disharmonic inter-folding. Bedding within the main sand-body comprise sets of horizontally- and trough-cross bedded sand, which are dissected to the northeast by a broad, shallow channel infilled by trough cross-bedded sand. Two subsequent episodes of faulting deform sediment within the upper parts of the exposure. F3 faulting comprises two steeply-dipping normal faults situated at the southwestern end of the exposure that form a down-faulted graben structure - the amount of throw is 25cm. Cross-cutting F3 are two further F4 faults (Figure 4). The first fault, located at the southwest end of the exposure, is a steeply-inclined reverse fault that dissects the entire observable sequence. The footwall-block within this fault has been downthrown towards the north by approximately 5cm. The second fault dissects the higher sands and uppermost gravelly sands and is a moderately-inclined reverse fault that dips towards the north-northwest.

Sand and gravel units within Exposure A detail subaqueous sedimentation driven by variations in flow regime and sediment supply. The lowermost horizontally-bedded fine sand records lower plane bed flow and subaqueous bar-top deposition (Miall, 1978). The overlying unit of well-sorted cobbles are interpreted as the product of bedload deposition from high-energy tractive sheet-flow with winnowing of the sand fraction. Subtle and highly-localised drops in flow regime enabled the deposition of occasional lens-shaped sand bodies. Overlying horizontally-bedded sands indicate a return to a lower plane bed flow regime and the deposition of fine to medium grained sand. Dissection of these sands by several cross-cutting channel structures record channelised flow associated with several small and laterally-migrating channels. Sedimentation within these channels was driven by the down-current migration of straight-crested (planar cross-bedding) and lunate (trough cross-bedding) sandy bedforms. The overlying unit of massive to faintly-bedded gravels with variable sorting suggest a switch-back to sedimentation of coarse clastic bedload from tractive sheet-flow characterised by frequent but subtle changes in flow regime and sediment supply. An overall fining-upwards in particle size is interpreted as evidence for reducing flow conditions. Sands and gravels are separated from the overlying sand unit by an erosion surface that includes the channel-structure at the northwest end of the exposure. This surface was probably generated by a high-energy tractive current that variably scoured and down-cut into the underlying unit. Sedimentation continued with the deposition of the horizontally-bedded sands under upper flow regime conditions, and the localised incision of small channels. Flame-like contacts and disharmonic inter-folding of the two units are indicative of rapid deposition and loading of a seemingly water-saturated sand and gravel.

Normal faulting and the graben structure (F3) are likely to be the product of consolidation induced by either drying of the sediment pile or loading. By contrasting, the three phases of reverse faulting (F1, F2 and F4) indicate the application of later shear-stresses to the sediment pile. Their geometric relationship to sediments within the exposure demonstrate that they were generated during (F1 and F2) and following deposition (F4).

Exposure B

Exposure B is situated approximately 100m to the southwest of Exposure A with sediments partly-obscured by talus (Figure 5). Basal horizons comprise thin (10-15cm thickness) sets of horizontal-laminated and planar cross-bedded fine-medium sand (with foresets dipping towards the southeast; Figure 3b) passing northeast-wards into rippled (Type-B) and horizontally-laminated sand. Occasional thin horizons of fine sand / silt exhibit small convolute bedding structures. Basal sand horizons are overlain conformably by a 1m thick unit of bedded gravel and sand. Gravel beds are variably clast- to matrix-supported, exhibiting weakly-developed horizontal stratification defined by subtle vertical changes in clast size and sorting. In the southwestern half of the section, gravel beds are separated by a thin (30cm thickness) bed of massive to horizontally-laminated fine sand and a small gravels lens with sand laminae often exhibiting convolute bedding. The base of this gravel unit is vertically offset between the southwest and northeast parts of the section by approximately 35cm. The conformable nature of the contact with underlying sandy units indicates, tentatively, that bedding could be offset by faulting.

The remaining 1.5m of the section is composed predominantly of sand. Horizontally-laminated, rippled (Type-A) and massive fine to medium sands drape the underlying beds of gravel. They are dissected at each end of the section by broad, shallow (upto 40cm) channel structures with gently undulating bases. Channels are infilled by sets of planar and trough cross-bedded sand with foresets dipping in a southeast to southwards direction (Figure 3b). Both channels are truncated in-turn by a 0.5m thick unit of horizontally-bedded, massive and rippled sand which forms the uppermost unit within the section. Extensional (normal) faulting deforms the lower horizons of this sand unit and the underlying left-hand channel margins. Faulting is steeply-inclined with the footwall block downthrown towards the south (Figure 4). A lens of finely-laminated silt and clay crops-out within the centre of the section. The lower contact of the lens possesses diffuse to flame-like margins. The lens is offset by a moderately-inclined reverse fault that dips northeastwards with a throw of 8cm (Figure 4). Deformation can be traced down-profile approximately 60cm with the fault truncated up-profile by artificial ground.

Sediments within Exposure B record subaqueous sedimentation associated with a variable flow regime. The basal horizontally-laminated fine-medium sand reflects deposition under lower plane bed conditions associated with subaqueous sediment transport over a bar-surface. Planar cross-bedding records the down-current migration of small straight-crested subaqueous bedforms. Type-B climbing ripples are produced by forward and vertical accretion of small ripples under a constant flow regime and sediment supply. Together with the convolute bedding structures, they suggest that sedimentation was rapid with localised sediment loading and dewatering. Overlying gravel beds record sedimentation from higher-energy bedload currents transporting gravel-sized particles by rolling and/or saltation. Changes in particle size and sorting between beds reflect minor changes in energy regime with the lateral (southwest) switch to sand-dominated deposition interpreted as lower flow conditions within a more marginal locality. Horizontally-bedded and massive sand units that cap the section reflect a switch to deposition under lower plane bed conditions probably associated with sediment-laden currents flowing over a bar-surface. Subtle drops in flow regime and sediment supply are demonstrated by the generation of small non-climbing ripples. Meanwhile, the development of shallow channel structures indicate temporary phases of incision, channelled-flow, and the progradation of straight-crested (planar cross-bedding) and lunate (trough cross-bedding) bedforms. At the top of the section, the silt and clay lens records a dramatic drop in flow regime to gently-agitated to still-water conditions. The lensoid geometry suggests that sedimentation probably occurred within a gentle undulation in the bed surface.

Exposure C

Exposure C is located within a temporary higher-level bench approximately 2m higher than the top of Exposures A and B (Figure 6). The exposure is dominated by sand-rich units which, based upon their elevation and sedimentology, appear to comprise a vertical continuation of sediments described within previous exposures.

The base of the sequence within Exposure C comprises sets of planar cross-bedded fine to medium sand which total 2.2m thickness with foresets dipping towards the southwest (Figure 3c). Within the lower horizons of the unit, a thin (15cm) lens of massive silt drapes an underlying foreset. Cross-bedding and the silt lens is truncated by a major bounding surface which is overlain by further planar cross-bedding. Palaeocurrent measurements show that foresets dip towards the south and southwest. Cross-bedded sands are truncated in-turn by a bounding surface that dips towards the southeast with overlying bedding comprising horizontally-laminated sands, passing upwards into massive and rippled (non-climbing) fine sands. Sands are unconformably overlain by stratified gravels and sands that progressively infill a scoured surface and form a wedge-shaped bed that thickens (20cm to 50cm) eastwards. The infill of the scoured surface comprise massive sand, passing upwards into trough cross-bedded sets of gravel and sand, horizontally-laminated sand, and finally, planar-cross-bedded gravel with foresets dipping variably towards the southwest, south and southeast (Figure 3c). They are overlain by planar- and trough cross-bedded sands and sandy gravels that rest upon a gently undulating lower bounding (erosional) surface. Sands pass vertically into horizontally-laminated sands that grade upwards into massive clayey silts, and in-turn, horizontally-laminated sand. Bedding is locally offset by a small steeply-inclined reverse fault (F5) that dips toward the northeast with a throw of about 1cm (Figure 4). Laterally these sands and silts are cross-cut by a broad and shallow channel structure containing a 30cm thick unit of massive, matrix-supported gravel that fines-upwards and grades laterally into planar-cross-bedded sand. The top of the sequence is marked by a 20cm thick unit of massive to horizontally-bed sand rests upon a sub-horizontal and slightly undulating lower erosion surface.

