Development of a subglacial drainage system and its effect on glacitectonism within the polydeformed Middle Pleistocene (Anglian) glacigenic sequence of North Norfolk, Eastern England

Emrys Phillips[1*] and Jonathan R. Lee[2]

[1]British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, Scotland, UK

[2]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

[*]corresponding author

telephone: +44 (0)131-667-1000 fax: +44 (0)131-668-2683 e-mail: erp@bgs.ac.uk

Abstract

The efficiency of subglacial drainage is known to have a profound influence on subglacial deformation and glacier dynamics with, in particular, high meltwater contents and/or pressures aiding glacier motion. The complex sequence of Middle Pleistocene tills and glacial outwash sediments exposed along the north Norfolk coast (Eastern England) were deposited in the ice-marginal zone of the British Ice Sheet and contain widespread evidence for subglacial deformation during repeated phases of ice advance and retreat. During a phase of easterly directed ice advance, the glacial and pre-glacial sequence was pervasively deformed leading to the development of a thick unit of glacitectonic mélange. Although the role of pressurised meltwater has been recognised in facilitating deformation and mélange formation, this paper provides evidence for the subsequent development of a channelised subglacial drainage system beneath this part of the British Ice Sheet filled by a complex assemblage of sands, gravels and mass flow deposits. The channels are relatively undeformed when compared to the host mélange, forming elongate, lenticular to U-shaped, flat-topped bodies (up to 20 to 30 m thick) located within the upper part of this highly deformed unit. This relatively stable channelised system led to an increase in the efficiency of subglacial drainage from beneath the British Ice Sheet and the collapse of the subglacial shear zone, potentially slowing or even arresting the easterly directed advance of the ice sheet.

Keywords

Subglacial drainage, glacitectonism, Middle Pleistocene, north Norfolk

1. Introduction

Subglacial drainage systems have been shown to exert a strong influence upon the processes operating within the beds of glaciers, sediment mobility and ultimately ice sheet dynamics (Kamb, 1987; Stokes and Clark, 2001; Breemer et al., 2002; Lowe and Anderson, 2003; Bell et al., 2007). The pathways followed by pressurised subglacial meltwater have been described as taking the form of either: (i) thin sheets or films developed along the ice-bed interface (Weertman, 1972; Alley, 1989; Sharp et al., 1990; Hubbard and Sharp, 1993) potentially leading to the decoupling of the ice from its bed and rapid forward motion of the ice; (ii) intergranular flow, with meltwater flowing through pore spaces (Darcian flow) within subglacial sediments (Hubbard et al., 1995; Boulton et al., 1995) promoting soft-sediment deformation of the bed (deforming beds); (iii) distributed flow through a network of linked cavities (Sharp et al., 1989) or braided canals (Shoemaker, 1986; Clark and Walder, 1994; Benn and Evans, 2010) between the ice and underlying bed; or (iv) discrete, highly efficient systems of drainage channels or tunnel valleys feeding meltwater to the margin of the glacier or ice sheet (Wingfield, 1990; Ó Cofaigh, 1996; Praeg, 2003; Huuse and Lykke-Andersen, 2003; Longeran et al., 2006).

Studies of the subglacial hydrology of contemporary ice sheets (e.g. Greenland) indicate that there is a direct correlation between the volume of meltwater entering the bed of the glacier and a seasonal increase in the velocity of the overriding ice (e.g. Zwally et al., 2002; Joughin et al., 2008; Schoof, 2010). This link is complex, with work by Schoof (2010) demonstrating that the subglacial drainage system switches between different modes as it adapts to the variable input of surface water into the bed, with the variability in meltwater input, rather than total volume, forming the main driver for ice-sheet acceleration (also see Lüthi, 2010). The introduction of meltwater into an actively deforming bed can promote the development of either relatively faster flowing ice streams which aid in the regulation of the size and shape of ice sheets, or transient surge-type flow behaviour of glaciers (Kamb, 1987; Siegert and Bamber, 2000; Breemer et al., 2002; Lowe and Anderson, 2003; Tikku et al., 2004; Bell et al., 2007). In contrast, the development of relatively stable channelised drainage systems beneath glaciers and ice sheets, associated with a steady supply of meltwater, may lead to the draining of the bed and deceleration of the overriding ice (Hubbard et al., 1995; Boulton et al., 2007a and b; Magnússon et al., 2010). In a Pleistocene context, there are several case studies that examine the range and distribution of preserved subglacial meltwater features (e.g. Piotrowski et al., 1999; Piotrowski et al., 2006; Piotrowski, 2006). However, it has proved difficult to relate these directly to processes operating within the subglacial bed, and in-turn, their controls on ice sheet behaviour.

This paper presents evidence from the coastal cliff sections in north Norfolk, Eastern England for the development of a subglacial drainage system beneath the eastern margins of the Middle Pleistocene (Anglian) British Ice Sheet (BIS). This system comprised a series of relatively undeformed, sand and gravel bodies comprising several stacked channels, linked by smaller channels which were eroded into the polydeformed sequence of ice-marginal tills, waterlain diamictons and outwash sediments. This sequence contains widespread evidence (at various scales) for subglacial deformation (Dhonau and Dhonau, 1963; Banham 1975, 1988; Hart, 1987; Hart and Boulton, 1991; Hart and Roberts, 1994; Phillips et al., 2008), deformable beds (Lee, 2001; Roberts and Hart, 2005; Hart, 2007) and the formation of a thick unit (up to 20 to 30 m thick) of glacitectonic mélange associated with large-scale subglacial shear zone beneath the Anglian BIS (Lee and Phillips, 2008; Phillips et al., 2008). The influence of the development of the subglacial drainage system on these subglacial deforming-bed processes is examined, in particular its effect on the style of deformation within the subglacial shear zone and ultimately the advance of the ice sheet across north Norfolk.

2. Location of study area and methodology

The present study focused on the coastal cliff sections between Weybourne (National Grid Reference (NGR: TG 111 437)) and Sheringham (NGR: TG 155 435), north Norfolk, Eastern England (Fig. 1). Cliff sections range in height from 5 m at Weybourne to 45 m along the 4.4 km length of the section to Sheringham. The cliff sections between Weybourne and Sheringham were mapped and described on the basis of their sedimentological, lithological and structural characteristics. A sequence of overlapping photographs were taken of the cliffs enabling the analysis of the larger-scale structures developed along the entire length of the coastal section. Due to significant changes in perspective between some of the photographs, the interpretive section is divided into several overlapping segments (Fig. 2). Large format (A0) supplementary publications of this photographic interpretation and structural synthesis of the Sheringham to Weybourne coastal section have been made available by the authors for download. Sedimentological analysis of the sands and gravels units within the proposed subglacial drainage channels were aided by constructing photo mosaics enabling the construction of a number of detailed graphic logs which show the geometry of the sediment packages identified within the individual parts of this system (Figs. 3 to 8). Detailed graphic logs showing the variation in bedding type, particle size, bed geometry and sedimentary structures were obtained through a number of the larger sand and gravel bodies (see Figs. 6, 7 and 8). The orientations of sedimentary and deformation structures were measured using a compass clinometer. The sense of asymmetry of various fold phases and movement on the faults, and inter-relationships between the various generations of structures were established. Successive generations of folds (F1, F2…..Fn), fabrics (S1, S2…..Sn) and lineations (L1, L2…..Ln) are distinguished by the nomenclature normally used in structural geological studies (S1 earliest fabric to Sn latest) (see Phillips et al., 2011). However, this nomenclature does not necessarily imply that these structures were developed in response to separate deformation events (D1, D2…..Dn).

3. Glacial geology of the North Norfolk coast

The study area lies just to the south of the Late Devensian ice limit (Pawley et al., 2006), but was glaciated during the Middle Pleistocene by the Anglian British Ice Sheet (BIS). Although the precise number of glaciations within this Pleistocene remains a contentious issue (see Clark et al., 2004; Preece et al., 2009; Rose, 2009; Lee et al., 2012 for overviews), the traditional view is that all of the glacial deposits in northeast Norfolk lying to the south of the Late Devensian ice limit are Marine Isotope Stage 12 in age (Bowen et al., 1986; Banham et al., 2001; Pawley et al., 2008; Preece et al., 2009). The geology of the Weybourne-Sheringham cliff section comprises Cretaceous chalk bedrock (Moorlock et al., 2002), overlain by the shallow marine sand and gravels of the Early to early Middle Pleistocene Wroxham Crag Formation (Table 1) (Reid, 1882; Pawley et al., 2004). These sediments are overlain by various sandy and chalky diamictons (tills) that belong to the Happisburgh, Lowestoft and Sheringham Cliffs formations, and outwash sands and gravels assigned to the Briton’s Lane Formation (Table 1) (Pawley et al., 2004). Deforming and overprinting this succession are a complex array of glaciotectonic structures which have led to this polydeformed sequence being referred to as the ‘Contorted Drift’ (Reid, 1882; Dhonau and Dhonau, 1963; Banham, 1965, 1975, 1988; Ehlers et al., 1987, 1991) or the ‘Laminated Diamicton’ (Hart and Boulton, 1991; Hart and Roberts, 1994). Whilst Eyles et al. (1989) interpreted the style of deformation to be the product of sub-aqueous gravity flows, the majority of workers conclude that the glacitectonic overprint is subglacial in origin (Hart, 1987; Hart et al., 1990; Hart and Boulton, 1991; Hart and Roberts, 1994; Phillips et al. 2008), interpreting the range of small-scale structures within the tills in terms of a deforming bed model of glacier movement (Lee, 2001, 2009; Roberts and Hart, 2005; Hart, 2007).

Phillips et al. (2008), using the regional stratigraphy of Lee et al. (2004) and Hamblin et al. (2005) (see Table 1), were able to unravel the complex, larger-scale glacitectonic history recorded by the glacial and preglacial sediments at West Runton, interpreting the main deformation event (D3 of Phillips et al., 2008), which led to the disruption of this sequence, in terms of a progressive proglacial to subglacial deformation model. Phillips et al. (2008) presented clear evidence for meltwater being present at the time of deformation, typically in the form of penecontemporaneous deformed proglacial outwash sands and gravels, with Lee and Phillips (2008) emphasising the role of pressurised porewater in the formation of a subglacial shear zone and development of a thick unit (up to 20 to 30 m thick) of glacitectonic mélange which characterised subglacial deformation beneath the easterly advancing BIS. These authors concluded that the variability in the porewater content of the glacier bed played an important role in regulating the mechanism(s) driving subglacial deformation and ultimately the advance of the ice sheet across North Norfolk. However, no direct evidence has previously been presented for the presence of a linked system of drainage channels and/or cavities beneath the BIS in this area, and much of the evidence for meltwater activity simply relates to localised high porewater conditions within the subglacial bed (Roberts and Hart, 2005; Lee and Phillips, 2008; Phillips et al., 2008) and proglacial outwash deposits (Boulton et al., 1984; Hart, 1992; Lunkka, 1994; Lee et al., 2004; Pawley et al., 2005).

4. The glacial and preglacial sequence between Sheringham and Weybourne

The preglacial and glacial sequence exposed along the coast between Sheringham and (TG 155 435) and Weybourne (TG 111 437) occurs within a westwards extension of the zone of subglacial deformation, associated with ice advance from the west, identified by Phillips et al. (2008) at West Runton (TG 181 432) located further to the east. In the present study area the glacial sequence is dominated by the mélange facies of the Bacton Green Till (Table 1, BGT; up to 30 m thick) which overlies the older Happisburgh Till (HT; up to 10 m thick) and pre-glacial Wroxham Crag Formation (Table 1, WCF; 1 to 5 m thick) (Reid, 1882; Pawley et al., 2004); the latter resting unconformably upon Cretaceous chalk bedrock (Moorlock et al., 2002). These sediments are locally eroded into by a sequence of well-bedded, outwash sands and gravels assigned to the Briton's Lane Formation (see Fig. 2) (Lee et al., 2004; Pawley et al., 2004). Between Weybourne and Sheringham, the grey coloured, relatively clay-rich HT thins westwards until it is eventually truncated between the BGT and underlying chalk. The BGT is a brown, sandy diamicton which possesses a well-developed glacitectonic foliation (S1 in age) defined by centimetre-scale compositional layering. Deformation structures developed within the BGT mélange and, where present, HT, include small- to large-scale asymmetrical, tight to isoclinal folds (F2 in age), ductile shear zones and brittle thrusts, that record a consistent easterly-directed sense of shear and deform the earlier developed S1 fabric present within the diamictons. The mélange locally contains elongate slab-like to rounded 'eye' or 'augen' shaped intraclasts of poorly consolidated sand. These intraclasts are aligned within and wrapped by the S1 foliation present within the BGT. The shape of the intraclast and asymmetry of the enveloping S1 fabric records an easterly directed sense of shear consistent within that recorded by the F2 folds, thrust and shears developed elsewhere within the BGT. Waller et al. (2011) concluded that the sand intraclasts were frozen (pore ice cement) during deformation, providing clear evidence for the easterly advancing BIS having overridden and deformed "warm" permafrost (also see Waller et al., 2009). These authors argued that deformation beneath the ice occurred at temperatures slightly below the pressure melting point, but in the presence of a significant liquid water content within the fine-grained matrix to the mélange.

The BGT is overlain by a thin (1 to 2 m thick), relatively laterally continuous, white to pale grey chalk-rich till exposed at the top of the cliff and correlated with the Weybourne Town Till (WTT) of Lee et al. (2004) whose stratotype is located just south of the study area at Weybourne Town Pit (TG 114 430).

4.1. Morphology and stratigraphical context of the sand and gravel bodies

The subglacially deformed sequence between Sheringham and Weybourne contains a number of relatively undeformed, elongate to crudely symmetrical, lenticular to U-shaped, flat-topped sand and gravel bodies located near to, or at the top of the mélange (i.e. near to the top of the cliff section) where they are capped by a relatively thin layer of BGT and/or WTT (Figs. 3, 4, 5, 7 and 9). The sand and gravel bodies range from 5 m to several tens of metres in width and comprise a locally thick (up to 20 to 30 m) sequence of pale yellow to brown sand, silty sand and clast-supported gravel (see Figs. 6, 7 and 8). The moderately to locally steeply-inclined bases of these bodies are gently curved (convex downward) to irregular (erosive) in form, cutting downward into the underlying BGT (Figs. 4, 5, 10a and b). Beneath the larger bodies the BGT thins rapidly or is locally cut out, with the sands and gravels resting directly upon, or cutting into the underlying WCF (Figs. 4, 10c and d). The gravels are composed of rounded to subangular pebbles and cobbles of flint, quartzite, vein quartz with occasional clasts of sandstone, crystalline erratics, chalk and broken shell debris. The presence of soft chalk and bioclastic material within the gravels provides further evidence that the sands and gravel bodies are partly derived from locally scoured bedrock and WCF. Although the bases of the sand and gravel bodies are clearly erosive, the foliation present within the BGT appears to 'wrap around' these contacts, with the sand and gravel having filled, or eroded into a broad open synformal structure developed within the diamicton.

Although relatively undeformed when compared to the mélange, bedding within sand and gravel bodies, and the foliation developed adjacent BGT are locally deformed by meso- to large-scale east to southeast-verging (F2) folds and thrusts (Figs. 9 and 11) indicating that they have both encountered the same easterly directed subglacial deformation event. This evidence clearly indicates that the sand and gravel bodies do not represent part of a later outwash sequence eroded into the BGT, but in fact form an integral part of this subglacial succession.

4.2. Sedimentology of the sand and gravel bodies

Detailed sedimentological analysis of the sands and gravel bodies is restricted due to their typical occurrence within the upper part of the cliff sections. However, lithological logs through the sequences within three of the larger sand and gravel bodies are shown in Figs. 6, 7 and 8, with the location of these logged sections being shown on Fig. 2 (also see supplementary publication). The sedimentary sequences within the individual bodies are highly variable, consisting of massive to well-bedded sand, silty sand and gravel (Fig. 6) with rare thin clay beds and sandy mass-flow deposits (Figs. 7f and g). Interbeds of finely laminated sand and silt locally show evidence of soft-sediment deformation (disharmonic folding, convolute bedding) and localised liquefaction (Figs. 8f, g, h). Primary sedimentary structures, including massive bedding (Fig. 6 c), thin horizontal-bedding, cross-lamination (Fig. 7d), climbing-ripple cross-lamination (types A and B; Fig. 7e), normal (Fig. 6d) and reverse graded-bedding and trough cross-bedding (Fig. 6e), are well preserved (Figs. 6 and 8), even immediately adjacent to the contacts with the BGT indicating that these primary erosive contacts have undergone very little glacitectonic modification. Initial palaeocurrent data obtained from the cross-bedded sands record potential sediment transport directions towards the northeast, east and southeast.

Fining and coarsening up-ward sequences (2 to 7 m in scale; Figs. 6 and 7) are punctuated by the influx of thick massive gravels. The recognition of fining-upward sequences within the logged sections (see Fig. 6) is consistent with waning flow conditions, and suggests periods of lower energy sedimentation under much lower flow regimes. Locally sedimentation was dominated by sand deposition, with influxes of coarse gravel only occurring within the upper part of the sequence (Fig. 8). In one sand and gravel body, the erosive base is immediately overlain by a complex, moderately to thinly bedded sequence of type-A climbing ripples to trough cross-bedded, fine- to medium-grained sands interbedded with internally highly deformed silty sands (Fig. 7). Syn-sedimentary soft-sediment deformation structures (disharmonic folds, ductile shears, thrusts; Figs. 7f and g) which characterise the silty sands as mass-flows record both easterly and westerly transport directions, consistent with the flow of these fluidised sediments towards the centre of the sand and gravel body from both side margins, and sedimentation within a channel or similar depression. The presence of load structures, convolute bedding, and water-escape conduits (Fig. 8h), coupled with normal (extensional) syn-sedimentary faults within the sands and silty sands (Fig. 8e) are indicative of loading and high sedimentation rates during deposition.

The internal structure of the smaller sand bodies is relatively simple, as they typically comprise a small number of 1 to 3 m thick units of sub-horizontally bedded sand and gravel that thin laterally towards the margins of the body (see Fig. 9), resulting in a distinctive channel-like cross-section morphology. Gravel dominated units are massive to poorly bedded indicative of rapid deposition and form either laterally extensive beds (that extend across the width of the body) or more restricted, lenticular, channelised units that erode into the underlying sands (Fig. 9c) or BGT (Figs. 9a and d).

In contrast to these relatively simple sequences, the larger sand and gravel bodies are internally complex. Detailed field and photographic analysis reveal that they comprise a series of cross-cutting, laterally and vertically stacked, lenticular (channelised) to tabular units of well-bedded sand and gravel (Figs. 3, 4, 5, 7 and 8). The cross-cutting relationships indicate that, in general, the sediment packages within each individual sand and gravel body become progressively younger towards the east (down-ice) (see Fig. 5). The geometry of these sand and gravel bodies, combined with their sedimentology indicate that they were deposited during a series of high energy pulses. Characteristic evidence includes the scoured and cross-cutting basal form of the sands and gravels (Figs. 4, 5, 10a and b), and occasional beds of massive gravel (Figs. 6a and c) indicative of large sediment influxes during high or peak flow with rapid sedimentation from bed-load transport. Equally significant are the fining-upward and coarsening-upward sequences of sand and gravel (Figs. 6a and 7c) that record pulsed sediment input into the sediment system of varying magnitudes. Coarsening-up sequences record an increase in the energy regime, with sharp changes in sedimentology between sand and gravel beds indicating that they form several, superimposed pulses of sedimentation.

