

The Middle Pleistocene glacial evolution of northern East Anglia, UK: a dynamic tectonostratigraphic–parasequence approach



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ABSTRACT: The Middle Pleistocene glacial history of northern East Anglia is a controversial topic with differing opinions surrounding chronology, provenance and the relative stratigraphic framework. Reconciling the stratigraphic framework of the region is an essential first step to developing onshore–offshore geological models and a robust event-driven chronological framework. Within this study a dynamic tectonostratigraphic–parasequence methodology is applied to deposits traditionally attributed to the Anglian Glaciation (Marine Isotope Stage 12). This approach offers an insight into ice-bed coupling during glaciation and how evolving boundary conditions influenced glacier dynamics. Six major tectonostratigraphic–parasequence assemblages (A1–A6) are recognized in northern East Anglia and correlate with successive advances into the region of North Sea or Pennine lobes of the British Ice Sheet. Individual tectonostratigraphic–parasequence assemblages are bound at their base by a sedimentary contact or, more commonly, a glacitectonic zone. The geometry and structural characteristics of these glacitectonic zones reflect temporal and spatial variations in ice-bed coupling (traction), a function of substrate rheology and, in turn, variations in lithology, porewater availability and thermo-mechanical properties. The role of permafrost may also be significant, promoting proglacial/ice-marginal thrust stacking in front of advancing ice and enhanced ice-bed decoupling during subsequent overriding and subglacial till accretion. © 2016 British Geological Survey, NERC Journal of Quaternary Science © 2016 John Wiley & Sons Ltd

KEYWORDS: East Anglia; glacitectonic; Middle Pleistocene; North Sea; stratigraphy.

Introduction

East Anglia borders the south-western margins of the North Sea Basin and possesses one of the best archives of Middle and Late Pleistocene environmental change in northern Europe (Ehlers and Gibbard, 1991; Rose, 2009; Candy *et al.*, 2011; Ashton and Lewis, 2012; Lee *et al.*, 2012; Preece and Parfitt, 2012; Bateman *et al.*, 2014). The region was glaciated during the Anglian [Marine Isotope Stage (MIS) 12] and Late Devensian (MIS 2) glaciations (Fig. 1a) with considerable research focused upon the Middle Pleistocene succession. Specific issues include: (i) the development of a coherent stratigraphic framework (Banham, 1968, 1988a; Hart and Boulton, 1991a; Lunkka, 1994; Lee *et al.*, 2004a; Pawley, 2006); (ii) reconciling age-related issues and the number of separate glaciations (Hamblin *et al.*, 2005; Pawley *et al.*, 2008; Preece *et al.*, 2009; Gibbard *et al.*, 2012); (iii) correlation with sequences elsewhere in Britain (Perrin *et al.*, 1979; Bowen *et al.*, 1986; Lewis, 1999; Rose, 2009; Lee *et al.*, 2011), the wider North Sea region and continental Europe (Ehlers and Gibbard, 1991; Lee *et al.*, 2012); and (iv) testing new and evolving concepts in glacial geology including glacitectonics and subglacial deforming bed processes (Banham, 1977a; Eyles *et al.*, 1989; Hart and Boulton, 1991b; Hart and Roberts, 1994; Lee and Phillips, 2008; Phillips *et al.*, 2008; Burke *et al.*, 2009; Waller *et al.*, 2011).

Despite a large body of published research, a consensus view on the number and chronology of Middle Pleistocene glaciations to affect northern East Anglia has proven elusive. This has significant implications for the timing and nature of environmental change (Rose, 2009), early human occupation (Preece and Parfitt, 2012) and glaciation (Böse *et al.*, 2012)

around the North Sea region during the Middle Pleistocene. Establishing a robust *relative* stratigraphic framework for the glacial sequence is an essential first step to resolving these issues although to date this has proven challenging because of the over-reliance on lithostratigraphic techniques (Rose and Menzies, 1996; Räsänen *et al.*, 2009; Hughes, 2010; Böse *et al.*, 2012). This study adopts a process-driven tectonostratigraphic–parasequence methodology to reconstruct a robust relative stratigraphic model for the glacial succession of the region. The approach employs regionally extensive *glacigenic boundaries* (both sedimentary and glacitectonic) as the ‘bounding surfaces’ that delineate distinctive event-related sediment/landform/glacitectonic assemblages. The geometry of these glacigenic boundaries, when used with other techniques (sedimentology, geomorphology and lithological analyses, etc.), provides additional insight into the wide range of erosional, depositional and glacitectonic (deformational) processes and boundary conditions that may have operated within a glacial environment. In this paper we: (i) outline the conceptual basis for a hybrid tectonostratigraphic–parasequence approach; (ii) review previous stratigraphic approaches in northern East Anglia and their associated problems; (iii) apply the proposed new approach to the stratigraphy of the region; and (iv) discuss its wider implications relative to glacitectonic/substrate evolution, palaeogeographical change and the applicability of lithological correlation of glacigenic units within stratigraphic studies.

Stratigraphic Approaches in Glaciated Terrains

A range of different *relative* stratigraphic techniques have been applied within lowland glacigenic terrains including lithostratigraphy, morphostratigraphy, allostratigraphy,

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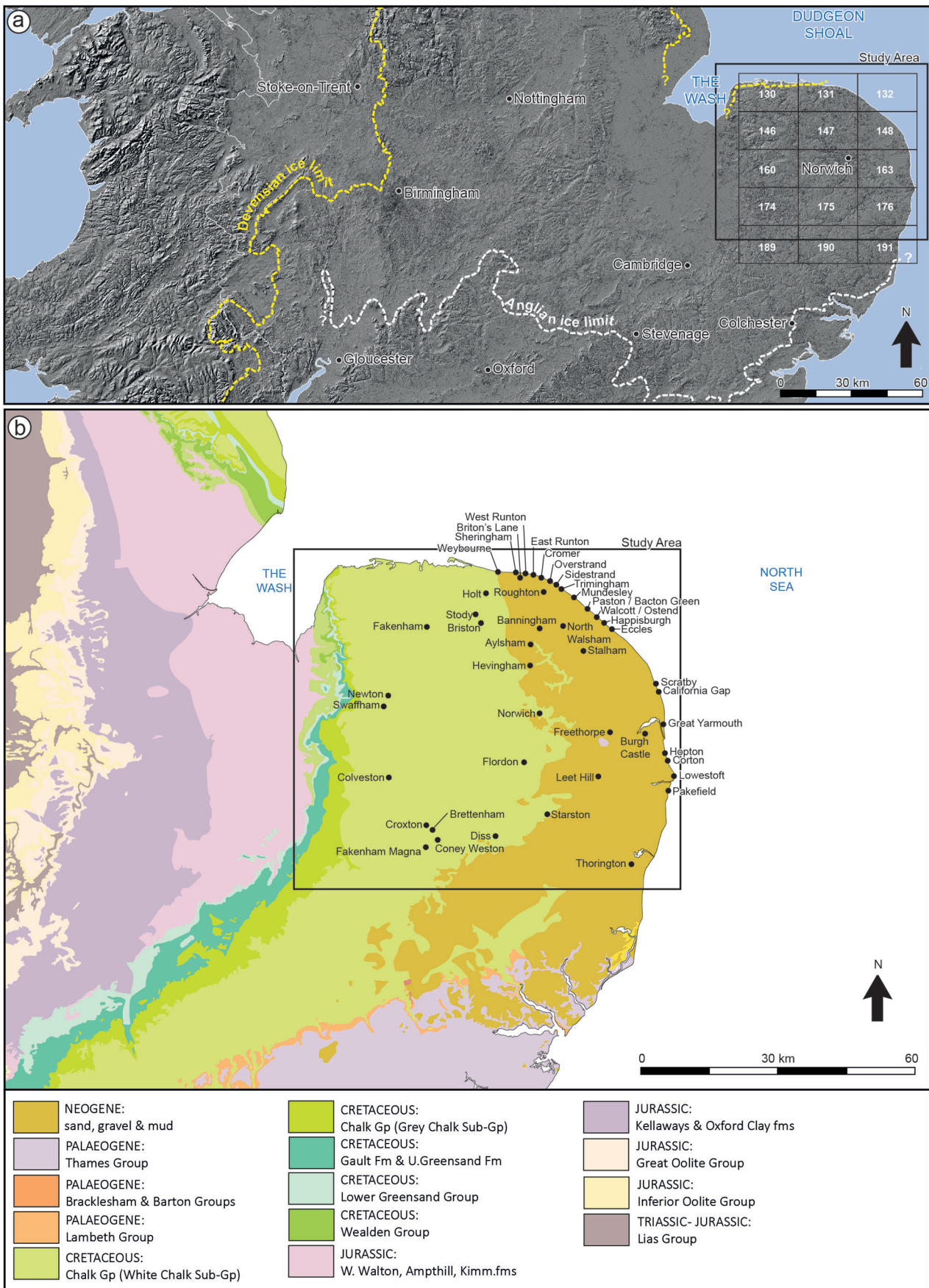


Figure 1. (a) Map of central and eastern Britain showing the study area relative to the Anglian and Late Devensian ice margins. Also shown on the map is the coverage for published 1: 50 000 geological maps: 130–Wells-next-the-Sea; 131–Cromer; 132/148–Mundesley/North Walsham; 146–Fakenham; 147–Aylsham; 160–Swaffham; 161–Norwich; 163–Great Yarmouth; 174–Thetford; 175–Diss; 176–Lowestoft; 189–Bury St Edmunds; 190 – Eye; 191–Saxmundham. (b) 1: 625 000 scale bedrock geological map of East Anglia and the East Midlands showing localities referred to in the text.

kinostratigraphy and glaciodynamic sequence stratigraphy. Lithostratigraphy has been widely deployed on glacial sequences, including those in East Anglia, that are either buried or possess a subtle or poorly preserved landform record. Lithostratigraphy is defined as the subdivision and correlation of sediments based upon their lithological properties (Salvador, 1994) with units conforming broadly to the Law of Superposition (Rawson *et al.*, 2002). Application of basic lithostratigraphic principals to glaciated terrains, however, is fraught with difficulties (Rose and Menzies, 1996; Räsänen *et al.*, 2009; Hughes, 2010; Böse *et al.*, 2012). Difficulties arise because glacial sequences are produced by a variable combination of both sedimentary and glaciectonic processes that act to control facies characteristics, geometry and relative superposition (Banham, 1977a; Berthelsen, 1978; Rose and Menzies, 1996; Benn and Evans, 2010). Collectively, these issues significantly restrict lithostratigraphic subdivision and long-range correlation providing a level of generalization that often masks the true genetic complexity of glacial sequences (Rose and Menzies, 1996).

To overcome these problems, this study employs a hybrid tectonostratigraphic–parasequence approach that places depositional stratigraphic elements within a glaciectonic–parasequence framework building upon similar approaches used elsewhere (Berthelsen, 1978; Thomas, 1984; Thomas and Summers, 1984; Thomas and Chiverrell, 2007; Phillips *et al.*, 2008; Pedersen, 2012). The approach adopts many core principals employed by structural geologists for reconstructing the evolution of polydeformed bedrock terrains (e.g. orogenic belts) (Mittra, 1988; Key *et al.*, 1997). It serves to highlight the importance that bounding surfaces play in stratigraphy by highlighting the significance of hiatuses, as well as demonstrating associations between erosional,

depositional and glaciectonic processes that operate in glacial environments. This approach has widespread applicability to other formerly glaciated lowland areas including onshore–offshore stratigraphic correlations and 3D geological modelling.

Glacigenic boundaries are identified as the regional-scale *bounding surfaces* (or zones) that delineate glacigenic events forming distinctive landform–sediment–tectonic assemblages (Fig. 2) (Banham, 1988a; Pedersen, 2012). Major bounding surfaces include: (i) subglacial shear zones and major glaciectonic décollements; (ii) major graded or intercalated (sedimentary) basal contacts of diamictos; and (iii) net influx of glacially sourced materials. They correspond to either major phases of ice advance (A1, A2, ... An) with smaller-scale structural features produced during ice-marginal retreat (A1-R1, A1-R2, ... A1-Rn). Site-specific structural nomenclature is denoted according to standard structural nomenclature depicting the relative ordering of deformation features (D1, D2, ... Dn, etc.).

A regional-scale stratigraphic package constrained by lower and upper major glacigenic boundaries is assigned *Formation* status as the major tectonostratigraphic unit. Intervening packages of sediment are termed a *glaciodynamic parasequence* and include diamicton units and broadly conformable sedimentary successions of genetically related deposits (cf. Thomas, 1984; Thomas and Summers, 1984; Thomas and Chiverrell, 2007; Pedersen, 2012). Individual lithofacies within the *glaciodynamic parasequence* are assigned *member* status. Purely for the purpose of communication, informal lithofacies descriptors are also included within stratigraphic nomenclature following standard Geological Society recommendations (Rawson *et al.*, 2002) and provide the user with a basic indication of ‘type-lithology’. A summary table showing

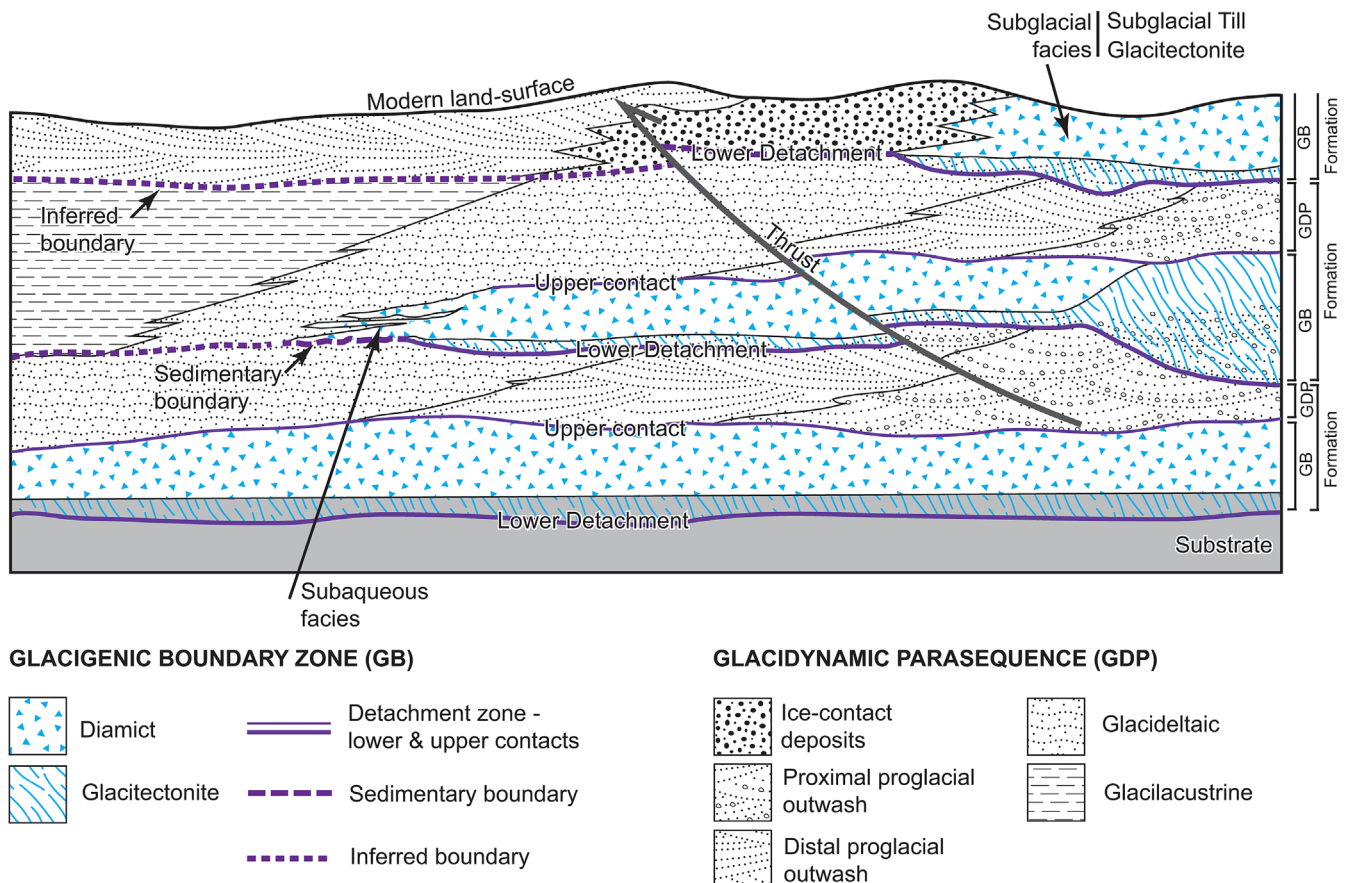


Figure 2. A conceptual tectonostratigraphic-parasequence model showing the development of glacigenic boundaries (tectonic and sedimentary) and glaciodynamic parasequences.

the stratigraphic nomenclature and lithofacies descriptions (including lateral variability) is presented later.

