Glacitectonic controls on subglacial to ice-marginal drainage: Sheringham to Weybourne

Emrys Phillips and Jonathan R. Lee

1. Introduction

Subglacial drainage systems have been shown to exert a strong control 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; 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, 1996) 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; Longeran *et al*., 2006).

Studies of the subglacial hydrology of contemporary ice sheets (e.g. Greenland) has shown a link between 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). The link between meltwater production and ice sheet velocity 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. As a consequence the development of channelised drainage systems beneath glaciers and ice sheets, associated with steady supply of meltwater, may in fact lead to deceleration and the draining of the bed. In a Pleistocene context, there are several case studies that examine the range and distribution of preserved subglacial meltwater features. However, it has proved largely difficult to relate these directly to processes operating within the subglacial bed, and in-turn, their controls on ice mass behaviour.

This chapter of the guide describes the influence of deforming bed processes upon the development of a subglacial drainage system preserved within the polydeformed sediments exposed in the coastal cliff sections (c. 4.4 km in length) between Sheringham and Weybourne.

Section Location: sections are located between Sheringham (TG 165 433) and Weybourne (TG 111 437) although access from Sheringham is quicker. Walk down onto the promenade at 'The Esplanade', turn west and continue beyond the end of the coastal at the lifeboat station and Skelding Hill for approximately 1km.

1. Background

The complex sequence of glacial and preglacial sediments exposed in the cliff sections between West Runton and Weybourne contain widespread evidence at various scales for subglacial deformation (Banham 1975, 1988; Hart, 1987; Hart and Boulton, 1991a; Hart and Roberts, 1994; Phillips *et al*., 2008), deformable beds (Lee, 2001, 2009; Roberts and Hart, 2005; Hart, 2007) and the formation of a large-scale subglacial shear zone beneath the Anglian British Ice Sheet (BIS) (Lee and Phillips 2008). 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. 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).

2. Description of the subglacial drainage system

The preglacial and glacial sequence exposed along the coast between Sheringham and Weybourne occurs within a westwards extension of the zone of subglacial deformation (Domain 3, see section 4.3) associated with ice advance from the west (A4) (Phillips *et al*., 2008). In this area the glacial sequence is dominated by the mélange facies of the Bacton Green Till (BGT; up to 30 m thick) which overlies the older Happisburgh Till (HT) and preglacial Wroxham Crag Formation (WCF) (Reid, 1882; Pawley *et al*., 2004); the latter resting upon Cretaceous Chalk bedrock (Moorlock *et al*., 2002). The Walcott Till, which throughout much of North Norfolk occurs in superposition between the HT and BGT (Lee *et al*., 2004; Hamblin *et al*., 2005), is absent from the Weybourne-Sheringham sequence. The subglacial sediments are locally eroded into by a sequence of well-bedded, outwash sands and gravels assigned to the Briton's Lane Formation (Lee *et al*., 2004; Pawley *et al*., 2004). Between Weybourne and Sheringham, the HT thins westwards until it is eventually truncated between the BGT and underlying chalk bedrock. Deformation structures developed within the BGT mélange and, where present, HT, include small- to large-scale asymmetrical, tight to isoclinal folds, ductile shear zones and brittle thrusts, that record a consistent easterly-directed sense of shear. 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 pervasive foliation present within the BGT. 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) (Lee *et al*., 2004) (see Chapter 14).

Present within the subglacially deformed sequence between Sheringham and Weybourne are 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. 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. 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. 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. 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 eroding into a broad open synformal structure developed within the till. 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 E to SE-verging folds and thrusts indicating that they have both encountered the same easterly directed subglacial (A4) deformation event. This evidence clearly indicates that the sand and gravel bodies do not represent part of a later (post-A4) outwash sequence eroded into the Bacton Green Till, but in fact form an integral part of this subglacial succession.

3.1. 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, graphic logs through the sequences within three of the larger sand and gravel bodies are shown in Figures 11.1 and 11.2. The sedimentary sequences within the individual bodies are highly variable, consisting of massive to well-bedded sand, silty sand and gravel with rare thin clay beds and sandy mass-flow deposits. Primary sedimentary structures, including massive bedding, thin horizontal-bedding, climbing-ripple cross-lamination (types A and B), normal and reverse graded-bedding and trough cross-bedding, are well preserved, even immediately adjacent to the contacts with the BGT; the latter 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 NE, E and SE.