Fining-upward gravel-sand sequences composed of graded, individual sets of sand and gravel record deposition during a series of smaller sediment pulses under an overall subsiding flow regime. Fining-up sequences of gravel to sand indicate deposition during ‘moderate pulse’ events which commenced with a smaller influx of coarse sediment followed by waning flow. Type-A and type-B climbing ripples record subtle temporal variations in the sediment supply and energy regime although the dominance of type-B climbing ripples, coupled with the presence of syn-depositional load structures, are suggestive of high sedimentation rates. ‘Low’ to ‘low-moderate’ flow events are characterised by massive, horizontal and cross-bedded sands. They characterise deposition mainly from bed load transport punctuated by a series of minor hiatuses, whilst trough-cross bedding records the migration of small subaqueous lunate bar forms under lower, probably background, energy regimes. Background sedimentation is then terminated during the next high energy flow event and the influx of coarser grained sand and gravel. The occurrence of thin clay and/or silty layers interbedded within the sand-dominated parts of the sequence record phases where the energy regime fell dramatically with background low-energy sedimentation occurring. The presence of mass-flow deposits within the lower energy sand dominated parts of the sequence indicates that the margins of the sand and gravel bodies were unstable leading to slumping during episodes of quiescence.

4.3. Deformation of the sand and gravel bodies

Although relatively undeformed when compared to the BGT, the sand and gravel bodies do show evidence that they have undergone the same easterly directed subglacial deformation as the mélange. This deformation, where present, is highly variable in its intensity, ranging from the simple tilting of bedding and over-steepening of the erosive bases of the sand and gravel bodies (Figs. 4, 10c and d), through to more complex folding and thrusting (Figs. 9 and 11; also see Fig.2 and supplementary publication). Importantly this deformation was, in the majority of cases, focused along the western (up-ice) side of the body. However, locally, the sands and gravels are apparently undeformed and the channel-like morphology is clearly preserved (Figs. 3 and 7). The pervasive foliation within the BGT wraps around the base of the channels with the sands and gravels occupying a broad, open, symmetrical to asymmetrical synform within the mélange.

In the least deformed examples, bedding has simply been over-steepened due to rotation towards the east (Figs. 4, 10c and d). However, the adjacent BGT, is deformed by meso- to large-scale, E/SE-verging, asymmetrical folds as well as SE-directed thrusts and ductile shear zones which led to the tectonic thickening of the till (Fig. 4). The steeply inclined to sub-vertical bedding within the sands and gravels is co-planar to the foliation within the BGT on the steep, overturned limbs of these large-scale folds.

Where deformation is more pronounced, the sands and gravels adjacent to the western (up ice) margin of the body are deformed by small- to meso-scale recumbent to moderately inclined, asymmetrical, SE-verging folds which also deform the adjacent BGT (Figs. 9c, d and e); indicating that they have both recorded the same easterly directed deformation event. The intensity of this folding and thrusting is, however, far greater within the BGT which has been tectonically thickened on the up-ice side of the sand and gravel bodies (see Fig. 4). The relationships between the thrusting of the BGT and formation of the sand and gravel bodies is complex. In a number of examples, the erosive bases of the sand and gravel bodies clearly cut the faults and shears, indicating that thrusting predated sedimentation. Elsewhere, however, the thrusts clearly propagated into and deformed bedding within these bodies (see Fig. 11), demonstrating that subglacial deformation continued during, or after deposition of the sands and gravels. The western margin of one large sand and gravel body (TG 13458 43555) is deformed by a large-scale asymmetrical synform with small to meso-scale east/southeast-verging folds and thrusts within its core (Fig. 11). The fold occurs within the footwall of a prominent westerly dipping thrust or shear zone which resulted in the displacement of a detached slab of BGT across the top of the sand and gravel (also see Figs. 9b and f). At this locality the locally intense folds and thrusts within the BGT are cross-cut (post-dated) by a 2 to 5 m wide, steeply inclined to subvertical water-escape conduit filled by red-brown, hematitic sand derived apparently from the structurally underlying WCF (Fig. 11). This large-scale water-escape feature (hydrofracture) is developed immediately adjacent to the sand and gravel body and clearly records the movement of overpressurised meltwater within the bed of the ice sheet.

In marked contrast to the folded and thrusted western (up-ice) margins of the sand and gravel bodies, their eastern (down-ice) terminations are typically undeformed and an original, channel-like morphology is preserved (see Figs. 3, 5 and 8).

5. Subglacial drainage system within the deforming bed of the Anglian BIS

It is clear from the above description that the sand and gravel bodies exposed in the cliff sections between Sheringham and Weybourne represent an integral part of the BGT subglacial succession and are not large-scale load structures or ‘sag basins’ as described elsewhere (Hart, 1987; Ehlers et al., 1991). This conclusion is demonstrated by the fact that the sands and gravels have undergone the same easterly-directed subglacial deformation as the BGT and are locally enclosed within this mélange. The internal structure and sedimentology of these bodies is consistent with them having formed part of a major subglacial drainage system (see Fig. 12) composed of channelised to tabular sands and gravels laid down in an overall high energy environment. Rapid changes in the style of sedimentation indicate that the energy of this environment varied dramatically, with high to low energy flow events being separated by periods of channel abandonment. The internal complexities identified within the larger sand and gravel bodies are consistent with the vertical and lateral stacking of these sequences, recording a shifting pattern of sediment dispersal within this high energy system which potentially fed detritus to the proglacial outwash sequence of the Runton Sands and Gravels (RSG) described by Phillips et al. (2008) 5 km to the east at West Runton.

The BGT on the western, up-ice side of the larger sand and gravel bodies is tectonically thickened, with sands and gravels apparently occupying or having been eroded into broad, open synforms within the mélange (Fig. 13). This relationship is analogous to that displayed by lee-side cavity fills developed down ice of bedrock highs or other similar large-scale perturbations within the glacier bed (Kamb, 1987; Benn and Evans, 2010). Consequently, it is possible that the larger sand and gravel bodies represent some form of ‘cavity fill’ composed of several laterally stacked channels, connected by a system of relatively minor channels (Fig. 12); the latter represented by the smaller sand and gravel lenses shown in Fig. 9. However, linked cavity networks described within the literature (Kamb, 1987; Hooke, 2005; Benn and Evans, 2010) are highly complex, tortuous systems typically formed between the glacier and underlying bedrock (see figs 3.15 and 3.23 of Benn and Evans, 2010). As a result they are considered to be an inefficient form of subglacial drainage with parts of the system becoming isolated, or cut off, as a result of the closure of the narrow connections linking the cavities due to continued ice movement. Such constriction leads directly to low water transit velocities within the linked cavity systems. The sedimentology and internal architecture of the sand and gravel bodies identified between Sheringham and Weybourne, however, clearly indicate that they record a shifting pattern of sedimentation within an overall high energy environment. Consequently, the preferred interpretation is that these sand and gravels bodies represent part of a channelised drainage system incised into the glacial and pre-glacial sediments beneath the easterly advancing Anglian BIS (Fig. 12).

Channelised drainage systems are more efficient at transporting meltwater through the subglacial environment and, therefore, can lead to the dewatering of the bed. Piotrowski et al. (1999) concluded that subglacial channel formation is initiated when the bed can no longer evacuate all the meltwater produced. The development of a potentially extensive subglacial drainage system below the Anglian BIS may tentatively be used to indicate a marked increase in the volume of meltwater reaching the bed, possibly as a result of increased melting of the ice sheet. The proposed drainage system formed within the upper part of the BGT (see Fig. 12), with the larger channel-fill sequences cutting downwards through this glacitectonic mélange (Fig. 5) and, in some cases, into the underlying WCF (Fig. 4), indicating that this highly deformed deposit had already largely been formed prior to the development of the channel system. The composition of the gravels within these channel-fill sequences (see section 4.1) indicates that the erosion of the glacial and pre-glacial sediments, as well as the underlying bedrock, provided part of the source of detritus which fed this essentially fluviatile system. The relatively undeformed nature of the sands and gravels, coupled with the locally complex relationships between the channel-fill sequences and the glacitectonic structures within the adjacent BGT, indicates that the drainage system did not become established until the later stages of the easterly-directed subglacial deformation event. This conclusion is supported by the fact that the bases of a number of the channels clearly cross-cut, and therefore postdate, the S1 foliation, east/southeast-verging F2 folds and thrusts present within the adjacent diamicton. However, the western (up-ice) margins of a number of the channels are deformed by F2 in age glacitectonic structures, indicating that subglacial deformation continued after the drainage system had been established.

5.1. The effect of increased subglacial drainage efficiency on deformation beneath the Anglian BIS

Phillips et al. (2008) demonstrated that subglacial deformation beneath the Anglian BIS as it advanced eastwards across northern Norfolk resulted in the glacitectonic thickening and disruption of the pre-existing glacial and preglacial sequences. Ductile shearing within the resulting mélange is thought to have accommodated the bulk of the forward motion of the overriding ice. This thick (up to 30 m thick) laterally extensive subglacial shear zone is composed of a complex, anastomosing system of shallowly to moderately west-dipping thrusts and broader ductile shear zones wrapping around apparently lower strain areas (Lee and Phillips, 2008; Phillips et al., 2008), and is responsible for much of the deformation seen in the Sheringham to Weybourne coastal cliff sections. This shifting (spatial and temporal) pattern of deformation partitioning recorded by the BGT is consistent with the model proposed by Piotrowski and Kraus (1997) (also see Evans et al., 2006; Lee and Phillips, 2008) for the development of actively deforming and stable (non-deforming) zones within the subglacial deforming bed in response to either water-induced decoupling at the ice-bed-interface (Hoffman and Piotrowski, 2001), or the ability of the subglacial bed to drain inter-granular pore water (Piotrowski et al., 2004).

Lee and Phillips (2008) and Phillips et al. (2008), using macroscopic structural evidence from Bacton Green and West Runton (respectively), argued that during the earlier stages of subglacial deformation, shear stress imposed by the overriding glacier ice was being transmitted throughout the entire bed resulting in the pervasive deformation of the BGT (cf. van der Meer et al., 2003; Menzies et al., 2006). As deformation progressed, however, deformation within the mélange was preferentially partitioned into discreet zones of enhanced ductile shear. Deformation partitioning is thought to have been controlled by the variation in pore water content and the rate of thickening of the BGT, with deformation being focused into the relatively weaker, 'water-rich' (dilated) parts of the sequence (cf. Evans et al., 2006; Lee and Phillips, 2008). Phillips et al. (2008) suggested that the subsequent dewatering of the bed beneath the BIS during the later stages of subglacial deformation probably led to the locking up of the subglacial shear zone and late-stage brittle thrusting. In the absence (at the time) of evidence for the existence of a contemporaneous subglacial channelised drainage system beneath the Anglian BIS, these authors considered the dewatering of the subglacial shear zone to have been instigated by the overburden pressure exerted by the overriding ice, assisted by the tectonic thickening and accretion of the deforming bed (cf. Lee and Phillips, 2008).

An alternative explanation for sub-marginal till thickening may also be applicable to this active temperate glacier margin. Several workers have recognised that till thickening can occur by the seasonal penetration of cold through a thin glacier snout and the freeze-on of basal ice to its bed (Matthews et al., 1995; Krüger, 1996). This so-called 'cold wave', combined with forward glacier motion, causes thrust-stacking of frozen till slices with subsequent decoupling during spring-melt enabling deposition and till thickening (Evans and Hiemstra, 2005). Possible attribution of this mechanism to the till thickening reported here is supported (circumstantially) by the regional existence of 'warm' permafrost within the mélange (Waller et al., 2011). The presence of permafrost would provide a seasonal dimension to water availability, plus provide an indication of the prevailing climate conditions. In a separate study, Christoffersen and Tulaczyk (2003) argued that this process of seasonal basal-freeze-on, and by inference till-thickening, could cause the subglacial deforming bed to consolidate and ‘lock’ leading to a cessation of fast flow behaviour.

Recent studies have shown that the development of relatively stable channelised drainage systems beneath glaciers and ice sheets can lead to the draining of the bed and deceleration of the overriding ice. Work by Hubbard et al. (1995) on the Glacier d’Arolla in Switzerland has demonstrated that during periods of high meltwater pressure/discharge, water can be forced out of subglacial channels into the adjacent sediments. Conversely, a reversed or negative pressure gradient is set up during periods of low meltwater discharge leads to water draining out of the bed into the channel. The formation of a relatively stable drainage system beneath the Anglian BIS would have resulted in an increase in the efficiency of the subglacial hydrological system, feeding meltwater more rapidly through this environment to the ice margin. The fluctuation in meltwater discharge/pressure beneath the BIS may have led to repeated periods of saturation (wetting) and draining (drying) of the BGT adjacent to the channels, affecting the physical properties of the diamicton and its response to any imposed glacitectonism. Evidence for the development of pronounced hydrostatic pressure gradients adjacent to the subglacial drainage channels and migration of overpressurised meltwater beneath the Anglian BIS is provided by the water-escape conduits cutting through the BGT (e.g. at TG 13458 43555; also see fig. 9a of Phillips et al., 2008). These features clearly cross-cut earlier formed ductile (folds) and brittle (thrusts) deformation structures (see Fig. 11), indicating that hydrofracturing occurred at a late stage and would further facilitated in the dewatering of the bed.

During the early stages of the evolution of the subglacial drainage system, the BGT may have maintained a relatively high degree of saturation, leading to a continuation of predominantly ductile (folding, shearing) deformation. However, with time, as the diamicton progressively dewatered, deformation would have become increasingly brittle in nature, leading to the observed late stage thrusting and tectonic thickening of the bed. This would have accompanied the progressive ‘collapse’ and ‘locking up’ of the subglacial shear zone beneath the BIS (c.f. Lee and Phillips, 2008; Phillips et al., 2008). As a direct result, the preservation potential of the sand and gravel-filled drainage system would have been greatly increased. Saturation of the glacier bed with pressurised meltwater is known to facilitate the forward movement of the overriding ice (Evans et al., 2006 and references therein). Consequently, the collapse of the water-lubricated, predominantly ductile subglacial shear zone beneath the BIS in response to the development of a relatively stable drainage system could have potentially resulted in the stalling, or even cessation, of the easterly advance of this ice sheet across northern Norfolk.

5.2. Potential structural control on the pattern of subglacial drainage?

One of the key features of the subglacial drainage system identified in the Sheringham to Weybourne sections is that the larger, internally more complex sand and gravel bodies occupy or have been eroded into large-scale synformal folds present within the BGT, with folding and thrusting on the up-ice side of these larger channel fill sequences leading to the tectonic thickening of the diamicton. The inferred 3D geometry and relationship of these large channels to the synform-antiform fold pair are shown in Fig. 12. This relationship suggests that the developing large-scale folds and thrusts within the BGT may have influenced the pattern of subglacial drainage beneath the Anglian BIS (see Figs. 12, 13 and 14). Field evidence indicates that the synforms acted as a focus for erosion with meltwater apparently diverted along the axis of the folds which would have developed transverse to the ice movement direction (see Figs. 12 and 13). Alternatively, tectonic thickening of the bed in response to folding and thrusting may have resulted in the localised decoupling of the ice from its bed forming a temporary 'cavity' in the lee of the developing antiform-thrust stack (see Fig. 13). This process is more likely to occur towards the ice margin as it requires the 'jacking-up' of overlying ice to accommodate the glacitectonic thickening of the bed. Consequently, the drainage system probably developed close to the ice margin when the ice sheet had either reached its maximum extent, or as this margin actively retreated westward. Benediktsson et al. (2009) and Benediktsson (2009) have similarly argued for glacitectonic thrusting and folding resulting in the lifting of the overriding ice during the formation of a submarginal end moraine associated with the final stages of the 1963-64 surge of Brúarjökull in Iceland. The stacking of the individual channel-fill sequences within the larger sand and gravel bodies recognised within the Middle Pleistocene glacigenic sequence of north Norfolk is consistent with an overall easterly, down-ice shift in the pattern of sedimentation. This is coincident with the main stress direction responsible for folding and thrusting within the BGT. Continued deformation during sedimentation may have forced this shift in the pattern of drainage with the smaller channels and cavities becoming ‘blocked’/‘choked’ as they were deformed or overridden by detached, thrust-bound slabs of BGT.

Figure 14 shows a 5 stage model proposed for the progressive development of larger drainage channels during subglacial deformation:

Stage 1 – large-scale folding and thrusting led to the variable tectonic thickening of the BGT and the localised ‘detachment’ of the ice from its bed potentially resulting in the opening of lee-side cavity within the core of large-scale synclinal folds (CH1 on Fig. 14a). The opening of such ‘cavities’ would have resulted in the ‘capturing’ of the subglacial drainage system, diverting meltwater flow through these glacitectonically controlled features. Although initially controlled by the developing synform, contemporaneous erosion during deposition of the high-energy sands and gravels would have facilitated downcutting and enlargement of the cavity system. Slumping and syn-sedimentary faulting within the sands and gravels indicates that the sides of the channel were unstable, with continued deformation of the adjacent BGT probably promoting further instability. The tectonic thickening of the BGT and opening of cavities down-ice of the evolving fold and thrust stack suggests that this process probably occurred close to the margin of the ice sheet;

Stage 2 – continued folding and thrusting led to the deformation of earlier formed parts of the cavity-fill sequence and forced a down-ice (easterly) shift in the active part of the drainage system (CH2 on Fig. 14b);

Stage 3 – cross-cutting relationships observed between the stacked channel-fills indicate that periodically the active part of the drainage system shifted back, up-ice (CH3 on Fig. 14c). This up-ice shift could have been induced by either: (i) a marked increase in the erosive energy of the drainage system ‘overriding’ the glacitectonic control exerted by the easterly propagating fold and thrust stack; (ii) the back-shifting of the channel could be driven by hydraulic jumps that occur under supercritical flows, when higher flow discharges into zones of lower flow causing the development of standing waves and possible upstream migration of bedforms (i.e. anti dunes); or (iii) a pause in thrust and fold propagation in response to episodic or polyphase deformation associated with an oscillating ice margin.

Stage 4 – continued deformation with folds and thrusts initially developed within the adjacent BGT propagating eastwards to deform the western, up-ice margin of the sands and gravels forcing a down-ice shift in the focus of active deposition (CH4 on Fig. 14d).

Stage 5 – final abandonment of the cavity (Fig. 14e) and diversion of the flow of meltwater into a different part of the subglacial drainage system. The presence of till overlying the cavities indicates a re-coupling of the ice to its bed and continued advance of ice eastwards across the site following abandonment of the cavity system.

6. Conclusions

Elongate to lenticular sand and gravel bodies present within the polydeformed mélange facies of the Bacton Green Till exposed between Sheringham and Weybourne on the North Norfolk coast form an integral part of this subglacial sequence. The sedimentology and internal architecture of these bodies is consistent with them having form part of a relatively stable system of subglacial channels formed within an overall high-energy, fluviatile environment. The energy of this environment, however, fluctuated dramatically, with high- to low-energy flow events being separated by periods of channel abandonment. Internal complexities present within the larger sand and gravel bodies are consistent with the vertical and lateral stacking of the channel-fill sequences, recording a shifting pattern of sediment dispersal, with the available palaeocurrent data recording an overall easterly flow direction. The relationships displayed between the channels and the large-scale glacitectonic structures developed within the adjacent Bacton Green Till indicate that there may have been a structural control on the pattern of subglacial drainage beneath this sector of the Middle Pleistocene BIS. Continued large-scale thrusting and associated folding during sedimentation resulted in the deformation of the western side of the channels, and 'forced' migration of the active part of the drainage system eastwards, down-ice.