East Anglia: geology and glacial legacy

Preglacial bedrock and Quaternary geology

The bedrock geology of East Anglia and adjoining areas comprises broadly N–S- or NE–SW-striking Mesozoic and Cenozoic strata that dip gently eastwards (Fig. 1b). In the west, the Late Triassic to Mid Jurassic Lias Group (mudstone, limestone) is overlain by limestone, sandstone and siltstone units belonging to the Great and Inferior Oolite groups (Mid Jurassic). These pass upwards beneath the Fen Basin into fossiliferous Mid to Late Jurassic mudstones forming the Kellaways, Oxford Clay, West Walton, Ampthill Clay and Kimmeridge Clay formations. Lower Cretaceous rocks form a prominent escarpment that fringe the eastern Fen Basin and include rocks from the Wealden Group (sandstone and mudstone), Lower Greensand Group (sandstone), Gault Formation (mudstone) and Upper Greensand Formation (sandstone). The crest and dip slope of this escarpment are formed of Chalk Group (limestone) rocks that dip eastwards (<1°) beneath the eastern half of the region. In the south-east, chalk is overstepped by Palaeogene rocks including the Lambeth (clay, gravel, sand) and Thames (mudstone, gravel, sand) groups. To the east of Weybourne, bedrock units are unconformably overlain by Late Pliocene to early Middle Pleistocene deposits, comprising sands and gravels, muds and peats of the Crag (shallow marine and coastal) and Dunwich groups (fluvial) (McMillan and Merritt, 2012).

Glacial deposits in northern East Anglia

Middle Pleistocene glacial deposits in northern East Anglia are widely attributed (although not exclusively) to the Anglian Glaciation (480–430 ka; MIS 12), the largest known Quaternary expansion of the British–Irish Ice Sheet (Bowen *et al.*, 1986; Clark *et al.*, 2004). Conventionally, the Anglian has been correlated with the Elsterian Glaciation of mainland

Europe (Ehlers *et al.*, 1984; Laban and van der Meer, 2011), although recent research suggests that some glacial deposits attributed to the Elsterian may relate to younger glaciations (Litt *et al.*, 2008; Lee *et al.*, 2012; Roskosch *et al.*, 2015).

Historically, Anglian-age deposits are believed to have been deposited contemporaneously by British and Scandinavian ice sheets (Perrin *et al.*, 1979; Bowen *et al.*, 1986; Ehlers and Gibbard, 1991; Lunkka, 1994; Gibbard and van der Vegt, 2012). However, the presence of Scandinavian ice in the region has been questioned (Moorlock *et al.*, 2001), with a British ice source proposed (Lee *et al.*, 2002, 2004a) and rare Scandinavian erratics within glacial deposits attributed to reworking from older deposits in the North Sea Basin (Hoare and Connell, 2005; Lee *et al.*, 2005; Larkin *et al.*, 2011; Hoare, 2012). The number of Middle Pleistocene glaciations in East Anglia has also proven controversial. Suggestions of additional pre-Anglian (Lee *et al.*, 2004b) and post-Anglian glaciations during various single (Baden-Powell, 1948; Straw, 1967, 1979, 1983, 2011; Lewis and Rose, 1991; Gibbard *et al.*, 1992, 2012; Boreham *et al.*, 2010; Langford, 2012; Westaway *et al.*, 2015) or multiple glaciation models (Hamblin *et al.*, 2005; Rose, 2009) have been strongly debated. Further discussion of these chronological debates is beyond the scope of this paper and readers are directed to other papers that provide a commentary (Preece *et al.*, 2009; Rose, 2009; Lee *et al.*, 2012).

In northern East Anglia, the *relative* stratigraphic framework is underpinned by the work of Reid (1882). The pioneering work of Reid and subsequent studies rely largely upon the lithostratigraphic correlation of major till units (Table 1) with progressive refinements in nomenclature and stratigraphic subdivision of sorted units as improved data became available (Solomon, 1932; Banham, 1968, 1971; Ehlers and Gibbard, 1991; Hart and Boulton, 1991a; Lunkka, 1994). Collectively, these schemes define three distinct assemblages (Fig. 3a): (i) a lower 'North Sea Drift' assemblage comprising sandy diamictos ('Cromer Till'), the 'Norwich Brickearth' and ice-marginal sediments laid down in association with a North Sea ice lobe (Solomon, 1932; Banham, 1968; Lunkka,

Table 1. Current (upper case) and previous (lower case) nomenclature for major diamicton units in northern East Anglia.

LOWESTOFT DIAMICTON MEMBER*

Boulder Clay², Lowestoft Boulder Clay³, Lowestoft Till^{5,6,7,10}, Lowestoft Till Member^{12,13}

WEYBOURNE DIAMICTON MEMBER*

Marly Drift^{1,4,8,11}, Weybourne Town Member¹², Weybourne Town Till Member¹³

WEST RUNTON MELANGE MEMBER*

Contorted Drift^{1,3}, Cromer Diamicton¹¹, Cromer Member¹², Bacton Green Melange¹⁴

BACTON GREEN DIAMICTON MEMBER*

Stony Loam¹, Third Cromer Till^{3,8}, Norwich Brickearth⁶, Walcott Diamicton^{9,11}, Mundesley–Trimingham Member¹², Bacton Green Till Member¹³

WALCOTT DIAMICTON MEMBER*

Second Till¹, Second Cromer Till^{4,8}, Walcott Diamicton¹¹, Walcott Member¹², Walcott Till Member¹³

STARSTON DIAMICTON MEMBER*

Lower Boulder Clay¹⁵, Starston Till^{12,16,17}

CORTON DIAMICTON MEMBER*

Loam with Boulders², Cromer Till^{3,5}, Norwich Brickearth^{6,7}, Eccles Diamicton⁹, Corton Till¹⁰, Corton Member¹², Corton Till Member¹³

HAPPISBURGH DIAMICTON MEMBER*

First Till¹, First Cromer Till^{4,8}, Happisburgh Diamicton^{9,11}, Happisburgh Member¹², Happisburgh Till Member¹³

Sources: ¹Reid (1882), ²Blake (1890), ³Baden-Powell (1950), ⁴Banham (1968), ⁵Banham (1971), ⁶Cox and Nickless (1972), ⁷Hopson & Bridge (1987), ⁸Ehlers *et al.* (1991), ⁹Hart and Boulton (1991a), ¹⁰Arthurton *et al.* (1994), ¹¹Lunkka (1994), ¹²Lewis (1999), ¹³Lee *et al.* (2004a), ¹⁴Lee and Phillips (2008), ¹⁵(1987), ¹⁶Lawson (1982), ¹⁷Mathers *et al.* (1993) and *this study.

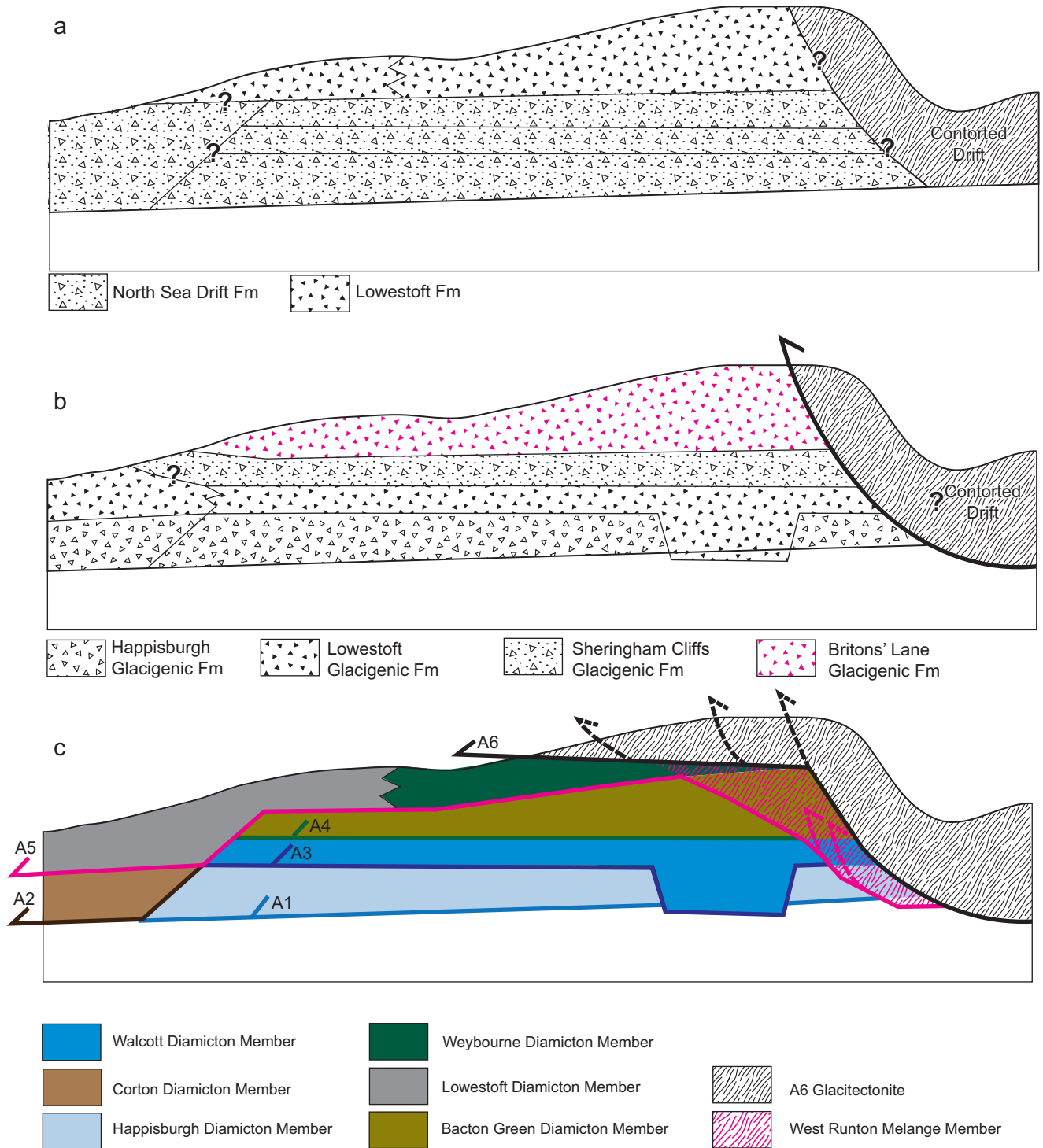


Figure 3. Historical stratigraphic models for northern East Anglia. (a) Conventional lithostratigraphy (e.g. Reid, 1882; Banham, 1968; Lunkka, 1994; Lewis, 1999). (b) Revised lithostratigraphy (Lee *et al.*, 2004a; Hamblin *et al.*, 2005). (c) Hybrid approach (this study). NB: for ease of communication, formations are not shown in this model (Fig. 4).

1988, 1994); (ii) a stratigraphically higher assemblage of chalky diamictons ('Marly Drift') and outwash sediments deposited by ice derived from the north and/or west (Banham and Ranson, 1965; Straw, 1973; Perrin *et al.*, 1979; Ehlers *et al.*, 1987, 1991; Lunkka, 1994) correlating with a chalky Jurassic-rich diamicton ('Lowestoft Till') across southern parts of the region (Baden-Powell, 1948; Banham, 1971; Rose and Allen, 1977; Perrin *et al.*, 1979; Hopson and Bridge, 1987; Allen *et al.*, 1991); and (iii) an intensely glacitectonized zone called the 'Contorted Drift' that occurs in north Norfolk (Reid, 1882; Dhonau and Dhonau, 1963; Banham and Ranson, 1965; Boulton *et al.*, 1984; Hart, 1987). While this scheme

has been widely accepted, several major stratigraphic problems have persisted. Specifically, many stratigraphic units could not be consistently mapped inland away from coastal stratotypes (Rose, 1989). This has proven particularly problematic in north-east Norfolk, where the stratigraphic relationship between the 'Norwich Brickearth', 'Marly Drift' and 'Contorted Drift' remained unclear, manifesting itself in spiral stratigraphies and implausible (i.e. vertical) geological boundaries (Geological Survey, 1882, 1883; British Geological Survey, 1975).

In an effort to resolve these issues, a major regional-scale programme was initiated in northern East Anglia,

underpinned by geological mapping, borehole drilling, lithological analyses and site investigation (Arthurton *et al.*, 1994; Moorlock *et al.*, 2000a, 2002a,b; Lee, 2003; Pawley, 2006). This approach identified firstly that the ‘Norwich Brickearth’ was a soil facies (Rose *et al.*, 1999a) and was diachronous with separate diamicton units both underling and overlying a chalky diamicton (Lee *et al.*, 2004a; Hamblin *et al.*, 2005). Secondly, tills previously attributed to a Scandinavian source were actually derived from northern Britain (Lee *et al.*, 2002). Thirdly, the middle ‘Cromer Till’ (Walcott Till) in north-east Norfolk was laid down coevally with the Lowestoft Till across southern and central East Anglia. The resulting lithostratigraphic scheme (Fig. 3b) eliminated several of the previous stratigraphic problems but the geometric relationship of several diamicton units and the ‘Contorted Drift’ remained resolved.