Deposits observed within Exposure C record phases of a rapidly-aggrading sediment sequence, interrupted by lateral sediment reworking associated with the migration of large subaqueous bedforms (dunes). Planar cross-bedded sands that crop-out at the base of the exposure characterise the down-current migration of straight-crested dunes. Sand-dominated sedimentation was punctuated by bedform stabilisation and suspension-settling of fine sediment under low-energy conditions. Reactivation of higher flow conditions, lateral sediment reworking and sandy bedform migration, is indicated by cross-cutting bounding surfaces and overlying cross-bedding. Bedding is progressively buried by horizontally-laminated, massive and rippled sands implying rapid deposition under lower plane bed conditions, culminating with a drop of energy regime and sediment supply (rippled sand). The overlying angular erosion surface records a phase of scouring with partial-infilling of the bed topography by migrating sand and gravel (lunate dunes) bedforms. Subsequent burial of this surface and the accreted sediments was driven by the reactivation of bedform migration indicated by sets of planar- and trough cross-bedded sands and gravelly sand. Plane-bed flow over bar-surfaces in suggested by overlying horizontally-laminated fine grained sands with a temporary drop in flow-regime enabling the massive to faintly-laminated clayey silts to be deposited. Deformation of bedding by a small reverse fault (F5) was produced by the lateral application of compressive stress to the sediments. Truncation and erosion of these deposits followed, with sedimentation of the massive gravels that grade upwards and laterally into gravelly sands and planar-cross-bedded sands. Collectively they indicate the transition from deposition of coarse bed-load deposition to the down-current migration of straight-crested sandy bedforms associated with a slight reduction in flow regime. At the top of the observed section, the massive and horizontally-laminated sands record a final switch to lower plane bed conditions and deposition upon the surfaces of subaqueous bedforms.

COMPOSITION OF GRAVEL LITHOLOGIES

Seven bulk samples were analysed to determine the clast lithological composition of gravel units (Table 3). Samples consist of high quantities of flint in both the 8-16mm (84.6-96.3%) and 16-32mm

(91.1-100.0%) fractions. Chatter-marked species become increasing prominent within the coarser size range and black flint (11.6-32.1%) is common within the 8-16mm fractions. Quartzose lithologies form a common component of the 8-16mm fraction representing between 3.3-8.2% of the total clast assemblage. Jurassic clasts, and Carboniferous cherts are present within most samples, whilst far-travelled exotics – including schistose lithologies, red sandstone, granite and porphyry, typically form less than 1% of the clast population.

DISCUSSION

Palaeoenvironmental Reconstruction

Exposures at Holt Quarry display packages of stratified sand and gravel that identify phases of unconstrained sheet-flow during high peak discharges, and lateral channel and bedform migration under lower flow conditions.

The base of the sequence within Exposures A and B comprises horizontally-laminated and planar cross-bedded sands. These sands record upper flow regime conditions developed on top of subaqueous bar-surfaces with a temporary drop in flow regime enabling small straight-crested dunes to form and migrate down-current. Angular and cross-cutting bounding surfaces, channel structures and associated channel-fills are interpreted as the product of lateral erosion and anastomosing channel migration upon a fluvial braid plain (Rust, 1972; Miall, 1977).

They are overlain (Exposures A and B) by massive to faintly-stratified, clast- to matrix-supported gravels deposited from bedload transportation (i.e. rolling / saltation) under high-energy flow conditions with, in-places, a winnowing of the sand fraction (clast-supported). Vertical and horizontal changes in sorting and clast size record subtle variations in flow regime and sediment supply. Gravel units typically occur as laterally-traceable sheets, dipping southwards, with conformable or slightly scoured basal contacts. These characteristics are typical of unconstrained subaerial sheet-flow associated with high-energy fluvial discharge (Ballance, 1984). The highly-rounded / spherical ‘cannon-shot’ morphology of many of the flint cobbles suggests that prior to subaerial deposition, their form has been modified by prolonged transport and mechanical abrasion within a high-energy turbulent system such as subglacial or englacial drainage channel (Brennand, 1994; Gale and Hoare, 2007). The occurrence of erratic clast lithologies, the coarse grain size coupled with their roundness and sphericity, implies the close-proximity of the site to a glacier drainage portal (Gustavson and Boothroyd, 1987; Zielinski and van Loon, 2003). The development of sheet-like gravel bodies within proglacial environments (known as outwash plains or sandur) has been widely recognised within modern glacial environments and attributed to unconstrained sheet floods associated with flood events (Maizels, 1993) including glacier outburst floods (Maizels, 1997; Marren, 2005).

Overlying the gravel-dominated units, are thick stratified sand units that occur within the upper parts of Exposures A and B, and further up-profile within Exposure C. These stratified sands are dominated by planar and trough cross-bedded sand resting upon irregular and angular bounding surfaces. The geometry of these bounding surfaces appears to reflect erosion by scouring, minor channelisation, and lateral and forward migration of large subaqueous bedforms (dunes) often up the foresets of adjacent dunes. Directional measurements from bedding foresets indicate bedform migration towards the southwest, south and southeast. Units composed of horizontally-laminated sands record lower plane bed conditions associated with flow across bar surfaces. Lenses composed of clayey silt are suggestive of occasional and abrupt reductions in flow regime enabling suspension-settling under low energy conditions. Collectively, these facies point to sedimentation within a subaerial braided drainage (outwash) system characterised by bedform migration, channelisation and scouring within a shallow, probably broad channel (McDonald and Banerjee, 1971; Rust, 1972; Miall, 1977). Channelised drainage, in addition to unconstrained sheet-flow, is also a common characteristic of many modern outwash sandur (McDonald and Banerjee, 1971; Maizels, 1993; Marren, 2005) and is typically attributed to periods of background drainage from an adjacent glacier (Maizels, 1993; Marren, 2005).

Of particular importance is the presence of the normal and reverse faulting. Normal faulting (F3) and graben development probably relates to consolidation associated with loading or localised drying of the sediment pile. Reverse and thrust faulting, by contrast, occurred during at least four (F1, F2, F4 and F5) discrete episodes and indicates the sustained application of lateral shear (compressive) stresses to the sediments. Critically, truncation of particular faults by ongoing sedimentation indicates that deformation occurred contemporaneously with sediment deposition. These reverse and thrust faults are interpreted as providing evidence for lateral-pushing and subsequent ice-contact deformation of the sediment by an adjacent glacier (Phillips *et al*., 2002) with structural measurements indicating that stresses were consistently applied from the north.

Geological and Stratigraphic Context

As established within earlier sections, sands and gravels at Holt Quarry provide evidence for proglacial outwash sedimentation on a rapidly-aggrading outwash plane or sandur. Sedimentation was driven by phases of unconstrained sheet-flow attributed to elevated discharge events, punctuated by active channel incision and migration (i.e. anastomosing braided channels) under background lower-energy flow conditions (McDonald and Banerjee, 1971; Rust, 1972; Miall, 1977, 1978). Such hydrological characteristics are common within modern sandur areas such as Iceland where background outwash drainage is frequently interrupted by abrupt discharge events including glacier outburst floods (Maizels, 1993, 1997; Zielinski and van Loon, 2003; Marren, 2005).

The presence of reverse and low-angle thrust faulting suggest that unidirectional compressive stresses were being applied to the sediment pile from a northerly direction. This is important because it implies that deposits at Holt were being actively deformed by ice-marginal to proglacial glacitectonic processes during sedimentation – specifically, that the sequence at Holt was ice-contact. Similar styles of syn-depositional glacitectonic deformation have been recognised elsewhere along the Cromer Ridge including Stody (Pawley, 2006; Lee *et al*., 2013); Briton's Lane Quarry (Banham, 1977) Roman Camp (Lee *et al*., 2013), Trimingham cliffs (Lee *et al*., 2013) and Gimingham Quarry near Trimingham (Lee *et al*., 2013).