The channelized subglacial drainage system developed during the later stages of glacitectonism associated with an easterly advance of the Anglian BIS across North Norfolk, possibly when the ice sheet had either reached its maximum extent or during active retreat. Its development would have resulted in a marked increase in the efficiency of subglacial drainage leading to the progressive 'collapse' and 'locking up' of the water lubricated ductile shear zone which had dominated the earlier stages of this deformation event. The collapse of the water-lubricated, predominantly ductile subglacial shear zone beneath the BIS could have potentially resulted in the stalling or even cessation of the easterly advance of this ice sheet across northern East Anglia.

7. Acknowledgements

This work forms part of the British Geological Survey's Geology and Landscape England project. Andrew Finlayson and Jon Ford are thanked for their comments on an earlier draft of the manuscript. We also wish to acknowledge the constructive discussions with the delegates during the QRA Glacitectonics Workshop (2011), in particular Jaap van der Meer, Richard Waller, Julian Murton, Dave Evans, Ívar Benediktsson, Izabela Szuman and Martin Warren. Jaap van der Meer and Richard Waller are also thanked for their constructive reviews of this paper. This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

8. References

Alley, R.B. 1989. Water-pressure coupling of sliding and bed deformation. Journal of Glaciology 35, 108-139.

Banham, P.H. 1965. Pleistocene deposits at Weybourne: new data. Proceedings of the Geologists Association 76, 77–82.

Banham, P.H. 1975. Glacitectonic structures: a general discussion with particular reference to the contorted drift of Norfolk. In Wright, A.E., Moseley, F. (Eds.). Ice Ages: Ancient and Modern. Seel House Press, Liverpool, 69-94.

Banham, P.H. 1988. Polyphase glacitectonic deformation in the Contorted Drift of Norfolk. In Croot (Ed.). Glaciotectonics: Forms and Processes. Balkema, Rotterdam, 27- 32.

Banham, P.H., Gibbard, P.L., Lunkka, J.P., Parfitt, S.A., Preece, R.C., Turner, C. 2001. A critical assessment of a 'new glacial stratigraphy' for eastern England. Quaternary Newsletter 93, 5-14.

Bell, R.E., Studinger, M., Shunan, C.A., Fahnestock, M.A., Joughin, I. 2007. Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. Nature 445, 904-907.

Benn, D.I., Evans D.J.A. 2010. Glaciers and Glaciation. Second Edition. Hodder Education, pp 802.

Benediktsson, Í.Ö., Ingólfsson, Ó., Schomacker, A., Kjær, K.H. 2009. Formation of submarginal and proglacial en moraines: implications of ice-flow mechanism during the 1963-64 surge of Brúarjökull, Iceland. Boreas 38, 440-457.

Benediktsson, Í.Ö. 2009. End moraines and ice-marginal processes of surge-type glaciers. Unpublished PhD, Faculty of earth Sciences, University of Iceland.

Boulton, G.S., Cox, F., Hart, J., Thornton, M. 1984. The glacial geology of Norfolk. Bulletin of the Geological society of Norfolk 34, 103-122.

Boulton, G.S., Caban, P., van Gijssel, K. 1995. Groundwater flow beneath ice sheets, Part I - large scale patterns. Quaternary Science Reviews 14, 545-562.

Boulton, G.S., Lunn, R., Vidstrand, P., Zatsepin, S. 2007a. Subglacial drainage by groundwater-channel coupling and the origin of esker systems: Part I – glaciological observations. Quaternary Science Reviews. 26, 1067-1090.

Boulton, G.S., Lunn, R., Vidstrand, P., Zatsepin, S. 2007b. Subglacial drainage by groundwater-channel coupling and the origin of esker systems: Part II – theory and simulation of a modern system. Quaternary Science Reviews. 26, 1091-1105.

Bowen, D.Q., Rose, J., McCabe, A.M., Sutherland, D.G. 1986. Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. Quaternary Science Reviews 5, 299-340.

Breemer, C.W., Clark, P.U., Haggerty, R. 2002. Modelling the subglacial hydrology of the late Pleistocene Lake Michigan Lobe, Laurentide Ice Sheet. Geological Society of America Bulletin 114, 665-674.

Christoffersen, P., Tulaczyk, S. 2003. Signature of palaeo-ice-stream stagnation: till consolidation induced by basal freeze-on. Boreas 32, 114-129.

Clark, P.U., Walder, J.S. 1994. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. Bulletin of the Geological Society of America 106, 304-314.

Clark, C.D., Gibbard, P.L., Rose, J. 2004. Pleistocene glacial limits in England, Scotland and Wales. In: Ehlers, J., Gibbard, P.L. (Eds.). Quaternary Glaciations - Extent and Chronology, Part I: Europe. Elsevier Publishers, Amsterdam, 47-82.

Dhonau, T.J., Dhonau, N.B. 1963. Glacial structures on the North Norfolk coast. Proceedings of the Geologists' Association 74, 433-438.

Ehlers, J., Gibbard, P.L., Whiteman, C.A. 1987. Recent investigations of the Marly Drift of northwest Norfolk, England. In: van der Meer (Ed.). Tills and Glaciotectonics. Balkema, Rotterdam, 39–54.

Ehlers, J., Gibbard, P.H., Whiteman, C.A. 1991. The glacial deposits of northwest Norfolk. In Ehlers, J., Gibbard, P. L., Rose, J. (Eds). Glacial Deposits of Great Britain and Ireland. Balkema, Rotterdam, 223-232.

Eyles, N., Eyles, C.H., McCabe, A.M. 1989. Sedimentation in an ice-contact subaqueous setting: the Mid-Pleistocene 'North Sea Drifts' of Norfolk, UK. Quaternary Science Reviews 8, 57-74.

Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., Auton, C.A. 2006. Subglacial till: formation, sedimentary characteristics and classification. Earth-Science Reviews 78, 115-176.

Hamblin, R.J.O., Moorlock, B.S.P., Rose, J., Lee, J.R., Riding, J.B., Booth, S.J., Pawley, S.M. 2005. Revised Pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. Geologie en Mijnbouw 84, 77-85.

Hart, J.K. 1987. The genesis of the north east Norfolk Drift. Unpublished PhD thesis, University of East Anglia.

Hart, J.K. 1992. Sedimentary environments associated with Glacial Lake Trimmingham, Norfolk, UK. Boreas 21, 119-136.

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

Hart, J.K., Boulton, G.S. 1991. The interrelation of glaciotectonic and glaciodepositional processes within the glacial environment. Quaternary Science Reviews 10, 335-350.

Hart, J.K., Roberts, D.H. 1994. Criteria to distinguish between glaciotectonic and glaciomarine sedimentation: I – Deformation style and sedimentology. Sedimentary Geology 91, 191-213.

Hart, J.K., Hindmarsh, R.C.A., Boulton, G.S. 1990. Different styles of subglacial deformation in the context of the Middle Pleistocene ice sheet. Earth Surface Processes and Landforms 15, 227-241.

Hoffmann, K., Piotrowski, J.A. 2001. Till melange at Amsdorf, central Germany: sediment erosion, transport and deposition in a complex, soft-bedded subglacial system. Sedimentary Geology 140, 215-234.

Hooke, R. Le B. 2005. Principles of Glacier Mechanics. Cambridge University Press.

Hubbard, B., Sharp, M.J. 1993. Weertman regelation, multiple refreezing effects and the isotopic evolution of the basal ice layer. Journal of Glaciology 39, 275-291.

Hubbard, B., Sharp, M.J., Willis, I.C., Nielsen, M.K., Smart, C.C. 1995. Borehole water-level variations and the structure of the subglacial hydrogeological system of the Haut Glacier d'Arolla, Valais, Switzerland. Journal of Glaciology 39, 572-583.

Huuse, M., Lykke-Andersen, H. 2000. Over-deepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. Quaternary Science Reviews 19, 1233-1253.

Joughin, I., Das, S.B., King, M.A., Smith, B.E., Howat, I.M., Moon, T. 2008. Seasonal speedup along the western flank of the Greenland Ice Sheet. Science 320, 781-783.

Kamb, B. 1987. Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. Journal of Geophysical Research 92 B, 9083-9100.

Krüger, J., 1996. Moraine ridges formed from subglacial frozen-on sediment slabs and their differentiation from push moraines. Boreas 25, 57-64.

Lee, J.R. 2001. Genesis and palaeogeographical significance of the Corton Diamicton (basal member of the North Sea Drift Formation), East Anglia, UK. Proceedings of the Geologists' Association 112**,** 29-43.

Lee, J.R. 2009. Patterns of preglacial sedimentation and glaciotectonic deformation within early Middle Pleistocene sediments at Sidestrand, north Norfolk, UK. Proceedings of the Geologists' Association 120, 34-48.

Lee, J.R., Booth, S.J., Hamblin, R.J.O., Jarrow, A.M., Kessler, H., Moorlock, B.S.P., Morigi, A.N., Palmer, A., Pawley, S.J., Riding, J.B., 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., 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., Busschers, F.S., 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.

Longeran, L., Maidment, S.C.R., Collier, J.S. 2006. Pleistocene subglacial tunnel valleys in the central North Sea Basin: 3-D morphology and evolution. Journal of Quaternary Science 21, 891-903.

Lowe, A.L., Anderson, J.B. 2003. Evidence for abundant meltwater beneath the palaeo-ice sheet in Pine Island Bay, Antarctica. Journal of Glaciology 49, 125-138.

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

Lüthi, M.P. 2010. Greenland’s glacial basics. Nature 468, 776-777.

Magnússon, E., Björnsson, H., Rott, H., Pálsson, F. 2010. Reduced glacier sliding caused by persistent drainage from a subglacial lake. The Cryosphere 4, 13-20.

Matthews, J.A., McCarroll, D., Shakesby, R.A. 1995. Contemporary terminal-moraine ridge formation at a temperate glacier: Styggedalsbreen, Jotunheimen, southern Norway. Boreas 24, 129-139.

Menzies, J., van der Meer, J.J.M., Rose, J. 2006. Till - as a glacial "tectomict", its internal architecture, and the development of a "typing" method for till differentiation. Geomorphology 75, 172-200.

Moorlock, B.S.P., Hamblin, R.J.O., Booth, S.J., Woods, M.A.. 2002. Geology of the Cromer district – a brief explanation of the geological map Sheet 131 Cromer. British Geological Survey, HMSO, London.

Ó Cofaigh, C. 1996. Tunnel valley genesis. Progress in Physical Geography 20, 1-19.

Pawley, S.M., Rose, J., Lee, J.R., Moorlock, B.S.P., Hamblin, R.J.O. 2004. Early and Middle Pleistocene sedimentology and lithostratigraphy of Weybourne, northeast Norfolk, England. Proceedings of the Geologists’ Association 115, 25-42.

Pawley, S.M., Lee, J.R., Riding, J.B., Moorlock, B.S.P., Hamblin, R.J.O., Rose, J., Crofts, R.G. 2005. The stratigraphy of the Briton’s Lane borehole and quarry, Beeston Regis, northeast Norfolk. Bulletin of the Geological Society of Norfolk 55, 15-41.

Pawley, S.M., Candy, I., 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., Bailey, R.M., Rose, J., Moorlock, B.S.P., Hamblin, R.J.O., Booth, S.J., Lee, J.R. 2008. Age limits on Middle Pleistocene sediments from OSL dating, north Norfolk, UK. Quaternary Science Reviews. 27, 1363-1377.

Phillips, E.R., Lee, J.R., 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., Lee, J.R., Evans, H.M. 2011. Glacitectonics, Field Guide. Quaternary Research Association, pp 269.

Piotrowski, J.A. 2006. Groundwater under ice sheets and glaciers. In Knight, P.G. (ed.) Glacier Science and Environmental Change. Blackwell Publishing, Oxford. 50-60.

Piotrowski, J.A., Kraus, A. 1997. Response of sediment to ice sheet loading in northwestern Germany: effective stresses and glacier bed stability. Journal of Glaciology 18, 731-751.

Piotrowski, J.A., Geletneky, J., Vater, R. 1999. Soft-bedded subglacial meltwater channel from the Welzow-Süd open-cast lignite mine, Lower Lusatia, eastern Germany. Boreas 28, 363-374.

Piotrowski, J.A., Larsen, N.K., Junge, F.W. 2004. Reflections on soft subglacial beds as a mosaic of deforming and stable spots. Quaternary Science Reviews 23, 993-1000.

Piotrowski, J.A., Larsen, N.K., Menzies, J., Wysota, W. 2006. Formation of subglacial till under transient bed conditions: deposition, deformation, and basal decoupling under a Weichselian ice sheet lobe, central Poland. Sedimentology. 53, 83–106.

Praeg, D. 2003. Seismic imaging of mid-Pleistocene tunnel valleys in the North Sea Basin – high resolution from low frequencies. Journal of Applied Geophysics 53, 273-298.

Preece, R.C., Parfitt, S.A., Coope, G.R., Penkman, K.E.H., Ponel, P., Whittaker, J.E. 2009. Biostratigraphic and aminostratigraphic constraints on the age of the Middle Pleistocene glacial succession in north Norfolk. Journal of Quaternary Science 24, 557-580.

Reid, C. 1882. The Geology of the Country around Cromer. Memoirs of the Geological Survey of England and Wales.

Roberts, D.H., Hart, J.K. 2005. The deforming bed characteristics of a stratified till assemblage in north East Anglia, UK: investigating controls on sediment rheology and strain signatures. Quaternary Science Reviews 24, 123-140.

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

Schoof, C. 2010. Ice-sheet acceleration driven by melt-supply variability. Nature 468, 803-806.

Sharp, M.J., Gemmell, J.C., Tison, J-L. 1989. Structure and stability of the former subglacial drainage system of the Glacier Tsanfleuron, Switzerland. Earth Surface Processes and Landforms 14, 119-134.

Sharp, M.J., Tison J.-L., Fierens, G. 1990. Geochemistry of subglacial calcites: implications for the hydrogeology of the basal water film. Arctic and Alpine Research 22, 141-152.

Shoemaker, E.M. 1986. Subglacial hydrology for an ice sheet resting on a deformable aquifer. Journal of Glaciology 32, 20-30.

Siegert, M.J., Bamber, J.L. 2000. Subglacial water at the heads of Antarctic ice stream tributaries. Journal of Glaciology 46, 702-703.

Stokes, C.R., Clark, C.D. 2001. Palaeo-ice streams. Quaternary Science Reviews 20, 1437-1457.

Tikku, A.A., Bell, R.E., Studinger, M., Clarke, G.K.C. 2004. Ice flow field over Lake Vostok, East Antarctica inferred by structure tracking. Earth and Planetary Science Letters 227, 249-261.

van der Meer, J.J.M., Menzies, J., Rose, J. 2003. Subglacial till: the deforming glacier bed. Quaternary Science Reviews 22, 1659-1685.

Waller, R., Murton, J., Whiteman, C. 2009. Geological evidence for subglacial deformation of Pleistocene permafrost. Proceedings of the Geologists' Association 120, 155-162.

Waller, R., Phillips, E.R., Murton, J., Lee, J.R., Whiteman, C. 2011. Sand intraclasts as evidence of subglacial deformation of Middle Pleistocene permafrost, north Norfolk, UK. Quaternary Science Reviews 30, 3481-3500.

Weertman, J. 1972. General theory of water flow at the base of a glacier or ice sheet. Reviews of Geophysics and Space Physics 10, 287-333.

Wingfield, R. 1990. The origin of major incisions within the Pleistocene deposits of the North Sea. Marine Geology 91, 31-52.

Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., Steffen, K. 2002. Surface melt-induced acceleration of Greenland Ice-sheet flow. Science 297, 218-222.

9. Figures

Fig. 1. Map showing the location of the Sheringham to Weybourne coastal section, North Norfolk, Eastern England. Green arrows denote main ice-flow direction during westerly directed ice advance.

Fig. 2. Detailed structural interpretation of part of the coastal section between Sheringham and Weybourne. The individual sections cover the whole of the exposed cliff sections with varying degrees of overlap (approximate height of cliff face = 20 to 40 m). The location of the variably deformed sand and gravel filled channels illustrated in Figs 3 to 8 are also shown.

Fig. 3. (a) Photomontage of a large, lenticular sand and gravel body within highly deformed Bacton Green Till [TG 13153 43587]; **(b)** Interpretation of the internal structure of the sand and gravel body showing the cross-cutting relationships between the various generations of sediment fill.

Fig. 4. (a) to **(c)** Photomontage of a large sand and gravel-filled body cutting downward through the highly deformed Bacton Green Till [TG 14869 43531]. Immediately adjacent to the western side of body bedding has been titled and is steeply dipping to subvertical in attitude. **(d)** to **(f)** Interpretation of the internal structure of the sand and gravel body showing the cross-cutting relationships between the various generations of sediment fill.

Fig. 5. (a) to **(c)** Photomontage of a large lenticular, sand and gravel-filled body cutting downward into the highly deformed Bacton Green Till [TG 13459 43556]. **(d)** to **(f)** Interpretation of the internal structure of the sand and gravel body showing the cross-cutting relationships between the various generations of sediment fill. **(g)** summary diagram showing overall geometry of channel complex comprising a cross-cutting sequence of sand and gravel fills. Note the marked difference between the highly folded, over-steepened western margin of the channel and its relatively undeformed eastern section.

Fig. 6. (a) Lithological log through the basal gravel-rich part of the sequence [TG 14869 43531]; **(b)** Photograph showing an overview of the basal gravel-rich part of the sediments filling a large sand and gravel body. Also shown is the location of the graphic log illustrated in Fig. 7a; **(c)** Massive, coarse-grained, clast supported gravel; **(d)** Graded bedding and cross stratification developed within sandy gravel beds; **(e)**

trough cross-bedded gravelly sand overlain by massive gravel unit containing a lens of sand; **(f)** Well-bedded, graded gravel to sand beds.

Fig. 7. (a) and (b) Photomontage and interpretation of the sedimentary sequence exposed at the base of a large sand and gravel body. Note the presence of the opposing fold vergence recorded by the disharmonic folds within the silty sands; the latter interpreted as mass flow deposits; **(c)** Lithological log through this basal sand and gravel sequence [TG 13458 43555]; **(d)** Cross-lamination developed within beds of fine sand; **(e)** Climbing ripple cross-lamination developed within beds of fine sand; **(f)** Soft-sediment deformation, including westerly verging folds, within a mass flow deposit; **(g)** Easterly verging recumbent disharmonic folding within a mass flow deposit.

Fig. 8. (a) and **(b)** Photomontage and interpretation of the sedimentary sequence exposed within a large sand and gravel body. Note the presence of the opposing fold vergence recorded by the disharmonic folds within the silty sands; the latter interpreted as mass flow deposits; **(c)** Lithological log through this sand-dominated sequence [TG 13155 43580]; **(d)** Undeformed, well-bedded sands and silty sands exposed immediately above the erosive contact with the underlying Bacton Green Till; **(e)** Small-scale, normal (extensional) faults off-setting bedding; **(f)** Soft-sediment deformation of thinly bedded to laminated sand and silty sand; **(g)** Soft-sediment deformation and localised liquefaction of laminated sands, silts and thin clays due to loading; **(h)** Subvertical water-escape conduit.