Fining and coarsening up-ward sequences (2 to 7 m in scale) are punctuated by the influx of thick massive gravels. The recognition of fining- upward sequences within the logged sections is consistent with waning flow

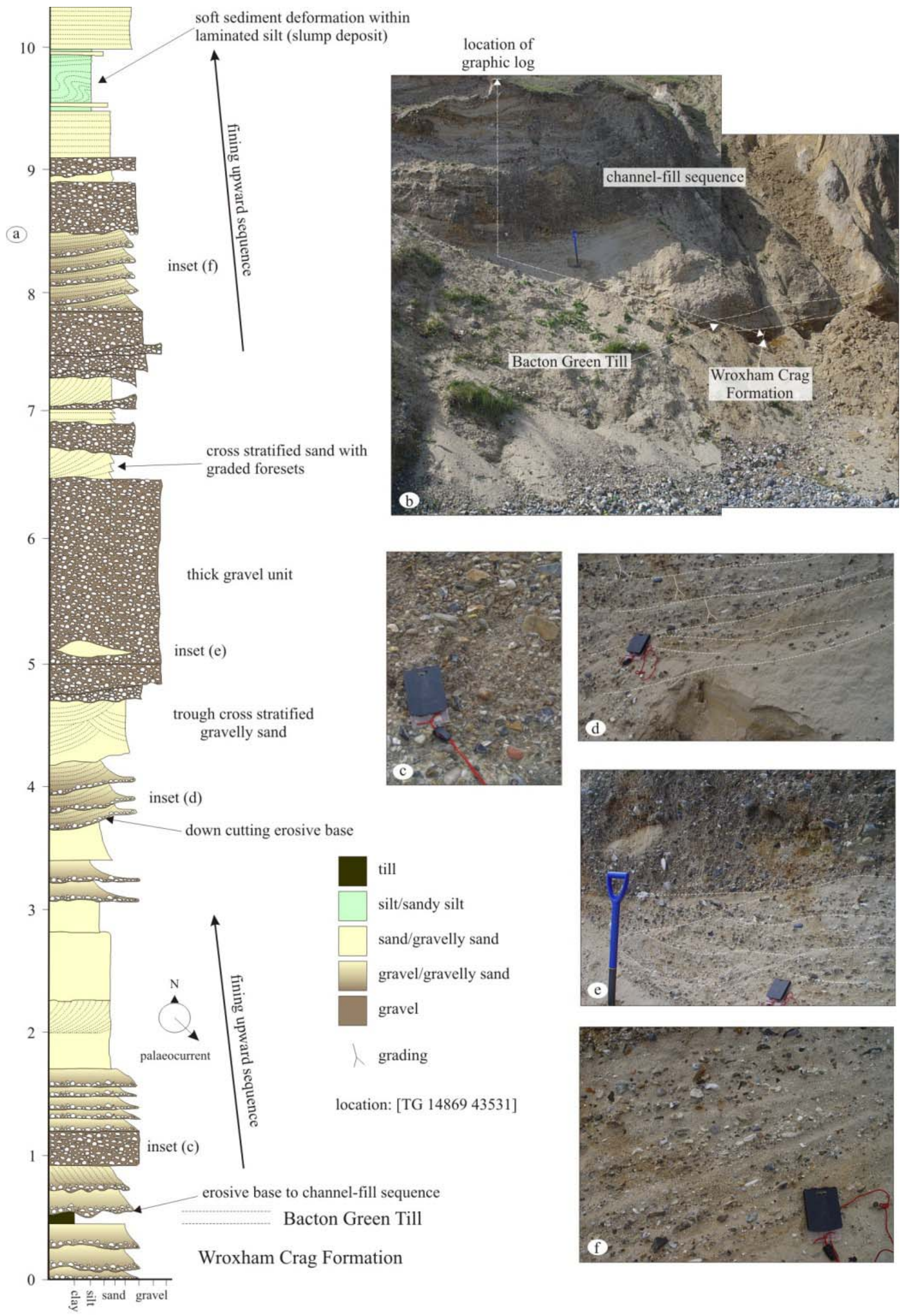

Figure 11.1 (previous page). Graphic log through the basal gravel-rich part of the sequence (TG 14869 43531); (b) Photograph showing an overview of the basal gravel-rich part of the sediments filling a large sand and gravel body. Also shown is the location of the graphic log illustrated in Fig. 7a; (c) 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

conditions, and suggests periods of more quiescent sedimentation under much lower flow regimes. Locally sedimentation was dominated by sand deposition, with the influx of coarse gravel only occurring within the upper part of the sequence.

