Development of a ‘soft deforming bed’ within a subglacial shear zone: an example from Bacton Green, north Norfolk

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1. Introduction

The concept of ‘soft deforming beds’, which has developed progressively over the past 25-30 years, has revolutionised our understanding of glacier-bed interactions (Boulton, 1986; Boulton and Hindmarsh, 1987; Murray, 1997). Many studies demonstrate the complex role played by ‘soft-deforming beds’ in controlling ice-mass behaviour from both modern and geological examples. However, despite a wealth of literature examining ‘soft deforming beds’ a number of questions and controversies are still to be resolved. In particular, the precise role played by porewater and its spatial and temporal distribution within the ‘soft deformable bed’ is generally poorly understood. This has implications for the amount and distribution of porewater and deformation within the bed, how it varies in time and space, and its role in controlling glacier behaviour.

In northern East Anglia, ‘soft deformable beds’ of various scales have been recognised at a number of sites (Banham, 1977; Hart, 1987; Hart *et al*., 1990; Hart and Boulton, 1991a,b; Hart and Roberts, 1994; Roberts, 1995; Fish *et al*., 2000; Lee, 2001, 2003, 2009; Roberts and Hart, 2005; Pawley, 2006; Hart, 2007; Lee and Phillips, 2008; Phillips *et al*., 2008; Waller *et al*., 2009). In this chapter, we examine a 14 m thick ‘soft deforming bed’ at Bacton Green, north Norfolk described previously by Lee and Phillips (2008). The site isn’t visited during the course of the workshop, although the deformation does occur at the same stratigraphic level, and forms part of the same shearing event, that formed the subglacial shear zone at West Runton described later (see Chapter 6; Phillips *et al*., 2008).

Site Location: the site is located at Bacton Green (TG 335347) beneath Bacton Gas Terminal. Car parking is available at Bacton (TG 343 343), with a 1km walk along the beach to the west. Access from Bacton may be restricted at low tide.

2. Site location and context

The location of this case study lies to the southeast of the Cromer Ridge at Bacton Green. Cliffs at Bacton Green (NGR: TG 338,345) are 15 m high and rise gently north-westwards towards the village of Mundesley (Figure 7.1). The Pleistocene succession at Bacton Green comprises five major stratigraphic units (Banham, 1966; Lunkka, 1994; Lee, 2003; Phillips *et al*., 2008). At the base of the succession, frequently obscured by modern beach material, are preglacial sands and gravels of the Wroxham Crag Formation that were deposited in a shallow marine and coastal setting (West, 1980; Lee, 2003). They are overlain by the basal glacigenic unit, between 2-4 m thick, which is called the Walcott Till. It is a dark grey, silt-rich matrix-supported diamicton that contains an abundance of chalk and flint clasts. The upper surface of the till is sharp and gently undulating, containing a number of small scoured hollows infilled by chalk-rich gravel. Overlying the till is a variably thick (12-20 m) sequence of highly-stratified micaceous and fine chalky sands, the Mundesley Sands, interpreted as glaciolacustrine top- and bottom-sets (Lunkka, 1994; Lee, 2003).

Overlying the deltaic sands is a 12-16 m thick dark olive brown (2.5Y 3/3) to dark brown (5Y 4/1) stratified diamicton called the Bacton Green Till. The boundary between the till and underlying sands is variable in nature. In places, the contact is gradational over a thickness of 0.8-1.2 m. Sediments are composed of alternate or interdigitating beds of sand, clay and diamicton with sandy beds containing frequent syn-depositional load structures. Elsewhere, the contact between the two units is sharp and planar in form. The till possesses two distinctive structural domains. Firstly, a basal

7 m ('basal facies') characterised by zones of highly deformed sediment, separated by low deformation zones where the primary sedimentary characteristics of the till may still be recognised. Secondly, a highly deformed upper 7 m composed of folded, faulted and fractured beds of sand and diamicton that together form an 'upper mélange facies'.