Application of a hybrid tectonostratigraphic–parasequence approach

This study provides a conceptual review-style application of the approach to the Middle Pleistocene glacial sequence of northern East Anglia. The stratigraphic scheme presented (Figs

3c and 4; Table 2) is underpinned by published 1: 50 000 geological maps of the region (Fig. 1a) and a range of related literature that describe the major lithofacies and readers are directed to those for further detail (Mathers *et al.*, 1993; Arthurton *et al.*, 1994; Moorlock *et al.*, 2000a, 2002a,b, 2008; Lee, 2003; Lee *et al.*, 2004a; Pawley, 2006).

A1 Tectonostratigraphic–parasequence Unit

Description and interpretation

The A1 Boundary represents the base of the glacitectonic succession, forming a regionally extensive zone, up to 7 m thick, separating the Happisburgh Formation from the underlying preglacial succession (Fig. 4). It comprises a lower glacitectonite derived from deformed preglacial sediments overlain by a largely homogenous subglacial traction till called the Happisburgh Diamicton Member.

Commonly, at sites including Trimingham (Fig. 5a) (Lee, 2001) and Ostend (Fig. 5b), the glacitectonite forms a <1-m-thick zone of deformed preglacial sand, silt and clay, bound by lower and upper décollement surfaces. Structures within the glacitectonite include disharmonic folding, convolute bedding and flame structures indicative of water-rich

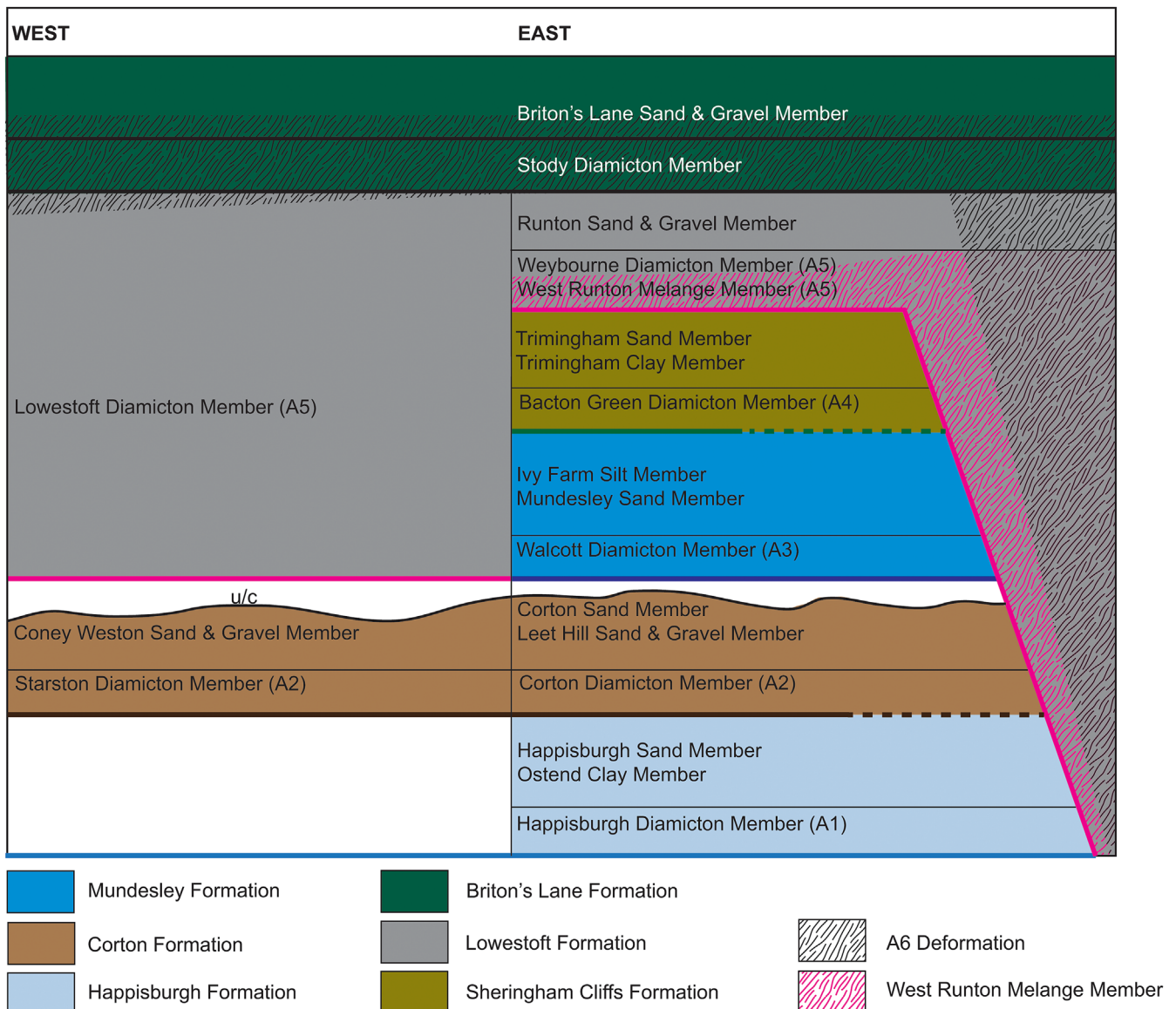


Figure 4. Simplified formation-level stratigraphic succession for northern East Anglia showing bounding A1–A6 Detachments and major geological units.

Table 2. A summary table showing the lithofacies descriptions and primary stratotype localities of the stratigraphic units outlined within the text. Descriptions are intended to provide an indication of the dominant lithofacies properties and highlight variability where appropriate. For further details including descriptions of minor stratigraphic units please refer to Lee *et al.* (2004a).

Stratigraphy	Stratotype	Lithofacies Description
BRITON'S LANE FORMATION	A6	
Briton's Lane Sand & Gravel Member	TG 168415, Briton's Lane Quarry, Beeston Regis	Coarse, horizontal and massive bedded flint-rich cobble gravels and sands ; erosional base; frequently deformed by syn-depositional thrusts; maximum observed thickness 40 m.
Stody Diamicton Member	TG 056345, Stody Pit, Hunworth	Highly consolidated, matrix- to clast-supported chalky diamicton of northern provenance, massive to stratified; sharp and planar base; maximum observed thickness of 5 m.
LOWESTOFT FORMATION	A5	
Lowestoft Diamicton Member	TM 546987, Corton Cliffs	Variable , white to dark grey, clay-rich, massive to faintly stratified, matrix-supported diamicton ; rich in opaque heavy minerals, chalk clasts and matrix calcium carbonate content; sharp erosive or planar lower contact; maximum observed thickness is 13 m but may be higher locally especially within buried valleys.
Runton Sand & Gravel Member	TG 180432, West Runton Cliffs	Stratified sands and gravels that occupy syn-tectonic basins formed within the West Runton Melange Member; sharp, commonly down-faulted marginal contacts; maximum observed thickness of 12 m.
Weybourne Diamicton Member	TG 122436, Weybourne Cliffs, Weybourne	Highly consolidated, matrix-supported chalky diamicton of western provenance, massive to stratified; sharp and planar base; maximum observed thickness of 6 m; lithological properties of the diamicton vary locally reflecting the incorporation of different admixtures of chalk and pre-existing Quaternary deposits.
West Runton Melange Member	TG 181433, West Runton Cliffs	Highly deformed glacetectonic melange comprising deformed Happisburgh, Walcott and Bacton Green Diamicton members, preglacial sediment, marl and occasional Chalk rafts; maximum observed thickness 25 m.
SHERINGHAM CLIFFS FORMATION	A4	
Trimingham Sand Member	TG 266397, Trimingham Cliffs	Stratified fine and medium sands ; erosional base; maximum observed thickness 0.8 m.
Trimingham Clay Member	TG 266397, Trimingham Cliffs	Massive clays and occasionally rhythmites of clay and silt; gradational lower contact with Bacton Green Diamicton Member; maximum observed thickness of 2 m.
Bacton Green Diamicton Member	TG 334347, Bacton Green Cliffs	Stratified diamicton complex composed of beds of diamicton and sorted sediments overlying a gradational base; the diamicton becomes largely massive and over-consolidated to the north of Marl Point, Mundesley; gradational lower contact; maximum observed thickness of 11 m.
MUNDESLEY FORMATION	A3	
Ivy Farm Silt Member	TG 268397, Sidestrand Cliffs	Massive beds of silt , rhythmically bedded silts and clays, occasional beds of marl and sand; gradational base with Mundesley Sand Member; maximum observed thickness of 22 m.
Mundesley Sand Member	TG325356, Mundesley Cliffs	Stratified sands , commonly chalky with an elevated opaque heavy mineral content (56.0–65.0%); occasional localized beds of laminated silt and clay; sharp but conformable base; maximum observed thickness of 12 m, thinning northwards and passing vertically and laterally into the Ivy Farm Silt Member.
Walcott Diamicton Member	TG 391304, Ostend Cliffs	Grey, massive to faintly stratified, matrix-supported diamicton with a silt-rich matrix texture; rich in black flint and chalk clasts (ca. 43–60%) and matrix calcium carbonate content (ca. 36%); laterally persistent properties; sharp planar base; maximum observed thickness 1.6 m.
CORTON FORMATION	A2	
Corton Sand Member	TM 543979, Corton Cliffs	Dominantly stratified fine- to medium- sands with localized thin beds of laminated silt and clay; comminuted chalk and shell grains are common; intraformational ice wedge casts, involutions and calcretes have also been recognized; forms 3 mappable cycles – each 8–10 m thick; erosive contact with Corton Diamicton Member and gradational contact with Leet Hill Sand and Gravel Member.
Coney Weston Sand & Gravel Member	TL 951798, quarry at Coney Weston	Stratified sands and gravels , grading upwards into more poorly sorted sands and gravels with silt and clay; erosional lower contact with bedrock or Starston Diamicton Member
Leet Hill Sand & Gravel Member	TM384926, Leet Hill Quarry, Kirby Cane	Channelled and stratified sands and gravels that are rich in flint; common erratic lithologies of British provenance; gradational lower contact with Bytham River deposits, erosional contact with Corton Diamicton Member; thickens westwards up to 9 m in vicinity of stratotype.
Starston Diamicton Member	TM 243844, pit at Starston	Brown, matrix-supported, over-consolidated diamicton , with locally high chalky matrix and clast content (when not decalcified); sharp erosional base; maximum observed thickness 7 m.
Corton Diamicton Member	TM 543979, Corton Cliffs	Brown and flint-rich matrix-supported diamicton with a sandy matrix , either

continued

Table 2. (Continued)

Stratigraphy	Stratotype	Lithofacies Description
HAPPISBURGH FORMATION	A1	massive or faintly stratified; sharp erosional base; properties are commonly laterally persistent but locally intercalated beds of clayey sand, sand and diamicton do occur; maximum observed thickness 8 m.
Happisburgh Sand Member	TG 388306, Happisburgh Cliffs	Stratified sands with channel structures within the upper horizons; erosional contact with Ostend Clay Member; maximum observed thickness 8 m.
Ostend Clay Member	TG 388306, Happisburgh Cliffs	Dominant clay ; grades upwards from stratified diamicton and clays occupying troughs on the upper surface of the Happisburgh Diamicton Member, into rhythmically bedded silts and clays with occasional sand ripples; maximum observed thickness 3.5 m.
Happisburgh Diamicton Member	TG 389305, Happisburgh Cliffs	Grey, over-consolidated, typically massive matrix-supported diamicton with a clayey–sandy matrix texture and common flint and quartzose pebbles; laterally persistent bulk lithological properties but with localized stratification and tectonic layering; sharp basal contact; maximum observed thickness 6.5 m.

soft-sediment deformation; fold attenuation and detachment including the development of tectonic laminations and boundingage via the deformation of pre-existing sediment inclusions; late-stage brittle deformation and thrusting along the A–B contact coincident with the initial accretion of the diamicton (Fig. 6a,b).

The Happisburgh Diamicton Member typically comprises a massive, matrix-supported diamicton (Table 2). Locally, such as at West Runton, the base of the diamicton is variably stratified with alternating diamictic–sorted bands including apparent ‘dropstone-type’ structures. Hart and Roberts (1994) and Roberts and Hart (2005) concluded that the diamicton was originally deposited subaquatically but subsequently overridden by ice forming a continuum from glacialacustrine sediments to glacitectorite to subglacial till. While certainly feasible, an alternative interpretation is that these ‘dropstone-type’ structures represent porphyroclast rotational systems formed by shearing of pre-existing sediment inclusions around more rigid clasts or cores (cf. Menzies, 2000). The consolidation, massive structure and inclusion of local and far-travelled materials indicate that the diamicton is a subglacial traction till. Small-scale thrusts that truncate its base suggest that deformation within the underlying glacitectorite was contemporaneous with subglacial till accretion.

The development of thicker and more complex styles of deformation are indicated by the local penetration of glaci-tectonic structures deeper into the preglacial sediment pile. At Sidestrang, deformation is partitioned into several discrete and cross-cutting structural zones that penetrate over 3 m into the substrate (Fig. 7) (Lee, 2009). Three sequential styles of deformation have been recognized: (1) sandy sub-horizontal strata and bedding contacts displaying dominantly soft-sediment deformation (e.g. flame structures, disharmonic folding, convolute bedding, wispy bedding) and localized shearing (D1); (2) brittle deformation (D2–D4) resulting in the development of more steeply inclined reverse faults with displacement (tens of cm) and occasional hanging-wall preservation of highly fluidized soft-sediment rafts; (3) truncation of 1 and 2 by a thin melange (D5–D6) and the A–B contact by small low-angle (>18°) thrusts (D7) (Fig. 6c). The superimposition of these deformation styles indicates earlier phases of dewatering (D1) and brittle thrusting (D2–D4), followed by melange development associated with a thin shear zone (T5–T6) and, finally, late-stage localized thrusting (D7) coeval with subglacial till accretion. This implies glaci-tectonic deformation (dewatering and thrusting) before the site was overridden by ice and subglacial shearing.

The *glacodynamic parasequence* records a phase of glacialacustrine sedimentation following retreat of the ice margin northwards. Deposition commenced with the deposition of the Ostend Clay Member, which forms a succession of on-lapping beds (Table 2) that thicken northwards from Happisburgh to Ostend, progressively infilling and draping the upper surface of the Happisburgh Diamicton Member. Their sedimentology records the infilling of several small basins developed on the irregular upper surface of the Happisburgh Diamicton Member and their progressive growth and coalescence into shallow lake basins (Lunkka, 1988; Hart, 1999; Lee *et al.*, 2008). Further to the north-west between Trimmingham and West Runton, the upper surface of the diamicton grades upwards into a series of glacialacustrine sediment gravity flows (Hart, 1992; Roberts and Hart, 2000; Lee, 2003) or the A5 glaci-tectonic melange (Phillips *et al.*, 2008). South of Happisburgh, the Ostend Clay Member is overlain by the Happisburgh Sand Member (Table 2), which records the growth of a small glacialacustrine delta under varying flow regimes and sediment supply (Hart, 1999; Lee *et al.*, 2008). Palaeocurrent measurements indicate a predominant sediment input from the north-east (Lee *et al.*, 2004a) with localized input from the south-east (Lunkka, 1994).

