An Introduction to the glacial geology and history of glacitectonic research in northeast Norfolk

Jonathan R. Lee, Emrys Phillips, Hannah M. Evans
and David Vaughan-Hirsch

1. Introduction

The glacial deposits of northeast Norfolk (Figure 5.1) have courted the interest of geologists for well over 150 years (Buckland, 1823; Lyell, 1840; Gunn, 1867; Reid, 1877). Indeed, it is no surprise that fundamental steps in scientific philosophy as well as paradigm shifts in the understanding of glacial processes have been developed, in-part, on research undertaken in northeast Norfolk (Slater, 1926; Whiteman, 2000). In this chapter, we provide a background to the role played by the region in the broader understanding of glacitectonics. We also provide a brief overview of the current understanding of the glacial geology of the region, setting the context for the site visits during the Workshop and the case studies presented later in this field guide.

2. History of research in northeast Norfolk

The recognition of the role played by glaciers in the landscape and the existence of past glaciations – the so-called *'Glacial Theory'*, was first postulated during the mid-late nineteenth century by geologists. Following the concepts of the early geological pioneers such as Charles Lyell and Jean Louis Rodolphe Agassiz, geologists undertaking detailed mapping surveys for the Geological Survey in East Anglia, soon recognised evidence for glaciers in the landscape. One of the best early representations of this evidence is the Old Series Cromer sheet and accompanying memoir (Reid, 1882). Whilst the Old Series map has since been superseded by a more modern survey (BGS, 2002), the quality and accuracy of Clement Reid's work should not be underestimated. Many of his ideas, descriptions and observations underpin much of what we understand both about the glacial history of the region, and more recent developments in our understanding of glacial processes.

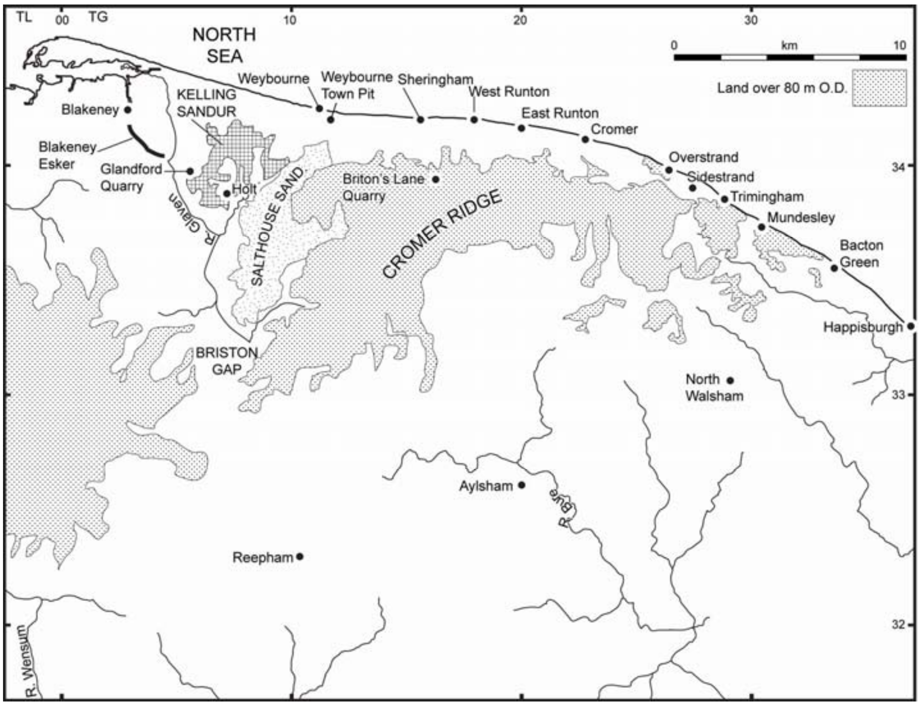

Figure 5.1. Northeast Norfolk and the location of sites referred to within this field guide. Major geomorphological features are highlighted

For example, the modern stratigraphy of northeast Norfolk is largely based upon the early work of Reid (Banham, 1968; Lunkka, 1994; Lee *et al*., 2004) and Reid also noted the *'disturbed chalk'* or chalk rafts and highly contorted drift sequences visible within the area and attributed the deformation to be caused by ice moving over the substrate *"…like a hand of a table cloth…"*. Clement Reid died in 1916, but not before his work influenced the work of geologists such as Woodward (1903) mapping drift sequences elsewhere in Eastern England.