Sediments at Holt form part of a far more extensive proglacial outwash system that covers the southern flanks of the Cromer Ridge, extending and thinning southwards towards Norwich where it drapes and infills the immediate post-glacial topography (Straw, 1973; Straw and Clayton, 1979; Boulton *et al*., 1984; Lunkka, 1994; Banham, 2000; Moorlock *et al*., 2002; Hamblin *et al*., 2005). Collectively outwash deposits in north Norfolk with this flint-dominated composition and geometric relationship to the underlying substrate form part of the Briton's Lane Formation (Lee *et al*., 2004). Thicknesses of the Briton's Lane Formation vary markedly, with in places, thicknesses of 40m attained (Pawley *et al*., 2005). However, the modern distribution of the Britons Lane Formation is probably far-less extensive than it was originally, with considerable volumes of sediment subsequently removed by slope processes and fluvial erosion.

Nevertheless, the sequence at Holt contributes to the wider understanding of ice-marginal retreat in north Norfolk during the Anglian Glaciation (Figure 7). Recently, Lee *et al*. (2013) presented a twelve-stage model for the last-known major Anglian ice advance (the A6 advance) into north Norfolk. Within this model, ice initially advanced much further south in north Norfolk than previous models suggest (Stage 1; Figure 7). A stepped 'active retreat' of the ice margin led to the development of several small lines of retreat moraines (Stage 2; Figure 7). This was followed by the establishment of a temporary still-stand along the line of the Cromer Ridge, and the construction of a prominent 'moraine complex' by repeated thrust-stacking during several minor 'superimposed' ice-marginal oscillations (Stages 3-8). The outwash sequence at Holt, was presumably generated when a considerable thickness of ice was abutting the ice-proximal (northern) side of the Cromer Ridge. This is because a suitably-thick mass of ice would be required to generate a sufficient hydraulic-gradient for meltwater drainage to be driven to elevations of at least 55m (assuming the Cromer Ridge wasn't originally ice-cored). Meltwater incision of the outwash sandur - generating the Briston Gap, enabled drainage to extend southwards and probably initiated the development of the post-Anglian Bure river valley. Subsequent thinning and withdrawal of ice from the Cromer Ridge, led to the stepped-development of several thrust-block morainic features as the ice margin retreated northwards (Stages 9-12; Figure 7). Identified remnants of these occur at Cromer (Banham, 1971), Weybourne Town Pit (Evans *et al*., 2011) and several rounded ice-contact hillocks between Overstrand and Weybourne (West, 1957; Lee *et al*., 2013).

CONCLUSIONS

- Aggregate extraction at Holt Quarry has exposed a complex sequence of sands and gravels deposited as part of a proglacial / ice-marginal braided outwash system during the later stages of the Anglian Glaciation.
- Glacitectonic structures preserved within the deposits reveals that deformation produced by glacier ice pushing into the sediment pile occurred during active outwash sedimentation.
- Outwash sediments at Holt form part of a more extensive glacial outwash system the remnants of which, extend southwards towards Norwich.

ACKNOWLEDGEMNTS

The author wishes to thank several individuals regarding their friendly and engaging discussions relating to the Cromer Ridge and the glacial geology of north Norfolk including Peter Allen, Stephen Booth, Helen Burke, David Evans, Richard Hamblin, Jane Hart, Brian Moorlock, Steve Pawley, Emrys Phillips, Adrian Read, Jim Riding, Jim Rose, David Vaughan-Hirsch and Martin Warren. Oliver Wakefield and Jenni Turner are warmly thanked for their comments on an earlier version of the manuscript. JRL publishes with the permission of the Executive Director of the British Geological Survey (NERC).

REFERENCES

BALLANCE, P.F. 1984. Sheet-flow-dominated gravel fans of the non-marine middle Cenozoic Simmler Formation, central California. *Sedimentary Geology*, **38**, 337-359.

Lee, J.R. 2014. Outwash sedimentation and glacitectonic deformation during accretion of the Cromer Ridge: evidence from Holt, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, 64, 3-31.

BANHAM, P.H. 1966. The significane of till pebble lineations and their relation to folds in two Pleistocene tills at Mundesley, Norfolk. *Proceedings of the Geologists' Association*, **77**, 469-474.

BANHAM, P.H. 1968. A preliminary note on the Pleistocene stratigraphy of northeast Norfolk. *Proceedings of the Geologists' Association*, **79**, 507-512.

BANHAM, P.H. 1975. Glaciotectonic structures: a general discussion with particular reference to the Contorted Drift of Norfolk. In: Wright, A E, and Moseley, F (eds.). *Ice Ages: Ancient and Modern*, 69-94, Seel House Press, Liverpool.

BANHAM, P.H. 1977. Glaciotectonites in till stratigraphy. *Boreas*, **6**, 101-105.

BANHAM, P.H. 1977. Stop 3. Briton's Lane Gravel Pit. In: West, R.G. (ed.). *East Anglia. Guidebook for Excursions A1 and C1, INQUA X Congress 1977*, 28-29, Geo Abstracts, Norwch.

BANHAM, P.H. 1988. Polyphase glaciotectonic deformation in the Contorted Drift of Norfolk. In: Croot, D. (ed.). *Glaciotectonics: Forms and Processes*, 27-32, Balkema, Rotterdam.

BANHAM, P.H. 2000. C.E. Ranson's data from the glacifluvial and other sands and gravels of north Norfolk, England. *Bulletin of the Geological Society of Norfolk*, **50**, 5-20.

BANHAM, P.H., GIBBARD, P.L., LUNKKA, J.P., PARFITT, S. A., PREECE, R.C. and TURNER, C. 2001. A critical assessment of 'a new glacial stratigraphy for eastern England. *Quaternary Newsletter*, **93**, 5-14.

BANHAM, P.H. and RANSON, C.E. 1965. Structural study of the Contorted Drift and disturbed chalk at Weybourne, north Norfolk. *Geological Magazine*, **102**, 164-174.

BOULTON, G.S. COX, F., HART, J.K. and THORNTON, M. 1984. The glacial geology of Norfolk. *Bulletin of the Geological Society of Norfolk*, **34**, 103-122.

BOWEN, D.Q., ROSE, J., MCCABE, A.M. and SUTHERLAND, D.G. 1986. Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews*, **5**, 299-340.

BRENNAND, T.A. 1994. Macroforms, large bedforms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario: implications for esker genesis and meltwater regime. *Sedimentary Geology*, **91**, 9-55.

CLARK, C.D., GIBBARD, P.L. and ROSE, J. 2004. Pleistocene glacial limits in England, Scotland and Wales. In: Ehlers, J. and Gibbard, P.L. (eds.). *Glaciations of the World, Europe*, 47-82, Elsever, Amsterdam.

Lee, J.R. 2014. Outwash sedimentation and glacitectonic deformation during accretion of the Cromer Ridge: evidence from Holt, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, 64, 3-31.

EHLERS, J, and GIBBARD, P L. 1991. Anglian glaciation and glacial deposits in Britain and the adjoining offshore regions. In: Ehlers, J., Gibbard, P.L. and Rose, J. (eds.). *Glacial deposits in Great Britain and Ireland*, 17-24, Balkema, Rotterdam.

EHLERS, J., GIBBARD, P.L. and WHITEMAN, C.A. 1987. Recent investigations of the Marly Drift of northwest Norfolk, England. In: van der Meer, J.J.M. (ed.). *Tills and glaciotectonics*, 39-54, Balkema, Rotterdam.

EHLERS, J., GIBBARD, P.L. and WHITEMAN, C.A. 1991. The glacial deposits of northwestern Norfolk. In: Ehlers, J., Gibbard, P.L. and Rose, J. (eds.). *Glacial deposits in Great Britain and Ireland*, 223-232, Balkema, Rotterdam.