Summary

The A1 Tectonostratigraphic Assemblage (Happisburgh Formation) occurs at the base of the structural sequence. Its basal boundary is defined by a thin metre-scale glaci-tectorite and overlying diamicton interpreted as a subglacial traction till. The geometric relationship between the two units demonstrates different structural mechanisms: (i) dewatering of the pre-existing sediment pile and thrusting before higher-level melange development and till accretion; and (ii) contemporaneous melange development and till accretion. Overlying this basal structural zone is a sedimentary parasequence comprising on-lapping glacialacustrine sediments and a thick sequence of deltaic sands.

A2 Tectonostratigraphic–parasequence Unit

Description and interpretation

The A2 Boundary oversteps successive underlying units and includes diamicton facies of the Corton Formation (Fig. 4). The base of the tectonostratigraphic unit outcrops discontinuously between 2 and 5 m OD in coastal sections between Happisburgh and Corton, rising westwards towards Aylsham and Norwich (up to 20 m OD), Diss (ca. 15–30 m OD) and

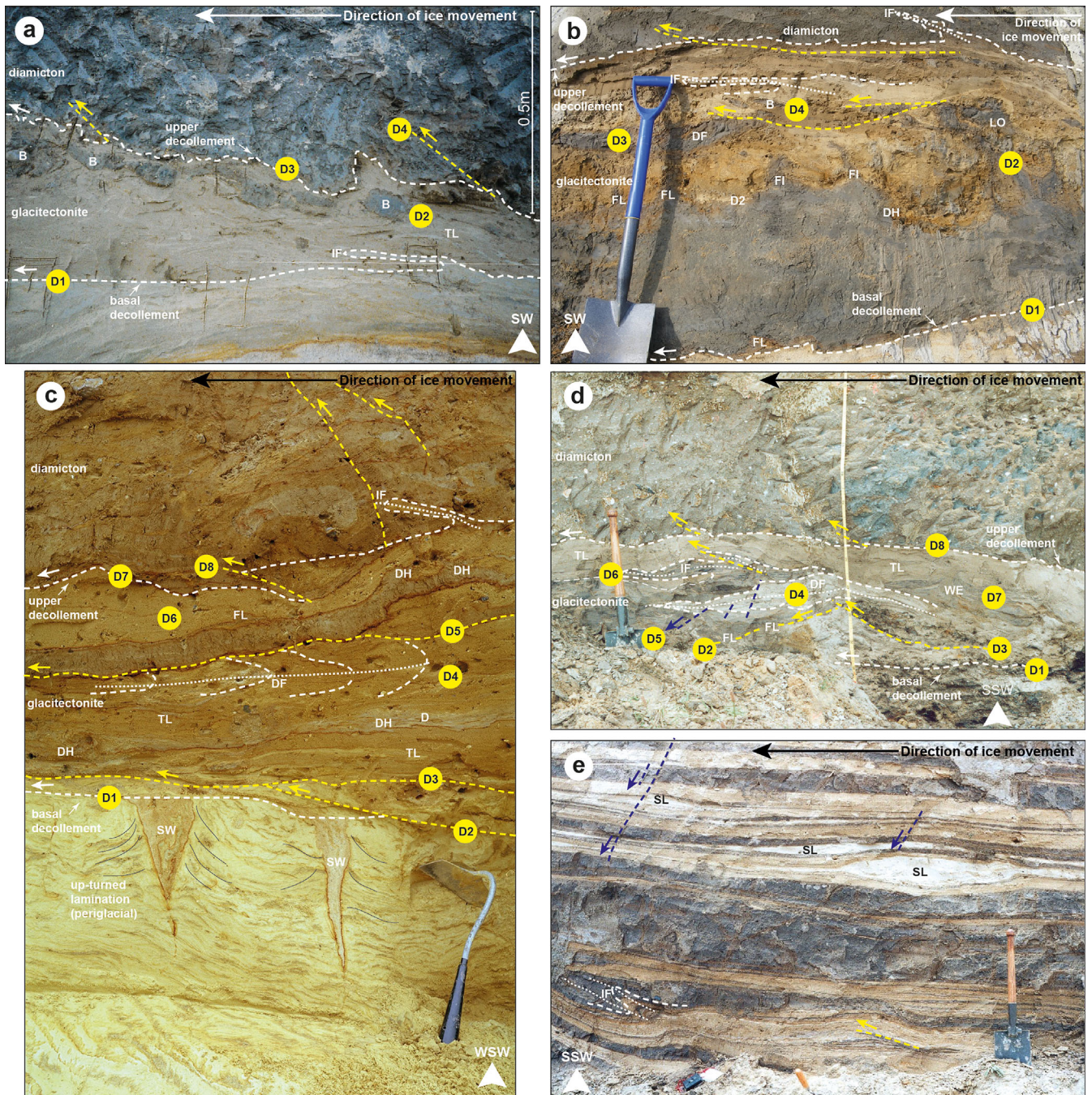


Figure 5. Annotated photos of the A1–A4 glacial boundary zones in north Norfolk. (a) A1 Detachment at Trimingham with a lower thin glacitectorite overlain by a massive diamicton (Happisburgh Till Member) bound by basal and upper décollements (D1–D3), intervening ductile deformation with tectonic attenuation and boundinage (D2) and late-stage thrusting (D4). (b) A1 Detachment, Happisburgh, showing a metre-thick glacitectorite and overlying diamicton (Happisburgh Till Member); the photo shows basal detachment (D1), fluid-rich soft-sediment deformation (disharmonic folding, flame and load structures) of grey muds (D2), shear-induced folding and fold nose detachment (D3), thrust truncation with minor boundinage (D4). (c) A2 Detachment at Hopton showing basal preglacial sands with sheared sand wedge casts (SW) overlain by well-developed glacitectorite and diamicton (Corton Diamicton Member); the photo shows the climbing of the basal detachment (D1–D3, D5–D7), with intervening phases of ductile folding (D4), soft sediment deformation (D5) and late-stage thrusting (D8). (d) Photograph of the A3 Detachment at Paston showing the Walcott Till Member resting upon glacitectorized sand, gravel and mud and undeformed preglacial deposits at the base, basal décollement (D1), thrusting (D2–D3), ductile deformation and isoclinal fold development (D4), extensional faulting (D5), thrust-propagation folding (D6), load-induced dewatering (D7) and upper décollement development (D8). (e) A4 Detachment at Bacton Green; subaqueous facies of the Bacton Green Diamicton Member comprising beds of laterally continuous mud and diamict (rain-out, mass-flows), sand (turbidity currents) with syndepositional slumping (folding, thrusting and sand lenses) and settling (extensional faults). Abbreviations: B – boundinage, DH – disharmonic folding, DF – detached fold nose, FL – flame structures, IF – isoclinal folding, LO – meso-scale load-structures, SL – sand lens, SW – sand wedge, TL – tectonic laminations, WE – water escape.

along the Waveney and Little Ouse river valleys to Fakenham Magna (38 m OD).

Generally, the A2 boundary comprises a thick glacitectorized zone but is locally marked by a sedimentary sequence including water-lain diamictons. At Hopton the detachment

zone comprises a thin (0.5 m thick) glacitectorite and overlying diamicton (Corton Diamicton Member) (Fig. 5c). The latter is interpreted as a subglacial traction till due to its overconsolidated nature, occurrence of occasional faceted and striated clasts including local and far-travelled clasts, and

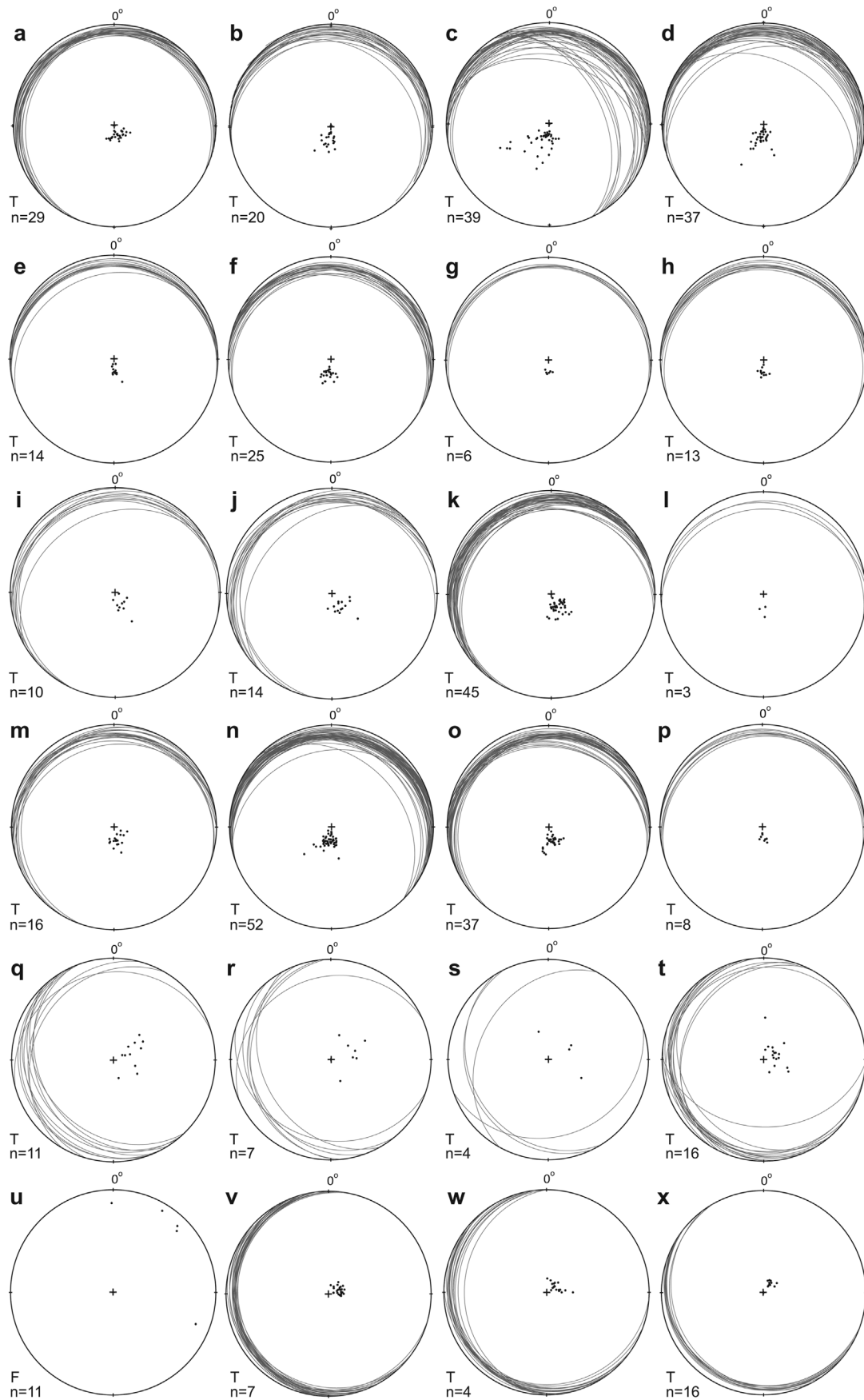


Figure 6. Stereographic projections (Schmidt) showing structural measurements from A1–A6. A1 Detachment: (a) Trimmingham, (b) Ostend, (c) Sidestrand, (d) Happisburgh. A2 Detachment: (e) Hopton (CDM); (f) Chedgrave (CDM), Freethorpe (CDM) and Witton (CDM), (g) Scratby (CDM), (h) Starston (SDM). A3 Detachment: (i) Paston, (j) Ostend, (k) Mundesley, (l) Overstrand, (m) Briston. A4 Detachment: (n) Mundesley–Trimingham, (o) Overstrand–Cromer, (p) Hevingham. A5 Detachment: (q) Brettenham Heath, (r) Croxton, (s) Colveston, (t–u) Starston, (v) Pakefield, (w) Hopton, (x,y) Scratby, (z–bi) Bacton Green, (ci,di) West Runton, (ei,fi) Weybourne. A6 Detachment: (gi,hi) Trimmingham, (ii) Holt, (ji) Roman Camp, (ki) Stody, (li) Weybourne Town Pit. Abbreviations: exposure (Exp.) type: C – coastal section, TP – Trial Pit, Q – Quarry Section; data type: T – thrust and reverse faults (poles to planes and great circles), F – fold axis; SL – stretched lineation; CL – crenulation lineations.