Fig. 9. (a) Relatively undeformed sand and gravel body [TG 14740 43540] showing cross-cutting relationships between different phases of sand and gravel fill. Also note that the erosive base of the sand and gravel body cuts through the foliation present within the underlying Bacton Green Till; **(b)** Relatively undeformed sand and gravel body composed of two distinct units of horizontally bedded sand. Note that the lower unit thins laterally towards the margins of the body; **(c)** Folded western edge of sand and gravel body [TG 13209 43582]. Note that the moderately to steeply inclined bedding within the lower part of the channel is cross-cut by the erosive base of a relatively younger phase of sediment fill; **(d)** Details of the complex, meso- to large-scale recumbent to downward-facing folds [TG 13209 43582] deforming the western margin of the sand and gravel body shown in Fig. 2c; **(f)** Deformed sand and gravel body folded by a distinctive open syncline [TG 11586 43673]. Note that syncline occurs within the footwall of a E/SE directed thrust.

Fig. 10. **(a)** Cross-cutting relationships between several generations of fill within a single large sand and gravel body [TG 13458 43555]; **(b)** Deformed sands and gravels at the western edge of a large sand and gravel body [TG 13458 43555]. Note that the steep sided lenses of sand and gravel in the central part are undeformed and cross-cut the earlier formed folds which deformed the well bedded sand and gravel along the western side of the body; **(c)** Tilted, over-steepened western margin of a very large sand and gravel-filled channel [TG 14873 43509]; **(d)** Details of erosive base of very large sand and gravel body illustrated in Fig. 10c [TG 14873 43509].

Fig. 11. SE-directed folding and thrusting of the western margin of a large sand and gravel-filled body [TG 13458 43555]. The SE-vergence of the deformation structures present within the channel is comparable to that recorded by the folds developed within the adjacent highly deformed Bacton Green Till.

Fig. 12. 3D block diagram showing the possible pattern of subglacial to proglacial drainage associated with the margin of the Anglian British Ice Sheet based upon field evidence from the North Norfolk coast (this study; Phillips et al., 2008).

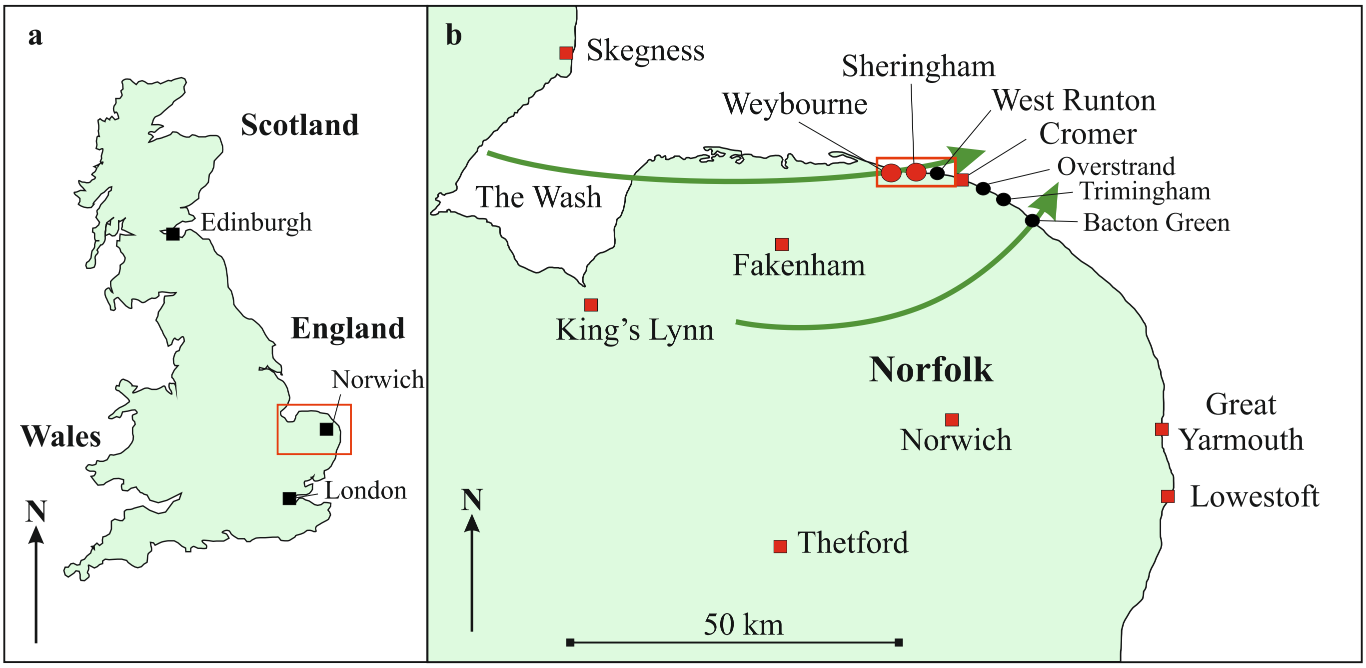
Fig. 13. Schematic diagram showing the 3D geometry of the sand and gravel-filled channel features developed within the mélange facies of the Bacton Green Till between Sheringham and Weybourne. Note that the larger channel features are located within a broad, open synform on the down-ice side eastern side of a large-scale fold and thrust stack developed within the till. Cross-cutting relationships displayed between the various sand and gravel bodies within the channel features indicate that, in general, the individual channels migrated down-ice direction (see text for details).

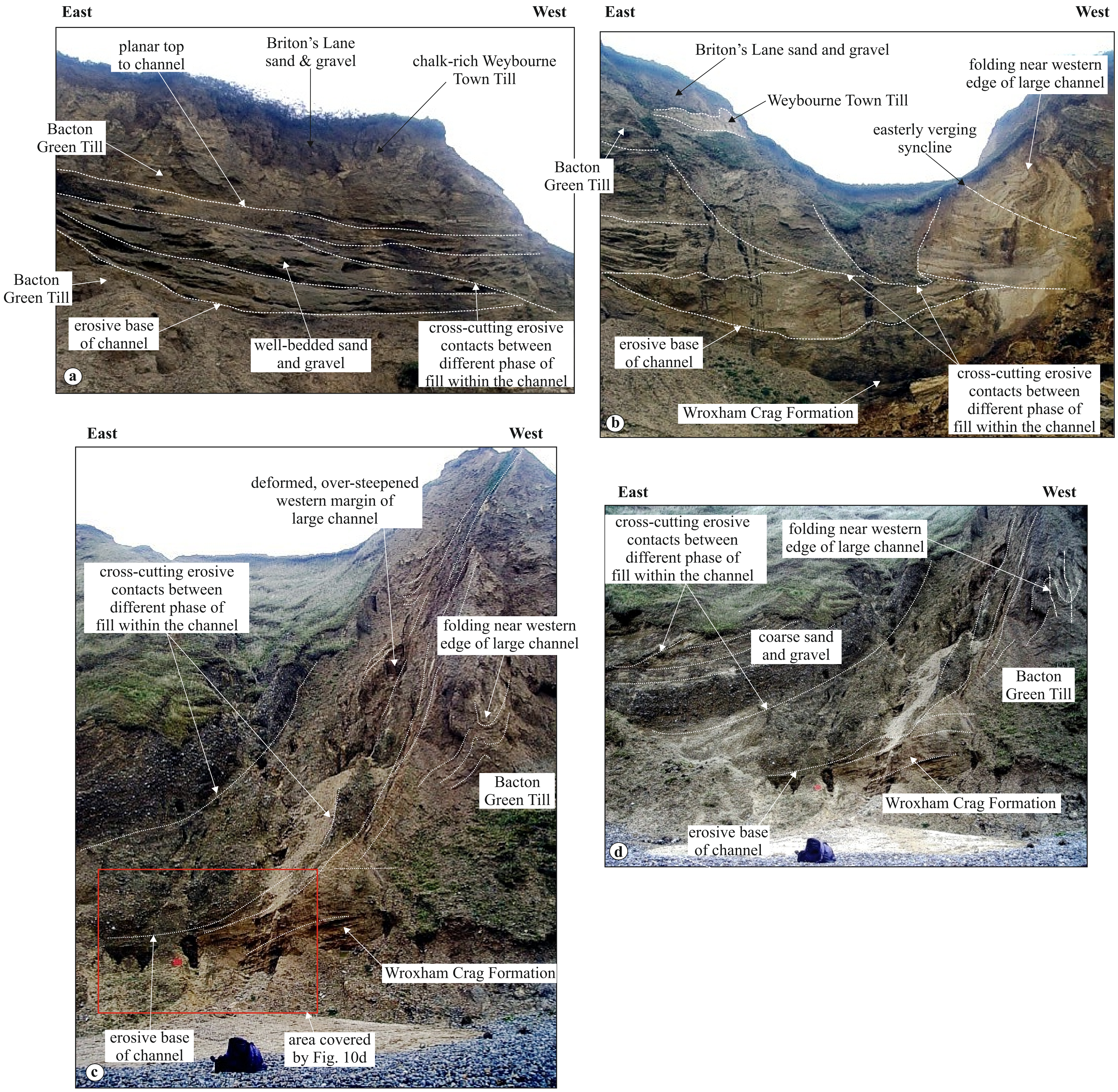
Fig. 14. Diagram showing the progressive development of the stacked channel sequences exposed between Sheringham and Weybourne highlighting the relationship between subglacial deformation and the location of these subglacial drainage channel complexes.

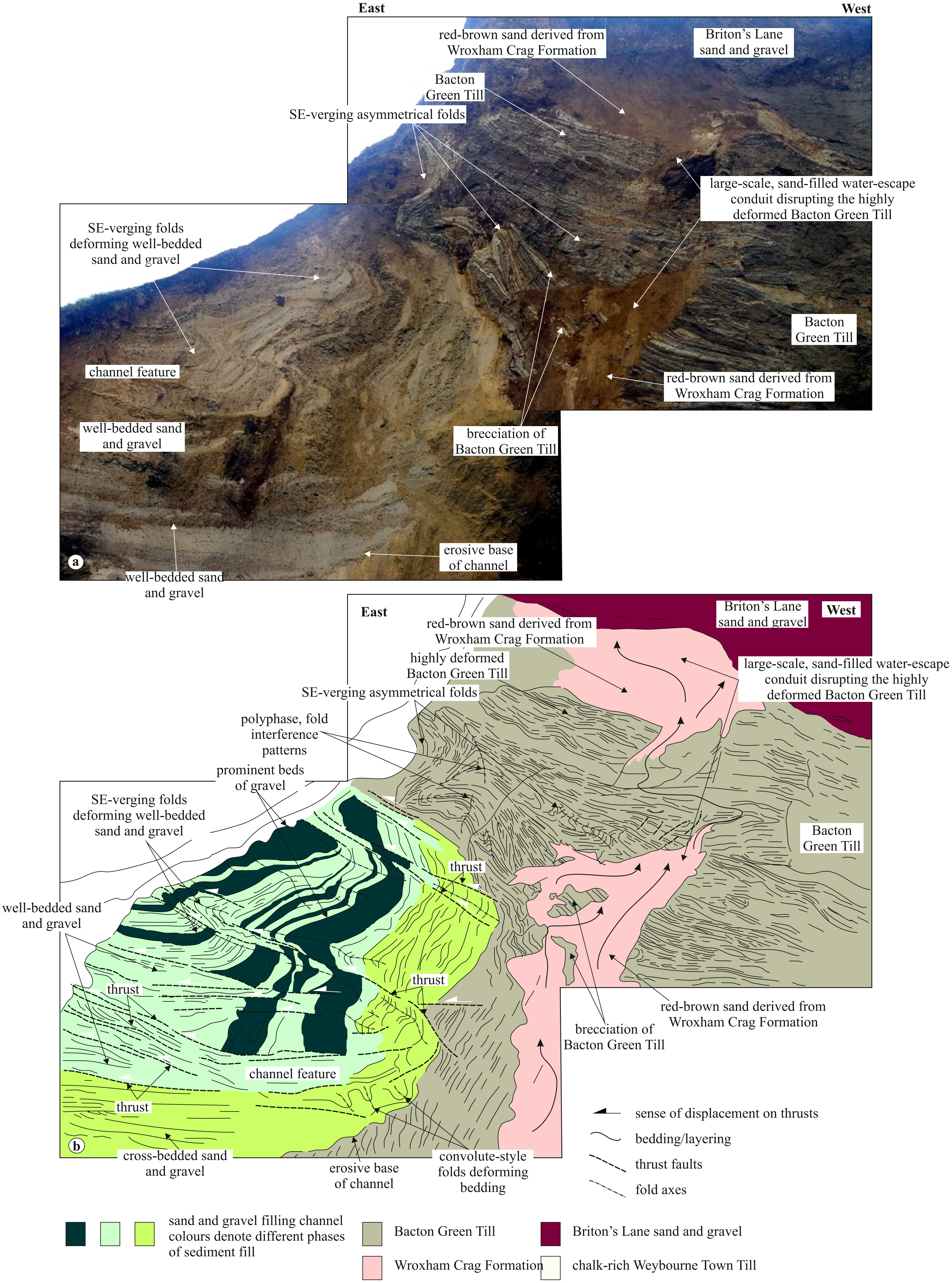
10. Tables

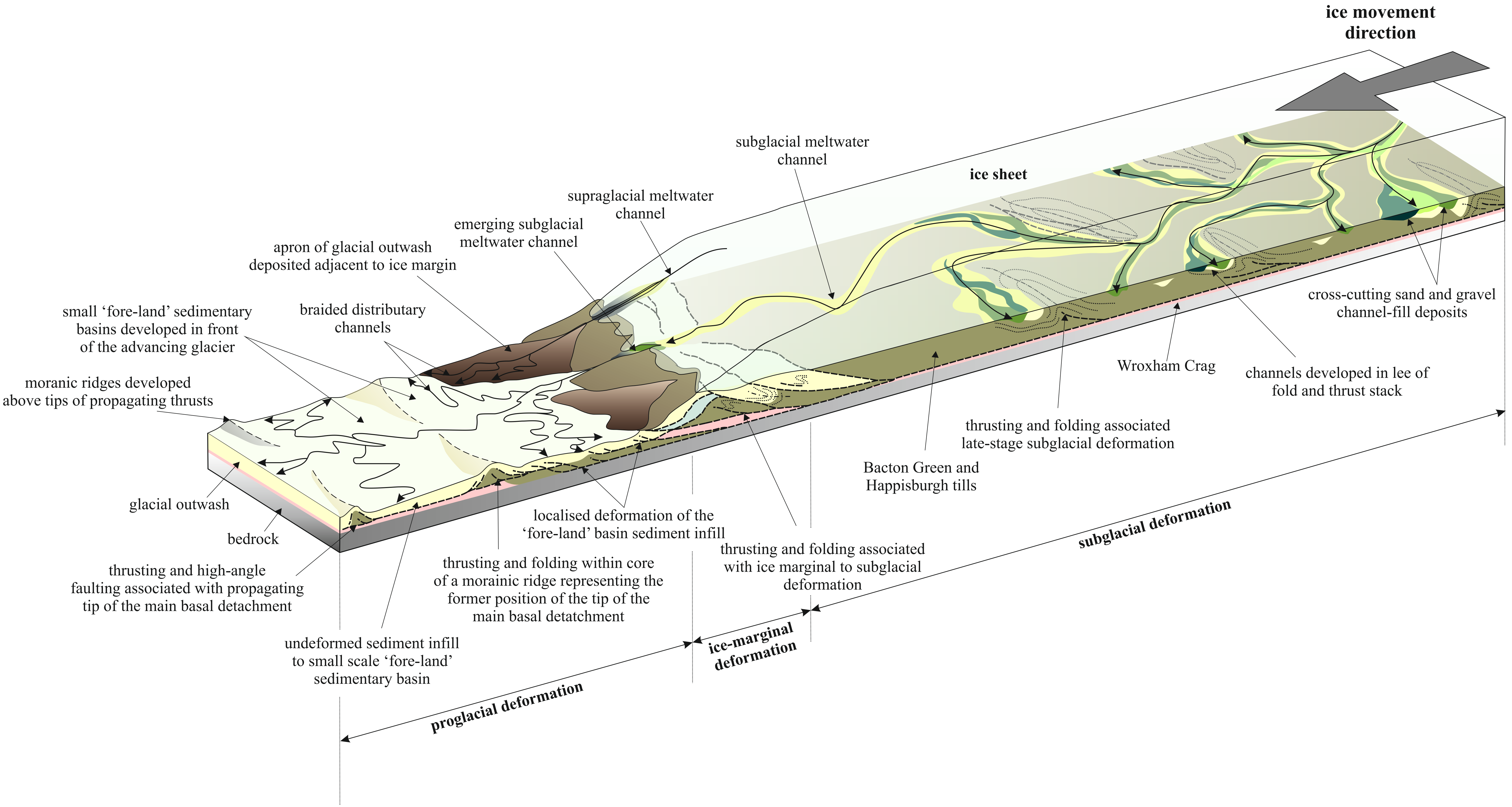
Table 1. Lower and lower Mid-Pleistocene stratigraphy of northern East Anglia with particular reference to units that crop-out within the Sheringham-Weybourne study area shown in bold (modified from Lee et al., 2004; Pawley et al., 2004).