The concept of *'glacial tectonics'* was first proposed by George Slater (Slater, 1926) in an eloquent and spirited paper to *Proceedings of the Geologists' Association*. Slater's theory was based upon both his extensive fieldwork as a glaciologist in the Alps and Spitsbergen, and research examining relict glacial sequences in Europe and North America. The latter included a series of papers focussing upon the structure of glacial sequences in southern East Anglia (Slater, 1927b), Alberta (Slater, 1927a) and Denmark (Slater, 1928a, b) which are well cited within modern literature. When outlining his ground-breaking concept, Slater drew attention to the bedrock and glaciological controls on *'glacial tectonic'* structure, highlighting the role played by *'cores of definite form'* that acted to propagate deformation. However, it is clear from Slater's paper that the *'glacial tectonic'* concept was controversial and received with a degree of scepticism and scorn by some parts of the geological community. One such opinion, described as *"…false and mischievous…"* by Slater (1926, p.395), was that of Sir H. H. Howorth who argued that *"…no section, however carefully drawn, is of more than ephemeral interest…"*. Sadly, Slater's extensive research in northeast Norfolk remains largely unpublished although his excellent cross-section diagrams are a valuable insight into his skill as a geologist and thought process (Figure 5.2). Following the publication of Slater's landmark conceptual paper in 1926, it was a further 40 years before *'glacial tectonic'* theory and process once again became actively studied in East Anglia.

The catalyst for this new era of research into glacier-induced deformation in East Anglia was the work of Peter Banham. Banham (1975) initially recognised that two different styles of deformation occurred, extensional and compressional deformation, and these related to the application of stresses beneath and in front of a glacier. Within a later paper, Banham (1977) introduced the now familiar term *'glacitectonite'* for subglacially sheared materials, and highlighted their analogy with structures and fabrics developed within mylonitic (metamorphic) shear zones. Critically, Banham (1977) recognised that two broad sub-divisions of subglacially sheared materials could be made: Firstly, sheared materials that retained to some extent the parent lithology and structure of the sheared material, these Banham called *'exodiamict glacitectonites'*; secondly, sheared materials called *'endiamict glacitectonites'* where the primary lithology and structure of the sheared material had been homogenised. Banham (1975) also played a major role in developing the nomenclature of proglacial glacitectonic landforms which have since been adopted and utilised by other schemes (Benn and Evans, 2010).

The ideas of Banham (Banham, 1975, 1977) combined with international views on glacitectonics were developed further during the 1980's and 1990's in East Anglia largely through the work of Jane Hart and co-workers. This work led to the establishment of the subglacial deformable bed concept (Boulton and Jones, 1979; Boulton, 1986; Boulton and Hindmarsh, 1987; Murray, 1997) and recognised different types of fabric alignment and deformation structures that could be linked to vertical strain, velocity and deformation profiles within relict deformable beds (Hart, 1987;

