Chapter 6

Progressive proglacial to subglacial deformation: West Runton to Sheringham

Emrys Phillips, Jonathan R. Lee and Helen F. Burke

1. Introduction

The analysis and interpretation of the structural features developed within subglacially and proglacially deformed sediments can provide important information on the character of glacier-induced deformation events (e.g. Berthelsen, 1979; van der Wateren, 1985; Hart, 1990; Benn and Evans, 1996; Boulton *et al*., 1996, 1999; van der Wateren *et al*., 2000; Hart and Rose, 2001; Phillips *et al*., 2007; Benediktsson *et al*., 2008; Lee and Phillips, 2008) and the nature of ice-marginal sedimentation and dynamics during glacial cycles (e.g. van der Wateren, 1985, 1995; Croot, 1988; Aber *et al*., 1989; Benn and Evans, 1993; Harris *et al*., 1997; Phillips *et al*., 2002, 2008; Hiemstra *et al*., 2005). This deformation typically involves folding and thrusting, comparable to structures found in foreland fold-and-thrust belts developed in response to crustal shortening and mountain building in areas of plate tectonic convergence. This has invariably led to the application of a thin-skinned thrust tectonic model to proglacially to subglacially deformed glacigenic sequences (e.g. Croot, 1987; Aber *et al*., 1989; Pedersen, 2005; Phillips *et al*., 2008).

This section of the guide describes the polydeformed sediments exposed in the coastal cliff sections (c. 1.5 km in length) between West Runton and Sheringham that have been glacitectonised by proglacial to subglacial deformation (Figure 5.1).

Location of sections: sections are located between West Runton (TG 181 341) and Sheringham (TG 165 433) and are best examined on an east to west traverse. Car parking is available at West Runton beach car park which also has a café and lavatories.

2. Background

West Runton is a classical site within the British Quaternary, being both the stratotype for the early Middle Pleistocene *'Cromerian'* interglacial stage, as well as possessing a spectacular array of highly-deformed preglacial and glacial sediments. Deformation between West Runton and Sheringham has resulted in the modification and locally intense reworking of the succession to the extent that many of the primary sedimentological characteristics and stratigraphic relationships of the succession have been overprinted (Banham, 1970; Phillips *et al*., 2008). Whilst there is no doubt over the highly deformed nature of the sequence, controversy exists over the mechanism of its deformation. Some considering the deformation to be induced by subaqueous slides and debris flows (Zalasiewicz and Gibbard, 1988; Eyles *et al*., 1989), whereas others consider it to be diagnostic of subglacial deformation (Hart *et al*., 1990; Hart and Boulton, 1991b; Hart and Roberts, 1994; Roberts and Hart, 2005; Phillips *et al*., 2008).

In their recent study, Phillips *et al*. (2008) divided the deformed sequence between West Runton and Sheringham into three distinctive structural domains (Figure 6.1) that record a change in structural style from proglacial deformation (Domain 1) at the eastern end of the coastal section, to ice-marginal (Domain 2) within the central part of the section, through to intense subglacial deformation (Domain 3) at its western end. They concluded that the simplest interpretation of this sequence was in terms of a single progressive proglacial to subglacial glacitectonic event associated with ice advancing from the west (advance A4, Table 5.2). Four key lithological units can be recognised in the section: *(i)* at the base of the glacigenic succession, the grey, massive to moderately foliated Happisburgh Till Member (HT) at the base of the cliff; *(ii)* this is overlain by the highly folded and foliated, brown, Bacton Green Till (BGT); *(iii)* the top of the succession is represented by outwash sand and gravel called the Runton Sand and Gravel (RSG); and *(iv)* a glacitectonic mélange derived from both the BGT and RSG. Structurally below this glacitectonised sequence are the essentially undeformed, preglacial shallow marine sediments of the Wroxham Crag Formation (WCF), exposed towards the eastern end of the section, and underlying chalk bedrock that crops out along the foreshore. Both the BGT and RSG contain thrust-bound, locally stacked slices or rafts of chalk and WCF, as well as Marl Bed (MB) and chalky Walcott Till (WT) which, in their original stratigraphical position, occur between the HT and BGT (see Table 5.1).