The upper-most unit within the succession is the Stow Hill Sands and Gravels (Lunkka, 1994; Lee, 2003). The deposit consists of massive and horizontal beds of flint-rich sand and gravel, and attains a thickness of up to 5 m. In places the gravels cut down into the underlying till within a series of broad channels. The sands and gravels can be traced discontinuously northwards towards Trimingham, and to Sidestrand where they form the upper sand and gravel of a large synform (Figure 13.1 – 1250 m).

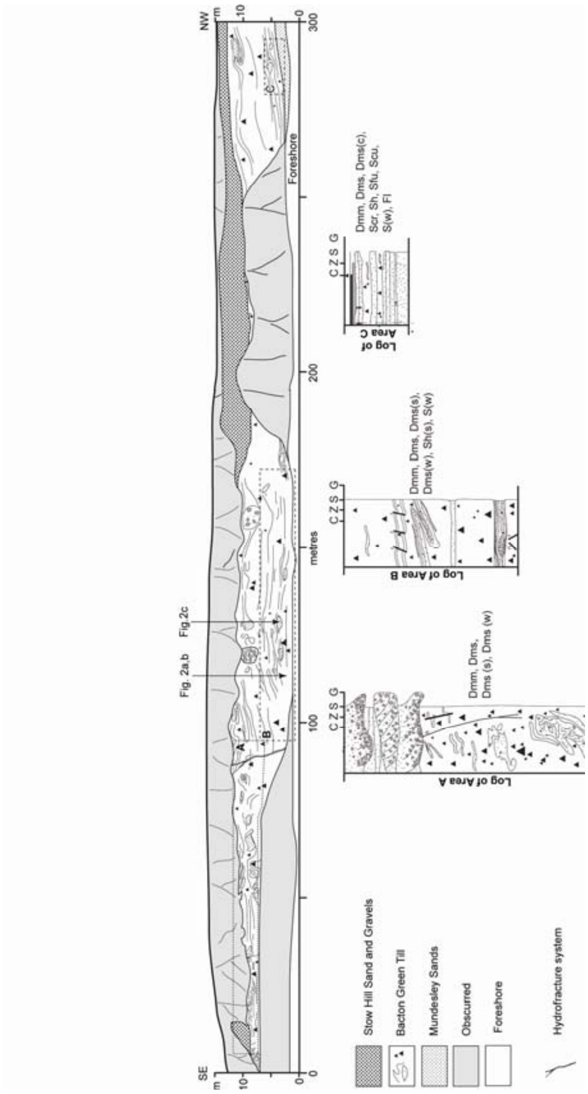

Figure 8.1. Cross section of the cliffs at Bacton Green, Norfolk, showing the stratigraphy and structure of the deposits investigated. Composite logs summarising the primary lithofacies and shown for three transects (A, B, C). Key to lithofacies codes: Dmm—diamicton, matrix-supported, massive; Dms—diamicton, matrix-supported, stratified; S—sand, massive; Sh—sand, horizontal; Scr—sand, climbing ripples; Sfu—sand, fining up; Scu—sand, coarsening up; Fl—fines, laminated; (c)—current reworking. (s)—shearing; (w)—dewatering

3. Sedimentology and Structure of the Bacton Green Till

3.1 Primary mode of sedimentation

Lower strain zones of the 'basal facies' are composed of alternate layers of massive to weakly-laminated, highly consolidate, diamicton separated by thin laminae and beds of silty sand and sand (0.01-0.4 m thick), that can be traced laterally for several tens of metres before passing into higher strain zones. Beds of diamicton occasionally contain thin stringers of normally-graded sand demonstrating a variably developed stratification. Sand laminae and beds exhibit massive, normal and reverse grading, and typically possess sharp and planar basal contacts. In places, sand beds contain small rounded intraclasts of diamicton aligned parallel to the bedding. The 'upper mélange facies', by contrast, consists of a contorted mélange of diamicton, with thin disrupted beds and laminae of sand, and large lenses of sand and gravel. Preservation of the primary sedimentary structures.