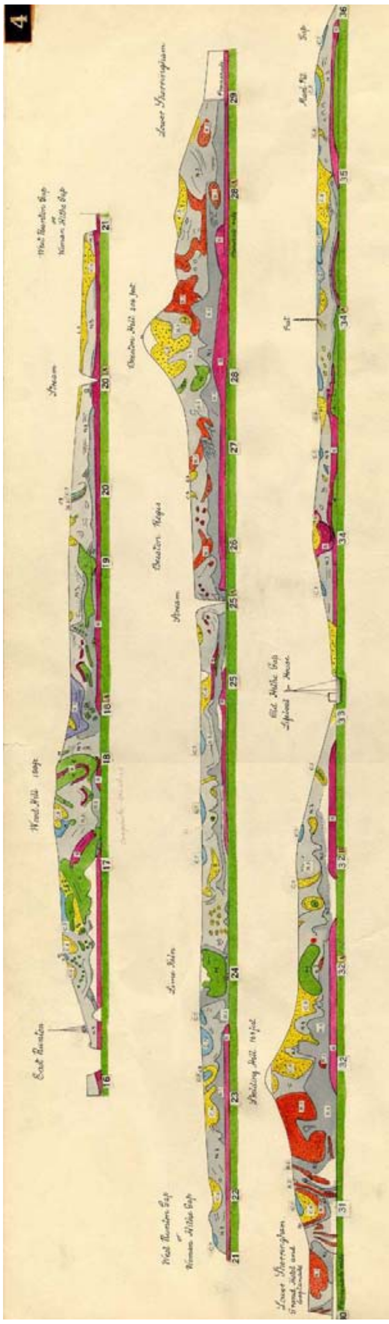

Figure 5.2. Coastal cross-section of the cliffs between East Runton and Sheringham compiled and drawn by George Slater. Slater constructed a further three cross-sections that encompass the structure of the cliffs further south and east between East Runton and Mundesley. Phil Gibbard (University of Cambridge) is gratefully thanked for enabling us to reproduce these here. They can be viewed and downloaded from:

http://www.qpg.geog.cam.ac.uk/resources/norfolkcoast/

Hart *et al*., 1990; Hart and Boulton, 1991b; Hart, 1994; Hart and Roberts, 1994; Roberts and Hart, 2005). However, the precise origin and mechanisms of many of these fabrics and structures have been debated extensively within the literature. Currently, there are arguments for subglacial till accretion/glacitectonites being generated either pervasively following the traditional deforming bed model (van der Meer *et al*., 2003; Menzies *et al*., 2006), or by temporal and spatial changes in deforming-bed processes (Piotrowski and Tulaczyk, 1999; Piotrowski *et al*., 2004; Evans *et al*., 2006). New research undertaken in the region tends to support the latter notion, highlighting the complex inter-relationship of deforming bed processes with bedrock (Lee *et al*., 2004; Burke *et al*., 2009), porewater content (Roberts and Hart, 2005; Hart, 2007; Lee and Phillips, 2008; Phillips *et al*., 2008; Lee, 2009) and permafrost (Burke *et al*., 2009; Waller *et al*., 2009; Waller *et al*., 2011). Whilst these scientific controversies and debates continue, the role of glacial deposits in northeast Norfolk should not be understated and will, no doubt, continue to be of importance in future glacitectonic research.

3. Glacial geology and geomorphology of northeast Norfolk

3.1 Lithostratigraphic overview

The relative succession of glacial deposits in northeast Norfolk is well established (Reid, 1882) and subsequent stratigraphic schemes have developed this early scheme, introducing progressive refinements of nomenclature and improved understanding of the glaciofluvial and glaciolacustrine facies that occur between the till units (Banham, 1968; Ranson, 1968; Lunkka, 1994; Lee *et al*., 2004).

Four separate till units were originally recognised in northeast Norfolk by Reid (1882), with the three lower more sandy tills subsequently referred to as the 'Cromer Tills' (Reid, 1882; Banham, 1968; Ranson, 1968). Research by Lunkka (1994) and Lee *et al*. (2004) led to the tills being renamed the Happisburgh Till, Walcott Till and Bacton Green Till and this nomenclature that is employed here (Table 5.1; Figure 5.3). The two lower tills are the Happisburgh and Walcott tills; both of which have widely been interpreted as subglacial deforming bed tills. The *Happisburgh Till* is a massive, dark grey, highly consolidated, matrix-supported diamicton. The texture of the matrix is a clayey-sand that contains numerous clasts of flint, chalk, quartzose material and a minor far-travelled component.

Lithostratigraphy	**Sediment**	**Genesis**
valley gravels	Sands and gravels	Valley colluvium
Briton's Lane Formation		
outwash	Sands and gravels	Glaciofluvial
Sheringham Cliffs Formation		
Weybourne Town Till	Highly chalky diamicton	Subglacial till
outwash	Sands, marl, varved muds	Glaciolacustrine
Bacton Green Till	Grey/brown sandy diamicton	Subaqueous flow till
outwash	Fine, micaceous sands	Deltaic
Lowestoft Formation		
Walcott Till	Light grey, silty, chalky diamicton	Subglacial till
Happisburgh Formation		

outwash	Sands and gravels, sands	Glaciofluvial
Corton Till	Brown sandy diamicton	Ice contact, subaqueous
outwash	Laminated muds and sand	Glaciolacustrine / deltaic
Happisburgh Till	Dark grey sandy diamicton	Subglacial till
Wroxham Crag Formation (pre glacial)	Sands, gravels and muds	Shallow marine, coastal and estuarine