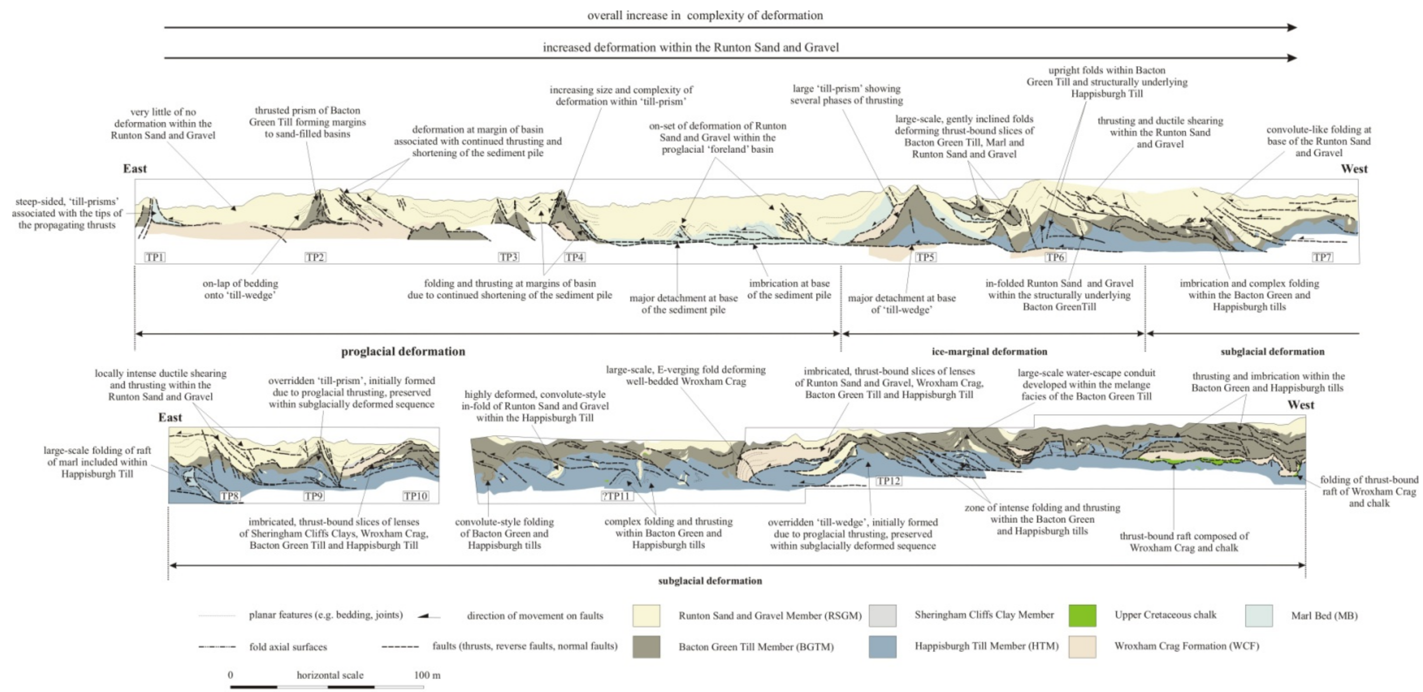

Figure 6.1. A composite section for the cliffs between West Runton and Sheringham showing the variation in the style and intensity of deformation from east to west (from Phillips *et al*., 2008)

3. Description of Glacitectonic Structures

3.1 Domain 1

In Domain 1 the glacial sequence is relatively undeformed consisting of several broad (50-150 m wide) basins filled by thick sequences (up to 15 m) of stratified glaciofluvial outwash sand and gravel (RSG). Detailed analyses of the sedimentology of the RSG reveal that the deposits are not inverted but the right way-up. Bedding is largely horizontal to very-gently dipping, but locally steepens to sub-vertical immediately adjacent to a number of wedge-shaped prisms of till, with the basins of RSG forming large, open, dish-like synform structures.

The contact between the basins and the sub-strata are variable. In places it is characterised by a scoured (erosive) sedimentary contact, whereas elsewhere, the RSG and sub-strata are separated by a major décollement surface located at the top of the structurally underlying WCF. In detail, this major detachment comprises a series of subhorizontal to gently westerly-dipping, easterly-directed thrusts (Figure 6.2a). Thrust-bound slices (<0.5 m thick) of MB and BGT occur along this décollement, and bedding within the slices are commonly off-set by small thrusts which link into the larger structures. Towards the centre and western end of Domain 1, larger-scale east-verging folds and thrusts which deform the MB locally propagate upwards into the overlying RSG, occasionally leading to flame-like folds and thrust-bound slices of MB material being tectonically emplaced into the lower part of the outwash sequence.