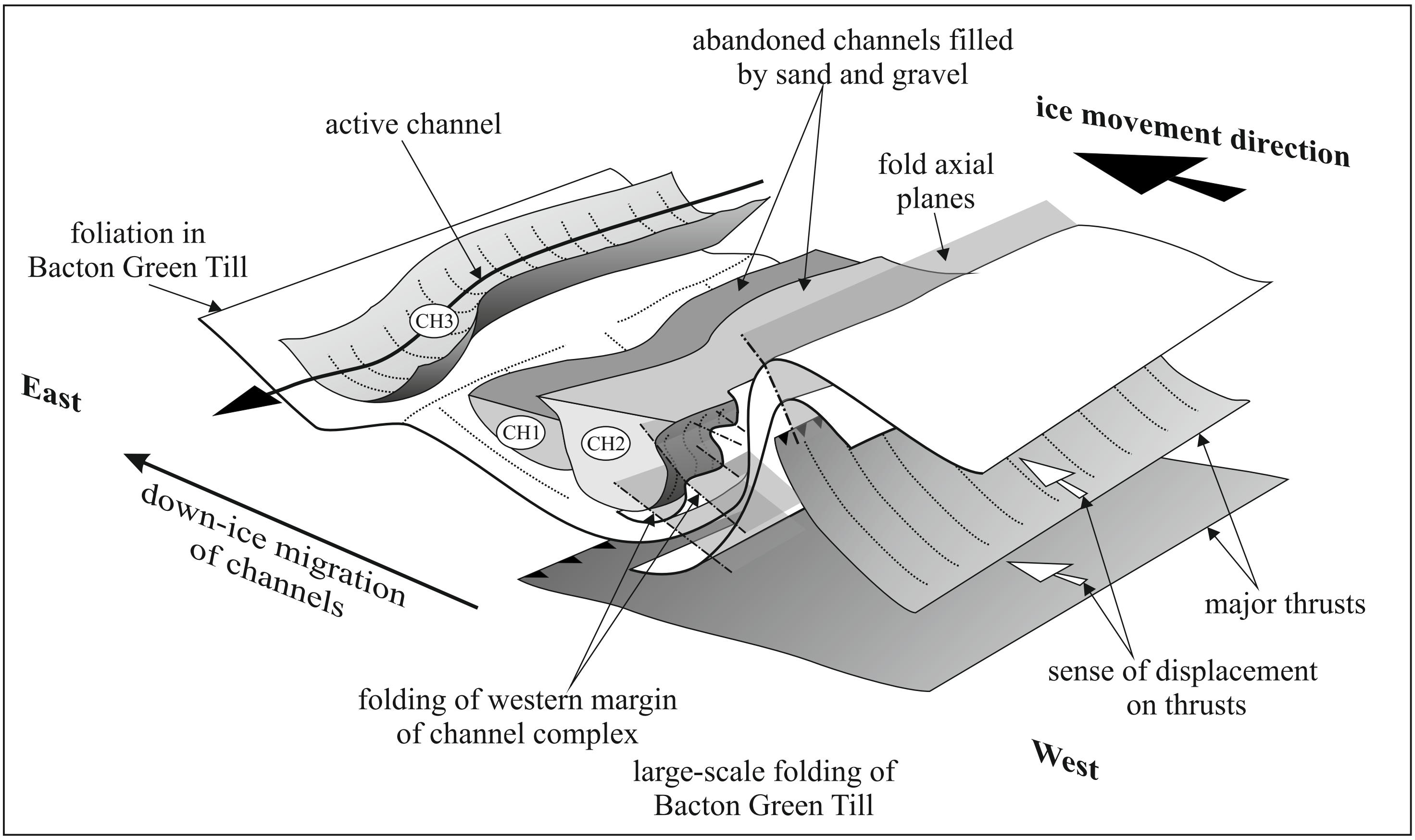
Lithostratigraphy (Subgroup / Formation / Member)	Sediment	Environment & Process	Chronostratigraphy
Briton's Lane Formation			
Briton's Lane Sand & Gravel Member	Sands and gravels	Proglacial outwash	
Runton Sand & Gravel Member (RSG)	Sands and gravels	Proglacial outwash	
Sheringham Cliffs Formation			
Weybourne Town Till Member	Very chalky diamicton	Subglacial till	
Bacton Green Till Member (BGT)	Sandy diamicton	Subglacial till	
Ivy Farm Laminated Member	Stratified silts and clays	Glaciolacustrine	
Marl Bed	Stratified marl	Glaciolacustrine	
			Mid-Pleistocene
Lowestoft Formation			
Lowestoft Till Member	Chalky, clayey diamicton	Subglacial till	
Walcott Till Member	Silty, clayey diamicton	Subglacial till	
Happisburgh Formation			
Happisburgh Till Member (HT)	Sandy, grey diamicton	Subglacial till	
Wroxham Crag Formation (WCF)			
Mundesley Member (MM)	Sands and gravels	Shallow marine	lower Mid-Pleistocene
Cromer Forest-bed Formation			
West Runton Freshwater Bed	Organic muds	Fluviatile, Floodplain	
Wroxham Crag Formation			
Mundesley Member	Gravels, sands & muds	Tidal, shallow marine	Lower Pleistocene
White Chalk Subgroup	White, flinty chalk	Deep marine	Upper Cretaceous

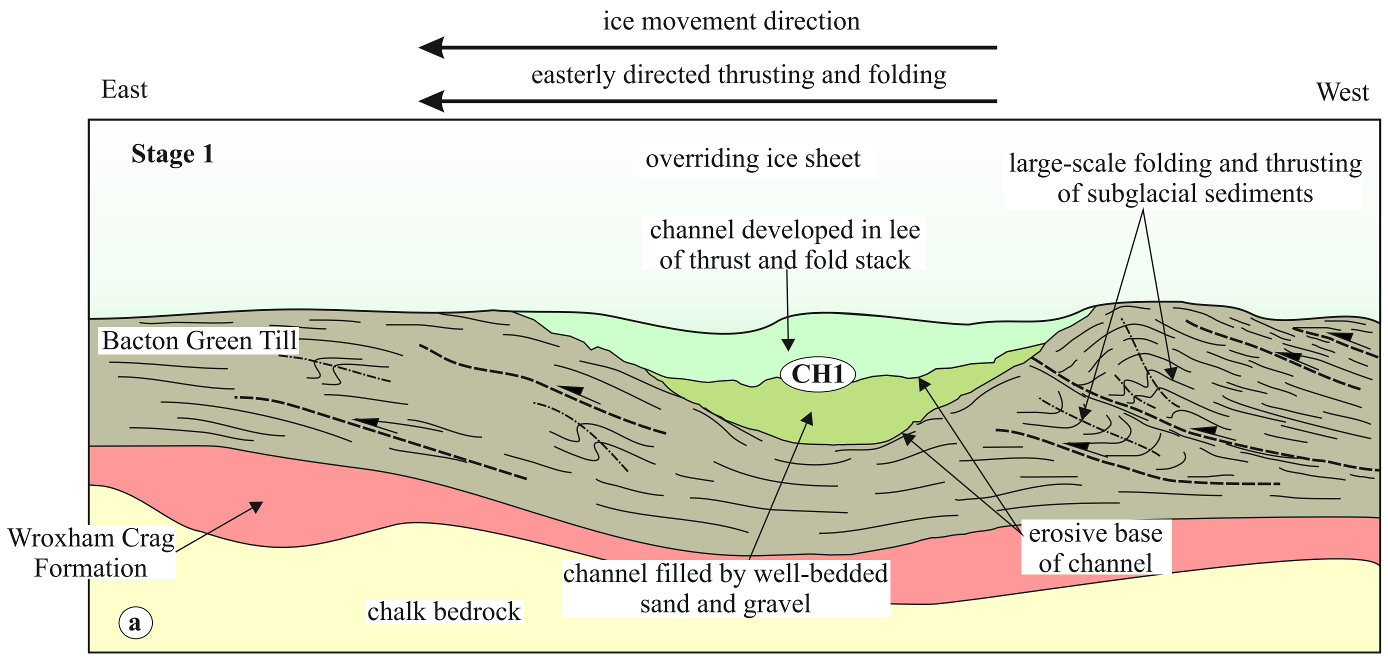

a
Scotland
Edinburgh
England
Norwich
Wales
London
N
b
Skegness
Sheringham
Weybourne
West Runton
Cromer
Overstrand
Trimingham
Bacton Green
The Wash
Fakenham
King's Lynn
Norfolk
Norwich
Great Yarmouth
Lowestoft
Thetford
N
50 km


East
West
planar top to channel
Briton's Lane sand & gravel
chalk-rich Weybourne Town Till
Bacton Green Till
Bacton Green Till
erosive base of channel
well-bedded sand and gravel
cross-cutting erosive contacts between different phase of fill within the channel
a
East
West
Briton's Lane sand and gravel
Weybourne Town Till
folding near western edge of large channel
easterly verging syncline
Bacton Green Till
erosive base of channel
Wroxham Crag Formation
cross-cutting erosive contacts between different phase of fill within the channel
b
East
West
deformed, over-steepened western margin of large channel
cross-cutting erosive contacts between different phase of fill within the channel
folding near western edge of large channel
Bacton Green Till
Wroxham Crag Formation
erosive base of channel
area covered by Fig. 10d
c
East
West
cross-cutting erosive contacts between different phase of fill within the channel
folding near western edge of large channel
coarse sand and gravel
Bacton Green Till
Wroxham Crag Formation
erosive base of channel
d

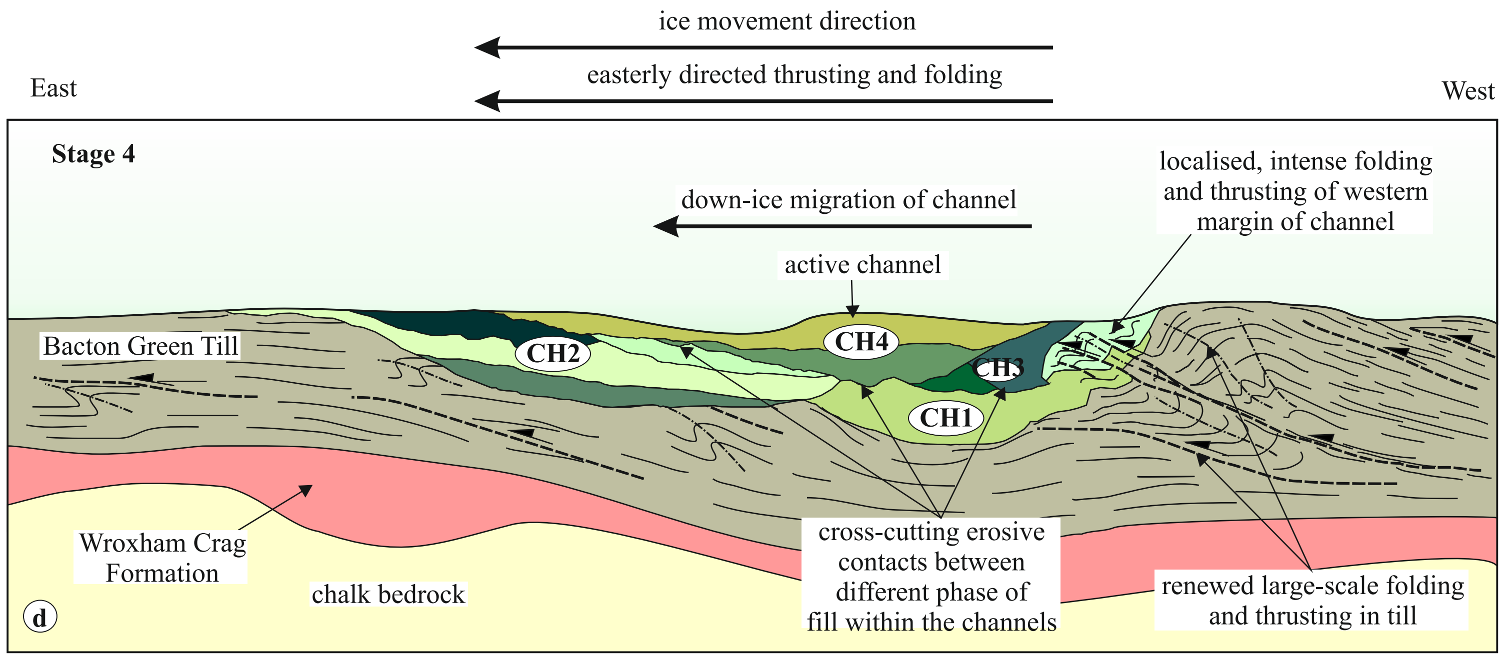

East
West
red-brown sand derived from Wroxham Crag Formation
Briton's Lane sand and gravel
Bacton Green Till
SE-verging asymmetrical folds
large-scale, sand-filled water-escape conduit disrupting the highly deformed Bacton Green Till
SE-verging folds deforming well-bedded sand and gravel
channel feature
well-bedded sand and gravel
Bacton Green Till
red-brown sand derived from Wroxham Crag Formation
brecciation of Bacton Green Till
erosive base of channel
a
well-bedded sand and gravel
East
red-brown sand derived from Wroxham Crag Formation
Briton's Lane sand and gravel
West
highly deformed Bacton Green Till
large-scale, sand-filled water-escape conduit disrupting the highly deformed Bacton Green Till
SE-verging asymmetrical folds
polyphase, fold interference patterns
prominent beds of gravel
SE-verging folds deforming well-bedded sand and gravel
Bacton Green Till
thrust
well-bedded sand and gravel
thrust
thrust
red-brown sand derived from Wroxham Crag Formation
brecciation of Bacton Green Till
channel feature
thrust
b
cross-bedded sand and gravel
erosive base of channel
convolute-style folds deforming bedding
sense of displacement on thrusts
bedding/layering
thrust faults
fold axes
sand and gravel filling channel colours denote different phases of sediment fill
Bacton Green Till
Briton's Lane sand and gravel
Wroxham Crag Formation
chalk-rich Weybourne Town Till


ice movement direction
ice sheet
subglacial meltwater channel
supraglacial meltwater channel
emerging subglacial meltwater channel
apron of glacial outwash deposited adjacent to ice margin
braided distributary channels
small 'fore-land' sedimentary basins developed in front of the advancing glacier
moranic ridges developed above tips of propagating thrusts
glacial outwash
bedrock
thrusting and high-angle faulting associated with propagating tip of the main basal detachment
undeformed sediment infill to small scale 'fore-land' sedimentary basin
thrusting and folding within core of a morainic ridge representing the former position of the tip of the main basal detatchment
localised deformation of the 'fore-land' basin sediment infill
thrusting and folding associated with ice marginal to subglacial deformation
Bacton Green and Happisburgh tills
thrusting and folding associated late-stage subglacial deformation
Wroxham Crag
channels developed in lee of fold and thrust stack
cross-cutting sand and gravel channel-fill deposits
proglacial deformation
ice-marginal deformation
subglacial deformation

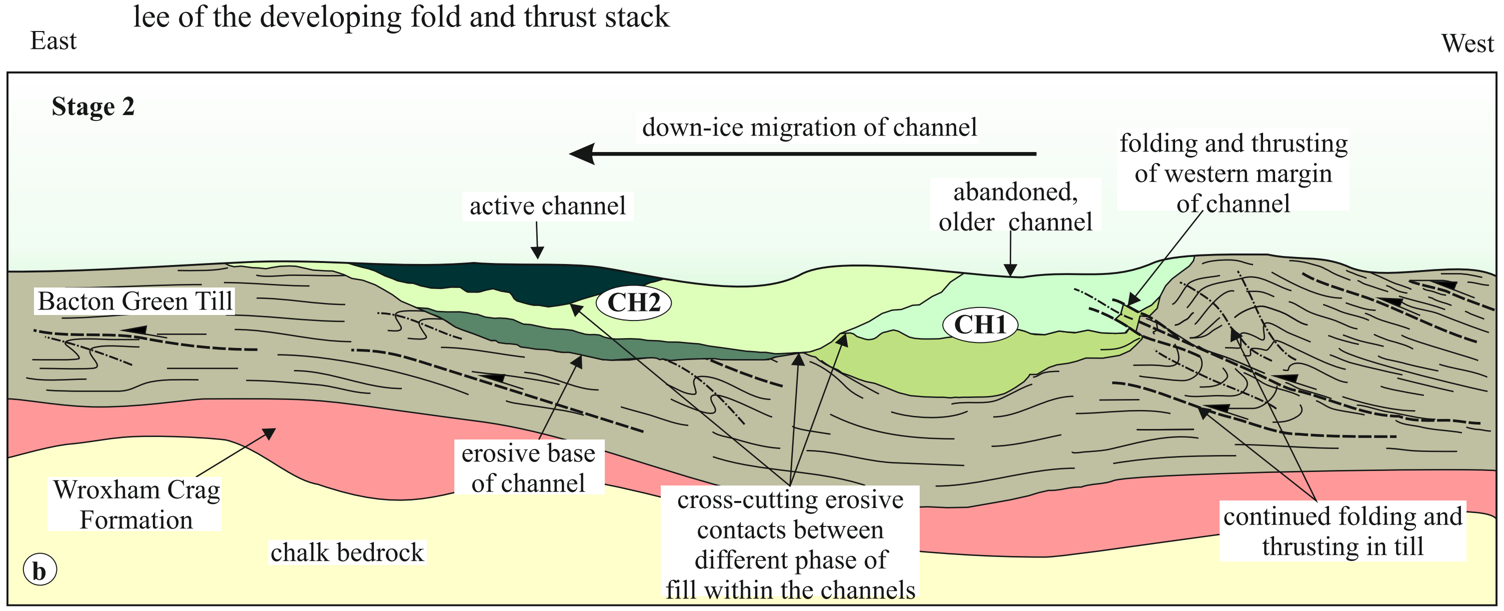

abandoned channels filled by sand and gravel
active channel
ice movement direction
fold axial planes
foliation in Bacton Green Till
CH3
East
CH1
CH2
down-ice migration of channels
major thrusts
sense of displacement on thrusts
folding of western margin of channel complex
West
large-scale folding of Bacton Green Till



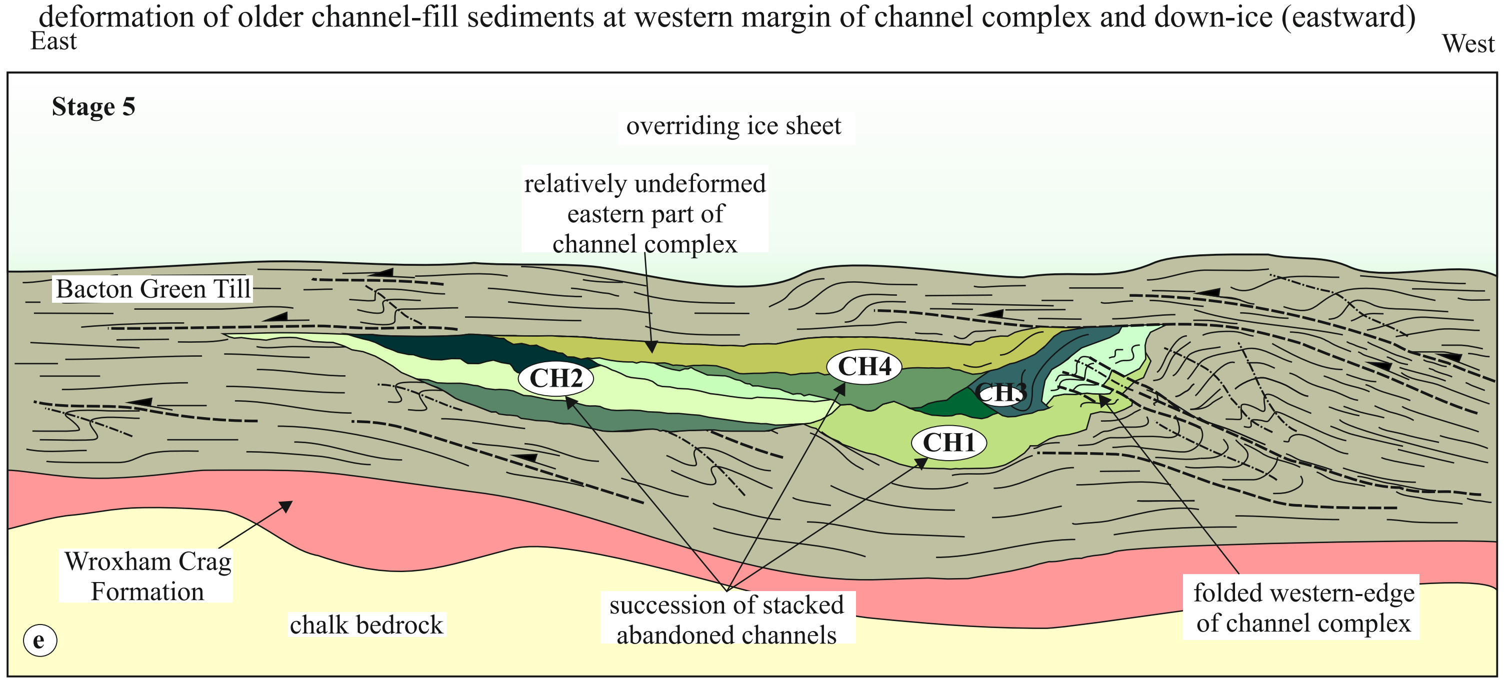
Stage 1: onset of large-scale subglacial folding and thrusting, and formation of a channel in the lee of the developing fold and thrust stack