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 inter-bedded with internally highly deformed silty sands; the latter are interpreted as mass-flow deposits. Syn-sedimentary soft-sediment deformation structures (disharmonic folds, ductile shears, thrusts) within the 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 indicative of sedimentation within a channel or similar depression. The presence of load structures, convolute bedding, and water-escape conduits, coupled with normal (extensional) syn-sedimentary faults within the sands and silty sands are indicative of 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, resulting in a distinct channel-like appearance. The gravel dominated units are massive to poorly bedded, forming either laterally extensive beds (that extend across the width of the body) or more restricted, lenticular, channelised units that erode into the underlying sands.

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. 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). The geometry of these sand and gravel bodies, combined with their sedimentology indicate that

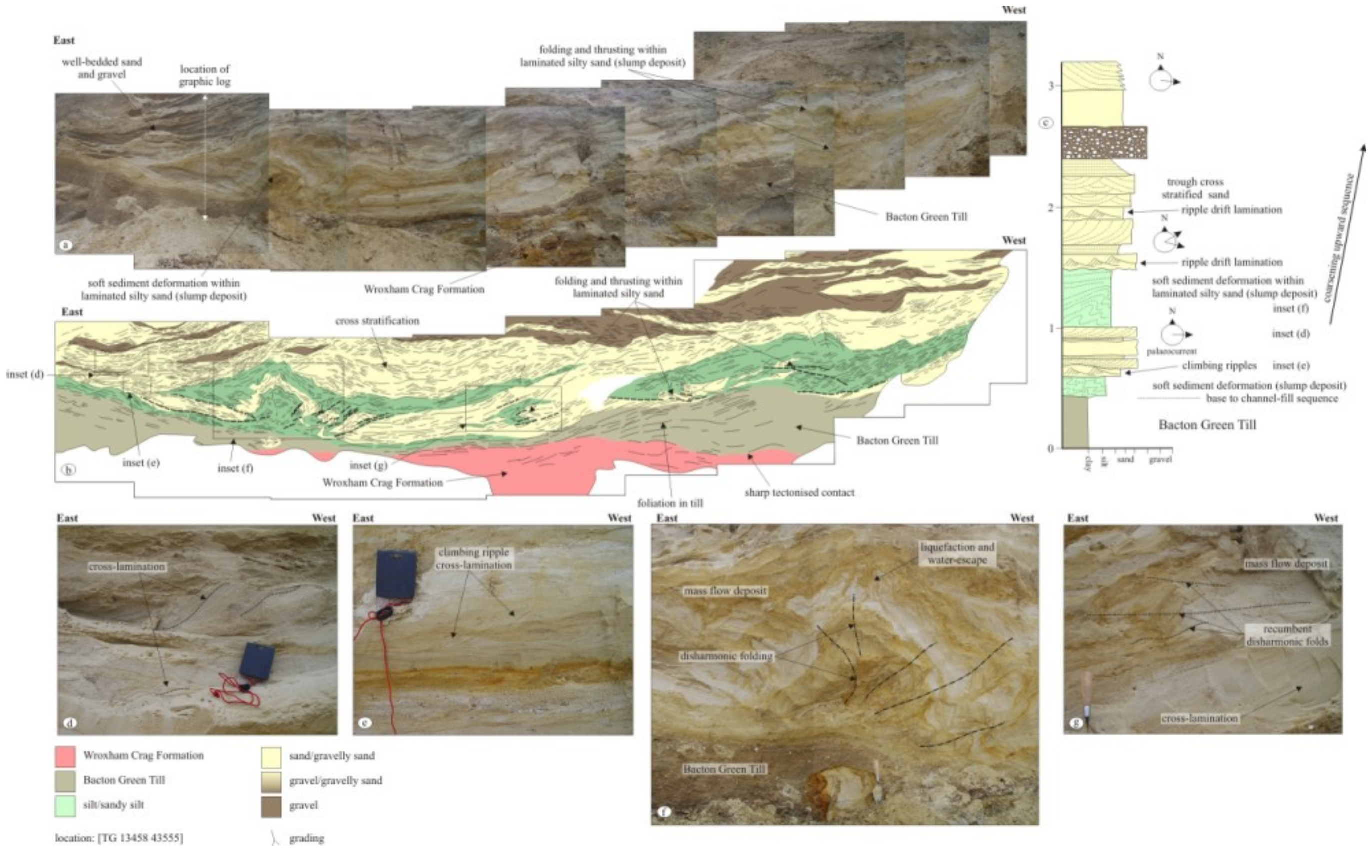
East
West
well-bedded sand and gravel
location of graphic log
folding and thrusting within laminated silty sand (slump deposit)
Bacton Green Till
soft sediment deformation within laminated silty sand (slump deposit)
Wroxham Crag Formation
cross stratification
folding and thrusting within laminated silty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