Table 5.1. Simplified stratigraphy of glacial deposits in northern Norfolk (modified from Lee *et al*., 2004)

Overlying the Happisburgh Till to the south of Happisburgh is the *Corton Till*. It is a brown, matrix-supported, sandy diamicton that is largely stratified in appearance, composed of beds of diamicton, clay and sand. The till pinches-out at Happisburgh where it is truncated by the *Walcott Till*, the boundary between the two deposits and intervening sands (the Corton Sands) represents a regionally-extensive and mappable angular unconformity. The *Walcott Till* consists of a massive, pale to medium grey, matrix-supported diamicton. It is distinctive due to its clayey-silt matrix texture, relative abundance of chalk clasts, and carbonate-rich matrix. The *Bacton Green Till* occurs above the Walcott Till and is highly heterogeneous in nature, reflecting deposition via subaqueous and/or subglacial processes, and post-depositional glacitectonic disturbance (Banham, 1975, 1988; Lunkka, 1994; Lee and Phillips, 2008). Facies vary from stratified sands, clays and diamicton, to largely massive beds of matrix-supported diamicton. Compositionally, beds of diamicton are strikingly similar to the Happisburgh Till being composed of a clayey-sand matrix rich in flint, chalk and quartzose clasts, but tend to exhibit a wider range of colours from grey through to brown. A fourth till, has been mapped extensively inland and can be observed sporadically in coastal sections. It occurs above the three other tills and has been called the *'Marly Drift'* (Banham, 1968; 1973; Perrin *et al*., 1979; Straw, 1979; Ehlers *et al*., 1987; Ehlers *et al*., 1991; Lunkka, 1994) or *Weybourne Town Till* (Lee *et al*., 2004; Pawley, 2007). The till is lithologically distinct due to the highly calcareous matrix and clasts content derived from the comminution and incorporation of local Cretaceous chalk bedrock. However, detailed lithological and structural analyses have shown that several different variants of the till exist (Perrin *et al*., 1979), reflecting differential subglacial incorporation of pre-existing substrate lithologies such as chalk and older till (Banham *et al*., 1975; Perrin *et al*., 1979; Fish *et al*., 2000; Pawley, 2006; Hart, 2007).

The provenance of the Happisburgh, Walcott and Bacton Green tills has also proved contentious. Previous interpretations of the provenance of the three till units led to the widely-held belief that they were deposited by Scandinavian ice impinging on northeast Norfolk (Perrin *et al*., 1979; Bowen *et al*., 1986; Ehlers and Gibbard, 1991). This interpretation is based upon occasional finds of erratics, such as rhomb-porphyry, from Oslofjord within the tills. However, detailed provenance analysis of the tills has subsequently shown that they are actually derived from northern and eastern Britain (Moorlock *et al*., 2001; Lee *et al*., 2002; Lee *et al*., 2004), with Norwegian erratics reworked from earlier incursions of Scandinavian ice into the North Sea (Hoare *et al*., 2006; Lee *et al*., 2006).

Separating each of the till units are sequences (of variable thickness) composed of sand, silt and clay that record ice-marginal and proglacial patterns of sedimentation during phases of ice retreat (Table 6.1). The sedimentology of these sorted deposits suggests that during successive phases of ice-marginal retreat, glaciolacustrine conditions prevailed. Sedimentation within these basins records the development of both proximal sedimentation with the progradation of large sand deltas, and more distal sedimentation, characterised by the deposition of rhythmic and varved lake deposits. Several beds within the lacustrine deposits form distinctive stratigraphic marker horizons, including the *'Trimingham Marl Bed'* (Hart, 1992) and the *'Mundesley Sands'* (Lee *et al*., 2004), and can readily be identified within deformed sequences such as West Runton (Phillips *et al*., 2008).