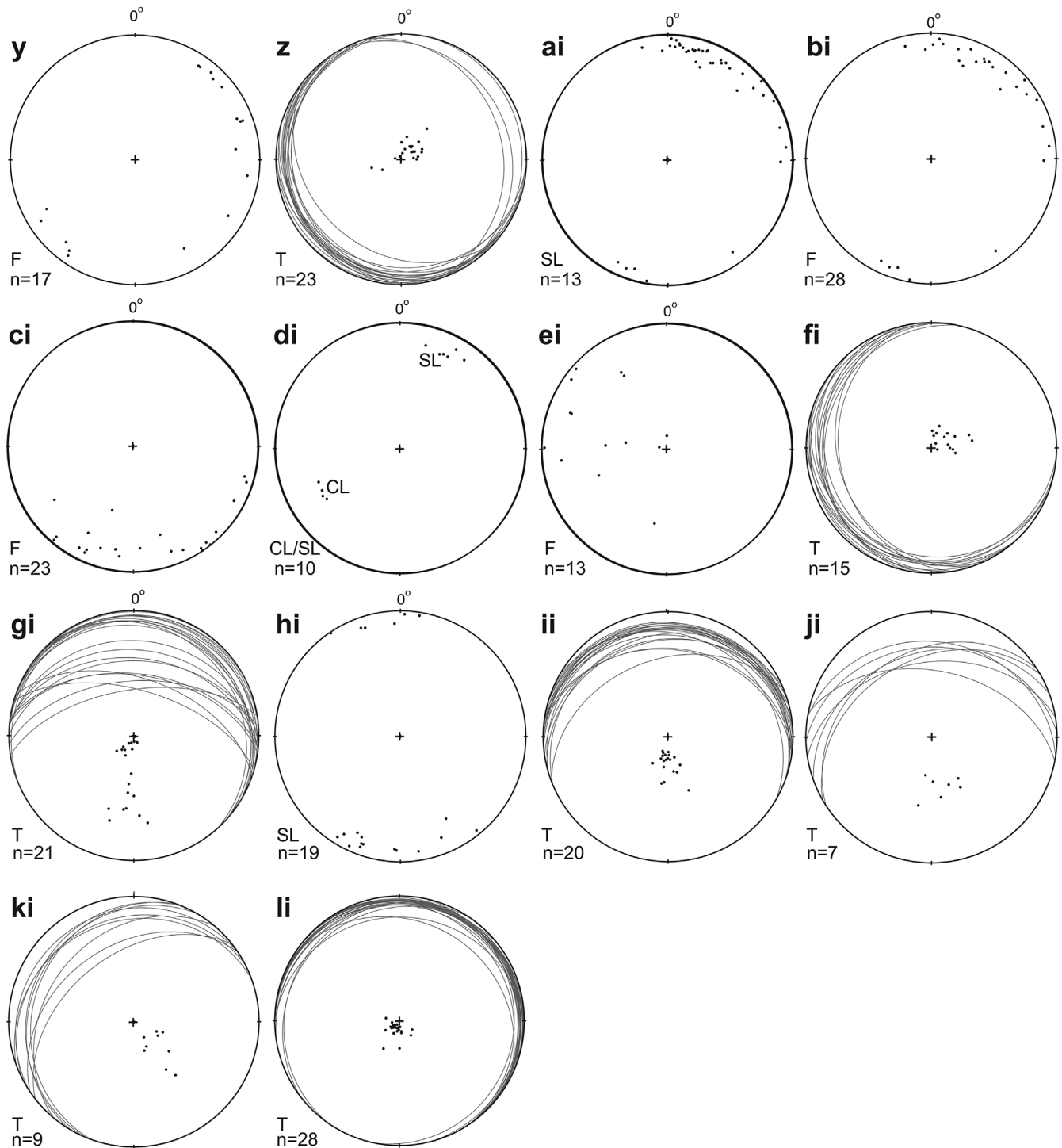


Figure 6. Continued.

the presence of sheared sediment inclusions. The underlying glacitectorite comprises detachments (D1, D3, D5, D7) generated by the repeated thrust-stacking of thin slices of pre-existing sediments that sequentially truncate zones (D4, D6) of soft-ductile-brittle deformation characterized by folds, disharmonic folds, flame structures and tectonic laminae. A stereographic projection shows low-angle thrusts with stress applied from the north-north-west (Fig. 6e) and mirrors directional data from sites elsewhere in the region (Fig. 6f–h) and other published work (Pointon, 1978). Structural evidence indicates repeated phases of dewatering and thrusting before the accretion of the subglacial till. Accretion of the basal horizons of this till coincide with late-stage (D8)

thrusting along the basal contact and the development of a subglacial shear zone during the overriding of the sediment pile.

The diamicton forms a discontinuous sheet across the southern part of the region although its bulk lithology varies spatially depending on substrate geology. Two diamicton facies are evident: (i) a brown sandy diamicton, the Corton Diamicton Member, located in areas of thick Quaternary substrate; and (ii) a chalkier (where not decalcified) brown diamicton, the Starston Diamicton Member, situated on substrate with only thin/localized/no drift. The Corton Diamicton Member (Table 2) occurs throughout south-east Norfolk and the lower Waveney Valley (Hopson and Bridge,

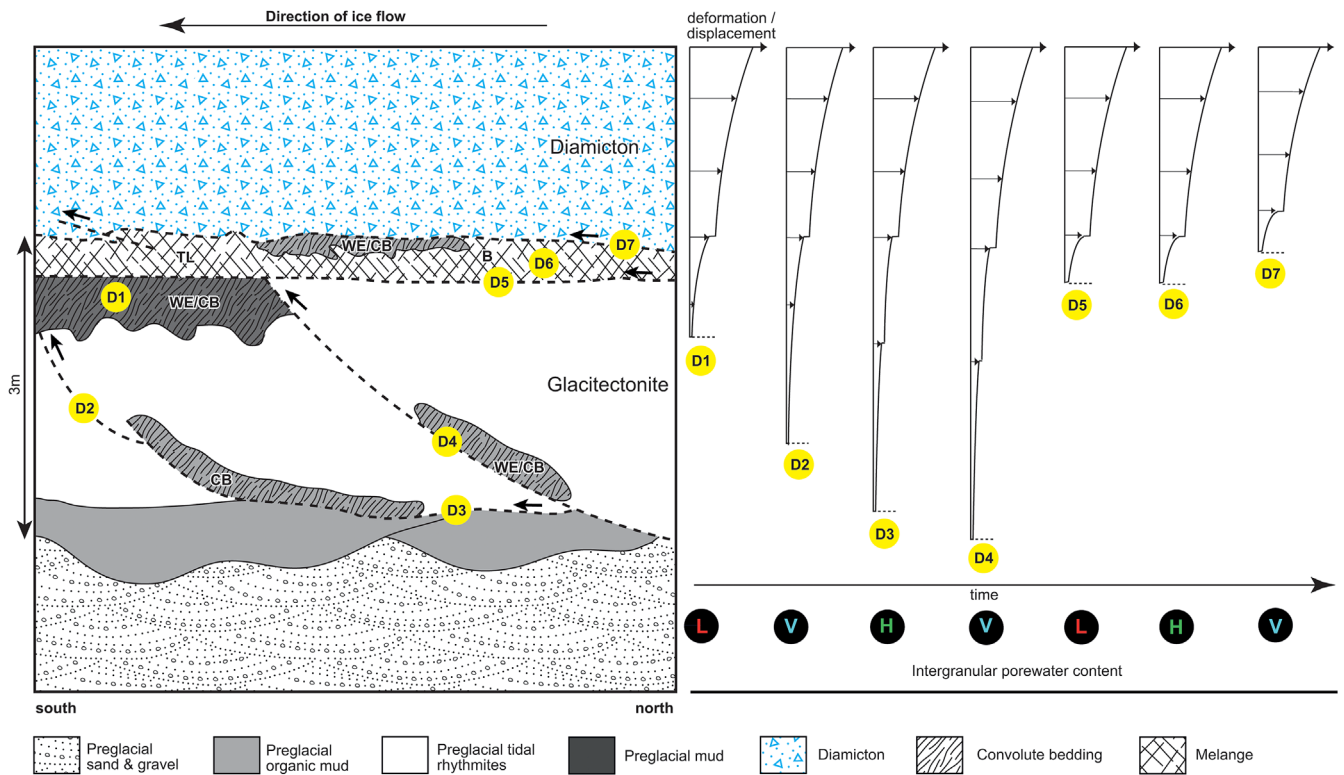


Figure 7. Schematic diagram of the structure and deformation history (D1–D7) of the A1 Detachment at Sidstrand based upon the cross-cutting relationship of tectonic structures (modified from Lee, 2009). The diagram shows suggested switches in the depth of deformation within the shear zone possibly driven by temporal and spatial changes in porewater availability. (D1) Development of mid-level thrust faults. (D2) Deepening of the deformation profile and development of the basal décollement along bedding surfaces within the preglacial organic muds (Sidstrand *Unio* Bed – SUB). Steepening of the décollement into a thrust fault with detachment and transportation of SUB rafts; part fluidization of SUB rafts within the hanging-wall and development of convolute bedding. (D3) Drainage of the hanging-wall along D1/D2 with hydration and deformation of overlying preglacial muds. (D4) Development of additional deep basal décollement within the preglacial organic muds (SUB). Steepening of the basal décollement and transportation of SUB rafts, hanging-wall fluidization with porewater expelled along faults into higher structural levels of the shear zone. (D5) Decoupling from lower shear zone along a basal décollement. (D6) Fluidization and thin melange development by ductile and brittle deformation with tectonic laminated, boundinage and advection of SUB rafts to base of the diamicton. (D7) Decoupling of diamicton from glacitectorite.

1987; Rose *et al.*, 2002). In coastal sections south of Happisburgh, the diamicton overlies the Happisburgh Formation within the northern limb of a syncline (Lee *et al.*, 2008). At Hopton, Scratby and California Gap, the diamicton is massive, over-consolidated and contains sheared sandy stringers and pods implying that the diamicton is a subglacial traction till (Arthurton *et al.*, 1994; Lee, 2003). In contrast, at Corton, Happisburgh and Burgh Castle, the diamicton locally possesses a gradational (i.e. sedimentary) lower contact and intercalated beds of sorted sediment and diamicton rafts with frequent graded-bedding and occasional dropstones. These facies have been interpreted as being deposited by rain-out, debris and turbidity flows at or adjacent to an ice-marginal grounding-line position (Lee, 2001; Riches *et al.*, 2006; Charman, 2013). The Corton Diamicton Member passes westwards into the Starston Diamicton Member (Table 2) in the mid-reaches of the Waveney Valley. It crops-out in the flanks of the Waveney Valley around Diss (Whitaker and Dalton, 1887; Lawson, 1982; Mathers *et al.*, 1987, 1993) and sub-crops within the buried preglacial Bytham River valley extending west to Fakenham Magna (Lewis, 1993; Lewis *et al.*, 1999; J. Rose, unpubl. data). The unit comprises an over-consolidated diamicton and typically contains angular clasts and rafts of chalk (Lawson, 1982; Mathers *et al.*, 1993). Few genetic studies of the Starston Diamicton Member have been undertaken but the over-consolidated nature of the deposit coupled with its localized intercalation with glaciofluvial deposits imply an ice-marginal or sub-marginal origin (Mathers *et al.*, 1993). Additionally, the presence of small

chalk clasts within the diamicton suggests subglacial incorporation of either locally crushed bedrock derived from the chalk by subglacial abrasion, plucking and raft detachment (cf. Hiemstra *et al.*, 2007) or a local chalk head deposit.

The *glaciodynamic parasequence* documents a period of ice-marginal retreat and outwash sedimentation (Bridge and Hopson, 1985; Lewis *et al.*, 1999; Rose *et al.*, 1999b). Coarse-grained proximal outwash deposits include the Leet Hill Sand and Gravel Member that crop out discontinuously within the Lower Waveney Valley (Table 2; Hopson and Bridge, 1987; Rose *et al.*, 1999b; Lee *et al.*, 2006) and the Coney Weston Sand and Gravel Member that occurs to the west of Diss (Table 2; Mathers *et al.*, 1993; Lewis *et al.*, 1999). Finer grained distal equivalents are the Corton Sand Member, which occurs extensively throughout the Waveney Valley and south-eastern Norfolk extending northwards to Happisburgh, North Walsham and Norwich (Bridge and Hopson, 1985; Postma and Hodgson, 1988; Moorlock *et al.*, 2000a; Rose *et al.*, 2002). The latter comprise three fining-upwards cycles, each approximately 8–10 m thick, that drape and infill the pre-existing topography (Table 2; Bridge and Hopson, 1985; Hopson and Bridge, 1987). Opinions have been divided between a marine (Blake, 1890), glaciomarine (Arthurton *et al.*, 1994), glaciolacustrine (West and Wilson, 1968; Pointon, 1978; Bridge and Hopson, 1985; Zalasiewicz and Gibbard, 1988) or glaciofluvial (Rose *et al.*, 1999b; Lee, 2001; Lee *et al.*, 2006) origin for these deposits. However, the presence of intraformational frost crack structures and involutions (Ranson, 1968; Rose *et al.*, 1999b; Lee, 2003) and

'pinstripe' cross-lamination (J. R. Lee, unpubl. data) indicate predominantly terrestrial processes with perhaps only localized basal conditions.

Summary

The A2 Tectonostratigraphic Unit (Corton Formation) overlies the Happisburgh Formation in north-east Norfolk, but directly overlies or is intercalated with preglacial deposits in the Waveney Valley. At the base of the unit is a diamicton that was variably deposited subaqueously or subglacially. The subglacial till facies is often associated with a thin glacitectorite generated by early-stage dewatering and thrusting, followed by thrusting along the basal diamicton contact coincident with subglacial till accretion. A thick glaciodynamic parasequence records proximal and distal glaciofluvial outwash facies.

A3 Tectonostratigraphic–parasequence Unit

Description and interpretation

The A3 Boundary comprises a subglacial shear zone that separates the Mundesley Formation from underlying sediments situated to the north of Happisburgh (Fig. 4) (Reid, 1882; Banham, 1968; Lunkka, 1994; Lee *et al.*, 2004a) occurring inland between Stalham, Flordon and Briston (Corbett, 2001; Pawley, 2006; British Geological Survey, 2014). This sub-horizontal detachment zone unconformably overlies the Happisburgh and Corton formations but, between Mundesley and Walcott, underlying glacial deposits have been eroded and the Mundesley Formation rests upon preglacial sediments.

The A3 detachment was observed discontinuously in coastal sections between Happisburgh and Overstrand and inland at Briston and is uniform in structure. Thrust fault measurements (Fig. 6i–m) demonstrate a sense of displacement that is consistent with an ice advance from the north-west (Banham, 1966; Banham and Ranson, 1970; Lunkka, 1994). At Paston, the lower part of the detachment zone, 0.4 m thick, includes deformed preglacial gravel, sand and peat (West, 1980; Lee, 2003) that collectively form a glacitectorite. The glacitectorite exhibits several low-angle thrust-bound slices (Fig. 6i; D1–D3, D8) of preglacial sediment that display internal ductile deformation (D4, D6; tectonic lamination, isoclinal folding) and soft-sediment dewatering (D7) structures (sand volcanoes, flame structures) (Fig. 5d). This evidence clearly indicates an early phase of ductile deformation followed by brittle thrusting. The structurally higher diamicton is called the Walcott Diamicton Member (Table 2; Lee *et al.*, 2004a). The diamicton is over-consolidated, possessing a massive to faintly stratified structure with occasional sheared inclusions of sand or laminated clay and is interpreted as a subglacial traction till. Diffuse to flame-like inclusions within the diamicton indicate elevated porewater pressures during shearing. Truncation of the base of the diamicton (D8) by small-scale thrusts suggests that the final stage of brittle deformation post-dates earlier phases of brittle–ductile deformation being broadly coeval with till accretion.

The *glaciodynamic parasequence* encompasses water-lain sands and laminated silts and clays that crop out in coastal exposures between Bacton Green and Cromer and inland within boreholes. The Mundesley Sand Member rests upon the irregular surface of the Walcott Diamicton Member (Banham, 1966; Banham and Ranson, 1970; Lunkka, 1994). It comprises a thick sequence of stratified chalky sand (Table 2; Reid, 1882; Solomon, 1932; Banham, 1968;

Lunkka, 1994; Lee *et al.*, 2004a) formed as SE-prograding glaciallacustrine bottomsets characterized by high sedimentation rates and variations in flow regime (Lunkka, 1994; Lee, 2003). This lithofacies pinches out north of Mundesley, passing into a finer-grained glaciallacustrine lithofacies (Hart, 1992; Lunkka, 1994; Lee *et al.*, 2004a) called the Ivy Farm Silt Member (Table 2; Lee *et al.*, 2004a). The lithofacies records variations in water depth, proximity to sediment input and seasonal overturn of the water column within the ice-distal part of a glaciallacustrine basin (Hart, 1992).