Primary sedimentary structures preserved within the lower strain zones of the 'basal facies' provide an indication of the pre-deformation sedimentary origin for the till sequence. The massive and highly consolidated beds of diamicton are typical of sediment homogenisation by subglacial shearing (Hart and Boulton, 1991b), with the thin sandy stringers representing the remnants progressively attenuated sand lenses that have been incorporated and sheared within the till (Hart and Boulton, 1991b; Hart and Roberts, 1994; McCarroll and Rijsdijk, 2003). However, the normal grading of these stringers implies a sedimentary origin, perhaps through the remobilisation and settling of sediments by subaqueous traction currents (Eyles *et al.*, 1983). In this scenario, massive and consolidated beds of diamicton could represent masses of subglacial till, that have been reworked subaqueously as cohesive mass-flows. Individual beds and laminae of sand and silty sand are interpreted as being deposited from the rapid rain-out of poorly-sorted sediment from dense sediment-laden underflows (Eyles and McCabe, 1989; Lee, 2001). Localised scouring and turbidity currents are suggested by the diamict intraclasts, plus the normal and reverse grading within the sand laminae and beds. Further supporting evidence for a sedimentary rather than tectonic origin is the absence of evidence indicative of subglacial deformation such as décollement surfaces, low-angle thrusts and folding. Instead, the geometry of the basal contact is more typical of a subaqueous style of sedimentation with alternate and intercalated beds of diamicton and sand reflecting pulses of diamicton being introduced into a standing body of water (Eyles *et al.*, 1985; Hart and Roberts, 1994).

3.2 Structure of the deformed facies

The Bacton Green Till contains zones of intense higher strain deformation, both as isolated zones within the 'basal facies' and, more pervasively, within the 'upper mélange facies'. These higher strain zones contain a range of structural styles including folding, thrusting, normal and reverse faulting, sand augen, hydro-fractures and water-escape structures.