Figure 11.2 (previous page). (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) Graphic 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

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, and occasional beds of massive gravel 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 that record pulsed sediment input into the sediment system of varying magnitudes. Coarsening-up sequences record an increase in the energy regime, although changes in sedimentology between sands and gravels indicates that they comprised 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 small 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 influx of coarser grained sand and gravel. The occurrence of thin clay and/or silty layers inter-bedded within the sand-dominated parts of the sequence shows that the energy of the depositional environment occasionally fell dramatically, possibly leading to the abandonment of the system, allowing the settling out of these very fine-grained sediments. 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.

The internal structure and sedimentology of the sand and gravel bodies within the subglacially deformed sequence between Sheringham and Weybourne is consistent with them having formed part of a major subglacial drainage system 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).

3.2 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 (A4) deformation event 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, through to more complex folding and thrusting. Importantly this deformation was, in the majority of cases, focused along the western (up-ice) side the body. However, locally, the sands and gravels are apparently undeformed and the channel morphology is clearly preserved (Figs. 2a and 3a). 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. 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. 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; indicating that they have both recorded the same easterly directed (A4) 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. 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 base 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 offset bedding within these bodies, demonstrating that thrusting 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 E/SE-verging folds and thrusts within its core. 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.

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.

3. Discussion and Conclusions

4.1 Structural control on the pattern of subglacial drainage

The sand and gravel bodies clearly represent an integral part of the BGT subglacial succession and are not large-scale load structures or *'sag basins'* as described elsewhere (cf. Ehlers *et al*., 1991). Their internal structure and sedimentology is consistent with them being composed of a series of vertically and laterally stacked, tabular to channelised sand and gravel units laid down in an overall high-energy, fluviatile environment. Marked changes in the style of sedimentation indicate that the energy of this environment fluctuated dramatically, with high- to low-energy flow events being separated by periods of channel abandonment. The stacking of the individual channel-fill sequences records a shifting pattern of sediment dispersal, with the available palaeocurrent data recording an overall easterly flow direction. Although relatively undeformed when compared to the BGT, the sand and gravel bodies do show evidence of having undergone the same easterly-directed (A4) subglacial deformation. The BGT on the western, up-ice side of the sand and gravel bodies is tectonically thickened, with sands