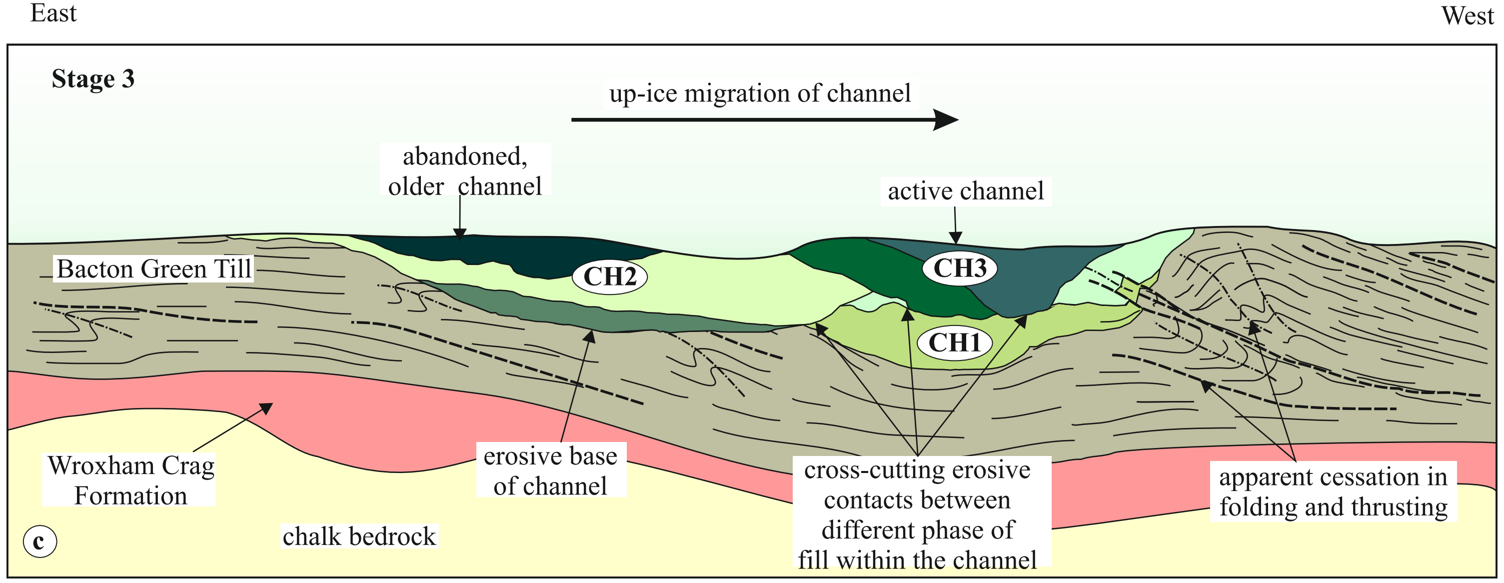
Stage 4: renewed subglacial deformation leading to abandonment of existing Stage 3 channel, continued deformation of older channel-fill sediments at western margin of channel complex and down-ice (eastward)



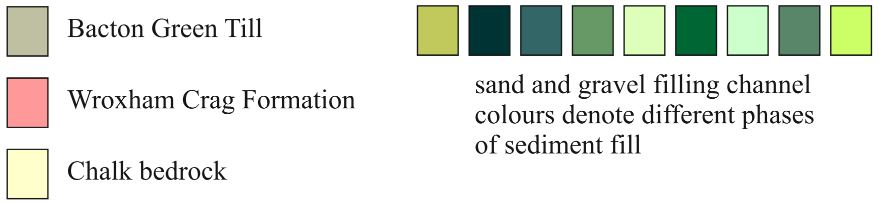
Stage 2: continued subglacial folding and thrusting leading to initial deformation of western margin of ‘older’ channel sequence and down-ice (eastward) migration of active channel system



Stage 5: renewed till deposition, channel abandonment, cessation in large-scale folding and thrusting, overall thickening of the subglacial sedimentary succession



Stage 3: apparent pause in subglacial deformation allowing the to up-ice (westward) migration of the active




East
West
Sheringham Coast Guard Sation
Briton's Lane sand and gravel
Weybourne Town Till
faults
large-scale, S-verging folds
Walcott Till
Bacton Green Till
debris
Bacton Green Till
sea wall
beach
large-scale, S-verging folds
Weybourne Town Till
no exposure
Bacton Green Till
raft of Walcott Till
debris
Boat House
large-scale, S-verging folds
raft of Walcott Till
Briton's Lane sand and gravel
Weybourne Town Till
Bacton Green Till
no exposure
chalk-rich gravel
Happisburgh Till
complex outcrop pattern of chalky till due to strike parallel section through large-scale S-verging fold
displaced (mass flow) block of Weybourne Town Till and Briton's Lane sand and gravel
meso-scale, E-verging fold
large-scale, S-verging fold
Walcott Till
Bacton Green Till
Briton's Lane sand and gravel
irregular, karst-like surface to Weybourne Town Till
large-scale, S-verging fold
?displaced block of pale chalky till
pale coloured chalky till
well-bedded sand and gravel
Happisburgh Till in core of fold
Wroxham Crag Formation
displaced (mass flow) block of Weybourne Town Till and Briton's Lane sand and gravel
irregular, karst-like surface to Weybourne Town Till
Briton's Lane sand and gravel
?displaced block of pale chalky till
bedded sand
chalk raft
Happisburgh Till
lens/augen of Walcott Till within Happisburgh Till
chalk-rich gravel
Briton's Lane sand and gravel
Weybourne Town Till
displaced (mass flow) block of Weybourne Town Till and Briton's Lane sand and gravel
Wroxham Crag Formation
?Briton's Lane sand and gravel
large-scale E-verging fold
thin chalk raft
raft of Walcott Till
raft of ?Cromer Forest Bed
lens of Walcott Till
irregular, erosive contact cutting down wards into Bacton Green Till
involved Weybourne Town Till within Briton's Lane sand and gravel
well bedded, relatively undeformed sand and gravel
large-scale channel
small chalk rafts
erosive contact
deformed, steeply inclined bedding in sand and gravel
cross-cutting, erosive bases to sand and gravel units
large-scale channel comprising cross-cutting lenses of sand and gravel
highly deformed and rotated sand intraclasts
large-scale E-verging fold
E-directed folding and thrusting
S-verging meso-scale folding at edge of chalk raft
raft of ?Cromer Forest Bed
irregular, karst-like surface to Weybourne Town Till
poorly exposed Wroxham Crag Formation
chalk raft
deformed channel composed of well-bedded sand and gravel
large-scale channel comprising cross-cutting lenses of sand and gravel
large-scale, E-directed folding and thrusting of the Happisburgh and Bacton Green tills
[TG 14784 43529]
small chalk rafts
raft of Wroxham Crag Formation
thrusting within chalk raft
deformed channel-like feature composed of well-bedded sand and gravel
erosive base to channel
irregular, karst-like surface to Weybourne Town Till
deformed channel-like feature composed of well-bedded sand and gravel
trough cross-bedding in Wroxham Crag Formation
large-scale, E-verging folding of Happisburgh and Bacton Green tills
folding of western margin of channel
erosive base to small sand and gravel filled channel
deformed sand intraclast
deformed lens of sand
irregular, folded area of coarse cobble gravel
irregular, ?involved surface to Bacton Green Till
small-scale folding within Bacton Green Till
folding of western margin of channel-like feature composed of well-bedded sand and gravel
deformed raft/intraclast of well-bedded sand and gravel
E-directed folding and thrusting in Bacton Green Till
deformed rafts/intraclasts of well-bedded sand and gravel
shallow channel feature within Wroxham Crag
channel-like feature composed of well-bedded sand and gravel
E-verging folding of western margin of channel
channel-like feature composed of well-bedded sand and gravel
large raft of Wroxham Crag Formation
large-scale cross bedding in Wroxham Crag Formation
irregular, erosive base to channel
E-directed thrusting in Bacton Green Till
chalk rafts
recumbent fold deforming chalk raft within Bacton Green Till
well-developed cross stratification
well-bedded sand and gravel
open, shallow valley near golf course
preglacial sequence
Wroxham Crag Formation (WCF)
Cromer Forest Bed
White Chalk Subgroup (bedrock)
subglacial sediments
Weybourne Town Till Member (WTTM)
Bacton Green Till Member mélange (BGTMm)
Happisburgh Till Member (HTM)
Walcott Till Member (WTM)
glacial outwash
Briton's Lane Sand and Gravel Member (BSGM)
sense of displacement on thrusts/faults
thrust faults
folds axial planes

Figure 2a

open valley near golf course
East
wide channel cutting downwards into deformed glacial sequence
West
Briton's Lane sand and gravel
no exposure
debris
large-scale, cross stratification
Wroxham Crag Formation
beach
Briton's Lane sand and gravel
no exposure
Wroxham Crag Formation
cross-cutting, erosive channel bases
lenses of coarse gravel
large-scale cross stratification
Bacton Green Till
East
West
lenses of coarse gravel
Briton's Lane sand and gravel
thick lens of coarse gravel
chalk rafts
Bacton Green Till
debris
no exposure
Happisburgh Till
well-bedded sand and gravel
beach
erosive base to channel
large channel within Wroxham Crag Formation
bedded sand
East
West
thin chalk raft
channel-like feature filled with well-bedded sand and gravel
steeply inclined E-verging fold
irregular karst-like surface to Weybourne Town Till
coarse sand and gravel
Briton's Lane sand and gravel
Bacton Green Till
Happisburgh Till
chalk raft
debris
Wroxham Crag Formation
cross-cutting erosive margin to channel
erosive base to channel
beach
displaced (mass flow) block of Weybourne Town Till and Briton's Lane sand and gravel
East
West
Briton's Lane sand and gravel
well-bedded sand and gravel
Bacton Green Till
debris
chalk rafts
large-scale, E-verging fold
folding and thrust repetition within the Happisburgh Till
large-scale, shallow channel within Wroxham Crag Formation
erosive base to channel
well-bedded sand and gravel
beach
East
West
large-scale channel
well-bedded coarse sand and gravel
well bedded, undeformed sand and gravel
Briton's Lane sand and gravel
debris
Happisburgh Till
chalk rafts sand and gravel
erosive base to channel
Happisburgh Till
beach
chalk bedrock
East
West
Briton's Lane sand and gravel
folded chalk rafts
debris
chalk raft
Happisburgh Till
chalk bedrock
beach
Wroxham Crag Formation
large-scale cross stratification
coarse shelly gravel at base of Wroxham Crag Formation
East
Bacton Green Till
Briton's Lane sand and gravel
West
large-scale, E-verging folds
folded chalk rafts
debris
well-bedded sand and gravel
Happisburgh Till
large-scale channel within Wroxham Crag Formation
East
highly deformed chalk rafts
thrust repetition of Happisburgh Till and rafts of Wroxham Crag
Briton's Lane sand and gravel
West
debris
chalk bedrock
well-bedded sand and gravel of Wroxham Crag Formation
East
thrust repetition of Happisburgh Till and rafts of Wroxham Crag
channel-like feature composed of well-bedded sand and gravel
West
erosive contact
irregular, karst-like surface to Weybourne Town Till
lens of coarse-grained gravel
well-bedded sand and gravel
Bacton Green Till
debris
no exposure
recumbent, isoclinal folding and thrusting within raft of Wroxham Crag
chalk bedrock
beach
Wroxham Crag Formation
East
channel-like feature composed of well-bedded sand and gravel
steeply inclined bedding in gravel
folded slab-like rafts of chalk
irregular, karst-like surface to Weybourne Town Till
West
erosive, cross-cutting base to sand-rich channel fill
Briton's Lane sand and gravel
well-bedded sand and gravel
chalk raft
chalk raft
Bacton Green Till
debris
erosive base to channel
large-scale, E-verging fold
Happisburgh Till
Happisburgh Till
large-scale cross stratification
chalk bedrock
Wroxham Crag Formation
beach
possible thrust repetition of Bacton Green and Happisburgh tills
well-bedded sand and gravel of Wroxham Crag
East
chalk rafts
highly convoluted/cryoturbated Weybourne Town Till
irregular, karst-like surface to Weybourne Town Till
West
large channel filled by well-bedded Briton's Lane sand and gravel
debris
Bacton Green Till
thin layer of Happisburgh Till
Wroxham Crag
erosive, cross-cutting base to channel within Wroxham Crag Formation
beach
East
irregular, karst-like surface to Weybourne Town Till
West
large channel filled by well-bedded Briton's Lane sand and gravel
Weybourne Town Till
lenticular raft of Wroxham Crag
rotated chalk raft
debris
E-verging, large-scale folding of Bacton Green Till
chalk bedrock
thin layer of Happisburgh Till
beach
cross-cutting margin to channel in Wroxham Crag
East
West
E-direct folding and thrusting of Bacton Green Till
irregular, karst-like surface to Weybourne Town Till
large channel filled by well-bedded Briton's Lane sand and gravel
Bacton Green Till
debris
Wroxham Crag Formation
beach
East
West
rapid thinning of Briton's Lane sand and gravel
Weybourne Town Till
Weybourne Town Till
erosive base to small sand and gravel filled channel
large channel filled by well-bedded Briton's Lane sand and gravel
lens of well-bedded coarse sand and gravel
weakly deformed western margin to large channel filled by well-bedded sand and gravel
Bacton Green Till
Bacton Green Till
debris
chalk bedrock
thick layer of weakly stratified, chalk-rich Weybourne Town Till
beach
Happisburgh Till
East
rapid thinning of Briton's Lane sand and gravel
West
Weybourne Town Till
deformed rafts of Marl Bed and sand
Bacton Green Till
debris
chalk bedrock
Happisburgh Till
beach
Wroxham Crag Formation
convolute folding/involutions of Briton's Lane sand and gravel, Weybourne Town Till and Bacton Green Till
East
deformed rafts of Marl Bed and sand
West
Bacton Green Till
Briton's Lane sand and gravel
erosive base to Briton's Lane sand and gravel
debris
chalk bedrock
folding and thrusting within Bacton Green Till
beach
shallow channel within Wroxham Crag
Happisburgh Till
East
West
Briton's Lane sand and gravel
deformed channel composed of well-bedded sand and gravel
Bacton Green Till
E-verging fold
Happisburgh Till
debris
chalk bedrock
beach
East
Weybourne Town Till
West
deformed channels composed of well-bedded sand and gravel
Bacton Green Till
irregular, erosive base to channel
debris
deformed sand intraclasts
chalk bedrock
Wroxham Crag Formation
beach
East
West
large-scale, E-verging fold
Bacton Green Till
debris
chalk bedrock
deformed channel composed of well-bedded sand and gravel
East
West
steeply inclined and folded bedding
debris
debris
chalk bedrock
erosive base to channel
E-directed thrusting in Bacton Green Till
Wroxham Crag filling large-scale water-escape conduit
East
steeply inclined and folded bedding
deformed channel composed of well-bedded sand and gravel
West
deformed channel composed of well-bedded sand and gravel
debris
debris
debris
erosive base to channel
beach
Wroxham Crag filling large-scale water-escape conduit
E-directed thrusting in Bacton Green Till
deformed channel composed of well-bedded sand and gravel
East
Briton's Lane sand and gravel
West
deformed sand intraclasts
debris
mesoscale, E-verging, asymmetrical folds
chalk bedrock
beach
E-directed thrusts in Bacton Green Till
East
deformed channel composed of well-bedded sand and gravel
Briton's Lane sand and gravel
West
Bacton Green Till
chalk bedrock
E-directed thrusting in Bacton Green Till
well bedded sand and gravel of the Wroxham Crag Formation
East
deformed channel composed of well-bedded sand and gravel
Briton's Lane sand and gravel
Weybourne Town Till
deformed sand intraclasts
West
small chalk rafts
debris
debris
debris
Happisburgh Till
highly deformed sand lens
chalk bedrock
beach
Wroxham Crag Formation
East
deformed sand lenses
West
Bacton Green Till
debris
debris
debris
chalk bedrock
cross-bedded sand and gravel of the Wroxham Crag Formation
Happisburgh Till
E-directed thrusting in Bacton Green Till


East
West
Briton's Lane
sand and gravel
small, slab-like
rafts of chalk
Bacton Green Till
Happisburgh Till
deformed lenses
(intrclasts) of sand
debris
debris
chalk bedrock
beach
Wroxham Crag Formation
East
West
irregular karst-like
surface to chalky till
deformed sand intraclast recording
a E-directed sense of shear
Briton's Lane
sand and gravel
Weybourne Town Till
deformed channel composed
of well-bedded
sand and gravel
Bacton Green Till
E-directed thrust
augen-like
chalk clasts
debris
debris
debris
erosive base
to channel
Wroxham Crag Formation
beach
East
West
deformed channel
composed of sand and gravel
complex folding of
western margin of channel
deformed channel
composed of sand and gravel
Briton's Lane
sand and gravel
Bacton Green Till
E-verging, asymmetrical fold
debris
Happisburgh Till
deformed lens of sand
well-bedded
sand and gravel
beach
East
West
E-directed thrusting
within Bacton Green Till
augen -like sand intraclasts
recoding an E-directed
sense of shear
channel fill composed
of well-bedded sand and gravel
well-bedded sand
and gravel
chalk rafts
erosive base
to channel
debris
E-verging asymmetrical folds
in Bacton Green Till
cross-cutting channel fills within
Wroxham Crag Formation
Happisburgh Till
beach
channel-like feature filled with well-bedded
sand and gravel
East
West
cross-cutting erosive margin
to channel
Bacton Green Till
deformed sand
intraclasts
debris
chalk bedrock
beach
erosive base to channel
East
West
cross-cutting
channel fills
thick gravel unit
within channel
folding of steeply
inclined bedding at
western margin of channel
Briton's Lane
sand and gravel
Happisburgh Till
Wroxham Crag Formation
debris
E-verging folds
chalk bedrock
beach
East
West
irregular karst-like surface to
Weybourne Town Till
Briton's Lane
sand and gravel
complex folding and thrusting in
Bacton Green Till
Bacton Green Till
debris
chalk bedrock
slab-like chalk rafts
large-scale channel within
Wroxham Crag Formation
large-scale,
E-verging fold
East
West
Weybourne Town Till
elongate, slab-like
chalk rafts
Bacton Green Till
debris
chalk bedrock
beach
thinning and cutting out
of Happisburgh Till
well-bedded and cross-stratified
sand and gravel
deformed raft of coarse,
poorly bedded gravel
East
West
chalk rafts
well-developed karst-like
surface to chalky till
well-developed recumbent to gently inclined
folds within Bacton Green Till
debris
chalk bedrock
Wroxham Crag Formation
deformed raft of
Wroxham Crag Formation
deformed lens
of coarse gravel
East
West
deformed channel composed of
sand and gravel
Briton's Lane
sand and gravel
complex folding of
margins of gravel raft
debris
chalk bedrock
beach
channel within Wroxham
Crag Formation
deformed raft of Wroxham
Crag Formation
East
West
highly deformed raft
of coarse gravel
well-bedded
sand and gravel
chalk bedrock
Wroxham Crag Formation
complex folding and thrusting
within Bacton Green Till
East
West
Briton's Lane
sand and gravel
lenticular, channel-fill composed
of sand and gravel
Bacton Green Till
chalk bedrock
well-bedded sand and gravel
of Wroxham Crag Formation
East
West
Briton's Lane
sand and gravel
lenticular, channel-fill composed
of sand and gravel
deformed rafts of Wroxham
Crag and pale yellow sand
erosive base to sand
filled channel
Bacton Green Till
debris
chalk bedrock
beach
Wroxham Crag Formation
East
West
irregular, karst-like surface to
Weybourne Town Till
lenticular rafts of
Wroxham Crag
recumbent folding of well-bedded
sand and gravel
deformed lens of
well-bedded sand
karst-like surface to
Weybourne Town Till
recumbent folding of well-bedded
sand and gravel
Bacton Green Till
Bacton Green Till
debris
debris
debris
debris
debris
convoluted/involuted
Weybourne Town Till
Happisburgh Till
thrust repetition and tectonic
thickening of Bacton Green Till
chalk bedrock
chalk bedrock
deformed lenses of massive
to well-bedded pale yellow sand
beach
Wroxham Crag Formation
well-bedded sand and gravel
of Wroxham Crag
East
West
recumbent folding of
well-bedded sand and gravel
highly convoluted/cryoturbated
Weybourne Town Till
E-verging fold within
deformed sand lens
Bacton Green Till
E-verging, asymmetrical folds
deformed sand lens
Wroxham Crag Formation
beach
chalk bedrock
East
West
irregular, karst-like
surface to Weybourne
Town Till
lens of sand
and gravel
Briton's Lane sand
and gravel
debris
debris
chalk bedrock
beach
well-bedded, cross-stratified and
channelised sand and gravel of
the Wroxham Crag Formation
E-directed thrusting
within Bacton Green Till
deformed sand lens
East
West
Briton's Lane
sand and gravel
irregular, erosive base to Briton's
Lane sand and gravel
small chalk rafts
erosive base to
large channel
large channel composed of
well-bedded pale yellow sand
Bacton Green Till
debris
debris
debris
chalk bedrock
Wroxham Crag Formation
large-scale cross-stratification in
Wroxham Crag Formation
East
West
large channel composed of
well-bedded pale yellow sand
rapid thinning of Briton's
Lane sand and gravel
sharp, erosive base Briton's
Lane sand and gravel
large channel filled by well-bedded
Briton's Lane sand and gravel
Briton's Lane sand
and gravel
Bacton Green Till
debris
debris
chalk bedrock
complex, cross-cutting series of
sand dominated channel-fills
beach
well-bedded sand and gravel
of Wroxham Crag Formation
East
West
Briton's Lane
sand and gravel
large channel filled by
well bedded, red-brown
sand and gravel
thickening westwards of
Briton's Lane sand and gravel
well-bedded red-brown
sand and gravel
Bacton Green
Till
Wroxham Crag
Formation
debris
debris
debris
thick gravel units within Briton's
Lane sand and gravel
debris
central portion of large channel
filled by Briton's Lane sand and gravel
thick gravel units within Briton's
Lane sand and gravel
debris
debris
debris
debris
debris
debris
chalk bedrock
chalk bedrock
beach
Bacton Green Till
cut out by erosive base of
Briton's Lane sand and gravel
well-bedded and cross-stratified
Wroxham Crag Formation
erosive base of Briton's Lane
cutting down into underlying
Wroxham Crag
Wroxham Crag Formation cut out by erosive
base of Briton's Lane sand and gravel
beach
involuted surface to
chalk bedrock
involuted surface to
chalk bedrock
Bacton Green Till
East
West
well-developed
cross stratification
thick gravel units within Briton's
Lane sand and gravel
western margin of large channel composed
of well-bedded sand and gravel
debris
chalk bedrock
Bacton Green Till
beach
involuted erosive
base to channel
East
Briton's Lane
sand and gravel
stacked, cross-cutting channel-fills
composed of well-bedded sand and gravel
debris
debris
debris
Bacton Green Till
beach
large-scale cross-stratification
East
West
thick gravel unit within Briton's
Lane sand and gravel
Weybourne Town Till
debris
debris
Bacton Green Till
well bedded sand and gravel of the
Briton's Lane sand and gravel
deformed sand lens yielding
E-directed sense of shear
highly deformed and
stratified Bacton Green Till
irregular erosive base to
Briton's Lane sand and gravel
East
West
well-developed
cross stratification
stacked, cross-cutting channel-fills
composed of well-bedded sand and gravel
debris
Bacton Green Till
beach
irregular erosive base to
Briton's Lane sand and gravel
deformed sand lens
Weybourne Town Till
thinning westwards of
Briton's Lane sand and gravel
East
West
Briton's Lane
sand and gravel
karst-like surface to
Weybourne Town Till
deformed sand
lens
debris
debris
debris
Bacton Green Till
chalk bedrock
well-developed
cross stratification
beach