A distinctive structural feature of Domain 1 is the occurrence of large (10-15 m high, 8-25 m across), symmetrical to asymmetrical, saw-toothed and fault-bound 'till-prisms' composed of MB and BGT (Figure 6.2a,c). These till-prisms separate the individual RSG outwash basins, and increase in size and complexity westwards towards Domain 2. The bases of these wedge-shaped structures are marked by either a sharp planar thrust or wider (0.1-0.3 m thick) ductile shear zone that extends into the décollement surface at the top of the WCF. The eastern-margins of the 'till-prisms' are steeply inclined and characterised by a normal fault (downthrow to east), or a number of steeply inclined (60-80˚), east/east-northeast-dipping, planar normal faults (also downthrow to east). The latter also occur within the adjacent RSG and result in localised drag folding and disruption of bedding within these sands. The western margins of the 'till-prisms' are curved, and marked by either the disturbed/tectonised erosive base of the RSG, or an arcuate, west-dipping, easterly-directed thrust which over steepens towards the tip of the 'prism'. Bedding within the RSG immediately

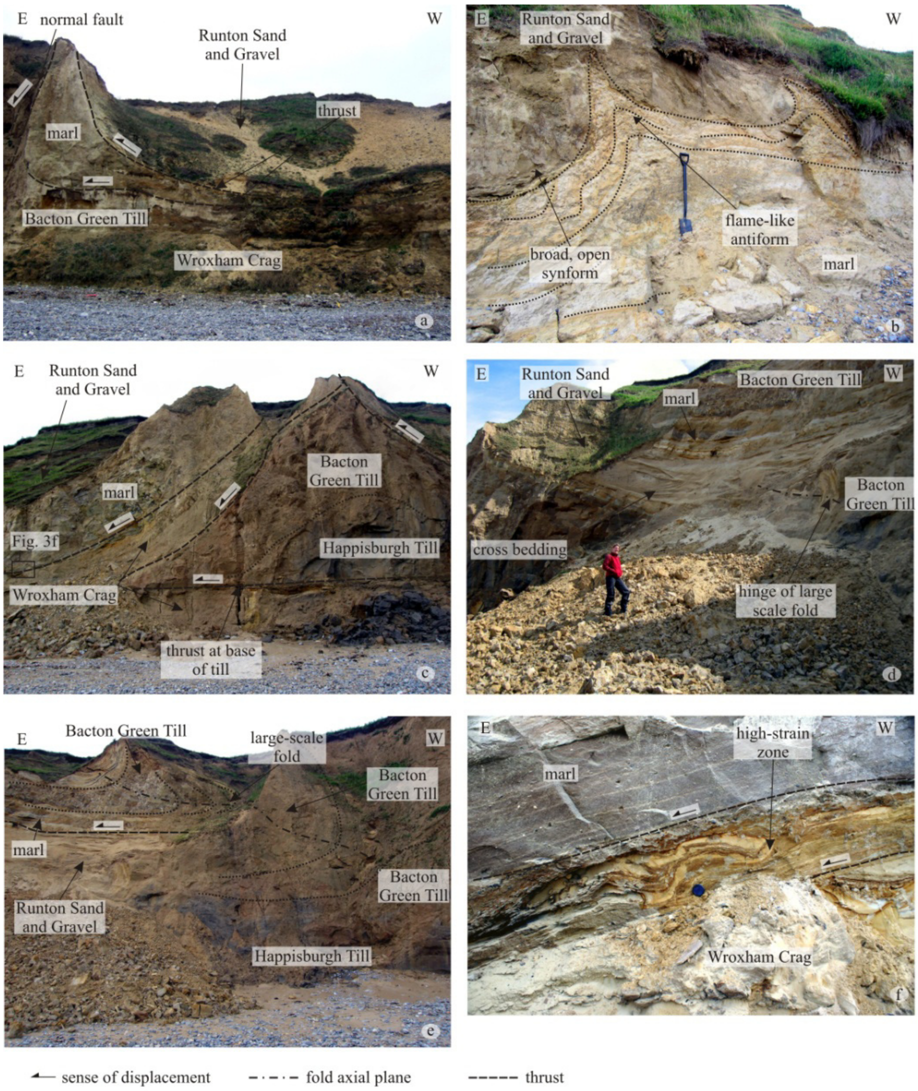

Figure 6.2. (a) Steep-sided, wedge-like feature ('till-prism', see text) composed of thrust-bound slices of BGTM and Marl. The planar thrust at the bottom of this thrust-related feature forms a décollement surface separating the deformed glacial sediments from the underlying preglacial deposits WCF; (b) convolute folding affecting the base of the RSGM and underlying Marl; (c) large, steep-sided, wedge-like feature composed of thrust-bound slices of BGTM, HTM, WCF and Marl; (d) well-bedded and cross bedded sands and gravels of the RSGM stacked with thrust-bound slices of Marl and BGTM; (e) large-scale synform deforming thrust-stacked sequence of RSGM, BGTM and Marl; (f) ductile shearing associated with thrusted base of a large, detached slab of Marl (from Phillips *et al*., 2008)

adjacent to the 'till-prism' occurs parallel to the tectonised contact. In the central part of Domain 1, bedding within the RSG defines two open anticlines linked by a syncline. These folds are developed above two smaller (8-10 m high), closely spaced 'till-prisms'. However, elsewhere individual sand and gravel beds thin towards the margin of the 'till-prism' and apparently either lap onto, or are truncated against this boundary. These relationships are best seen at the eastern end of the domain, as further west the RSG becomes increasingly deformed.