EVANS, D.J.A., PHILLIPS, E.R., HIEMSTRA, J.F. and AUTON, C.A. 2006. Subglacial till: Formation, sedimentary characteristics and classification. *Earth-Science Reviews*, **78**, 115-176.

EVANS, H.M., LEE, J.R. and RIDING, J.B. 2011. A thrust-stacked origin for inter-stratified till sequences: an example from Weybourne Town Pit, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, **61**, 23-49.

FISH, P.R. and WHITEMAN, C.A. 2001. Chalk micropaleontology and the provenancing of Middle Pleistocene Lowestoft Formation Till in eastern England. *Earth Surface Processes and Landforms*, **26**, 953-970.

FISH, P.R., WHITEMAN, C.A., MOORLOCK, B.S.P., HAMBLIN, R.J.O. and WILKINSON, I.P. 2000. The glacial geology of the Weybourne area, north Norfolk: a new approach. *Bulletin of the Geological Society of Norflok*, **50**, 21-45.

FLEMING, E.J., STEVENSON, C.T.E. and PETRONIS, M.S. 2013. New insights into the deformation of a Middle Pleistocene glaciotectonised sequence in Norfolk, England through magnetic and structural analysis. *Proceedings of the Geologists' Association*, **124**, 834-854.

GALE, S.J. and HOARE, P.G. 1991. *Quaternary sediments : petrographic methods for the study of unlithified rocks*. Wiley, Chichester.

GALE, S.J. and HOARE, P.G. 2007. The age and origin of the Blakeney esker of north Norfolk: implications of the glaciology of the southern North Sea Basin. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F. and Hubbard, B.P. (eds.). *Glacial Sedimentary Processes and Products*, 203-234, International Association of Sedimentologists, Special Publication 39, Blackwell, Oxford.

GUSTAVSON, T.C. and BOOTHROYD, J.C. 1987. A depositional model for outwash, sediment sources, and hydrologic characteristics, Malaspina Glacier, Alaska: a modern analog of the southeastern margin of the Laurentide Ice Sheet. *Geological Society of America Bulletin*, **99**, 187-200.

HAMBLIN, R.J.O., MOORLOCK, B.S.P., ROSE, J., LEE, J.R., RIDING, J.B., BOOTH, S.J. and PAWLEY, S.M. 2005. Revised Pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. *Geologie en Mijnbouw*, **84**, 77-85.

Lee, J.R. 2014. Outwash sedimentation and glacitectonic deformation during accretion of the Cromer Ridge: evidence from Holt, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, 64, 3-31.

HART, J.K. 1990. Proglacial glaciotectonic deformation and the origin of the Cromer Ridge push moraine, north Norfolk, England. *Boreas*, **19**, 165-180.

HART, J.K. 2007. An investigation of subglacial shear zone processes from Weybourne, Norfolk, UK. *Quaternary Science Reviews*, **26**, 2354-2374.

HART, J.K and BOULTON, G.S. 1991. The glacial drifts of northeastern Norfolk. In: Ehlers, J., Gibbard, P.L. and Rose, J. (eds.). *Glacial deposits in Great Britain and Ireland*, 233-243, Balkema, Rotterdam.

LEE, J R. 2003. *Early and Middle Pleistocene lithostratigraphy and palaeoenvironments in north-eastern East Anglia, UK.* Unpublished PhD thesis, Royal Holloway, University of London.

LEE, J.R., BOOTH, S.J., HAMBLIN, R.J.O., JARROW, A.M., KESSLER, H., MOORLOCK, B.S.P., MORIGI, A.N., PALMER, A.P., RIDING, J.B. and ROSE, J. 2004. A new stratigraphy for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham, and Cromer, East Anglia, UK. *Bulletin of the Geological Society of Norfolk*, **53**, 3-60.

LEE, J.R., BUSSCHERS, F.S. and SEJRUP, H.P. 2012. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. *Quaternary Science Reviews*, **44**, 213-228.

LEE, J.R., PAWLEY, S.M., ROSE, J., MOORLOCK, B.S.P., RIDING, J.B., HAMBLIN, R.J.O, CANDY, I., BARENDREGT, R.W., BOOTH, S.J. and HARRISON, A.M. 2008. Pre-Devensian lithostratigraphy of shallow marine, fluvial and glacial sediments in northern East Anglia – Field Guide. In: Candy, I., Lee, J.R. and Harrison, A.M. (*eds*.). The Quaternary of northern East Anglia, 42-59, *Quaternary Research Association*, London.

LEE, J R and PHILLIPS, E.R. 2008. Progressive soft sediment deformation within a subglacial shear zone-a hybrid mosaic-pervasive deformation model for Middle Pleistocene glaciotectonised sediments from eastern England. *Quaternary Science Reviews*, **27**, 1350-1362.

LEE, J.R. and PHILLIPS, E. 2013. Glacitectonics – a key approach to examining ice dynamics, substrate rheology and ice-bed coupling. *Proceedings of the Geologists' Association*, **124**, 731-737.

LEE, J.R., PHILLIPS, E., BOOTH, S.J., ROSE, J., JORDAN, H.M., PAWLEY, S.M., WARREN, M. and LAWLEY, R.S. 2013. A polyphase glacitectonic model for ice-marginal retreat and terminal moraine development: the Middle Pleistocene British Ice Sheet, northern Norfolk, UK. *Proceedings of the Geologists' Association*, **124**, 753-777.

LEE, J.R., PHILLIPS, E., EVANS, H.M. and VAUGHAN-HIRSCH, D. 2011b. An introduction to the glacial geology and history of glacitectonic research in northeast Norfolk. In: Lee, J.R., Phillips, E.

Lee, J.R. 2014. Outwash sedimentation and glacitectonic deformation during accretion of the Cromer Ridge: evidence from Holt, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, 64, 3-31.

and Evans, H.M. (eds.). *Glacitectonics - Field Guide*, 101-115, Quaternary Research Association, London.

LEE, J.R., ROSE, J., HAMBLIN, R.J., MOORLOCK, B.S.P., RIDING, J.B., PHILLIPS, E., BARENDREGT, R.W. and CANDY, I. 2011a. The Glacial History of the British Isles during the Early and Middle Pleistocene: Implications for the long-term development of the British Ice Sheet. In: Ehlers, J., Gibbard, P.L. and Hughes, P.D. (ed.). *Quaternary Glaciations–Extent and Chronology, A Closer look*, 59-74, Development in Quaternary Science 15, Elsevier, Amsterdam.

LUNKKA, J.P. 1994. Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of northeast Norfolk. *Journal of Quaternary Science*, **9**, 209-233.

MAIZELS, J. 1993. Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics. *Sedimentary Geology*, **85**, 299-325.

MAIZELS, J. 1997. Jökulhlaup deposits in proglacial areas. *Quaternary Science Reviews*, **16**, 793-819.

MARREN, P.M. 2005. Magnitude and frequency in proglacial rivers: a geomorphological and sedimentological perspective. *Earth-Science Reviews*, **70**, 203-251.

MCDONALD, B.C. and BANERJEE, I. 1971. Sediments and bed forms on a braided outwash plain. *Canadian Journal of Earth Sciences*, **8**, 1282-1301.

MIALL, A.D. 1977. A review of the braided-river depositional environment. *Earth-Science Reviews*, **13**, 1-62.

MIALL, A.D. 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: Miall, A.D. (ed.). *Fluvial Sedimentology*, 597-604, Canadian Society of Petroleum Geologists, Memoir 5.

MOORLOCK, B.S.P., BOOTH, S.J., FISH, P., HAMBLIN, R.J.O, KESSLER, H., RIDING, J.B, and ROSE, J. 2000. Briton's Lane Gravel Pit, Beeston Regis (TG 168415). In: Lewis, S.G., Whiteman, C.A. and Preece, R.C. (eds). *The Quaternary of Norfolk and Suffolk*, 115-118, Quaternary Research Association, London.