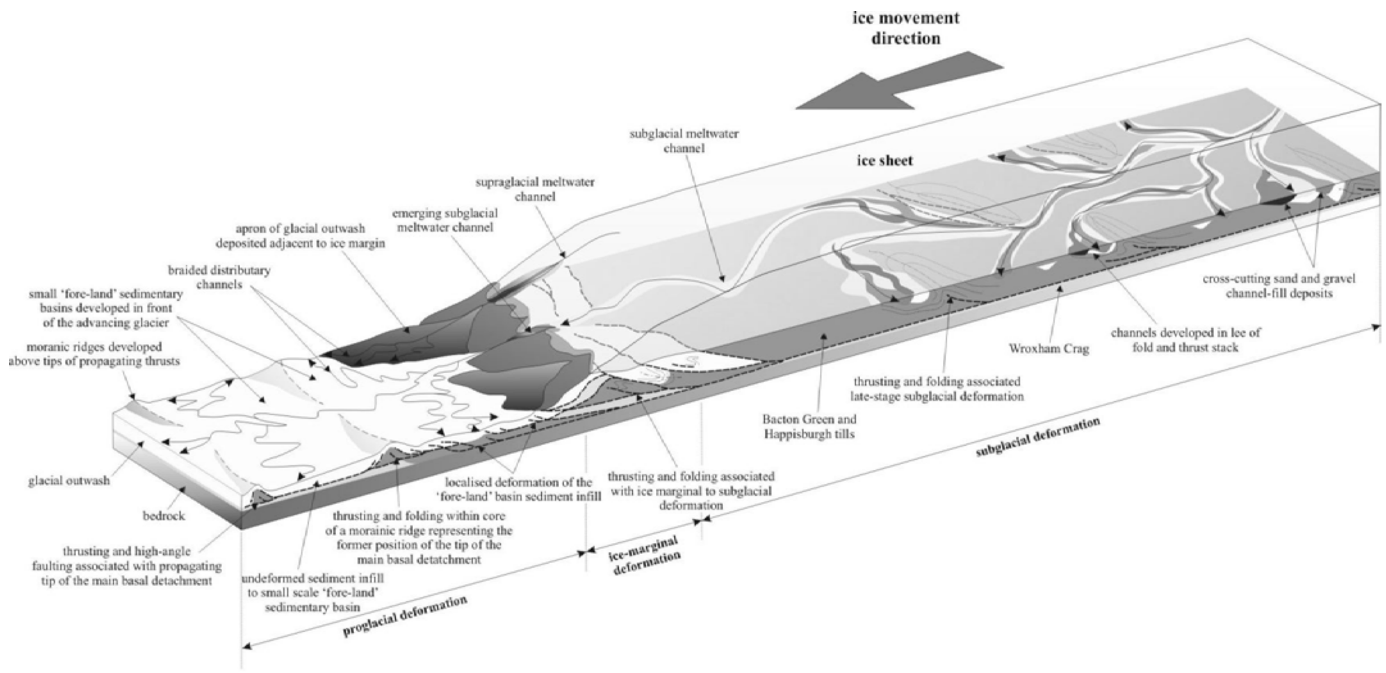

Figure 11.3. Schematic 3D block diagram illustrating the possible pattern of subglacial to proglacial drainage that developed at the margins of the BIS (modified from Phillips *et al*., 2008)

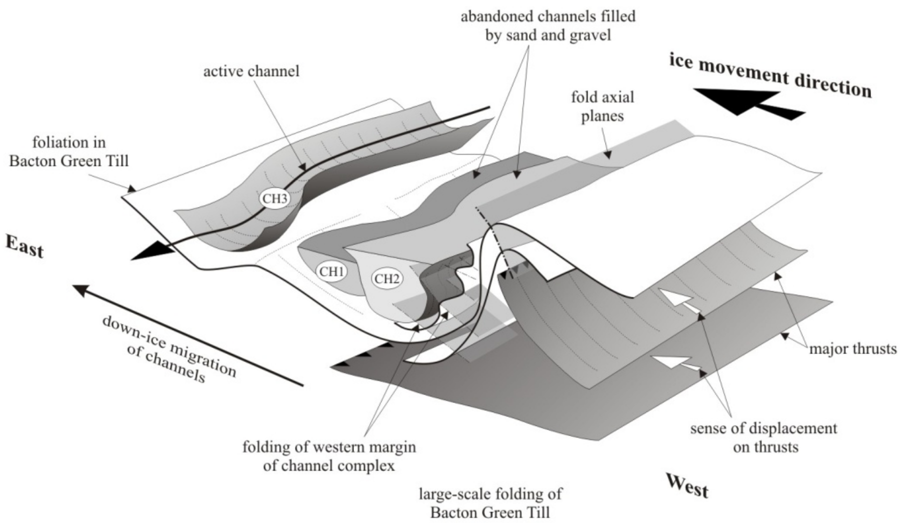

Figure 11.4. Schematic diagram showing the 3D geometry of the sand and gravel-filled channel features developed within the mélange facies of the Bacton Green Till between Sheringham and Weybourne. Note that the larger channel features are located within a broad, open synform on the down-ice side eastern 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)

and gravels occupying broad, open synforms within the mélange. This relationship is analogous to that displayed by sedimentary, lee-side cavity fills developed down ice of bedrock highs or other similar large-scale perturbations within the glacier bed.