3.2 Geological Structure

Southeast of Trimingham, the glacial deposits of northeast Norfolk conform to a relatively simple layer-cake succession (Figure 5.3). To the north of Trimingham, and extending westwards around the coast to Weybourne, the glacigenic succession becomes progressively more deformed (the *'Contorted Drift'* of Reid, 1882; Banham and Ranson, 1965; Banham, 1970; Boulton *et al*., 1984). Several workers have argued that the 'Contorted Drift' is the product of waterlain mass-movement and debris flows (Zalasiewicz and Gibbard, 1988; Eyles *et al*., 1989). However, the widespread view is that the deformation structures seen within the northeast Norfolk sequences are glacitectonic in origin. Indeed, Boulton *et al*. (1984) and Phillips *et al*. (2008) argue that a large part of the glacial succession within the *'Contorted Drift'* has been completely re-worked by glacitectonic deformation and thus relates to an event(s) that post-date the original deposition of the sequence. Despite the often intense glacitectonic deformation, several studies have established that elements of the pre-existing stratigraphy are mappable through this zone (Banham, 1970; Phillips *et al*., 2008). Phillips *et al*. (2008) have taken this a step further by arguing that the rheology of the pre- existing glacial sequence controlled the styles and mechanics of later glacitectonic deformation.

Research on the structure of the ‘*Contorted Drift’* has identified two main types of deformation, proglacial and subglacial deformation (Hart *et al*., 1990), and transitions between the two (Phillips *et al*., 2008). Proglacial