MOORLOCK, B.S.P., HAMBLIN, R.J.O, BOOTH, S.J. and KESSLER, H. 2002. Geology of the Cromer district - a brief description of the geological map. *Sheet Explanation of the British Geological Survey, 1:50 000 Sheet Cromer 131 (England and Wales)*, British Geological Survey, Nottingham.

PAWLEY, S.M. 2006. *Quaternary glaciations of north and west Norfolk*. Unpublished PhD Thesis. thesis, University of London.

Lee, J.R. 2014. Outwash sedimentation and glacitectonic deformation during accretion of the Cromer Ridge: evidence from Holt, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, 64, 3-31.

PAWLEY, S.M., BAILEY, R.M., ROSE, J., MOORLOCK, B.S,P, HAMBLIN, R.J.O., BOOTH, S.J. and LEE, J.R. 2008. Age limits on Middle Pleistocene glacial sediments from OSL dating, north Norfolk, UK. *Quaternary Science Reviews*, **27**, 1363-1377.

PAWLEY, S.M., CANDY, I, and BOOTH, S.J. 2006. The Late Devensian terminal moraine ridge at Garrett Hill, Stiffkey valley, north Norfolk, England. *Proceedings of the Yorkshire Geological Society*, **56**, 31-39.

PAWLEY, S.M., LEE, J.R., RIDING, J.B., MOORLOCK, B.S.P., HAMBLIN, R.J.O., ROSE, J. and CROFTS, R.G. 2005. The stratigraphy of the Briton's Lane borehole and quarry, Beeston Regis, north-east Norfolk. *Bulletin of the Geological Society of Norfolk*, **55**, 15-42.

PERRIN, R.M.S., ROSE, J. and DAVIES, H. 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. *Philosophical Transactions of the Royal Society of London*, **B287**, 535-570.

PHILLIPS, E, and LEE, J.R. 2013. Development of a subglacial drainage system and its effect on glacitectonism within the polydeformed Middle Pleistocene (Anglian) glacigenic sequence of north Norfolk, Eastern England. *Proceedings of the Geologists' Association*, **124**, 855-875.

PHILLIPS, E., LEE, J.R. and BURKE, H.F. 2008. Progressive proglacial to subglacial deformation and syntectonic sedimentation at the margins of the Mid-Pleistocene British Ice Sheet: evidence from north Norfolk, UK. *Quaternary Science Reviews*, **27**, 1848-1871.

PHILLIPS, E.R, EVANS, D.J.A and AUTON, C.A. 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. *Sedimentary Geology*, **149**, 157-182.

PREECE, R.C., PARFITT, S.A., COOPE, G.R., PENKMAN, K.E.H, PONEL, P. and WHITTAKER, J.E. 2009. Biostratigraphic and aminostratigraphic constraints on the age of the Middle Pleistocene glacial succession in north Norfolk, UK. *Journal of Quaternary Science*, **24**, 557-580.

REID, C. 1882. *The geology of the country around Cromer*. H.M.S.O Memoir of the Geological Survey, England and Wales, London.

ROSE, J. 2009. Early and Middle Pleistocene landscapes of eastern England. *Proceedings of the Geologists' Association*, **120**, 3-33.

RUST, B R. 1972. Structure and process in a braided river. *Sedimentology*, **18**, 221-245.

SCHEIB, A.J., LEE, J.R., BREWARD, N. and RIDING, J.B. 2011. Reconstructing flowpaths of the Middle Pleistocene British Ice Sheet in central-eastern England : the application of regional soil geochemical data. *Proceedings of the Geologists' Association*, **122**, 432-444.

Lee, J.R. 2014. Outwash sedimentation and glacitectonic deformation during accretion of the Cromer Ridge: evidence from Holt, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, 64, 3-31.

SLATER, G. 1926. Glacial tectonics as reflected in disturbed drift deposits. *Proceedings of the Geologists' Association*, **37**, 392-400.

SOLOMON, J.D. 1932. On the heavy mineral assemblages of the Great Chalky Boulder-clay and Cannon-shot Gravels of East Anglia. *Geological Magazine*, **69**, 314-320.

STRAW, A. 1973. The glacial geomorphology of central and north Norfolk. *The East Midland Geographer*, **5**, 333-354.

STRAW, A. 1979. In: Straw, A. and Clayton, K.M. *The geomorphology of the British Isles*. Methuen, London.

STRAW, A, and CLAYTON, K. 1979. *The geomorphology of the British Isles*. Methuen, London.

WALLER, R.I., PHILLIPS, E., MURTON, J.B., LEE, J.R. and WHITEMAN, C.A. 2011. Sand intraclasts as evidence of subglacial deformation of Middle Pleistocene permafrost, North Norfolk, UK. *Quaternary Science Reviews*, **30**, 3481-3500.

WEST, R.G. 1957. Notes on a preliminary map of some features of the drift topography around Holt and Cromer, Norfolk. *Transactions of the Norfolk and Norwich Naturalists' Society*, **18**, 24-29.

WEST, R.G. and DONNER, J.J. 1956. The glaciations in East Anglia and the East Midlands: a differentiation based on stone-orientation measurements of the tills. *Quarterly Journal of the Geological Society of London*, **112**, 69-91.

ZIELINSKI, T. and VAN LOON, A.J. 2003. Pleistocene sandur deposits represent braidplains, not alluvial fans. *Boreas*, **32**, 590-611.

Figure Captions

Figure 1. (a) Map of Eastern England showing the location of the Anglian and Devensian ice limits (Bowen *et al*., 1986; Clark *et al*., 2004; Pawley *et al*., 2006); (b) Inset map of north Norfolk showing the location of sites referred to within the text and the Cromer Ridge.

Figure 2. Diagram of Exposure A showing the sedimentology of the sands and gravels. Bold letters refer to lithofacies codes (see Table 2).

Figure 3. Palaeocurrent measurements from cross-bedding foresets taken throughout exposures: (a) Exposure A; (b) Exposure B; (c) Exposure C. Grey ticks equate to mean flow directions.

Figure 4. Lower hemisphere stereographic projection (Schmidt) of normal and reverse / thrust faults measurements showing poles to planes, great circles and contours. Data points (poles to planes) are attributed Exposures A-C or to small un-described section (infilled black circles and squares).

Figure 5. Diagram of Exposure B displaying the sedimentology and geometry of the sand and gravel deposits. Bold letters refer to lithofacies codes (see Table 2).

Figure 6. Diagram of Exposure C displaying the sedimentology and geometry of the sand and gravel deposits. Bold letters refer to lithofacies codes (see Table 2).