Consequently, the bodies of sand and gravel contained within the BGT are interpreted as representing parts of a linked cavity drainage system (Benn and Evans, 1996) which developed beneath the margin of the easterly advancing BIS (Figure 11.3). The drainage system developed within the upper part of the BGT, with the larger cavity fills cutting downwards through this glacitectonic mélange and, in some cases, into the underlying WCF, indicating that this highly deformed deposit had already largely been formed prior to the initiation of a subglacial drainage system beneath this part of the ice sheet. The relatively undeformed nature of the sands and gravels, coupled with the locally complex relationships between the cavity fill sequences and the glacitectonic structures within the adjacent BGT, indicate

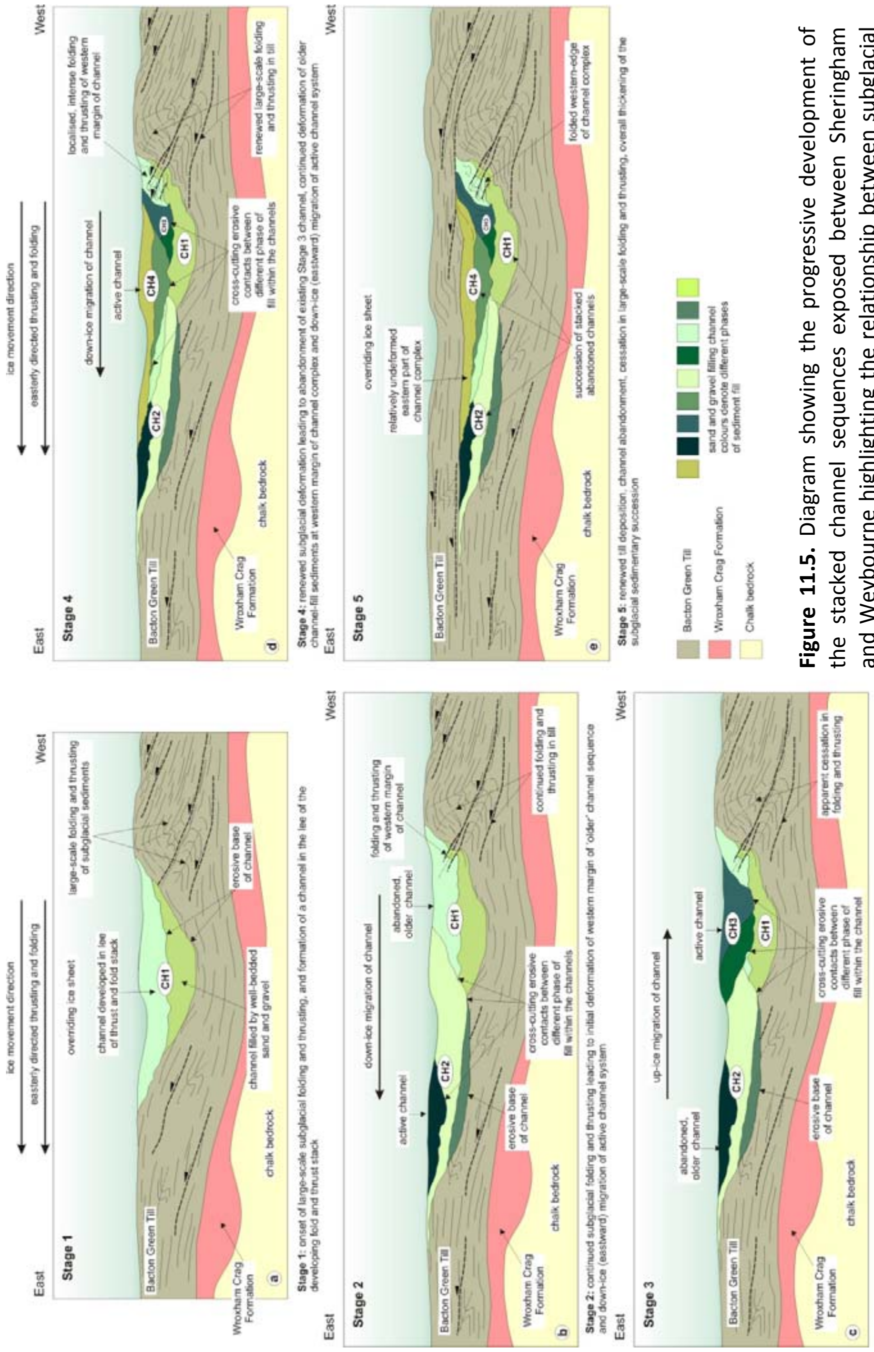

Figure 11.5. Diagram showing the progressive development of the stacked channel sequences exposed between Sheringham and Weybourne highlighting the relationship between subglacial deformation and the location of these subglacial drainage channel complexes.

that the drainage system did not become established until the later stages of A4.