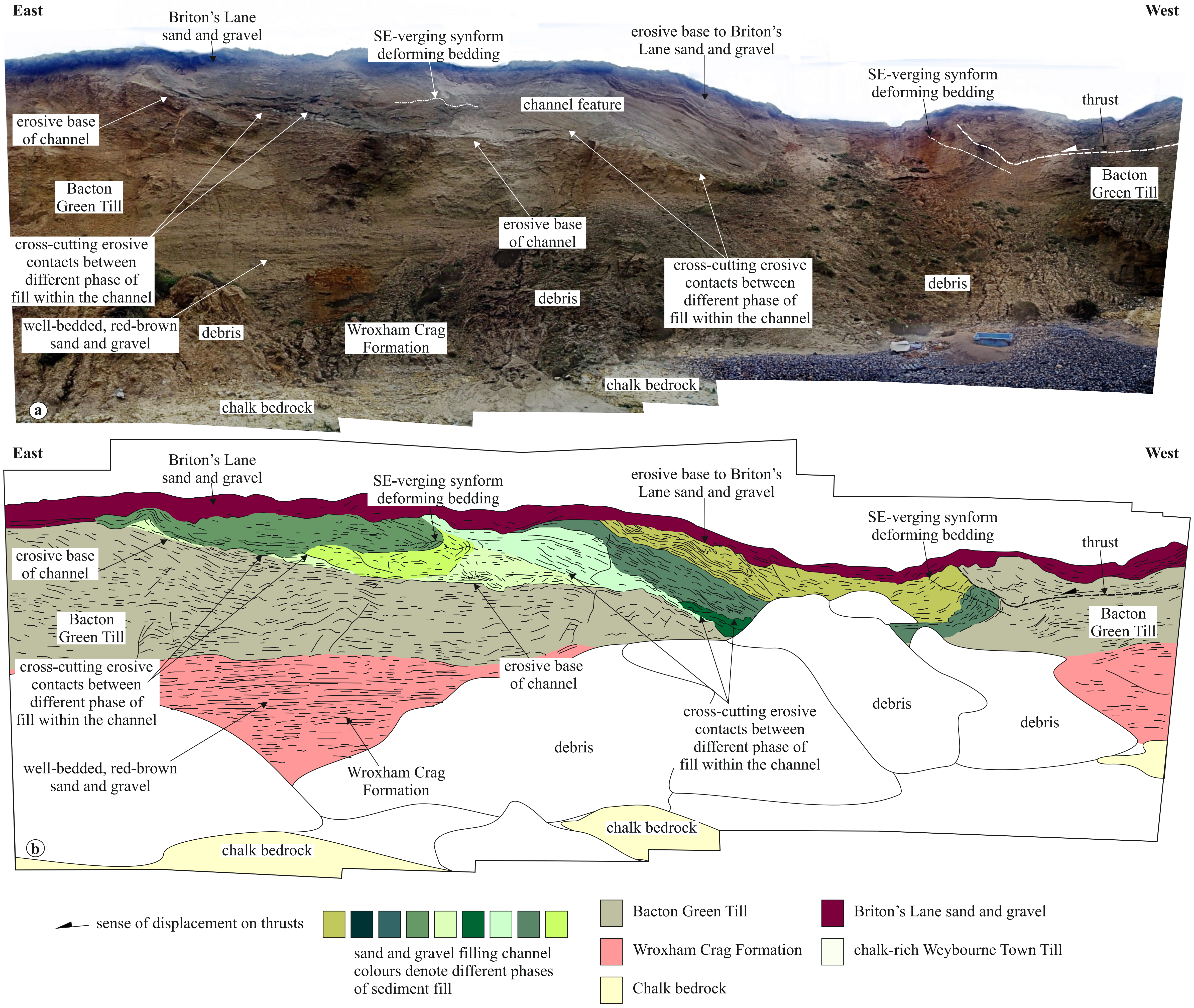
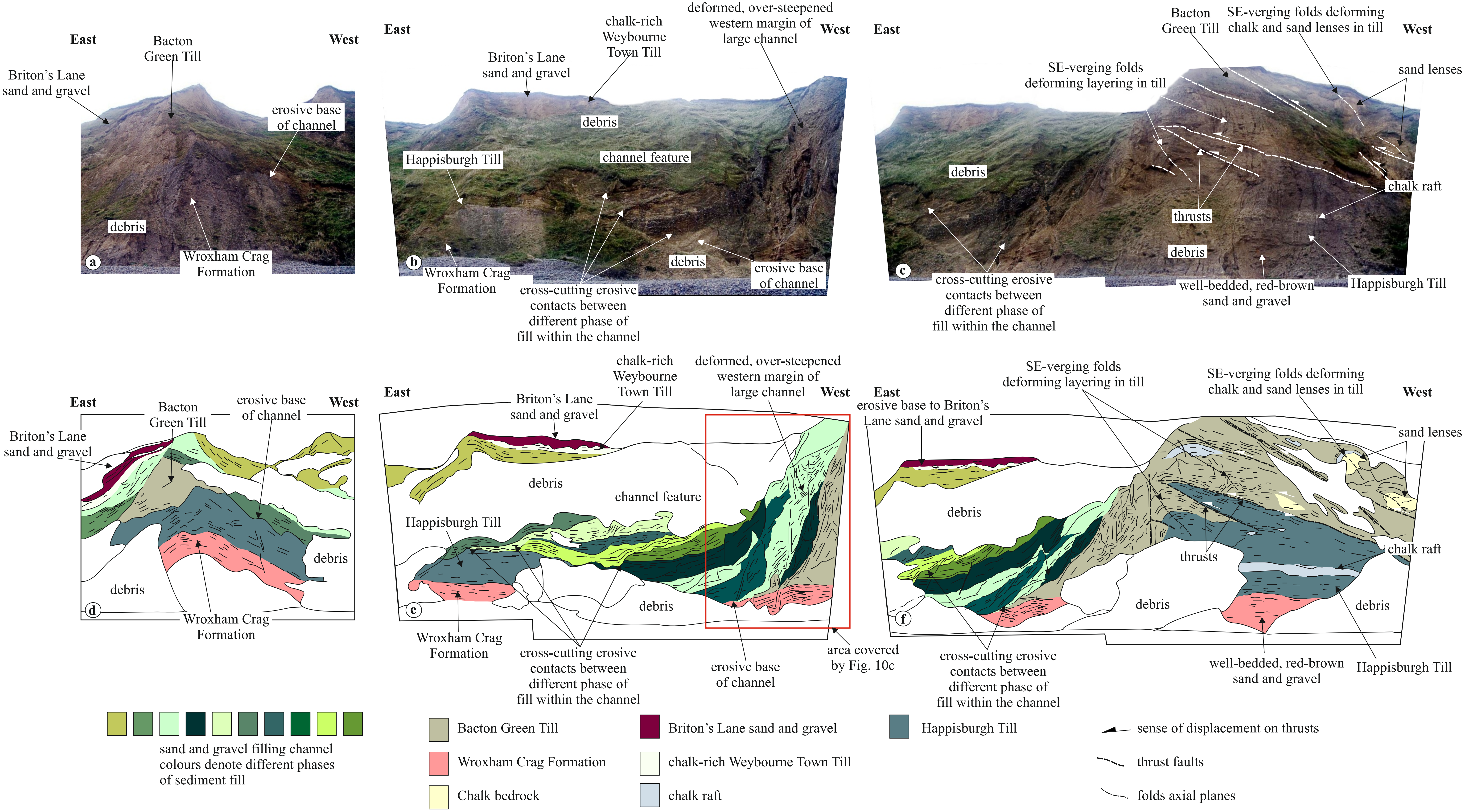

East
West
Briton's Lane sand and gravel
SE-verging synform deforming bedding
erosive base to Briton's Lane sand and gravel
SE-verging synform deforming bedding
thrust
erosive base of channel
channel feature
Bacton Green Till
Bacton Green Till
cross-cutting erosive contacts between different phase of fill within the channel
erosive base of channel
cross-cutting erosive contacts between different phase of fill within the channel
debris
debris
well-bedded, red-brown sand and gravel
debris
Wroxham Crag Formation
chalk bedrock
chalk bedrock
a
East
West
Briton's Lane sand and gravel
SE-verging synform deforming bedding
erosive base to Briton's Lane sand and gravel
SE-verging synform deforming bedding
thrust
erosive base of channel
Bacton Green Till
Bacton Green Till
cross-cutting erosive contacts between different phase of fill within the channel
erosive base of channel
debris
debris
debris
cross-cutting erosive contacts between different phase of fill within the channel
well-bedded, red-brown sand and gravel
Wroxham Crag Formation
chalk bedrock
chalk bedrock
b
sense of displacement on thrusts
sand and gravel filling channel colours denote different phases of sediment fill
Bacton Green Till
Wroxham Crag Formation
Chalk bedrock
Briton's Lane sand and gravel
chalk-rich Weybourne Town Till

Figure 3


East
West
Briton's Lane sand and gravel
Bacton Green Till
erosive base of channel
debris
Wroxham Crag Formation
a
chalk-rich Weybourne Town Till
deformed, over-steepened western margin of large channel
Happisburgh Till
channel feature
erosive base of channel
cross-cutting erosive contacts between different phase of fill within the channel
b
SE-verging folds deforming layering in till
SE-verging folds deforming chalk and sand lenses in till
sand lenses
chalk raft
thrusts
well-bedded, red-brown sand and gravel
c
d
e
area covered by Fig. 10c
erosive base to Briton's Lane sand and gravel
f
sand and gravel filling channel colours denote different phases of sediment fill
Bacton Green Till
Wroxham Crag Formation
Chalk bedrock
Briton's Lane sand and gravel
chalk-rich Weybourne Town Till
chalk raft
Happisburgh Till
sense of displacement on thrusts
thrust faults
folds axial planes

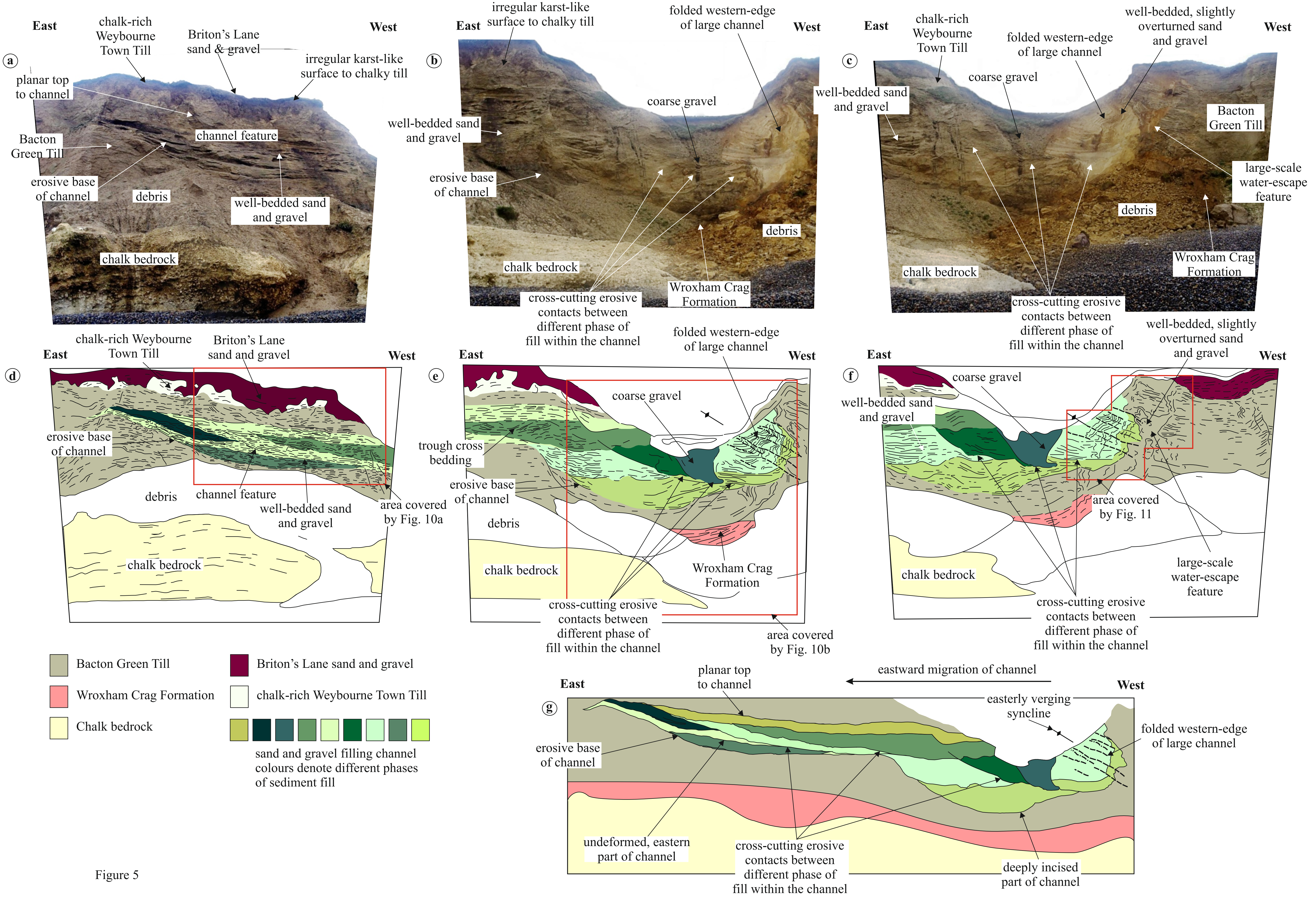

a
East
chalk-rich Weybourne Town Till
Briton's Lane sand & gravel
West
planar top to channel
irregular karst-like surface to chalky till
channel feature
Bacton Green Till
erosive base of channel
debris
well-bedded sand and gravel
chalk bedrock
b
East
irregular karst-like surface to chalky till
folded western-edge of large channel
West
coarse gravel
well-bedded sand and gravel
erosive base of channel
debris
chalk bedrock
Wroxham Crag Formation
cross-cutting erosive contacts between different phase of fill within the channel
c
East
chalk-rich Weybourne Town Till
folded western-edge of large channel
well-bedded, slightly overturned sand and gravel
West
coarse gravel
well-bedded sand and gravel
Bacton Green Till
large-scale water-escape feature
debris
Wroxham Crag Formation
chalk bedrock
cross-cutting erosive contacts between different phase of fill within the channel
d
East
chalk-rich Weybourne Town Till
Briton's Lane sand and gravel
West
erosive base of channel
debris
channel feature
well-bedded sand and gravel
area covered by Fig. 10a
chalk bedrock
e
East
folded western-edge of large channel
West
coarse gravel
trough cross bedding
erosive base of channel
debris
chalk bedrock
Wroxham Crag Formation
cross-cutting erosive contacts between different phase of fill within the channel
area covered by Fig. 10b
f
East
well-bedded, slightly overturned sand and gravel
West
coarse gravel
well-bedded sand and gravel
area covered by Fig. 11
chalk bedrock
large-scale water-escape feature
cross-cutting erosive contacts between different phase of fill within the channel
Bacton Green Till
Wroxham Crag Formation
Chalk bedrock
Briton's Lane sand and gravel
chalk-rich Weybourne Town Till
sand and gravel filling channel colours denote different phases of sediment fill
g
East
planar top to channel
eastward migration of channel
West
easterly verging syncline
folded western-edge of large channel
erosive base of channel
undeformed, eastern part of channel
cross-cutting erosive contacts between different phase of fill within the channel
deeply incised part of channel