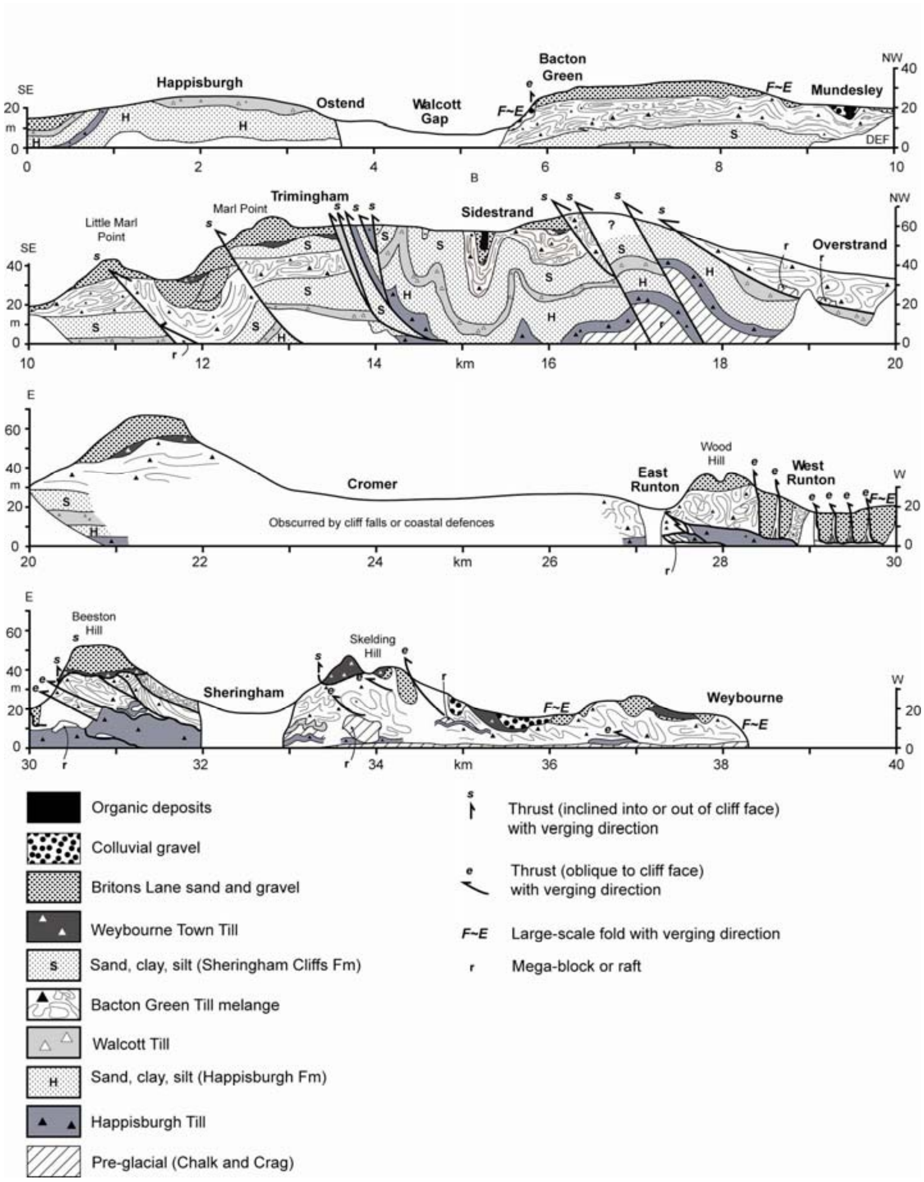

Figure 5.3. Schematic cross-section of the cliffs between Happisburgh and Weybourne

deformation is characterised by the generation of large-scale open folds, thrust-ramps, and thrust-stacked sequences bounded by listric thrust faults (including repetitive sequences). It has been recognised within coastal exposures between Mundesley and Sidestrand (Hart, 1990; Lee, 2003), inland within boreholes at Beeston Regis (Pawley *et al*., 2005), quarry exposures at Glandford (Pawley, 2008) and Weybourne (BGS, unpublished data), and in coastal sections between Sheringham and Weybourne. Together, these form part of the Cromer Ridge; a series of composite thrust ridges that form part of a regional-scale push-moraine complex. At a much smaller-scale, proglacial deformation has been recognised between East Runton and Sheringham where a series of small thrust moraines have been interpreted within the eastern part of the cliff sections (Phillips *et al*., 2008). Associated fault-bound extensional sand basins have also been recognised with their mode of generation analogous to extensional basins within foreland-fold thrust-belt terrains (Phillips *et al*., 2008). Previously, these basins were interpreted as so-called *'sag basins'* formed by the large-scale loading of a water-saturated till pile by sands and gravels (Banham, 1975; Boulton *et al*., 1984; Hart, 1987). Further westwards towards Sheringham, the style of deformation changes to become more pervasive, encompassing the whole 20-30 m thick glacigenic sediment pile (Phillips *et al*., 2008). Here the deformation includes a range of medium- to large-scale structures characteristic of deformation within a subglacial shear zone experiencing frequent changes in porewater content and pressure. Structures include overturned and disharmonic folds, crenulation cleavage, fluidised soft-sediment inter-mixing, attenuation and homogenisation of sediment inclusions, hydrofractures, thrusts and reverse faulting (Phillips *et al*., 2008). Other examples of large-scale subglacial deformation have been reported from sites such as Bacton Green (Banham, 1966; Lee and Phillips, 2008) and Weybourne (Banham and Ranson, 1965; Pawley *et al*., 2004; Hart, 2007). A similar range of structures, albeit at smaller-scale, have been recognised in association with the accretion of individual till units at other sites in northeast Norfolk (Hart, 1987; Lunkka, 1994; Lee, 2001, 2003, 2009).

Whilst recent research has identified different types and scales of glacitectonic deformation, it has become increasingly clear that the larger-scale deformation within the *'Contorted Drift'* was formed by at least two major events (Banham, 1988; Phillips *et al*., 2008). Much of the large-scale subglacial glacitectonic deformation in northeast Norfolk was produced by an easterly-directed ice advance that in-part reworked pre-existing Happisburgh, Walcott and Bacton Green tills (Banham, 1966; Lee and Phillips, 2008; Phillips *et al*., 2008). This deformation event clearly post-dates the deposition of these three tills and may be associated with the deposition of the Weybourne Town Till (Phillips *et al*., 2008) or another chalky till across the region (see Chapter 14). Superimposed upon this is a second fabric associated with a southern-directed ice advance that formed the Cromer Ridge push-moraine, and a series of thrust-stacked features between the Cromer Ridge and the coastline. Spatially, these southerly-directed thrust features form a stepped succession that has been interpreted as indicating active retreat during ice-marginal retreat.

One of the most enigmatic structural features of the northeast Norfolk coast are the large glacitectonic rafts and mega-blocks of chalk bedrock and Wroxham Crag which can observed at numerous sites between Mundesley and Sheringham (Figure 5.3). The most famous of these occur at Overstrand (Banham, 1975; Aber *et al*., 1985; Burke *et al*., 2009) and they will be visited during the course of the workshop (see Chapter 12).