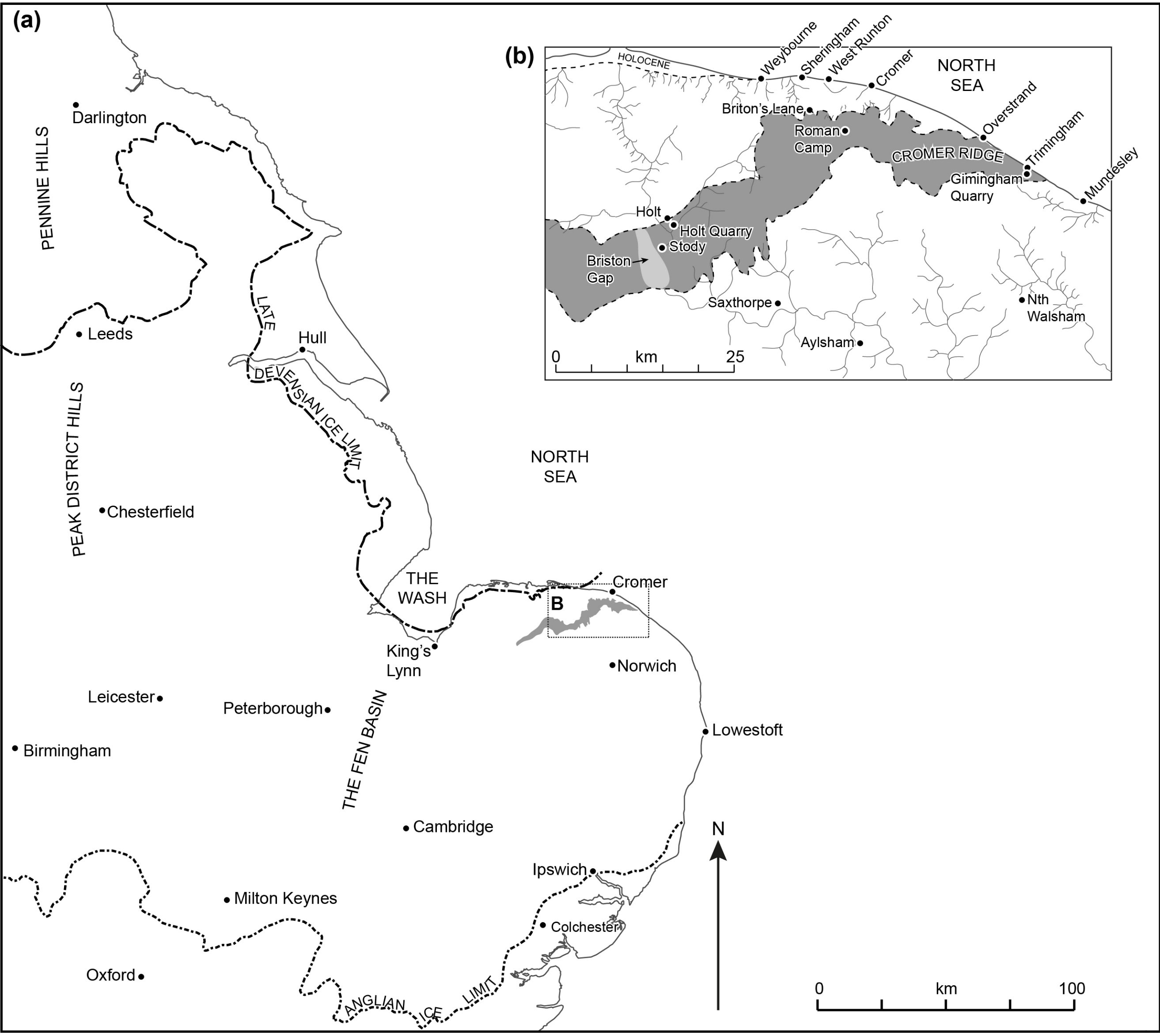
Figure 7. Tentative model of ice-marginal retreat reconstructed from structural and geomorphological evidence (modified from Lee *et al*., 2013).

Table Captions

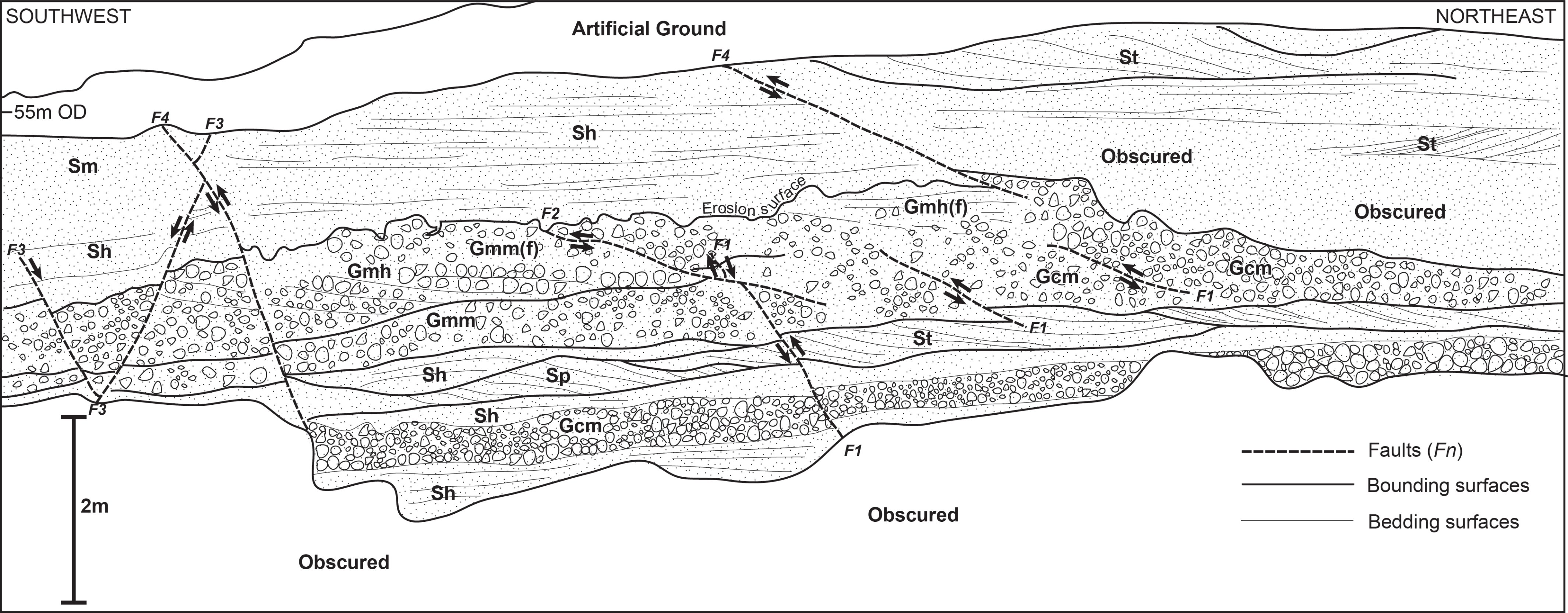
Table 1. Tectonostratigraphic scheme for northern East Anglia showing the primary structural elements relating to the six main Middle Pleistocene ice advances into the region (from Lee *et al*., 2011b, 2013).

Table 2. Lithofacies coding scheme for nomenclature employed within exposure diagrams.

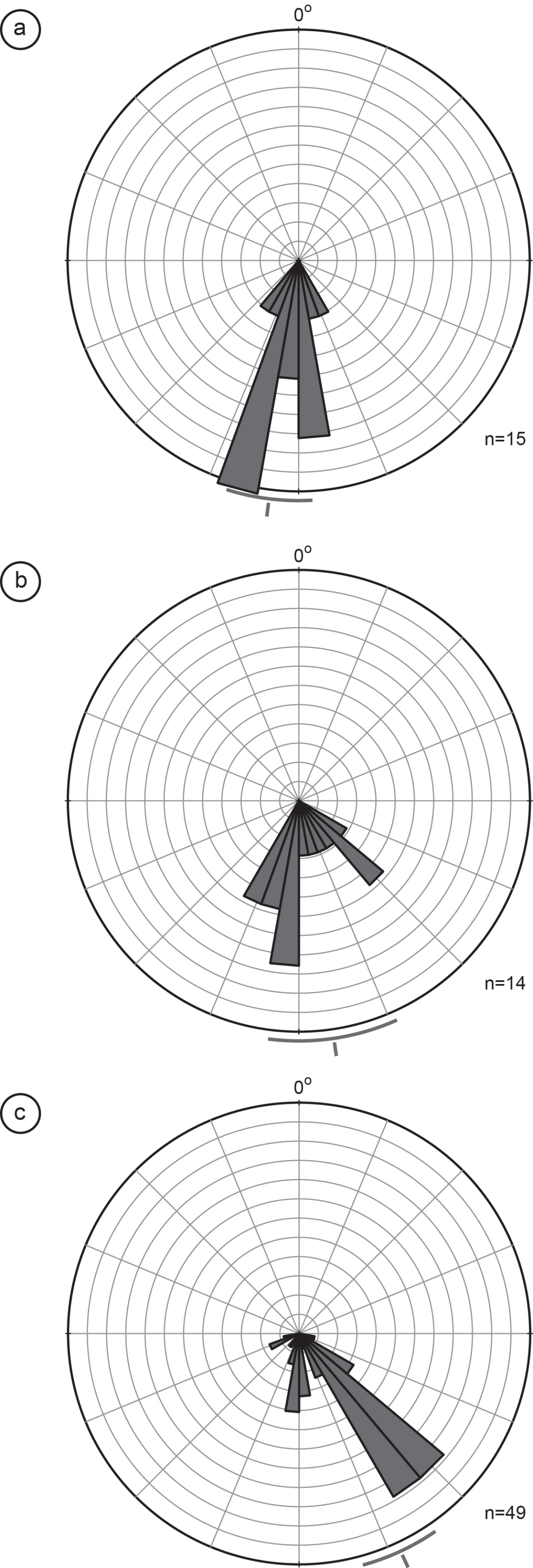
Table 3 (a) Lithological composition of the 8-16mm and 16-32mm size fractions of gravel samples from Holt Quarry; (b) Distinctive lithological sub-fractions of the 8-16mm and 16-32mm ranges.