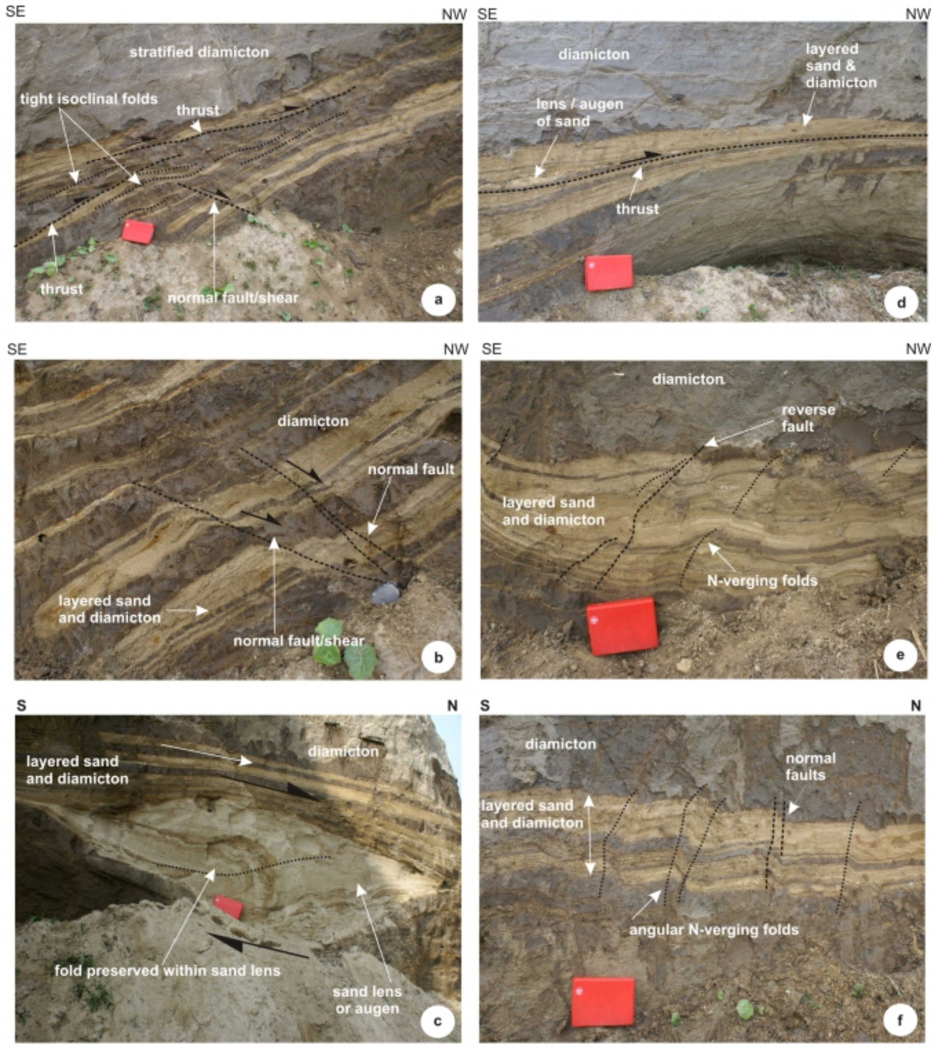

Figure 7.2. Photographs showing deformation structures within the Bacton Green Till Member. (a) Isoclinal folding and thrust planes developed in sand layers; (b) sand beds offset by northerly dipping normal fault and associated extensional shear band; (c) an augen or lens of laminated sand deformed internally by an asymmetrical fold. The lamination within the fold hinge is deformed by small-scale disharmonic, parasitic folds. The shape of the augen/lens and fold asymmetry record the application of shear from the southwest; (d) layered beds of sand and diamicton deformed by a long-angle thrust plane; (e) thinly laminated sand and diamicton showing reverse faulting and north-verging kink-like folds; (f) en echelon kink folding developed within thin beds of diamicton (from Lee and Phillips, 2008)

3.2.1 Sand augen

Symmetrical to asymmetrical augen shaped sand lenses occur throughout the deformed facies (Figure 7.2c). They range in scale from 0.2 to 2.0 m and lie broadly parallel to layering within parts of the 'basal facies', and as isolated bodies within the 'upper mélange facies'. The heavy mineral content of the sands was examined by Lee (2003) and demonstrated that the sand augen are derived from the Mundesley Sands.

Augens within the 'basal facies' show a degree of compositional layering (i.e. bedding and lamination) that wrap around the structure. Their tails extend laterally for several metres before pinching-out within the layering of the host sediment. Internally, bedding and lamination are partly deformed by variably developed asymmetrical, tight, gently inclined to isoclinal north-verging folds that are enclosed by an envelope of massive sand (Figure 8.2c). Often the primary sedimentary structure have been overprinted and destroyed. Small reverse and thrust faults are often developed in the hinges of folds and formed as the folds tightened during shearing. In places, parasitic folds are developed around the hinges of these folds. They are often disharmonic or flame-like in nature forming a crude foliation developed parallel to the axial planes of the larger fold structures.

The truncation of folding by the margins of the augen structures suggests that they are tectonic rather sedimentary in origin. Disharmonic and flame-like folds indicate that porewater pressure increased during folding resulting in the liquefaction and flow of the sand layers relative to the diamicton layers. The direction of fold asymmetry and geometry of the sand lenses is consistent with a southwest to northeast direction of shearing. The internal structure of these augen, plus their geometry, is consistent with them being the detached, rootless hinges of originally much larger fold structures.

3.2.2 Recumbent folding

Beds of sand and diamicton are locally folded by a number of tight to isoclinal, recumbent to gently inclined folds (Figure 7.2a) which are developed in the hanging wall of several low-angle thrusts. The fold amplitudes range from centimetre to metre scale with the fold limbs orientated parallel to the foliation, with asymmetrical folds verging towards the northeast and north. In places, the morphology of the folds have been modified, with thickened hinges often showing disharmonic parasitic fold development, with progressively attenuated and thinned limbs, leading to the boudinage and fold detachment.

The highly attenuated and rootless recumbent fold structures developed in response to ductile shear. Disharmonic parasitic folding demonstrates that porewater content and/or pressure remained high during deformation resulting in a reduction of cohesive shear strength, and folding, attenuation and detachment occurring under lower strain rates.