3.3 Geomorphology

The geomorphology of northeast Norfolk is dominated by the Cromer Ridge which extends westwards from the coast at Trimingham towards Holt, and reaches elevations of 80 metres O.D. in the vicinity of the Beeston Regis (Figure 5.1). The ridge (Figure 5.3) is a composite landform composed of a thrust-stacked push moraine complex (Hart *et al*., 1990; Pawley *et al*., 2005), draped by a thick sequence (up to 40 m) of outwash sands and gravels (Lee, 2003; Pawley *et al*., 2005). It is broadly asymmetrical in form, possessing a steep northern ice-contact slope, and a more gently-inclined ice-distal slope which slopes southwards and has been heavily dissected and modified by modern drainage and slope processes (Straw, 1973, 1979; Boulton *et al*., 1984). By contrast, the northern flank of the ridge is a steep ice-contact slope which has a relatively fresh 'gully-spur' morphology formed by spring-sapping or seasonal permafrost melt during subsequent Pleistocene cold stages. Examination of the hinterland zone (c. 0.5-1.5 km wide) between the ice-contact slope and the coastline reveals a complex geomorphology. Between Overstrand and Weybourne, the topography is hummocky and dissected by a series of north-south trending minor valleys, many of which possess no modern surface drainage. In the vicinity of Weybourne, several of these valleys can be traced to small alluvial fans situated within gullies incised into the ice-proximal slope of the Cromer Ridge and extend northwards to the coast. Several valleys, infilled with braided sands and gravels, intersect the coastline between Weybourne and Sheringham and will be examined during the workshop. To the west of Weybourne lie the Glaven Valley, and the Kelling and Salthouse heaths (Figure 5.1). Kelling and Salthouse heaths form the remnants of a heavily-degraded outwash sandur that formed as the ice-margin retreated from the western end of the Cromer Ridge (Sparks and West, 1964; Straw, 1973; Pawley, 2006). Previously, it was considered that Kelling and Salthouse represent separate sandurs formed at progressively lower elevations as ice retreated from the Glaven Valley (Sparks and West, 1964; Straw, 1973; Boulton *et al*., 1984; Pawley, 2006). However, digital terrain models (DTMs) reveal that the maximum elevation of both sandurs is similar, suggesting that they may represent a single heavily-degraded landform. Also occurring within the Glaven Valley are an esker; the Blakeney Esker (Gray, 1997; Gale and Hoare, 2007), and reportedly, a series of kames and kame terraces (Sparks and West, 1964) although the form and genesis of the latter is tenuous and an erosional genesis by fluvial incision rather than ice-contact sedimentation has been proposed. To the east of the Glaven Valley and situated along the modern coastline between Weybourne and West Runton, are a series of small, steep-sided hills composed of till and gravel. Many workers have speculated on the origin of these hills, with several arguing that they represent the erosional remnants of a previously more extensive outwash plain (Pawley, 2006). Recent structural investigations reveal that the hills are constructional in form, representing small thrust-stacks of pre-existing till and gravel that probably formed part of a more extensive terminal moraine which has subsequently been eroded as a result of by coastal retreat.

4. A tectono-stratigraphic framework for northeast Norfolk

The relative arrangement and cross-cutting relationship of the major geological units and tectonic structures in northeast Norfolk provides a means by which a tectono-stratigraphic model for the area can be constructed (Banham, 1988). Six major tectono-stratigraphic events can be recognised (Table 5.2). Event A1 is characterised by the deposition of the Happisburgh Till by an ice advance from the north. It resulted in the deposition of a subglacial till and localised tectonisation of underlying preglacial deposits (Hart and Boulton, 1991a; Lunkka, 1994; Lee, 2001, 2009).

Following a minor retreat of the ice-margin, a readvance resulted in

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

		(subglacial and subaqueous).	soft-sediment deformation.
A3	Ice advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of Walcott Till.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, décollement surfaces.
A2	Readvance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of Corton Till.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, soft-sediment deformation.
A1	Ice advance from N	Local-scale glacitectonism associated with subglacial deforming processes (<8m); accretion of Happisburgh Till.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, décollement surfaces.