3.2 Domain 2

To the west of Domain 1, Domain 2 is characterised by a marked increase in the intensity and complexity of deformation. At the eastern end of Domain 2 is a large (c. 25 m high, c. 35 m wide) wedge-shaped structure composed of east-dipping, fault/thrust-bound slabs of MB and WCF, juxtaposed against the eastern side of a 'till-prism' (Figure 6.2c); the latter comprising an outer layer of BGT overlying a core of HT. The western margin of the 'till-prism' is formed by an arcuate, steeply to gently dipping thrust which becomes progressively shallower dipping westwards, where it passes into a highly tectonised zone separating the BGT and RSG. The eastern margin of the wedge-shaped structure is a primary sedimentary contact formed by the erosive base of the RSG, resting upon a 3 to 4 m thick slab of MB. The base of the MB is marked by a 0.25-0.4 m thick shear zone composed of highly foliated and folded sand derived from the underlying WCF (Figure 6.2f). Fold asymmetry and sigmoidal S-C-like fabrics record a sense of shear towards the east/east-northeast. Slabs of MB and WCF which form the eastern face of this till-prism dip towards the east and terminate near the top of the cliff, forming a fault-bound hollow with 'stepped' sides and filled by RSG. Bedding within the sand is deformed by an upright, open synform. To the west of the 'till-prism', the RSG contains a number of thrust-bound lenses of MB and BGT (Figure 6.2d) with this imbricate/thrust stacked sequence being deformed by a large, recumbent to gently inclined syncline with the axial surface dipping westwards (Figure 6.2e).

The folded and thrusted sequence is structurally underlain by highly deformed BGT, which overlies in-turn the HT. The boundary between the tills and overlying sands is tectonic and locally off-set by steeply west/northwest-dipping reverse faults.