Figure 5

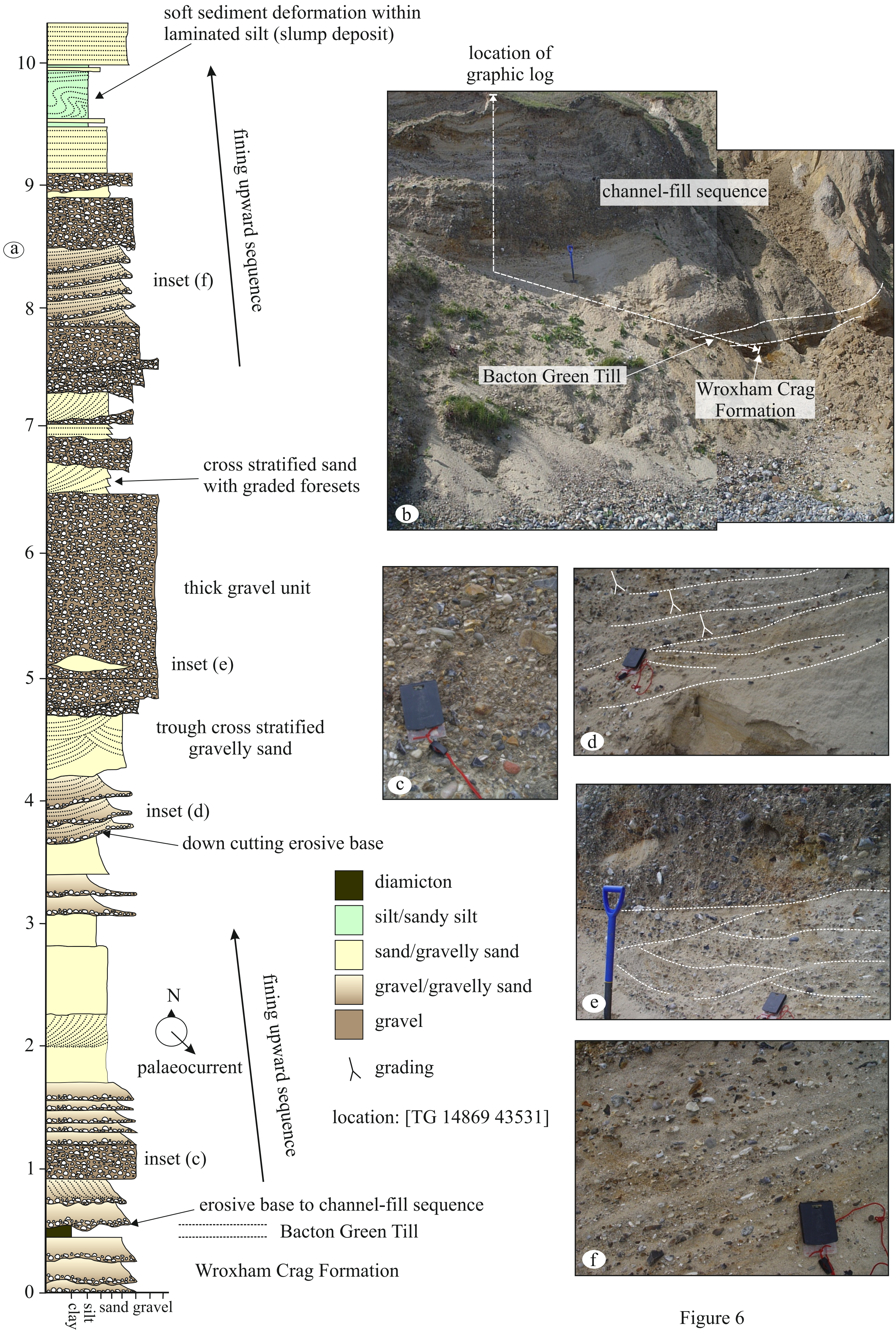

soft sediment deformation within laminated silt (slump deposit)
10
9
8
7
6
5
4
3
2
1
0
ⓐ
fining upward sequence
inset (f)
cross stratified sand with graded foresets
thick gravel unit
inset (e)
trough cross stratified gravelly sand
inset (d)
down cutting erosive base
N
palaeocurrent
fining upward sequence
inset (c)
erosive base to channel-fill sequence
Bacton Green Till
Wroxham Crag Formation
clay
silt
sand
gravel
diamicton
silt/sandy silt
sand/gravelly sand
gravel/gravelly sand
gravel
grading
location: [TG 14869 43531]
location of graphic log
channel-fill sequence
Bacton Green Till
Wroxham Crag Formation
b
c
d
e
f

Figure 6

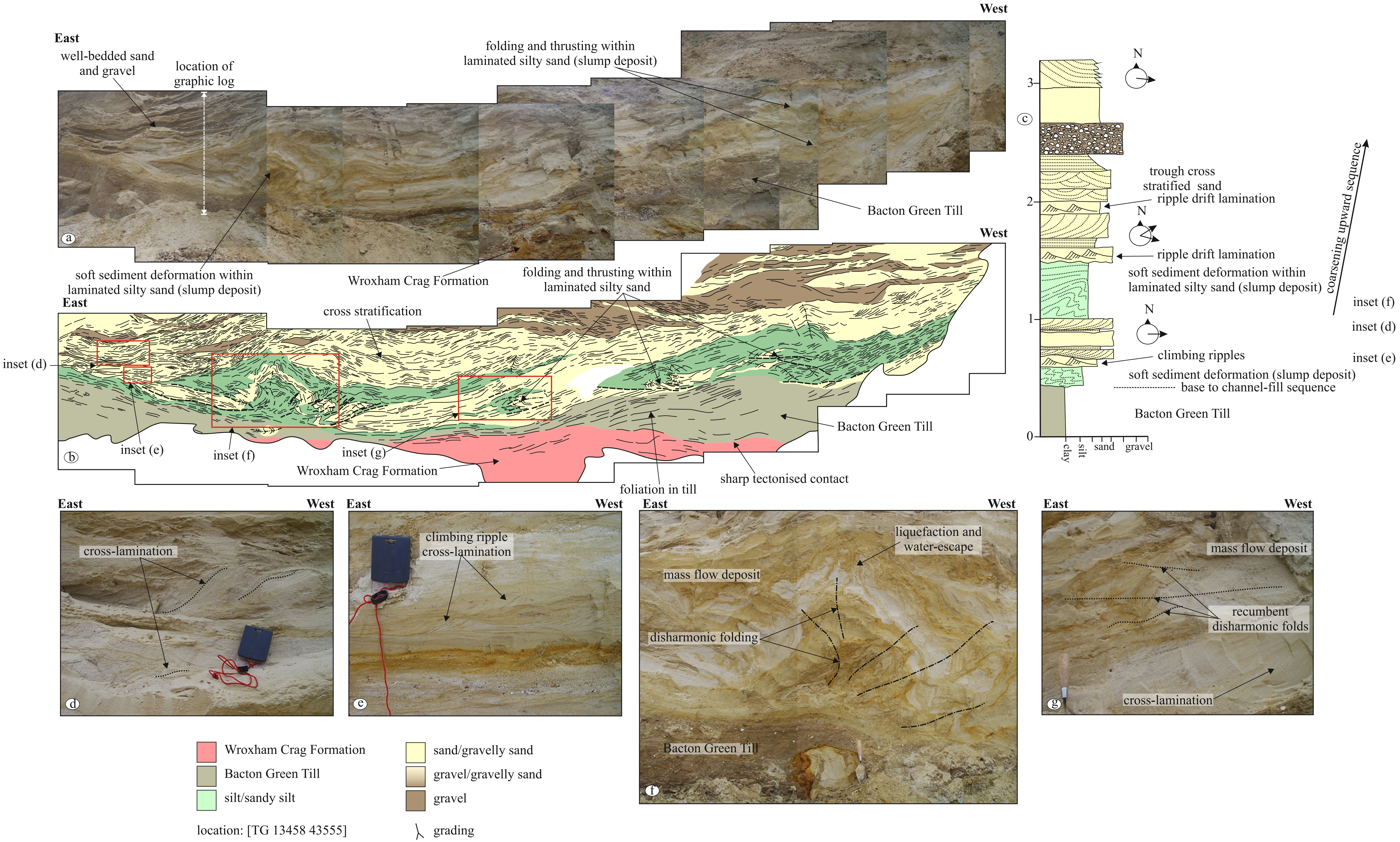
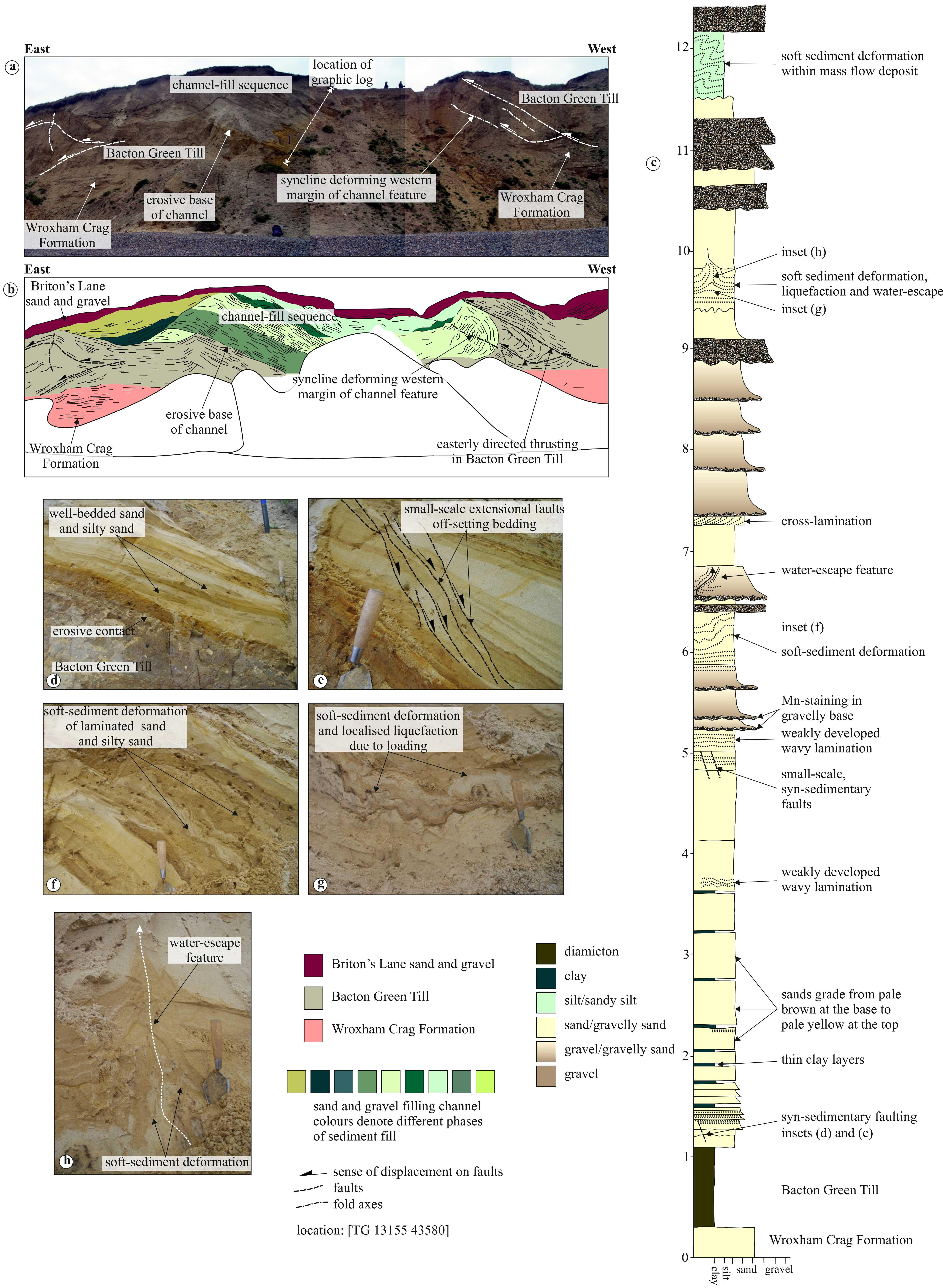
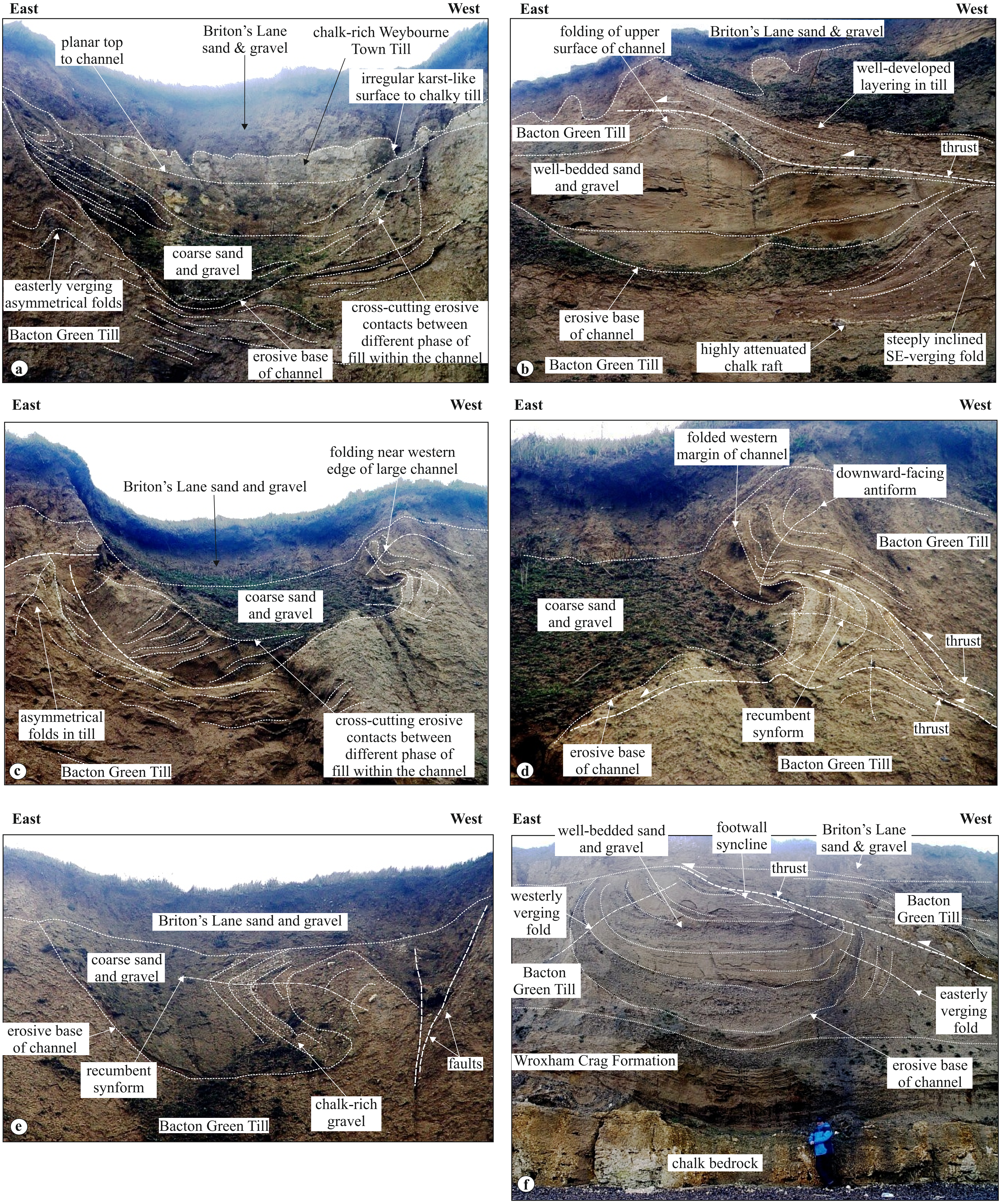

East
West
well-bedded sand and gravel
location of graphic log
folding and thrusting within laminated silty sand (slump deposit)
Bacton Green Till
a
soft sediment deformation within laminated silty sand (slump deposit)
Wroxham Crag Formation
folding and thrusting within laminated silty sand
cross stratification
inset (d)
inset (e)
inset (f)
inset (g)
Wroxham Crag Formation
foliation in till
sharp tectonised contact
b
3
2
1
0
c
N
trough cross stratified sand
ripple drift lamination
ripple drift lamination
soft sediment deformation within laminated silty sand (slump deposit)
climbing ripples
soft sediment deformation (slump deposit)
base to channel-fill sequence
Bacton Green Till
clay
silt
sand
gravel
coarsening upward sequence
inset (f)
inset (d)
inset (e)
cross-lamination
d
climbing ripple cross-lamination
e
liquefaction and water-escape
mass flow deposit
disharmonic folding
Bacton Green Till
f
mass flow deposit
recumbent disharmonic folds
cross-lamination
g
Wroxham Crag Formation
Bacton Green Till
silt/sandy silt
sand/gravelly sand
gravel/gravelly sand
gravel
grading
location: [TG 13458 43555]

Figure 7


a
East
West
location of
graphic log
channel-fill sequence
Bacton Green Till
Bacton Green Till
syncline deforming western
margin of channel feature
erosive base
of channel
Wroxham Crag
Formation
Wroxham Crag
Formation
b
East
West
Briton's Lane
sand and gravel
channel-fill sequence
syncline deforming western
margin of channel feature
erosive base
of channel
Wroxham Crag
Formation
easterly directed thrusting
in Bacton Green Till
d
well-bedded sand
and silty sand
erosive contact
Bacton Green Till
e
small-scale extensional faults
off-setting bedding
f
soft-sediment deformation
of laminated sand
and silty sand
g
soft-sediment deformation
and localised liquefaction
due to loading
h
water-escape
feature
soft-sediment deformation
Briton's Lane sand and gravel
Bacton Green Till
Wroxham Crag Formation
sand and gravel filling channel
colours denote different phases
of sediment fill
sense of displacement on faults
faults
fold axes
location: [TG 13155 43580]
diamicton
clay
silt/sandy silt
sand/gravelly sand
gravel/gravelly sand
gravel
c
12
11
10
9
8
7
6
5
4
3
2
1
0
clay
silt
sand
gravel
soft sediment deformation
within mass flow deposit
inset (h)
soft sediment deformation,
liquefaction and water-escape
inset (g)
cross-lamination
water-escape feature
inset (f)
soft-sediment deformation
Mn-staining in
gravelly base
weakly developed
wavy lamination
small-scale,
syn-sedimentary
faults
weakly developed
wavy lamination
sands grade from pale
brown at the base to
pale yellow at the top
thin clay layers
syn-sedimentary faulting
insets (d) and (e)
Bacton Green Till
Wroxham Crag Formation


East
West
planar top to channel
Briton's Lane sand & gravel
chalk-rich Weybourne Town Till
irregular karst-like surface to chalky till
coarse sand and gravel
easterly verging asymmetrical folds
Bacton Green Till
erosive base of channel
cross-cutting erosive contacts between different phase of fill within the channel
a
East
West
folding of upper surface of channel
Briton's Lane sand & gravel
well-developed layering in till
Bacton Green Till
thrust
well-bedded sand and gravel
erosive base of channel
highly attenuated chalk raft
steeply inclined SE-verging fold
b
Bacton Green Till
East
West
folding near western edge of large channel
Briton's Lane sand and gravel
coarse sand and gravel
asymmetrical folds in till
cross-cutting erosive contacts between different phase of fill within the channel
c
Bacton Green Till
East
West
folded western margin of channel
downward-facing antiform
Bacton Green Till
coarse sand and gravel
thrust
thrust
recumbent synform
erosive base of channel
d
Bacton Green Till
East
West
Briton's Lane sand and gravel
coarse sand and gravel
erosive base of channel
recumbent synform
faults
chalk-rich gravel
e
Bacton Green Till
East
well-bedded sand and gravel
footwall syncline
Briton's Lane sand & gravel
West
thrust
westerly verging fold
Bacton Green Till
Bacton Green Till
easterly verging fold
Wroxham Crag Formation
erosive base of channel
chalk bedrock
f