3.2.3 Thrusts

Beds within the deformed zone of the ‘basal facies’, have in places, been cut or off-set by a series of low-angle thrusts that record a sense of displacement towards the northeast (Figure 7.2d). Thin lenses of sand locally occurring within the hanging walls of some thrusts can be traced laterally into the larger sand augen, and represent fragments detached from these rootless fold structures.

The northerly sense of displacement recorded by the thrusts is consistent with the sense of shear obtained from the previously described folds and sand augen, indicating that all of these structures developed during the same northerly directed deformation event as the recumbent fold structures referred to previously.

3.2.4 Normal faults and extensional shears

In places the diamicton is deformed by a several low- to moderate-angle normal faults and associated extensional shears (Figure 7.3b), which possess throws of between 1 and 30 cm. They occur throughout the higher strain facies, with down-thrown fault blocks indicating a sense of displacement towards the north and northeast. Minor drag folding occurs within both the hanging and footwall blocks of the normal faults and probably developed during a phase of ductile deformation prior to brittle faulting.

3.2.5 Kink folds and associated folds

Asymmetrical kink folds occur within the sand beds at the northern end of the section within the ‘basal facies’ (Figure 7.2e,f). The axial surfaces dip steeply towards the south and verge northwards. Minor faulting occurs within the fold hinge or the steeply-inclined short limb of the folds and record a sense of displacement towards the north. Brittle faulting probably occurred in response to tightening of the previously formed folds.

3.2.6 Transposed bedding

Original sedimentary bedding within the ‘upper mélange facies’ has been altered or transposed during deformation to form a laterally persistent tectonic layering that included 1-30 cm thick beds of massive sand contained within masses of diamicton. This layering maintains a relatively consistent thickness with sharp and planar margins, and wraps around the sand augen.

3.2.7 Hydrofractures

A number of sand-filled hydrofractures were recognised within the ‘upper mélange facies’ and consist of sand-filled sub-vertical fractures that truncate the recumbent folds and related structures. The stratified sandy fill of the fractures suggests that they were formed by rapid polyphase water-escape from a confined aquifer. As they cross-cut the structures described previously, they post-date their generation.

4. Glacitectonic shear zone development

4.1 Glacitectonic model

The primary sedimentary features, where preserved within the ‘basal facies’, enable the primary genesis of the Bacton Green Till at this locality to be reconstructed. The gradational transition from the Mundesley Sands into the Bacton Green Till records the switch from a fine-grained outwash delta to debris fan associated with an ice advance into the margins of a glacilacustrine basin. The sedimentology of the till indicates that it was deposited subaqueously as a series of cohesive debris flows composed of reworked masses of subglacial till (diamict beds), rapid deposition from sediment plumes (poorly sorted sands and muds), turbidity and traction currents (cf. Eyles and McCabe, 1989).

Following deposition, geological structures indicate that the sediment pile was partly deformed by a north to northeast directed shearing. This was related to an ice advance from the south to southwest resulted in pre-existing sediments becoming remobilised by subglacial deforming bed processes. The presence of structures characteristic of ductile deformation (e.g. folds), demonstrate that the sediment pile had not dried between its primary deposition and secondary reworking. This implies a short time interval between the two events. The geometry of the glacitectonic structures plus the cross-cutting relationship enables the temporal and spatial evolution of deformation to be established.

Variations in the style and intensity of subglacial deformation indicate that it was controlled to a large extent, by temporal and spatial changes in inter-granular porewater content and pressure during accretion and thickening of the subglacial sediment pile. Deformation from this single progressive shearing event can be sub-divided into three broad phases (D1-D3). Initial deformation (D1) was characterised by ductile deformation within the higher strain parts of the deformed zone. Disharmonic and flame-like folds demonstrate that high porewater contents and/or pressures existed during D1 that reduced the effective shear strength, enabling the formation of the highly attenuated, recumbent to detached folds. Liquefaction of sandy beds during progressive shearing would have aided attenuation, and eventually, boudinage and detachment of the fold hinges. Storage of porewater was accommodated by the sand (permeable) and diamicton (impermeable) layers. These layers acted to compartmentalise and confine water within the subglacial bed, thus impeding drainage. Together with the overburden pressure exerted by the overriding glacier, they acted to progressively increase porewater pressure throughout parts of the bed.