Summary

The A3 Tectonostratigraphic Unit unconformably overlies the Happisburgh Formation across much of north-east Norfolk, but locally rests upon preglacial deposits. At the base is a glacitectorite and related subglacial traction till. The lower horizons of glacitectorite record initial phases of dewatering, thrusting and folding before subglacial till accretion. Subsequent overriding and shearing of the sediment pile led to the development of the upper décollement, localized thrust displacement and coeval accretion of the till. Resting upon the surface of the till is a thick glaciodynamic parasequence comprising glacideltaic and glaciallacustrine deposits.

A4 Tectonostratigraphic–parasequence Unit

Description and interpretation

The A4 Boundary is thin and separates the Sheringham Cliffs Formation from underlying deposits across much of north Norfolk, extending westwards to Fakenham and Hevingham to the south (Fig. 4).

Coastal sections between Bacton Green and Mundesley reveal a graded sedimentary contact with sorted sands (Mundesley Sand Member) and silts/clays (Ivy Farm Silt Member) passing upwards into a stratified dark yellowish brown to dark grey sandy diamicton. The diamicton, called the Bacton Green Diamicton Member (Table 2), comprises a complex of stratified beds of diamicton and sorted sediment (Fig. 5e). Rhythmically bedded silts and clays record rain-out and seasonal suspension settling within an ice-distal environment (Gilbert *et al.*, 1997). Horizontally bedded and graded sands are the products of turbidity currents (Eyles *et al.*, 1985), whereas stringers record localized traction-current reworking (Eyles and Eyles, 1983). Beds of sandy diamicton, fold noses and sand lenses are produced by subaqueous slumps or debris flows of glaciogenic diamicton (Eyles, 1987) with sharp bedding contacts indicating hydroplaning (Mohrig *et al.*, 1998). Load and dewatering structures characterize rapid sedimentation rates and elevated porewater pressures (Owen, 2003). Collectively, these facies are interpreted as being deposited in a glaciallacustrine environment adjacent to a subaqueous grounding-line position (Lunkka, 1994; Lee and Phillips, 2008).

At Marl Point, Mundesley, the basal boundary is marked by two sharp décollement surfaces constraining glacitectorized sediments and an overlying diamicton (Lunkka, 1994; Lee, 2003). The glacitectorite is 0.3–0.5 m thick and exhibits lower and upper décollement surfaces and several discrete N-dipping low-angle thrusts (Fig. 6n) that truncate thin slices of variably deformed sand and clay. Individual thrust-slices exhibit both ductile (isoclinal and recumbent folding) and soft-sediment (disharmonic folding and convolute bedding) deformation, implying progressive dewatering during tectonism that resulted in a switch from ductile (earlier) to brittle (later) deformation. The overlying massive, silty, matrix-supported, over-consolidated, brown to brownish grey

diamicton is interpreted as a subglacial traction till (Banham, 1970; Lunkka, 1994). The south- and south-east directions of thrust displacement at Marl Point mirror the direction of applied stresses (Fig. 6o,p) from other localities in the region (Lunkka, 1994).

These facies grade upwards into a consolidated, matrix-supported and stratified diamicton, including laterally extensive sand laminae, sandy stringers, sand lenses, rhythmic or massively bedded silts or clays and occasional dropstones (Lunkka, 1994; Lee, 2003). These facies characterize deposition from subaqueous rain-out, debris/turbidity flows and traction-current reworking within a proximal ice-marginal setting (Eyles and Eyles, 1983; Eyles, 1987). They demonstrate the switch from subglacial to subaqueous sedimentation coinciding with either floatation of the glacier snout or retreat of the grounded margin towards the north. Around Trimmingham, the subaqueous diamicton grades upwards into a sequence of glaciallacustrine clays (Trimingham Clay Member) with localized deltaic input (Trimingham Sand Member) (Table 2; Hart, 1992; Lee *et al.*, 2004a).

Summary

The A4 Tectonostratigraphic Unit occurs throughout north Norfolk. In the southern distribution area, the gradational lower contact comprises a diamicton deposited subaqueously by mass-flows, rain-out and turbidity currents. To the north, the boundary forms a tectonic detachment comprising a lower glacitectorite and overlying subglacial till. The absence of thrust structures cross-cutting the contact implies, at least locally, that all deformation with the glacitectorite pre-dated subglacial overriding of the sediment pile. An upwards transition from subglacial till to subaqueous diamicton suggests ice-bed decoupling caused by floatation or ice-marginal retreat.

A5 Tectonostratigraphic–parasequence Unit

Description and interpretation

The A5 Boundary forms a regionally extensive detachment zone separating the Lowestoft Formation from underlying glacial/preglacial deposits and bedrock (Fig. 4).

In west Norfolk and north-west Suffolk, the sequence overlying the A5 boundary comprises a highly variably, clast- to matrix-supported, olive brown, chalk-rich, over-consolidated diamicton, the Lowestoft Diamicton Member, resting upon preglacial deposits or unconformably upon chalk bedrock. The matrix is composed of disaggregated chalk with variable proportions of striated Jurassic and Triassic lithologies derived from the west (Perrin *et al.*, 1979; Fish and Whiteman, 2001; Scheib *et al.*, 2011). The diamicton crops out discontinuously, forming ‘smears’ around/over bedrock highs and as infills to bedrock lows (British Geological Survey, 2010). At Brettenham Heath, Croxton and Colveston the diamicton is dissected by several low to moderately inclined thrusts dipping towards the west, south-west and north-west (Fig. 6q–s) recording local variance in the direction of thrust displacement. The consolidation of the diamicton and the presence of striated bedrock clasts suggest a subglacial till (Lewis *et al.*, 1999) produced by the detachment of rafted or plucked bedrock and subsequent abrasion to form a till (cf. Benn and Evans, 1996; Hiemstra *et al.*, 2007).

To the east, the detachment forms an undulating zone that separates the Lowestoft Diamicton Member from underlying Quaternary deposits (Hopson and Bridge, 1987; Mathers *et al.*, 1993; Rose *et al.*, 2002). The geometry of the detachment varies depending on the nature of the substrate. In areas of variable substrate lithology, thicker (up to 1.2 m)

and more complex glacitectorites develop exhibiting multiple cross-cutting domains of brittle, ductile and soft-sediment deformation (Hart *et al.*, 1990; Read *et al.*, 2000; Richards, 2000). This complex rheological response to strain is illustrated by kinematic data from trial pits at Starston (Fig. 6t–u) which show generally low, but occasionally moderately inclined, thrust faults. By contrast, in areas of sandy substrate, glacitectorites are thinner (<0.3 m) with low-angle thrusting and folding developing (Fig. 6v–y). At Hopton the detachment comprises a thin glacitectorite (0.25 m) overlain by a massive to weakly stratified, clay-rich, over-consolidated, matrix-supported diamicton (Fig. 8a). The glacitectorite is bound by several W-dipping low-angle décollement surfaces (Fig. 6w) that form the base (D1, D3 and D4) and top (D6) of the structural unit. The cross-cutting relationships of D1, D3 and D4 indicate that the focus of strain migrated as different substrate zones were progressively incorporated into the glacitectorite. Constrained between the basal and upper décollement zones is a highly deformed unit (D5) of sand, silt and diamicton. Pre-existing bedding and inclusions of diamicton within D5 have been inter-folded and, at a smaller scale, attenuated to form tectonic laminae and boudinage structures that record the ductile–brittle response to applied shear stresses. Loading of the primary structural boundaries (D1 and D6) following the cessation of shearing led to localized dewatering (disharmonic folding and flame structures) and extensional faulting. The direction of displacement recorded by the folds and thrusts from all sites indicate NE- or E-directed stresses (Fig. 6v–y).

The Lowestoft Diamicton Member occurs within the detachment throughout the eastern part of the study area (Banham, 1971; Pointon, 1978; Allen *et al.*, 1991). Here, it comprises a dark grey to brownish grey, clay- and chalk-rich matrix-supported diamicton, over-consolidated with localized inclusions of clay, sand or gravel. The bulk lithological properties are similar to facies that occur in the west of the region but possess a more prominent Jurassic-mudstone matrix component (Blake, 1890; Baden-Powell, 1948; Perrin *et al.*, 1973; Hopson and Bridge, 1987; Scheib *et al.*, 2011). Its sharp basal contact, over-consolidated nature, the occurrence of local and far-travelled lithologies, plus the presence of tectonic laminations, boundinage and sheared sediment inclusions, collectively indicate that the diamicton is a subglacial traction till (Pointon, 1978; Hart *et al.*, 1990; Read *et al.*, 2000; Richards, 2000). The till sheet is heavily dissected and can be mapped across southern and central Norfolk and northern Suffolk where it extends as far north as Eccles and Banningham (Trimmer, 1858; Blake, 1890; Baden-Powell, 1948; Hopson and Bridge, 1987; Arthurton *et al.*, 1994; Moorlock *et al.*, 2000a). Boreholes prove the diamicton to infill or partially infill buried subglacial and sub-marginal drainage channels that may locally be incised up to 65 m beneath the base of the till sheet (Woodland, 1970; Cox, 1985; Mathers and Zalasiewicz, 1986; Bricker *et al.*, 2012; Gibbard and van Vegt, 2012).

Across north-east Norfolk, A5 is composed of a large-scale variably pervasive glacitectoritic melange – the West Runton Melange Member, and an associated thin, highly discontinuous, diamicton called the Weybourne Diamicton Member (Ehlers *et al.*, 1987; Lee and Phillips, 2008; Phillips *et al.*, 2008). This glacitectoritic melange crops out discontinuously along the coast between Bacton Green (Lee and Phillips, 2008; Fleming *et al.*, 2013) and Weybourne (Phillips and Lee, 2013) and incorporates glacial/preglacial/bedrock strata from lower structural levels (Banham *et al.*, 1975; Pawley *et al.*, 2004; Phillips *et al.*, 2008). At Bacton Green, the glacitectoritic melange is approximately 12 m thick and superimposed

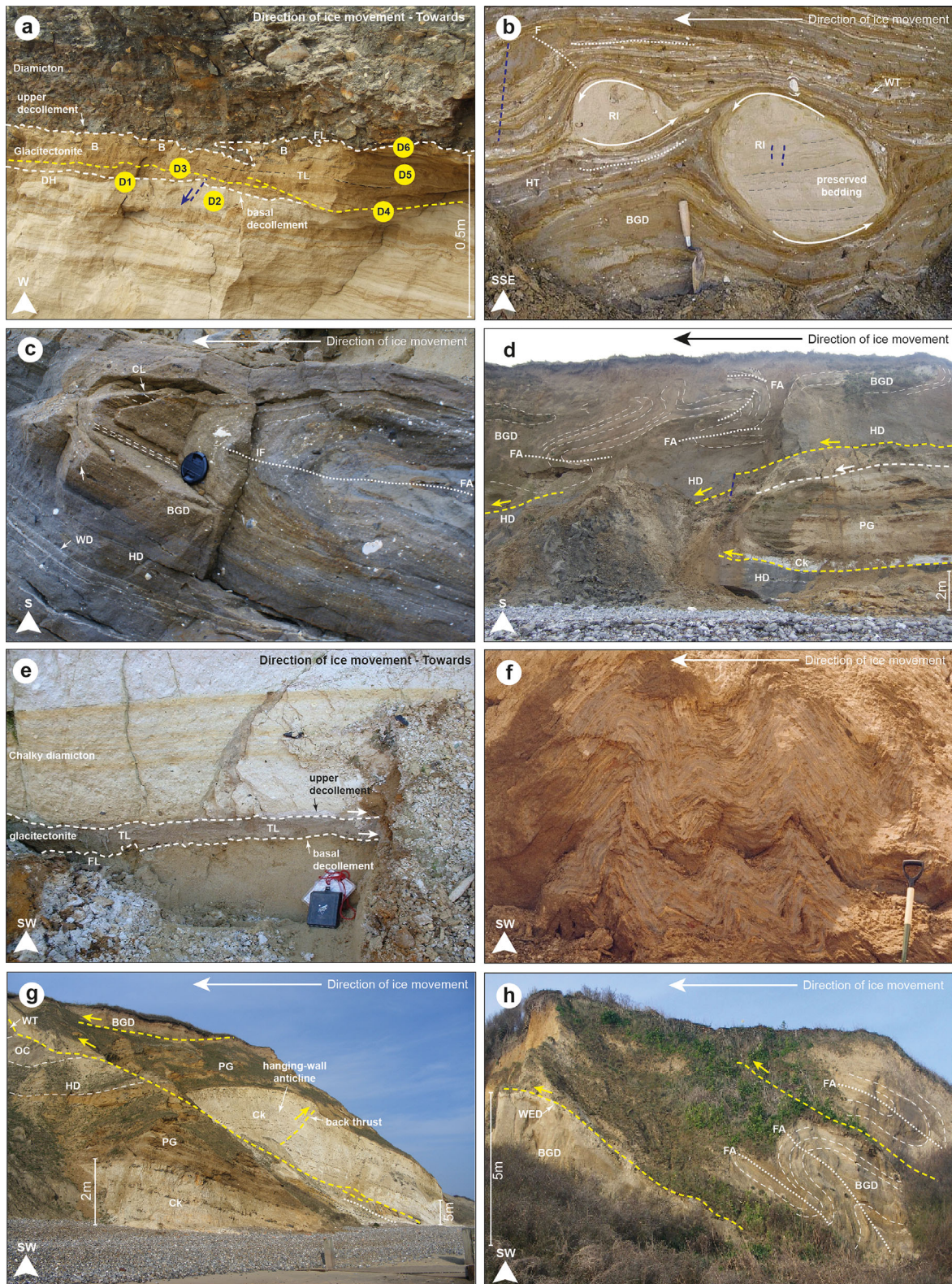


Figure 8. Annotated photos of the A4–A5 glacial boundary zones and A6 deformation in north Norfolk. (a) The A5 Detachment at Hopton showing a thin zone of glactectonized sand and upper diamiction (Lowestoft Diamiction Member). (b) The lower part of the West Runton Melange Member (A5 Detachment) at West Runton showing rotated intraclasts of preglacial sand with preserved bedding. A striking feature of the melange is the soft-sediment mixing and assimilation of pre-existing till units including the Happisburgh Diamiction Member, Walcott Diamiction Member and the Bacton Green Diamiction Member. (c) A recumbent isoclinal fold composed of Happisburgh Till Member and Bacton Green Diamiction Member with crenulation lineations in the fold hinge. Produced during A5, West Runton. (d) A thrust-bound glactectonic raft composed of chalk bedrock and preglacial sand and gravel emplaced out-of-sequence above the Happisburgh Diamiction Member and overlain in turn by the West Runton Melange Member (A5 Detachment). (e) The base of the A5 Detachment at Trimmingham showing a highly chalky diamiction resting upon a thin (5–7 cm) glactectonite composed of preglacial sand. (f) Chevron folding developed within the Ivy Farm Silt Member at Trimmingham; produced in response to lateral shortening (A6) of the sediment pile driven by raft emplacement several kilometres to the north at Overstrand (Fig. 8g). (g) Glactectonic rafts composed of chalk bedrock and preglacial sands and gravels developed during A6 at Overstrand. (h) Isoclinal folding and thrust detachments developed within the Bacton Green Diamiction Member at Overstrand produced during A6. Abbreviations: B – boundingage, BGD – Bacton Green Diamiction Member, Ck – chalk, DH – disharmonic folding, FA – fold axis, HDM – Happisburgh Diamiction Member, IF – isoclinal folding, OC – Ostend Clay Member, PG – preglacial deposits, RI – rotated sand intraclasts, TL – tectonic laminations, WD – Walcott Diamiction, WED – Weybourne Diamiction Member.