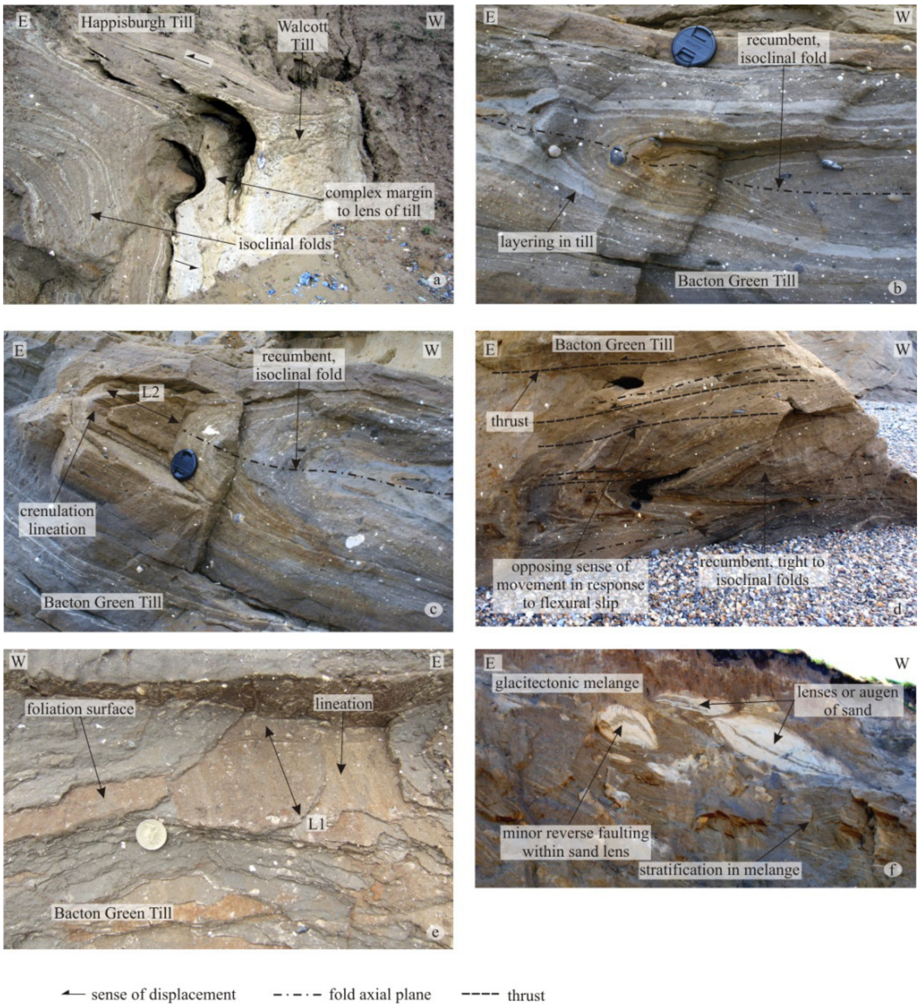

Figure 6.3. (a) Irregular, highly deformed 'raft' of Walcott Till wrapped by the foliation within the HTM. Elongate, tail-like off shoots from the chalky Walcott Till extend into the foliation within the host; (b) recumbent to gently-inclined, isoclinal fold deforming the layering/S1 foliation present within the upper part of the BGTM; (c) crenulation lineation (L2) developed in the hinge of a recumbent fold deforming the S1 foliation within the BGTM; (d) recumbent folds cut by later thrusts within the BGTM showing that ductile folding was followed by at least one phase of E-directed brittle faulting; (e) well-developed stretching lineation (L1) developed upon S1 foliation surfaces within the BGTM; (f) asymmetrical, sheared lenses or augen of sand within the glacitectonic mélange facies of the BGTM (from Phillips *et al.*, 2008)

3.3 Domain 3

Domain 3, at the western end of coastal section, is the most structurally-complex of the three domains, and is marked by a dramatic increase in the combined thickness (up to 40 m) of the HT and BGT, with the contact between the two tills being sharp and irregular in form. The HT is exposed at the base of the cliff with the intensity of deformation increasing upwards towards the contact with the structurally overlying BGT. Below this contact the HT possesses an intense domainal foliation (S1) which is deformed by tight to isoclinal, locally intrafolial, recumbent to gently inclined folds (F1/2). Eye-shaped fold interference patterns also occur within the HT, showing that folding within the till is polyphase. The S1 foliation is defined by pale grey layers and stringers of disaggregated chalk and chalk-rich till which have undergone progressive attenuation and boudinage. Fabric geometries associated with ductile shearing (S-C) and extensional crenulation cleavage (ECC) development, as well as fault off-sets, record a consistent easterly-directed sense of shear. The HT locally contains highly distorted augen or rafts of pale chalky WT (Figure 6.3a). Flame-like projections and tails extending from the WT pass laterally into the banded S1 fabric within the HT. This suggests that the compositional layering within the HT was partially derived from the incorporation of the WT into the host till during deformation. S1 in the HT is co-planar to the locally intense foliation present within the BGT and glacitectonic layering within the structurally overlying mélange. Although the orientation of S1 within both tills is locally variable, dip and dip azimuth data obtained for this fabric shows that overall it dips at a shallow angle towards the east-northeast, or more steeply towards the northwest.

S1 within the BGT is deformed by easterly-verging, small- to meso-scale, tight to isoclinal, recumbent to gently-inclined folds (F1/2) (Figures 6.3b,c and d). Folding is disharmonic with the S1 foliation becoming progressively diffuse towards the hinge suggestive of locally high porewater contents within the till. Meso-scale folds (F1/2) are developed within the hanging walls of S1-parallel easterly-directed thrusts and ductile shear zones. The folds deform a locally well-developed stretching lineation (L1) developed upon S1 surfaces which plunge towards the north/north-northeast (Figure 6.3e). A second, southwest-plunging crenulation lineation (L2) is locally developed in the hinges of the F1/2 folds. The early recumbent to gently inclined folds are themselves deformed by later upright to moderately inclined, asymmetrical, easterly verging small to meso-scale folds (F2/3) which plunge towards the southeast.

At the eastern end of Domain 3, the boundary between the BGT and the overlying RSG is largely gradational and irregular in form. Although highly deformed (folded and thrusted) the bedded nature of the outwash sands and gravels has retained. Further west, however, bedding within the RGS rapidly becomes increasingly disrupted and overprinted by a glacitectonic layering which is co-planar with the S1 fabric developed in underlying the BGT. In this part of the section, the RSG is cut out and the BGT is much thicker (up to 20 m thick) and comprises a brown sandy till which grades upwards, over several metres, into a highly-deformed mélange facies composed of mixed BGT and RSG. The intensity of deformation within the mélange, which includes both ductile folding and later brittle thrusting, are spatially variable and partitioned into discrete zones. The mélange is characterised by the presence of slab-like, asymmetrical to tightly folded sand intraclasts contained within a highly folded and foliated (S1) till matrix (Figure 6.3f).