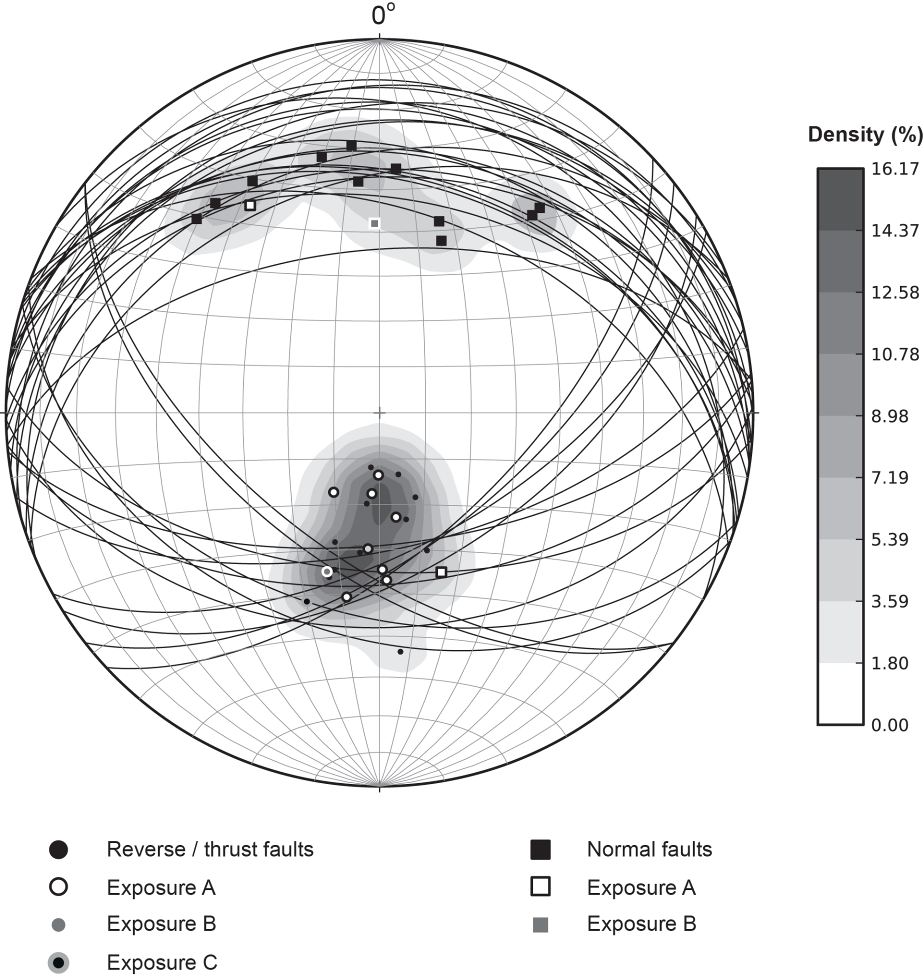


(a)
PENNINE HILLS
Darlington
Leeds
Hull
LATE DEVENSIAN ICE LIMIT
PEAK DISTRICT HILLS
Chesterfield
NORTH SEA
THE WASH
Cromer
B
King's Lynn
Norwich
Leicester
Peterborough
Lowestoft
Birmingham
THE FEN BASIN
Cambridge
N
Ipswich
Milton Keynes
Colchester
Oxford
ANGLIAN ICE LIMIT
0
km
100
(b)
HOLOCENE
Weybourne
Sheringham
West Runton
Cromer
NORTH SEA
Briton's Lane
Roman Camp
Overstrand
CROMER RIDGE
Trimingham
Mundesley
Gimingham Quarry
Holt
Holt Quarry
Stody
Briston Gap
Saxthorpe
Aylsham
Nth Walsham
0
km
25



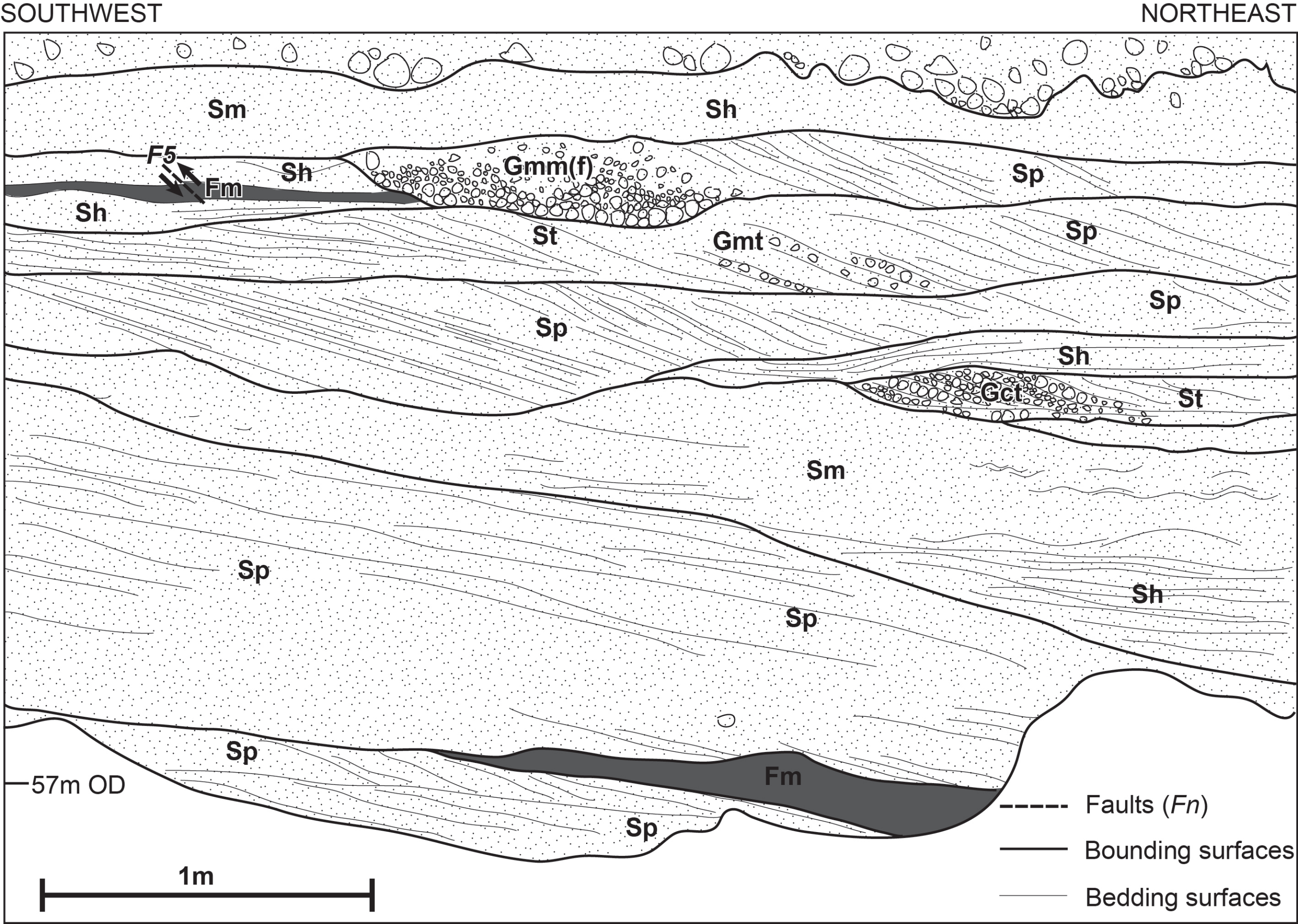
SOUTHWEST
NORTHEAST
Artificial Ground
55m OD
F4
F3
F2
F1
Sm
Sh
St
Obscured
Erosion surface
Gmh(f)
Gmm(f)
Gmh
Gmm
Gcm
Sp
2m
Faults (Fn)
Bounding surfaces
Bedding surfaces