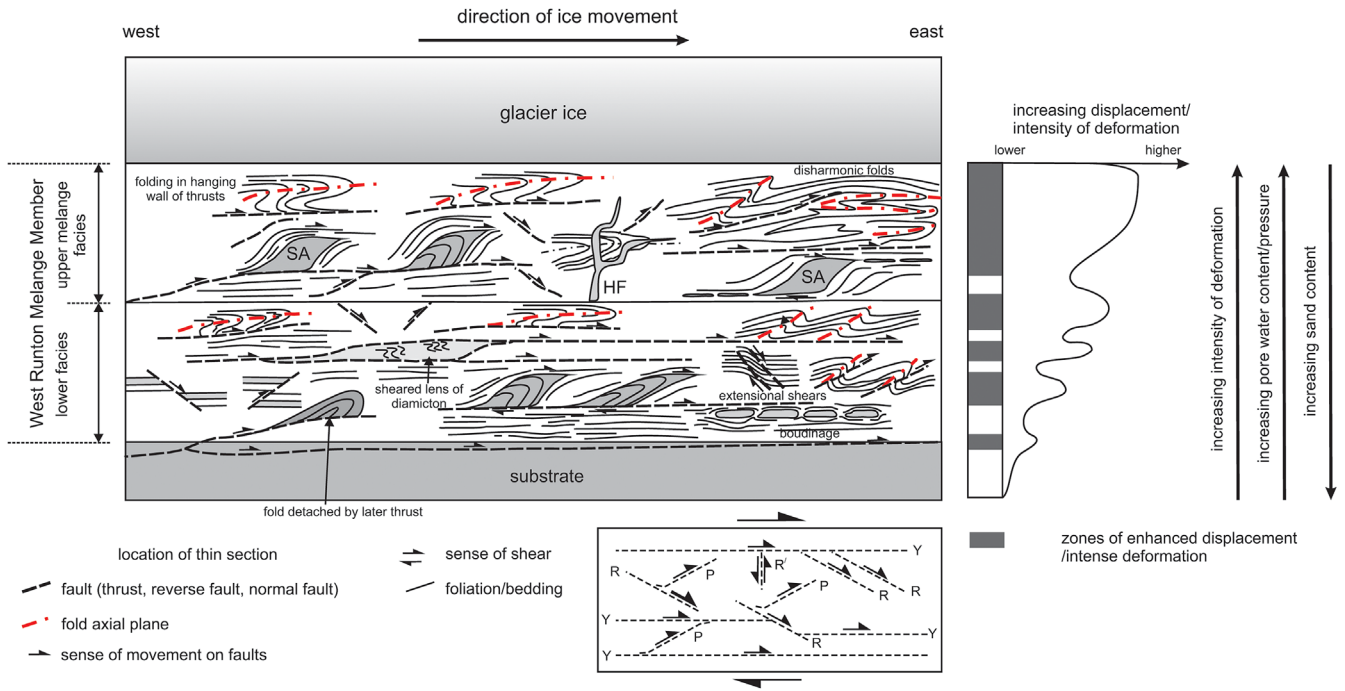


Figure 9. Schematic model showing the progressive evolution of the A5 Detachment at Bacton Green, north Norfolk with the accretion of the West Runton Melange Member superimposed upon the pre-existing Bacton Green Diamicton Member (modified from Lee and Phillips, 2008). Abbreviations: SA – sand augen, HF – hydrofractures.

upon the Bacton Green Diamicton Member (Lee and Phillips, 2008; Fleming *et al.*, 2013). Sediments are interpreted to have been deformed by progressive subglacial shearing that occurred in response to: firstly, ductile folding and sediment remobilization; secondly, brittle faulting and Reidel shear development; and finally, hydrofracturing and associated sediment remobilization (Fig. 9) (Lee and Phillips, 2008). Kinematic indicators including folds, thrusts and stretching lineations record stresses being applied to the sediment pile from the south-west (Fig. 6y–ai).

Further west, between East Runton and Weybourne, the melange is up to 40m thick, encompassing pre-existing glacial units and parts of the preglacial and bedrock succession (Dhonau and Dhonau, 1963; Hart *et al.*, 1990; Ehlers and Gibbard, 1991; Pawley *et al.*, 2004; Roberts and Hart, 2005; Hart, 2007; Waller *et al.*, 2011; Phillips and Lee, 2013; Vaughan-Hirsch *et al.*, 2013). Generation of the melange involved the reworking of several parent lithologies, most notably the Happisburgh and Bacton Green Diamicton members, and the disruption and glacetectonic rafting of preglacial sediment and bedrock (Fig. 8b–d) (Phillips *et al.*, 2008). Structures reveal an east to west continuum comprising proglacially, ice-marginally and subglacially deformed sediments (Phillips *et al.*, 2008). Proglacial glacetectonism involved the eastwards propagation of thrust faults into the glacier foreland, leading to the development of wedge-shaped thrust moraines and syn-depositional outwash sedimentation within small inter-morainic basins (Phillips *et al.*, 2008). Ice-marginal deformation is indicated by the tectonic stacking of large-scale thrust slices and folds onto the stoss-side of larger thrust moraines. It passes westwards into a progressively thicker and complex zone of subglacial shearing characterized by heterogeneous folding, thrusting and pervasive soft-sediment deformation (Phillips *et al.*, 2008; Phillips and Lee, 2013). To the west of Sheringham, this zone also encompasses the inter-folding of a structurally higher chalk-rich diamicton called the Weybourne Diamicton Member (Banham and Ranson, 1965; Pawley *et al.*, 2004; Hart, 2007; Phillips and Lee, 2013).

Kinematic indicators indicate stresses applied to the sequence from the west to south-west (Fig. 6bi–fi).

The Weybourne Diamicton Member crops out sporadically in coastal sections (Lunkka, 1994; Lee, 2003) and inland westwards towards Swaffham where it passes into the Low-estoft Diamicton Member that crops out to the south and west (Pawley, 2006). Formerly called the ‘Marly Drift’ because of its distinctive calcareous clast and matrix composition (Boswell, 1914, 1916), the diamicton possesses several lithological variants reflecting differential incorporation of chalk and earlier Quaternary deposits (Banham *et al.*, 1975; Perrin *et al.*, 1979; Ehlers *et al.*, 1987, 1991; Fish and Whiteman, 2001). Analysis of the provenance of disaggregated/fragmented chalk and matrix lithologies (microfossils and heavy minerals) reveal that the diamicton was sourced from Jurassic mudstones within the Fen Basin and adjacent Cretaceous strata (Perrin *et al.*, 1979; Riding in Lee, 2003). Where observed, for example at Trimingham, the diamicton is underlain by a very thin glacetone with tectonic laminations and flame structures indicating elevated pore-water pressures (Fig. 8e).

In west Norfolk, A5 is more complicated. At Newton, the detachment comprises a thin lower dark sandy diamicton interpreted as a subglacial traction till. It exhibits attenuated tectonic laminations and sheared inclusions of substrate material; structurally it is overlain by a highly stratified chalky diamicton interfolded with thin beds of brown sandy diamicton with common chalk laminae and strain shadows (Pawley, 2006). The upper diamicton was interpreted by Pawley (2006) as a subglacial traction till with clast fabric and macro-scale structural measurements indicating compressive stresses applied from the south-west (Ehlers *et al.*, 1987; Pawley, 2006).

Summary

The A5 Tectonostratigraphic Unit occurs throughout northern East Anglia but is spatially variable in structure and geometry. In the south and west, the detachment comprises a thin

(metre-scale) glacitectorite and an overlying subglacial till rich in derived Jurassic mudstone and chalk clasts that thicken eastwards. Structures within the glacitectorite demonstrate shearing of pre-existing substrate with an initial phase of brittle (thrusting) deformation and subsequent phase of ductile (folding, tectonic attenuation) deformation coincident with till accretion. Structural evidence for loading (extensional faulting) and dewatering (disharmonic folding, flame structures) indicates a water-rich shear zone. By contrast, in north Norfolk, the detachment forms a thick melange with only localized accretion of a thin (metre-scale) chalk-rich subglacial traction till. Sediments within the melange were deformed by progressive subglacial shearing and hydrofracturing. Around East Runton and Weybourne, the melange forms a continuum reflecting proglacial and ice-marginal deformation (including syn-tectonic sedimentation) and a thicker zone of subglacial deformation.

A6 Tectonostratigraphic–parasequence Unit

Description and interpretation

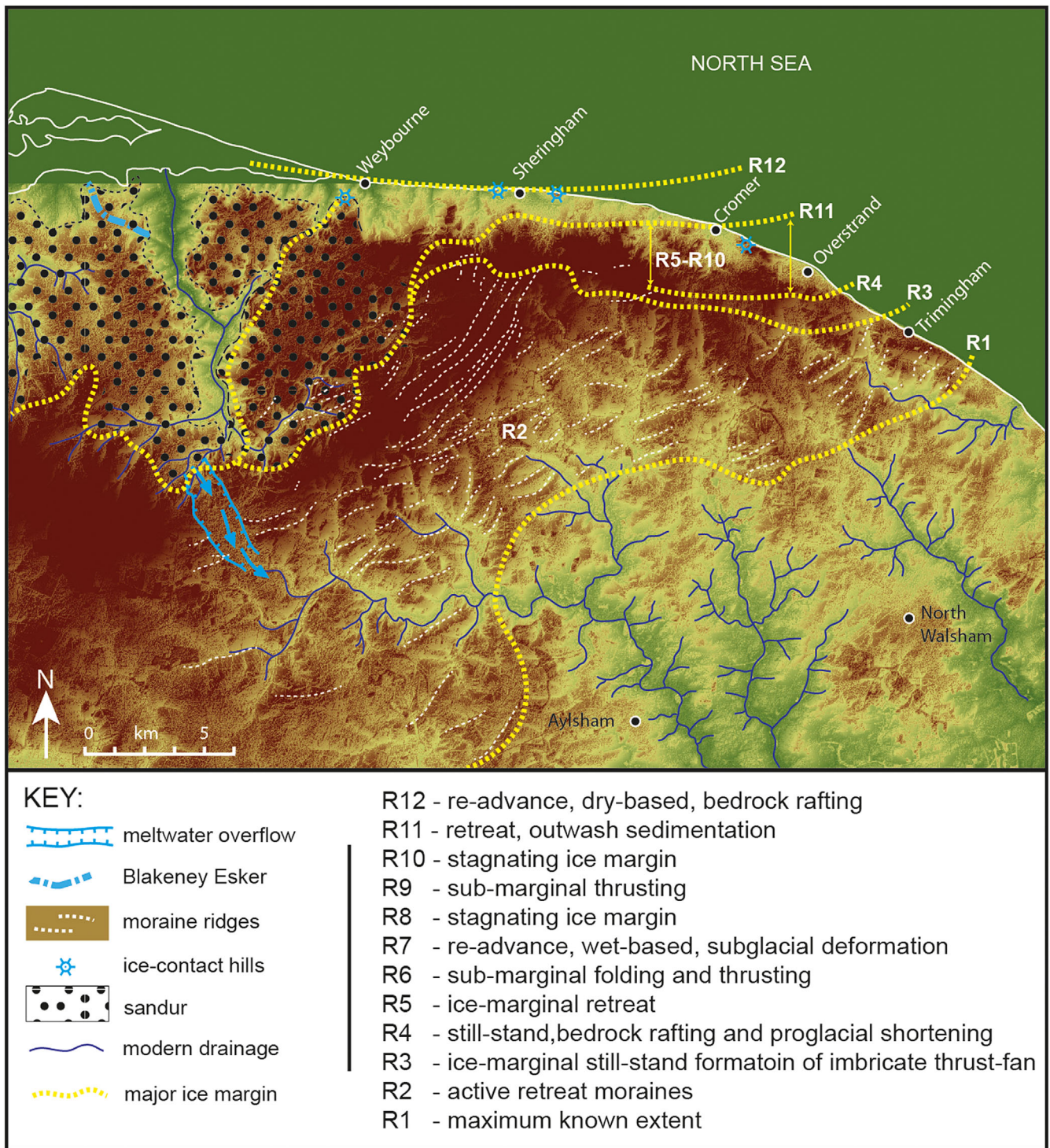
The A6 Tectonostratigraphic–parasequence Unit occurs extensively across northern East Anglia and separates the Briton's Lane Formation from underlying glacial deposits (Fig. 4; Fig. 3c). The unit is highly variable, comprising both sedimentary and tectonized elements formed during a southwards ice advance into the north of the region. Subsequent northwards retreat produced a series of cross-cutting geomorphological and glacitectoric domains that record various phases of dynamic ice-marginal behaviour (Lee *et al.*, 2013).

The maximum known ice advance (A6-R1) is recorded by the southernmost extent of a heavily dissected broadly SW–NE-trending S-shaped lineament (Fig. 10). This lineament comprises numerous low-amplitude (30–80-m wavelength), straight, crenulated or lobate ridges. Individual ridges are up to 5 m high, symmetrical to asymmetrical in cross-section and composed of thrust-stacked slabs of remobilized sandy Bacton Green Diamicton Member or chalky Weybourne Diamicton Member, or undifferentiated sorted sandy and mud-rich facies. The geometry and composition of these ridges suggests that they are thrust-block moraines produced by active retreat (A6-R2) of the ice margin (Lee *et al.*, 2013). A6-R3 intersects coastal sections at Trimmingham forming a N-dipping imbricate thrust fan (Fig. 11, 100–825 m) (Hart, 1990; Lee *et al.*, 2013). The thrust stack comprises four moderately to steeply inclined listric reverse faults (T2–T5) branching from a sole thrust (T1) developed within the laminated silts and clays. The orientation of thrusts and stretching lineations (Fig. 6gi–hi) demonstrate stress application from the north with individual thrust slices younging north-westwards. This thrust geometry was produced by the over-thrusting of progressively older geological units at higher levels within the thrust fan. The steeply inclined and 'long' thrust style implies a comparatively dry or more rigid substrate (Dahlen *et al.*, 1984; Nieuwland *et al.*, 2000; Williams *et al.*, 2001) with thrusting occurring during an ice-marginal still-stand (Lee *et al.*, 2013). A younger thrust stack (A6-R4) is recorded further north at Overstrand (Fig. 11, 2500–3000 m) with thrusting accommodated by foreland shortening (17%) and development of open-style buckle (macro-scale) and chevron (meso-scale) folds within the existing sediment pile (Figs 8f and 11). This younger thrust stack contains several large (10–15-m-thick, 1–50-m-long) glacitectoric rafts composed of largely undeformed chalk bedrock, preglacial sediment and Happisburgh Diamicton Member (Fig. 8g) (Burke *et al.*, 2009; Vaughan-Hirsch *et al.*, 2011). The upper raft forms a S-verging, large-scale asymmetrical anticline developed within

the hanging-wall of a gentle to moderately inclined (25–35°) thrust marking the main décollement of the raft. Preglacial deposits immediately (top 1 m) beneath the thrust are partly overturned, forming a closed to tight moderately inclined syncline displaced by small N-dipping thrusts and Riedel shears yielding a sense of displacement towards the south (Vaughan-Hirsch *et al.*, 2011).