Along the length of the coastal section, the contact between the BGT and HT occasionally rises to form a series of large (10-15 m wide), symmetrical and asymmetrical ridges. The shape of these ridges and associated deformation (including imbrication of the sequence) is comparable to that observed within the till-prisms observed further towards West Runton. Adjacent to these features the BGT and mélange contain a number of stacked, fault-bound slices of WCF, MB and RSGM, the largest of these is a 50 m long, 10-15 m thick raft of well-bedded WCF. The eastern end of this raft is deformed by a large-scale, southeast-plunging antiform. Towards the western end of Domain 3, the boundary between the HT and RGT is marked by a thin (≤ 2-3 m thick), but laterally extensive thrust-bound raft of WCF overlying chalk which preserves intact the sharp, erosive contact between the well-bedded preglacial sands and gravels, and underlying bedrock. In contrast, the chalk (10 to 40 cm thick) is massive and putty-like in texture, and cut by narrow (1-3 cm wide) shear zones composed of highly deformed HTM.

4. Glacitectonic Interpretation

The simplest interpretation of the glacitectonic signature recorded by the sedimentary sequence exposed between West Runton and Sheringham is in terms of a thin-skinned, progressive proglacial to subglacial thrust model (Figure 6.1; Phillips *et al*., 2008), induced by the active retreat of a major ice advance from the west/southwest. The three structural domains show a change (east to west) from relatively simple proglacial thrusting (Domain 1), to ice-marginal large-scale thrusting folding and imbrication (Domain 2) leading to the tectonic thickening of the sediment pile, through to more complex polyphase subglacial deformation (Domain 3) involving initial ductile folding and shearing, followed by more brittle thrusting. Kinematic indicators (e.g. asymmetrical folds, shear fabrics, sense of displacement on thrusts) clearly demonstrate that deformation in all three domains was as a result of the same overall easterly directed stress regime.

4.1. Proglacial deformation (Domain 1)

Proglacial deformation within Domain 1 imposed a relatively simple deformation history on the sequence dominated by eastwardly-directed thrusting. The basal detachment or sole thrust was located near to, or at the top of the WCF, with proglacial ductile shearing and thrusting leading to the reactivation of a pre-existing décollement surface at the base of the HT. Over much of Domain 1 the overlying RSG shows very little evidence of deformation, apart from immediately adjacent to the 'till-prisms' (labelled TP1 to TP 4), where bedding steepens rapidly, and is locally off-set by normal faults. Towards the western end of the Domain, however, towards the ice-margin, the intensity of proglacial deformation increases and westerly-dipping thrusts ramp upwards from the basal detachment leading to localised folding of these outwash sediments and emplacement of thrust-bound slices of MB into the lower part of the RSG (Figure 6.4); probably reflecting an increase in the degree of shortening within the hanging wall of the basal décollement nearer to the ice-margin

Phillips *et al*. (2008) interpreted the 'till-prisms' Domain 1 as proglacial thrust-block moraines that developed at the propagating tips of proglacial thrusts as they ramped upwards through the sequence in response to an oscillating ice-margin. Deformation at the ends of these thrusts initially led to folding of BGT, followed by thrusting and stacking of detached slices of BGT and HT, and, in some instances, the underlying preglacial sediments (HT and WCF). The size of the till-prisms appears to increase in an up-ice (westwards) direction, with their steep margins representing the original geometry of these glacitectonic features. The upward growth of the till-prisms resulted in localised folding and normal faulting within the adjacent RSG as these unconsolidated sediments collapsed off of the sides of these thrust-related structures. The RSG between these thrust-block moraines is relatively undeformed and in-fills broad, open, dish-like synclines or basins. Due to the 2D nature of the coastline, the 3D geometry of the till-prisms is unclear. However, coastal