Table 5.2. A tectonostratigraphic scheme for the glacial succession of northeast Norfolk showing the primary tectonic events

A2 and the deposition of the Corton Till. The till was deposited by a mixture of subglacial and subaqueous processes as the ice-margin advanced over a series of basins, locally deforming the underlying sediment pile (Lee, 2001; Riches *et al*., 2006; Lee *et al*., 2008b). A3 is characterised by the deposition of a subglacial till, the Walcott Till, by a separate ice advance from the north. Very localised shearing of underlying sediments has been recognised (Lunkka, 1994; Lee, 2003). A further ice advance from the north resulted in the deposition of the Bacton Green Till (A4). At its southern-most extent between Bacton Green and Mundesley, the 'till' is subaqueous in origin (Lunkka, 1994; Lee and Phillips, 2008), but further to the north it was deposited subglacially (Hart and Boulton, 1991a; Lunkka, 1994). To the north of Mundesley, localised deformation of underlying strata due to shearing can be recognised. A5 is characterised by a more pervasive scale of shear-induced deformation that has in places encompassed the entire glacigenic sediment pile. The Bacton Green mélange was generated during an ice advance from the west and is probably associated with the same ice advance that deposited the westerly-derived facies of the Weybourne Town Till across parts of north Norfolk (Lee and Phillips, 2008; Phillips *et al*., 2008). The depth of the deforming layer, which in places was 40 m thick, is highly unusual and represents a marked up-scaling in deformation that contrasts strongly with the more localised and thinner deforming-bed profiles developed beneath the other tills. Lee and Phillips (2008) argued that the complex style of brittle and ductile deformation was compartmentalised, driven by temporal and spatial fluctuation in porewater content and pressure within the deforming bed. Hart (2007) and Phillips *et al*. (2008) have also highlighted the importance of the different rheological components within this mélange in controlling the styles of deformation observed. The final A6 event is associated with an ice-advance from the north. This resulted in the formation of the large Cromer Ridge push-moraine complex by proglacial thrusting and the duplex-stacking of blocks of pre-existing glacigenic sediment (Boulton *et al*., 1984; Hart, 1990; Pawley *et al*., 2005).

5. Age of glacial deposits and glacitectonic events

Precise correlation of the glacial deposits and glacitectonic events of northeast Norfolk with the marine isotope chronology has proved problematic and controversial (see Rose (2009) for an overview). This is due to the absence of interglacial deposits within the glacial sequence, the limited availability of suitable materials for radiometric dating, and the possibility that the true age of the deposits lies either at or beyond the limit of most conventional geochronological techniques. Traditionally, all of the glacial deposits in northeast Norfolk lying to the south of the Last Glacial Maximum ice limit have been assigned a MIS 12 age (Bowen *et al*., 1986; Bowen, 1999) due to constraint by *'Cromerian Complex'* (West, 1980; Preece and Parfitt, 2000; Preece, 2001) and Hoxnian/Holsteinian interglacial deposits (Hart and Peglar, 1990). Subsequent work suggested that the glacial succession may be the product of multiple glaciations between MIS 16-6 (Hamblin *et al*., 2000; Hamblin *et al*., 2005; Rose, 2009) although this has been disputed by others (Banham *et al*., 2001; Pawley *et al*., 2008; Preece *et al*., 2009). Taken at face value, the MIS 12 OSL age of the

Cromer Ridge gravels (Britons Lane Formation) coupled with the occurrence of MIS 11 organic deposits infilling an apparent kettle hollow (Hart and Peglar, 1990; Preece *et al*., 2009) within the Britons Lane Formation do appear to support a minimum age of MIS 12.

6. Conclusions

- Glacigenic sequences of northeast Norfolk possess some of the most spectacular and famous glacitectonic structures in Britain that have attracted the attention of geologists for well over a century. Over the years, a number of major studies have been undertaken and each has played a major role in not only enhancing our understanding of glacitectonic processes, but the wider linkage between subglacial processes and ice mass behaviour.
- At least six major Middle Pleistocene glacitectonic events (A1-6) can be reconciled based upon styles of deformation, cross-cutting geometries, together with sedimentary and landform evidence. The absolute timing of these events is still a matter of conjecture.