D1 was followed by a separate phase of brittle deformation (D2) characterised by thrusting and the development of normal and reverse faults that form Reidel shears. The presence of faulting suggests that the bed had been drained of porewater resulting in the increase of the cohesive shear strength of the sediment pile and eventual ‘locking’ of the subglacial shear zone. Drying of the bed enabled low-angle to sub-horizontal thrusts to propagate through the diamicton layers causing a tectonic thickening and stacking of slices of sand and diamicton. It led to the detachment and transportation of the folded masses of sand (lenses/augen structures) from the underlying Mundesley Sand, upwards along low-angle thrust planes and into the deforming bed. Continued deformation led to the increase in porewater pressures and the formation of hydrofractures, localised liquefaction and the injection of fluidised sand into a network of cross-cutting veins (D3). Sand-filled hydrofractures are only present within the ‘upper mélange facies’ suggesting that hydro-fracturing was not exclusively responsible for the dewatering of the subglacial shear zone. An additional dewatering mechanism could relate to the intergranular flow of porewater caused by loading during subglacial sediment thickening.

4.2 Temporal and spatial patterns of shear zone development

Structural relationships within the till mélange demonstrate a temporal and spatial complexity to shear zone evolution. The dominant factors appear to be variability in the inter-granular porewater content and the rate of till thickening with ductile deformation concentrated within the upper weaker 'water-rich' (dilated) zones of the sequence (Figure 7.3; Lee and Phillips, 2008).

At Bacton Green, this 'water-rich' dilatant zone corresponds to the 'upper mélange facies' and demonstrates, as recognised elsewhere, that the intensity of deformation generally increase upwards through the deforming bed profile (cf. Boulton and Hindmarsh, 1987; Hart and Boulton, 1991b; Benn and Evans, 1996; Evans *et al*., 2006; Hart, 2007). In the case of the 'upper mélange facies', repeated charging of this aquifer (e.g. D1) led to an increase in dilation and lowering of the cohesive shear strength of the sediment pile, causing the shear zone to migrate and expand downwards and laterally. In theory this process of subglacial shear zone expansion would lead to a continuum from heterogeneous (c.f. Piotrowski and Kraus, 1997; Hoffman and Piotrowski, 2001) to more pervasive (c.f. van der Meer *et al*., 2003; Menzies *et al*., 2006) deformation occurring beneath the glacier. However, if the porewater content of the sediment was reduced, fluid enhanced shearing would cease, leading to the 'lock-up' and collapse of the subglacial shear zone. Thus, temporal changes in porewater content and/or pressure within the subglacial environment may lead to the repeated 'expansion' and 'contraction' of the subglacial bed (Lee and Phillips, 2008) and the generation of 'mosaic'-like distribution of deformation (Figure 7.4; Piotrowski *et al*., 2004). Evidence for this would manifest itself in a complex structural cross-cutting sequence of ductile and brittle deformation structures (Lee and Phillips, 2008; Phillips *et al*., 2008; Evans and Thomson, 2010; Rijsdijk *et al*., 2010). With reduced porewater content, shear stresses would have been accommodated by brittle failure along thrust planes resulting in tectonic accretion and a relative rise in the elevation of the base of the deforming bed (e.g. D2) (cf. Boulton, 1987; Hart *et al*., 1990).