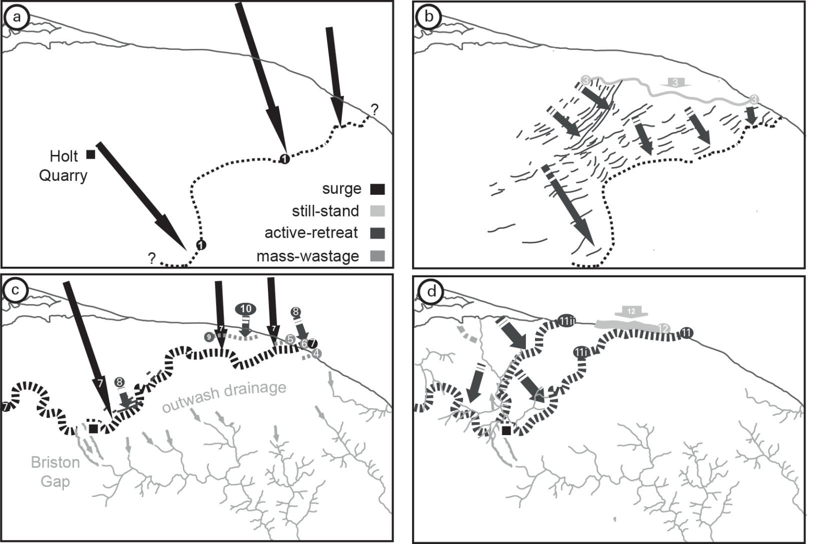

a
0°
n=15
b
0°
n=14
c
0°
n=49



0°
Density (%)
16.17
14.37
12.58
10.78
8.98
7.19
5.39
3.59
1.80
0.00
Reverse / thrust faults
Exposure A
Exposure B
Exposure C
Normal faults
Exposure A
Exposure B


SOUTHWEST
NORTHEAST
Artificial Ground
55m OD
F4
Fl(c)
Sr
Sh
Sh
F3
Sp
St
Sh, Sm
Sr
Sh
Gch
Gcm(c)
Sh, Sm
Gmm
Sh(c)
Obscured
Gch
Sr(c)
Gcm
Sh
Sp
Sh
Faults (Fn)
Bounding surfaces
Bedding surfaces
1m


SOUTHWEST
NORTHEAST
Sm
Sh
F5
Fm
Sh
Gmm(f)
Sp
Sh
St
Gmt
Sp
Sp
Sp
Sh
Gct
St
Sm
Sp
Sh
Sp
Sp
57m OD
Fm
Sp
1m
Faults (Fn)
Bounding surfaces
Bedding surfaces


a
Holt
Quarry
surge
still-stand
active-retreat
mass-wastage
b
c
outwash drainage
Briston
Gap
d

	ICE ADVANCE	**GLACITECTONIC SIGNATURE**	**STRUCTURAL EVIDENCE**
A6	Re-advance from N	Large-scale glacitectonism associated with ice-marginal thrust-stacking; Cromer Ridge and smaller ice-contact features.	Listric thrust faults, thrust duplex structures, inverted stratigraphy, large- and small-scale open folding.
A5	Ice advance from W	Large-scale glacitectonism associated with subglacial deforming bed processes (<30m); generation of Bacton Green Till melange; development of terminal moraine – extensional basin complexes; and accretion of 'western facies' *Weybourne Town Till*.	Sheath folding, thrusts, crenulation cleavage, hanging-wall anticlines, over-turned folding, small-scale soft-sediment deformation.
A4	Re-advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of *Bacton Green Till* (subglacial and subaqueous).	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, decollement surfaces, small-scale soft-sediment deformation.
A3	Ice advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of *Walcott Till*.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, décollement surfaces.
A2	Re-advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of *Corton Till*.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, soft-sediment deformation.
A1	Ice advance from N	Local-scale glacitectonism associated with subglacial deforming processes (<8m); accretion of *Happisburgh Till*.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, decollement surfaces.

Table 1

G	**Gravel**
S	**Sand**
F	**Fines (silt and clay)**
-m-	Matrix-supported
-c-	Clast-supported
--h	Horizontally-bedded
--p	Planar cross-bedded
--t	Trough cross-bedded
--m	Massive
--l	Finely laminated
--r	Ripples
---(c)	Convolute bedding

Table 2

SAMPLE	n	CARB.	TRIASSIC				JURASSIC			CRETACEOUS					PAL-PL		IGN, META. & SED.		UNKN.
		chert	qtzite	vein qtz	schorl	TOTAL	*Rhax.* chert	sstn, lstn, irnstn & shell	TOTAL	sstn, lstn, irnstn & shell	Green. chert	Chalk	Flint	TOTAL	C-M Flint	TOTAL FLINT	N.Eng / Scot	Wales	
8-16 MM FRACTION																			
4/2c	628	0.0	0.8	2.3	0.2	3.3	0.7	0.0	0.7	0.0	0.2	0.0	87.0	87.2	7.6	96.3	0.9	0.0	0.2
9/3a	252	0.0	2.0	2.4	1.2	5.6	0.4	0.0	0.4	0.0	0.0	0.0	85.3	85.3	8.3	93.6	0.4	0.0	0.0
8/1a	347	0.0	3.8	3.2	0.0	7.0	0.0	0.3	0.3	0.3	0.0	0.0	79.0	79.3	12.4	82.1	1.9	0.0	0.3
7/g	689	0.1	2.2	2.6	0.0	4.8	0.0	0.0	0.0	0.0	0.6	0.0	83.0	83.6	11.0	84.6	0.5	0.0	0.1
5/2a	740	0.4	2.2	1.9	0.0	4.1	0.5	0.3	0.8	0.0	0.0	0.0	85.0	85.0	9.4	94.5	0.2	0.0	0.0
7/6	606	0.0	1.5	2.8	0.8	5.1	0.0	0.0	0.0	0.0	0.2	0.0	83.0	83.2	12.4	95.6	0.0	0.0	0.0
3/1a	536	0.0	3.1	4.7	0.4	8.2	0.2	0.6	0.8	0.0	0.6	0.0	81.5	82.1	7.5	89.0	0.6	0.0	0.0
16-32 MM FRACTION																			
4/2c	25	0.0	4.0	0.0	0.0	4.0	4.0	0.0	4.0	0.0	0.0	0.0	28.0	28.0	64.0	92.0	0.0	0.0	0.0
9/3a	50	0.0	4.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	60.0	60.0	36.0	96.0	0.0	0.0	0.0
8/1a	81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.7	40.7	59.3	100.0	0.0	0.0	0.0
7/g	81	0.0	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.8	35.8	58.0	93.9	1.2	0.0	0.0
5/2a	66	0.0	0.0	1.5	1.5	3.0	0.0	0.0	0.0	0.0	0.0	0.0	76.9	76.9	19.7	97.0	0.0	0.0	0.0
7/6	86	0.0	2.3	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	32.6	32.6	43.0	96.7	0.0	0.0	0.0
3/1a	90	0.0	2.2	3.3	0.0	5.5	1.1	0.0	1.1	0.0	0.0	0.0	73.3	73.3	17.8	19.4	2.2	0.0	0.0