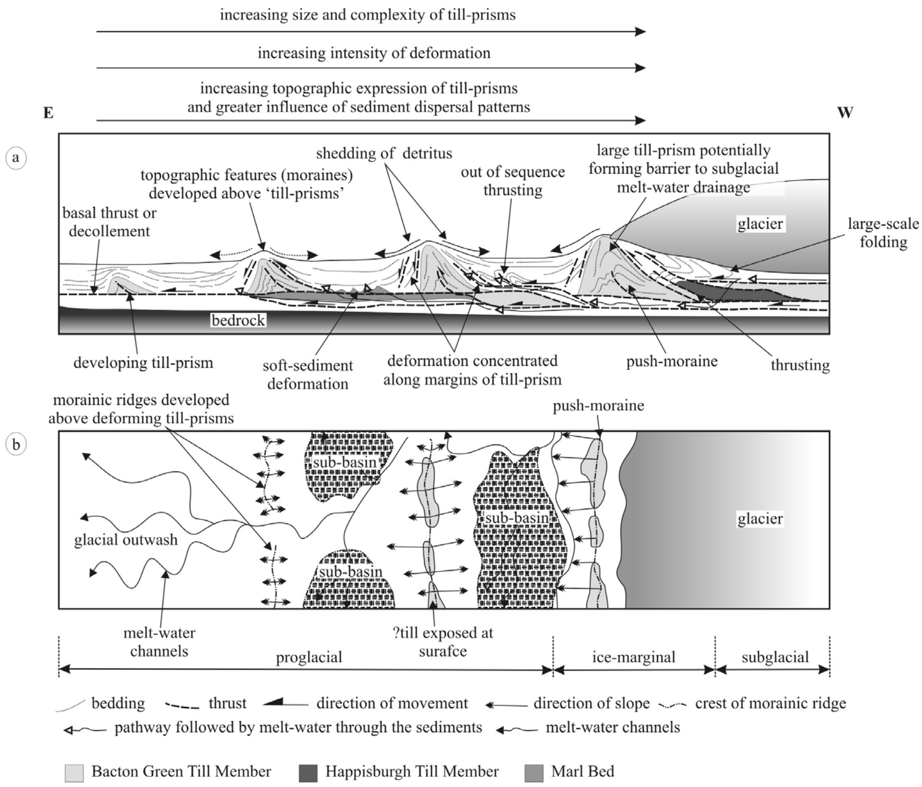

Figure 6.4. Cross-section (a) and plan-view (b) schematic models showing the proglacial to ice-marginal model to explain the structural features observed between West Runton and Sheringham (from Phillips *et al*., 2008)

erosion since the publication of Phillips *et al*. (2008) has revealed that the width and height of these thrust-related moraines varies laterally, from relatively wide (up to several tens of metres) and high within the core, thinning and descending rapidly towards their terminations. This variation is comparable to the morphology of the end moraines associated with the 1890 surge of Brúarjökull, Iceland described by Benediktsson *et al*. (2008). During the early stages of deformation and fault propagation, the tip of the basal thrust at West Runton is likely to have been composed of several short segments resulting in the growth of several short, arcuate moraines associated with each thrust-segment. As deformation continued the individual these segments may have coalesced, leading to the development of a single elongate, sinuous, ridge-like moraine.

Phillips *et al*. (2008) argued that the thrust-block moraines probably formed positive topographic features within the foreland of the ice sheet, potentially influencing the pattern of sedimentation/sediment dispersal on the proglacial sandur (Figure 6.4). Consequently, Phillips *et al.* interpreted the large RSG-filled basins as syn-tectonic basins scoured and infilled by glaciofluvial outwash. Many of the previous workers (Banham, 1975; Hart, 1987; Ehlers *et al*., 1991; Hart and Boulton, 1991a) have considered them to be *'sag basins'* produced by sediment loading of the underlying till pile by the RSG. However, this would require the complete removal of a laterally extensive (50-150 m wide), thick (20-25 m) layer of till from beneath the sand bodies so that the RSG could rest locally directly upon the preglacial WCF, without disrupting the bedding at the base of the basins. Furthermore, no large-scale diapirs of BGT or HT, associated with the lateral displacement or expulsion of these tills, have been recognised adjacent to the basins.

4.2 'Ice-marginal' deformation (Domain 2)

Ice-marginal deformation within Domain 2 is characterised by a marked increase in the intensity of deformation with large-scale thrusting, folding and imbrication leading to a marked tectonic thickening of the glacigenic sediment pile. The accretion of a large, relatively impermeable wedge-shaped, proglacial thrust-block moraines (till-prisms) onto the eastern margin of the ice-marginal imbricate thrust stack is likely to have locally affected the pattern of subglacial drainage beneath the ice sheet. It may have impeded or effectively blocked the flow of meltwater from beneath the ice sheet, leading to an increase in porewater pressure and/or content within the adjacent submarginal to subglacial environments. Meltwater from beneath the ice would have then been forced to change, flowing around the margins of the till-prism, or even beneath this accreted proglacial moraine. The laterally extensive and permeable WCF could have provided an ideal pathway for the escaping meltwater, feeding pressurised porewater directly into the proglacial environment. This may have lubricated the basal décollement at the base of the deforming sequence, leading to thrust-gliding and change of thrust geometry as well as facilitating the detachment of long thrust sheets leading to the limited disturbance seen within the RSG basins. The effects of soft-sediment deformation and water-enhanced thrusting would have decreased away from the ice-margin as the meltwater escaped through the permeable sands and gravels of the WCF and RSG.