The migration of expelled porewater, and its concentration elsewhere, would lead to ductile shearing being switched (partitioned) into a weaker part of the sediment pile. The result would be a shifting, anastomosing pattern of deformation within the deforming bed. This process of 'switching' between actively deforming zones, means that the D1 to D3 sequence of deformation is time-transgressive migrating through the sediment pile with time. Mechanisms for expelling sediment could relate to

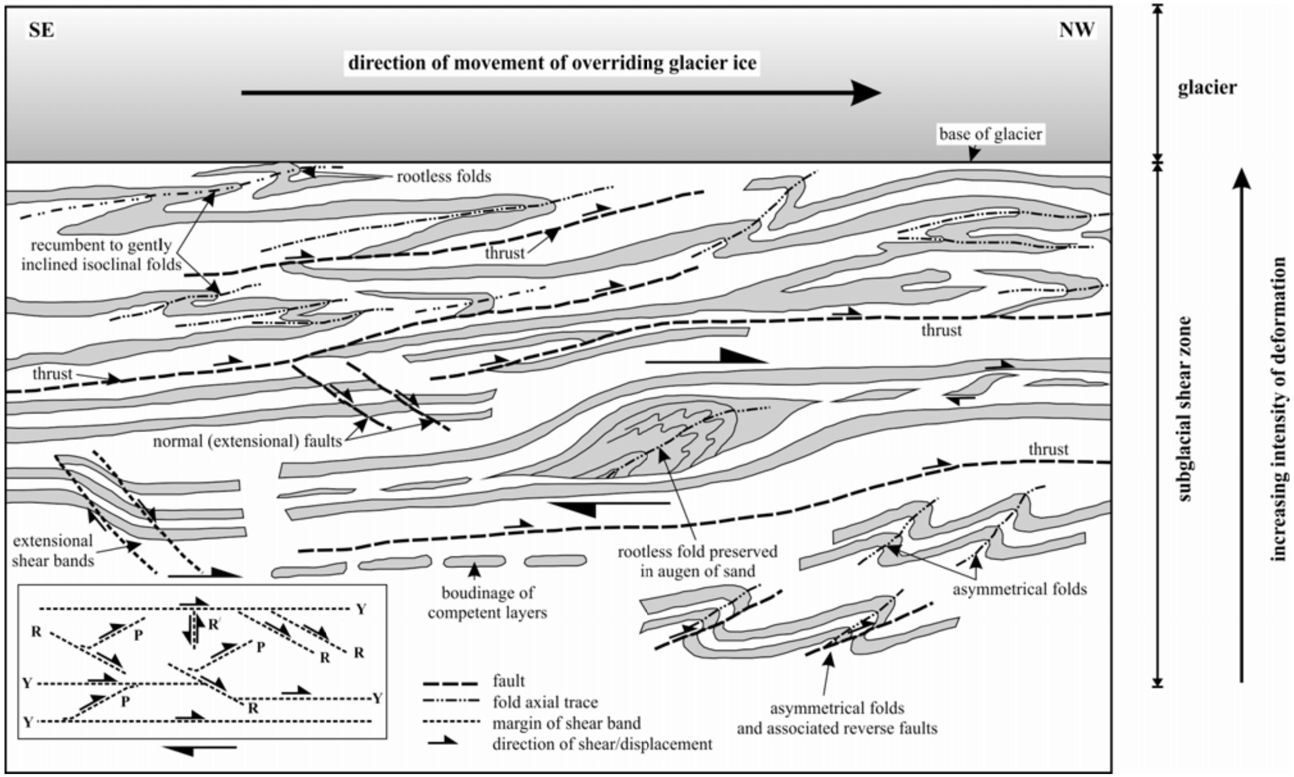

Figure 7.3. Schematic diagram showing the range of deformation structures associated with the development of the subglacial shear zone and an overall increase in the apparent intensity of deformation upwards through the sequence (from Lee and Phillips, 2008)