One of the key features of the subglacial drainage system is that the larger, internally more complex sand and gravel bodies occupy large-scale synformal folds present within the BGT, with folding and thrusting on the up-ice side of the cavity fill leading to the tectonic thickening of this glacitectonite. Consequently, there is an apparent direct relationship between the formation of the subglacial drainage system and large-scale glacitectonism of the BGT during the latter part of A4 (Figure 11.4). The stacking of the individual channel-fill sequences within the larger sand and gravel bodies is consistent with an overall easterly, down-ice shift in the pattern of sedimentation. This is coincident with the main stress direction responsible for A4 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 11.5 shows a 5 stage model proposed for the development of a linked cavity drainage system during subglacial deformation:

Stage 1 – large-scale folding and thrusting (A4) led to the variable tectonic thickening of the BGT and the localised 'detachment' of the ice from its bed resulting in the opening of lee-side cavity within the core of large-scale synclinal folds (CH1 on Figure 11.5a). 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 cavity 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 Figure 11.5b);

Stage 3 – cross-cutting relationships observed between the stacked channels-fills indicate that periodically the active part of the drainage system shifted back, up-ice (CH3 on Figure 11.5c). 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 Figure 11.5d).

Stage 5 – final abandonment of the cavity (Figure 11.5e) and diversion of the flow of meltwater into a different part of the subglacial drainage system.

3.2. Effect of increased drainage efficiency on subglacial deformation beneath the British Ice Sheet

One remaining question is *"why weren't the sand and gravel cavity fills and smaller channel fills more intensely deformed, or even destroyed, during continued subglacial deformation?"*. An important factor is that field evidence indicates that the proposed linked cavity system did not develop until the later stages of A4 (see above) when the easterly advance of the BIS had either reached its maximum extent, or the ice-margin was undergoing active retreat. Prior to A4, subglacial drainage beneath the ice was probably dominated by Darcian porewater flow through the actively deforming mélange of the BGT. The permeability of the silty to locally clayey tills, which dominate this actively deforming zone, would have been relatively low leading to an inefficient system of meltwater discharge from beneath the ice sheet (cf. Alley, 1989). This would have resulted in the retention of meltwater beneath the ice she*et al*lowing the build-up of locally high porewater contents and pressures facilitating ductile subglacial deformation (Lee and Phillips, 2008; Phillips *et al*., 2008). The subsequent development of a relatively stable linked cavity system beneath the margin of the BIS would have led to a marked increase in the efficiency of subglacial drainage and the probable development of a coupled porewater flow and channelized drainage system.

Hydrogeological studies (e.g. Hubbard *et al*., 1995) have demonstrated that during periods of high meltwater pressure/discharge water can be forced out of subglacial channels into the adjacent till. Conversely, the reversed pressure gradient set up during periods of low meltwater discharge leads to water draining out of the till back into the channel. The fluctuation in meltwater discharge/pressure beneath the BIS could have resulted in repeated periods of saturation (wetting) and draining (drying) of the BGT adjacent to the sand and gravel filled cavities, affecting the physical properties of the till and its response to any imposed deformation. During the early stages of the development of the drainage system, the BGT may have maintained a relatively high degree of saturation, leading to a continuation of predominantly ductile deformation. However, with time, as the till progressively 'dried out', deformation would have become increasingly brittle in nature, leading to the observed thrusting and localised tectonic thickening of the bed. The increasing efficiency of the drainage beneath the BIS would have lead to the progressive 'collapse' and 'locking up' of the subglacial shear zone which dominated the earlier stages of A4 deformation (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 linked cavity drainage system could have potentially resulted in the stalling, or even cessation, of the easterly advance of this ice sheet across northern Norfolk.