4.3 Subglacial deformation (Domain 3)

Domain 3 at the western end of the West Runton to Sheringham coastal section represents the most pervasively deformed part of the entire sequence, with the intensity of this deformation increasing rapidly westwards, accompanied by a marked increase in the thickness of the BGT (Figure 6.1). This thick till can be divided into a lower, highly foliated facies, structurally overlain by a pervasively deformed glacitectonic mélange. The complex association of folding, thrusting, mélange generation recorded by the HT, BGT and RSG is interpreted as having occurred in response to progressive subglacial deformation (Banham, 1977; Hart and Boulton, 1991b; Hart and Roberts, 1994; Benn and Evans, 1996; Roberts and Hart, 2000; Roberts and Hart, 2005; Evans *et al*., 2006; Lee and Phillips, 2008; Phillips *et al*., 2008). The deformation histories recorded by the HT (A1) and overlying BGT (A3) are clearly polyphase and include several phases of folding and fabric development. The earliest deformation events recorded by these tills would have accompanied their initial deposition. However, these primary fabrics are not easily recognisable due to the pervasive nature of the secondary deformation (A4; Table 5.2) and it is likely that they were transposed or over-printed during this event. Indeed, WT (A2; Table 5.2) is not present as a mappable till lithology within the succession, and is only recognisable as attenuated inclusions within either the HT or BGT.

The curvilinear form of the F1/2 fold axial traces, the locally diffuse nature of the S1 fabric combined with disharmonic folding strongly suggest that at the time of deformation (A4), the BGT possessed a relatively high porewater content. It suggests that either the porewater content of the HT and BGT were recharged between the primary deposition of these tills (A2 and A3 respectively; Table 5.2) and secondary deformation (A4), or more likely, that only a short time period separated these events and the deposits maintained a relatively high porewater content. As A4 deformation continued, folds (F1/2) and fabrics (S1) developed earlier became refolded by moderately to steeply-inclined fold (F2/3) structures that record an eastern direction of shear. This later phase of folding also led to the infolding and part-incorporation of masses of RSG into structurally lower units (HT, BGT). The part-convolute nature of the folds demonstrates that relatively high porewater contents and/or pressures were maintained during folding.

The easterly-directed thrusts largely truncate the earlier formed F2/3 folds, indicating a switch to more focused, brittle deformation possibly as a result of fluctuating porewater pressures during later stages of D4.

Thrusting resulted in the detachment and stacking of the HT, BGT and RSG, and the tectonic thickening of the sediment pile beneath the ice sheet. It is possible that many of these thrusts formed earlier during A4 and in a more ice-marginal, or even, proglacial position, becoming reactivated during the later stages of the subglacial deformation as the sedimentary pile began to dewater (Figure 6.1). As these thrusts and ductile shear zones propagated upwards, deformation within their hanging walls resulted in the development of meso- to large-scale symmetrical and asymmetrical antiforms (F3/F4) within the BGT. On the eastern (up-ice) side of one of these antiforms, the mélange is cut by a large-scale water-escape conduit. The base of this water-escape feature terminates or roots into the contact between the BGT and underlying HT, suggesting that pressurised porewater was flowing along this lithological boundary. The presence of water-escape features provides further evidence that the BGT was saturated with water at the time of deformation (A4) and that porewater pressures locally exceeded the cohesive shear strength of the material.

5. Conclusions

- The simplest interpretation of the glacitectonic structures exposed within the coastal cliffs between West Runton and Sheringham is one of a progressive to subglacial deformation model.
- Proglacial deformation occurred at the eastern end of the sections, and was dominated by thrusting which led to the generation of steep-sided moraines composed of blocks of deformed till. The basal detachment surface was located along a lithostratigraphic boundary that separates the glacial from the preglacial sequence.
- Large-scale folding and thrusting within the ice-marginal domain led to the stacking of material derived from up-ice with accretion occurring on the stoss-side of the moraine features.
- Subglacial deformation was highly variable in style characterised by folding and thrusting through to more pervasive homogenisation and ductile shearing and the formation of a subglacial shear zone superimposed upon earlier deformation styles.
- The complexity and thickness of the shear zones increases towards the west in an up-ice direction where it forms a distinctive glacitectonic mélange.