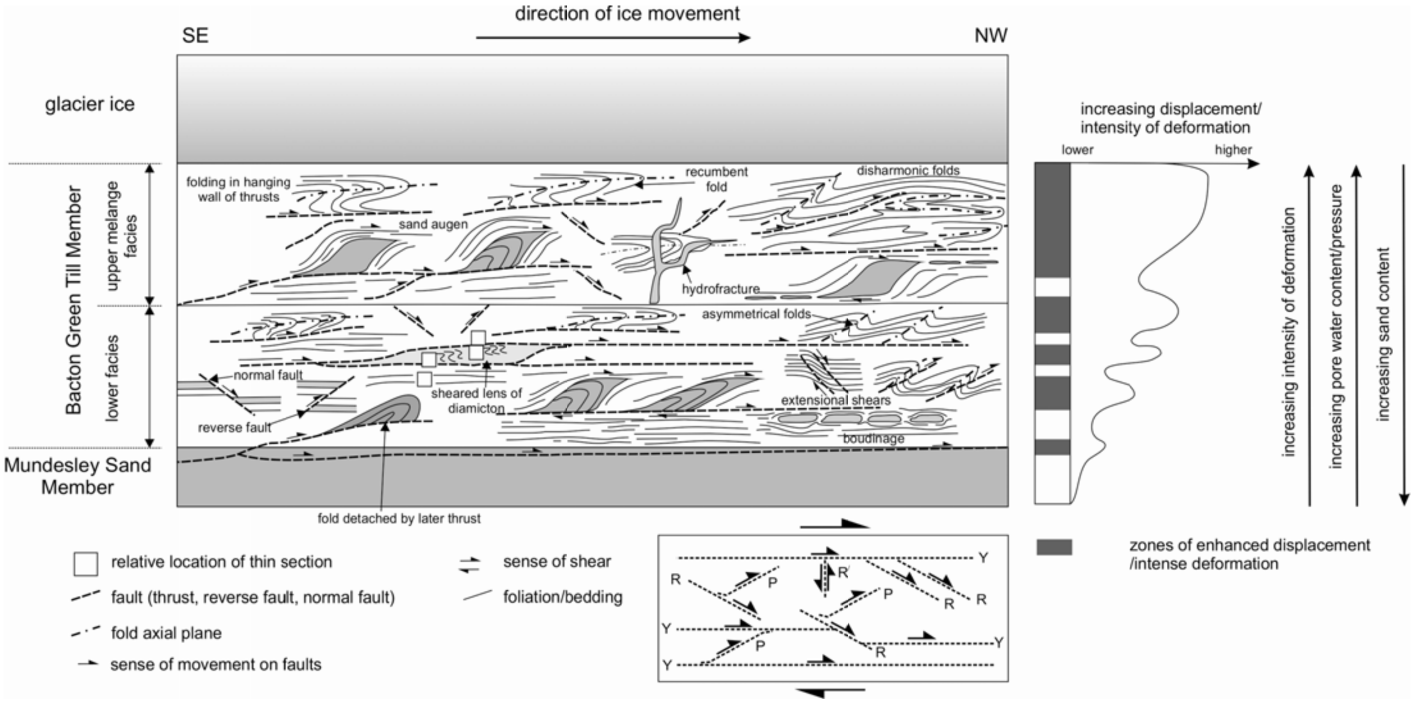

Figure 7.4. Progressive deformation model showing the development of various shear structures using a hybrid ‘mosaic’ and ‘pervasive’ deforming bed model (from Lee and Phillips, 2008)

either: *(i)* continued subglacial deformation; and *(ii)* continued tectonic thickening or accretion of the subglacial sediment pile which would either isolate porewater beneath the base of the deforming bed profile (Hart and Boulton, 1991b), or increase the overburden pressure.

5. Conclusions

- The Bacton Green Till at Bacton Green Till was originally deposited as series of subaqueous debris flows but has been subsequently glacitectonised during an ice advance from the south to southwest.
- Glacitectonic deformation was partitioned into ‘lower’ and ‘higher’ strain domains. The later records three separate deformation events relating to phases of ductile (D1) and brittle (D2) deformation, and hydrofracturing related to rapid de-watering (D3).
- Events D1-D3 are considered to be driven by temporal and spatial changes in porewater content and pressure within the subglacial deforming bed. Mechanisms for porewater expulsion includes tectonic thickening and continued deformation.
- The recognition of a ‘mosaic’ style of deformation, as recognised by other studies, highlights the role of water migration through the subglacial bed and has direct implications for the stability and behaviour of ice masses.