Domains A6-R5 to A6-R8 can be seen within coastal sections at Overstrand (Fig. 11; 3000–4500 m). A6-R5 occurs towards the base of the cliff sections and shows Happisburgh and Mundesley formations that have undergone structural shortening (5%; open buckle folds) in response to S-directed lateral stresses. Folding is truncated by a N-dipping décollement with, in the hanging-wall, a zone of low-angle thrust-bound folds and nappe structures composed of Bacton Green Diamicton Member (Fig. 8h; A6-R6). A6-R6 structures have subsequently been variably over-printed by soft-sediment deformation associated with a later (A6-R7) minor readvance including the development of asymmetrical, broadly recumbent over-turned SE-verging folds. Flame-like to diapiric contacts between deformed units and meso-scale water-escape structures indicate elevated porewater content during deformation. Rapid load-induced dewatering of the substrate was followed by the formation of large-scale diapirs and hydrofractures (A6-R8) that truncate earlier deformation structures. These styles of glacitectorism record a continuum through proglacial compression and buckle-folding (A6-R5), low-angle brittle and ductile deformation associated with sub-marginal thrusting (A6-R6), sub-horizontal subglacial shearing with elevated porewater pressures (A6-R7) and, finally, load-induced dewatering (A6-R8) (Lee *et al.*, 2013).

Subsequent zones of glacitectoric deformation occur northwards towards the coast, forming progressively younger structural domains characterized by sub- to ice-marginal glacitectorism (A6-R9 and A6-R11) and substrate dewatering (A6-R10) (Lee *et al.*, 2013). A6-R9 was observed at Holt Quarry (Lee, 2014), Briton's Lane Quarry (Banham, 1977b; Pawley *et al.*, 2005) and the Roman Camp near Aylmerton (Lee *et al.*, 2013). The zone comprises diamicton (Sheringham Cliffs and Lowestoft formations) and outwash sands and gravels (Briton's Lane Formation) locally displaced by N-dipping, moderately inclined thrusts (Fig. 6ii–ji). The moderate inclinations of the faults imply a relatively dry or cohesive substrate with subtle changes in porewater content, cohesion and stress-field geometry driving local variance in thrust geometry (Dahlen *et al.*, 1984; Nieuwland *et al.*, 2000; Williams *et al.*, 2001). At Holt Quarry, thrusting is restricted to the lower horizons of outwash deposits indicating initial syn-tectonic sedimentation (Lee, 2014). These higher-level outwash deposits (Pawley *et al.*, 2005; Lee *et al.*, 2013; Lee, 2014), called the Briton's Lane Sand and Gravel Member (Table 2), form part of an extensive cap to some of the larger buried morainic elements. They form a distinctive region of elevated relief (the Cromer Ridge) across north Norfolk with gravels extending southwards as a thin sheet heavily degraded by post-glacial fluvial incision and hillslope processes (Reid, 1882; Straw and Clayton, 1979; Boulton *et al.*, 1984; Hart and Boulton, 1991a; Moorlock *et al.*, 2000b, 2002b). Lower-level thrust sequences (A6-R11) have also been noted at Stody Pit (Pawley, 2006) and Weybourne Town Pit (Evans *et al.*, 2011) and encompass the deposition of a northern provenance chalky diamicton (Stody Diamicton Member; Table 2) and sub-marginal deformation associated with a much thinner and lower-elevation ice margin. Sections reveal N-dipping, low- to moderate-angle (Fig. 6ki–li) thrust-bound stacks of sand and gravel and/or diamict (Fig. 12). The low-to-moderate (Weybourne Town Pit) and variable-angle (Stody



NEXTMap Britain elevation data from Intermap Technologies.

Figure 10. Colour-ramped digital surface model (DSM) of north-east Norfolk showing the sequential pattern of A6 ice-marginal retreat (R1–R12) reconstructed using landforms and glacitectonic data. Northwards retreat of the ice margin was driven by changes in ice thickness and substrate drainage. A summary of the processes operating during each retreat stage is indicated in the table key and outlined in the text.

Pit) of the thrust faults indicate brittle deformation of substrate with low to variable cohesive properties (Dahlen *et al.*, 1984; Nieuwland *et al.*, 2000; Williams *et al.*, 2001).

A6-R12 represents the youngest onshore structural domain in north Norfolk. It is composed of several distinctive steep-sided, conical-shaped ice-contact hills that are dissected by the modern coastline (Fig. 10). Internally, these hills exhibit steeply inclined folded and thrust masses of pre-existing diamict, sand and gravel and occasional chalk bedrock rafts with kinematic indicators demonstrating a southwards direction of emplacement (Lee *et al.*, 2013). The composition and

form of these ‘glacitectonic hills’ suggest that they are probably the remnants of a late-stage thrust-block morainic feature. However, unlike many of the previous A6 domains, the steep inclination of the folding and thrust structures imply a dry substrate (Dahlen *et al.*, 1984; Nieuwland *et al.*, 2000; Williams *et al.*, 2001).

Summary

The A6 Tectonostratigraphic–parasequence Unit occurs throughout north Norfolk. It contains a range of landforms, zones of glacitectonism and sediment (outwash) facies that

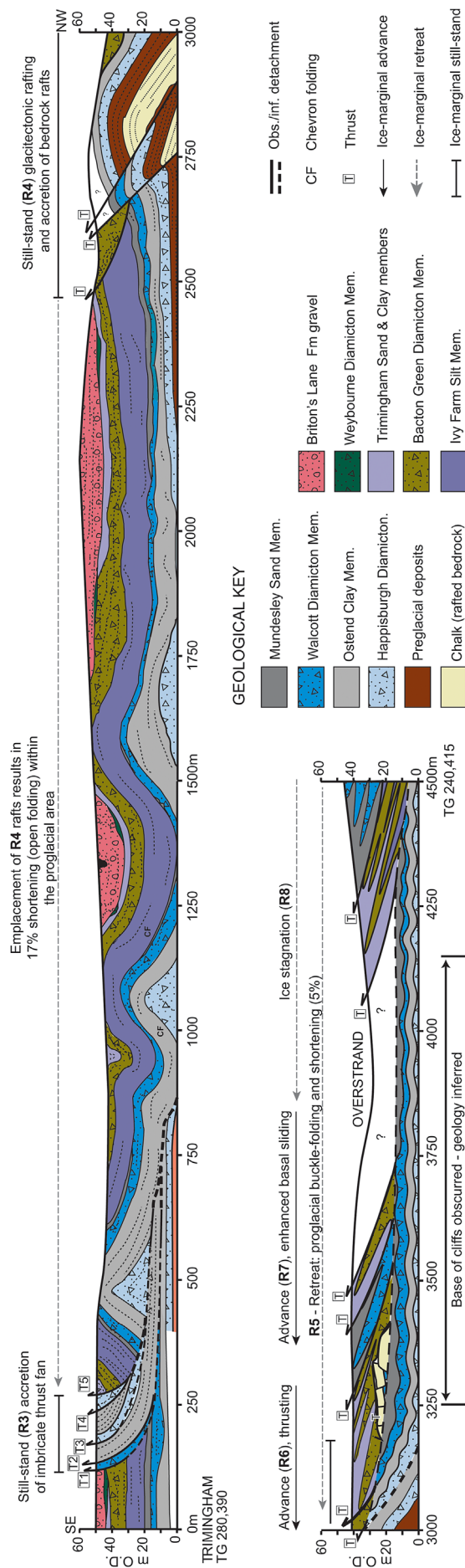


Figure 11. Cross-section of the coastal cliff sections between Trimingham and Overstrand recording glacitectonic phases (R3–R8) of northwards A6 ice-marginal retreat.

collectively record a 12-stage (A6-R1 to R12) pattern of northwards ice-marginal active retreat. Zones of glacitectonism include: a series of small thrust moraines (A6-R2); a large-scale, N-dipping, moderate to steeply inclined thrust-stack (A6-R3); moderately inclined thrust-stack including bedrock rafts and zone of foreland shortening (A6-R4); a further zone of structural shortening (A6-R5); N-dipping décollement with hanging-wall thrust-bound nappes and folds (A6-R6); soft-sediment deformation and sub-horizontal (recumbent) folding (A6-R7); hydrofracturing, diapirism and rapid substrate dewatering (A6-R8); outwash sedimentation and coeval N-dipping moderate-angle thrusting (A6-R9); diapirism and dewatering (A6-R10); low- to moderate-angle thrusting (N-dipping) and stacking of sediment blocks (A6-R11); and ice-contact (esker) and proglacial (sandur) landform development including the development of ‘glacitectonic hills’ and glacitectonic rafting (A6-R12).

Discussion

Evolution of glacitectonic boundaries

The geometry and structure of the glacitectonic component of the A1–A6 Glacigenic Boundary Zones depict a marked variability in glacitectonic and glacial processes (subglacial to ice-marginal to proglacial) operating between lower (A1–A4) and higher parts (A5–A6) of the structural sequence.

Glacitectonic boundaries within the lower part of the structural sequence (A1–A4, part of A5) commonly form thinner metre-scale shear (boundary) zones displaying well-developed and partitioned structural units (Banham, 1977a; Benn and Evans, 1996; Evans *et al.*, 2006). This style of ‘thin’ glacitectonism [e.g. Sidestrand (A1), Corton (A2), Paston (A3) and Hopton (A5)] is commonly generated by an early stage of ductile folding followed by dewatering leading to more brittle deformation (large-scale thrusting) with both occurring before till accretion (Figure 13). One explanation is that thrusting occurred subglacially. However, this creates an ‘accommodation space’ problem that cannot easily be reconciled without somehow lifting the glacier from its bed. Thus, the simplest explanation, and the one adopted here, is that incremental thrusting and dewatering was initiated either proglacially or ice-marginally in response to the propagation of compressive shear stresses in front of the advancing glacier (Evans and Hiemstra, 2005; Ó Cofaigh *et al.*, 2011). Subsequent overriding (subglacial) of the substrate causes the glacitectonite to be decoupled from the shear zone by a major décollement surface and accretion of the subglacial till. Transmission of strain downwards into the glacitectonite appears to have been very limited, resulting where present in either localized ductile (inter-folding) or brittle (small-scale thrusting) deformation of the two units along the main contact. However, the general paucity of deformation along and beneath the primary décollement surface demonstrates that both structural units were either completely or rapidly decoupled during the initial stages of subglacial till accretion. This implies a strong rheological contrast between the two structural units. Specifically, the subglacial traction till was likely to have been water-saturated and absorbed much or all the strain within the shear zone. At Trimingham and Overstrand (A1) the style of deformation is slightly different. Here, the basal glacitectonite was deformed by dewatering, soft-sediment and ductile deformation and is separated from the higher-level subglacial traction till by an interfolded and thrust-displaced décollement surface. The absence of lower-level thrusts within the glacitectonite implies that deformation was not initiated proglacially or ice-marginally but by direct ice-

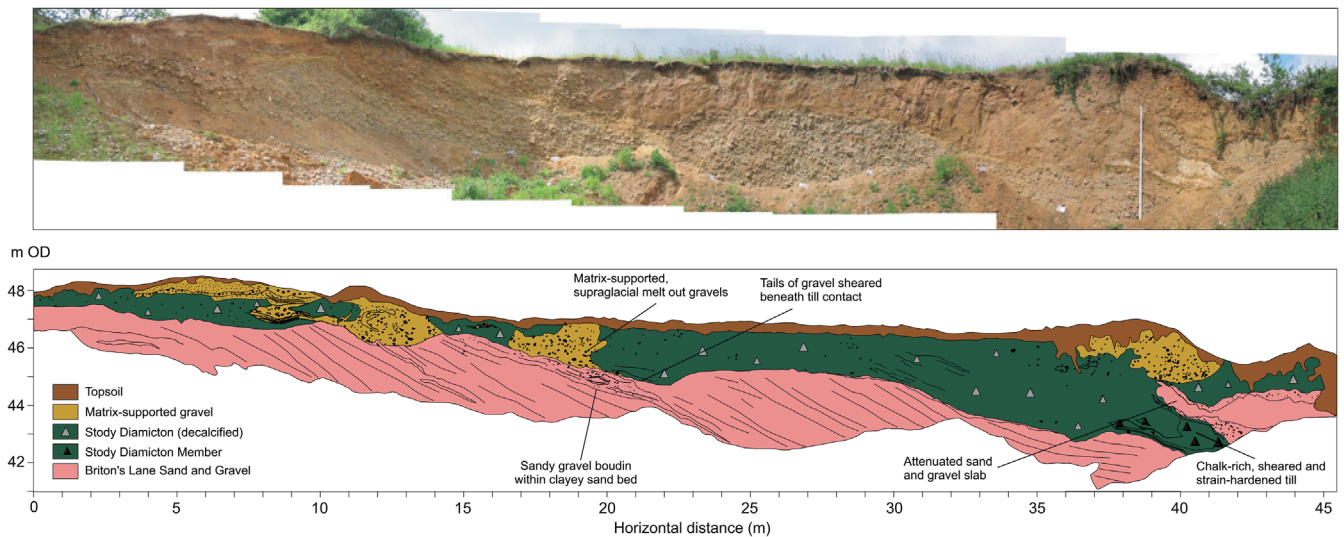


Figure 12. Glacitectonized diamict (Stody Diamicton Member) and sand and gravel at Stody, north Norfolk, produced during the A6 event (from Pawley, 2006; Lee *et al.*, 2013).

substrate shearing. Accretion of the overlying subglacial traction till led to localized traction causing minor folding and thrusting along the décollement and rapid decoupling.

Both of these mechanisms of ice–substrate decoupling limit traction and strain being transmitted into the underlying substrate during glacier overriding. In East Anglia, this has acted to preserve preglacial sediments that contain an internationally significant palaeoenvironmental and archaeological archive (West, 1980; Rose, 2009; Candy *et al.*, 2011; Ashton and Lewis, 2012; Preece and Parfitt, 2012). However, local elements of the preglacial succession have been heavily glacitectonized by ice-bed traction. At Sidestrand, glacitectonism (A1) has deformed parts of the preglacial succession including a regionally important marker unit (Sidestrand *Unio* Bed) (Lee, 2009). Tectonic inversion, soft-sediment deformation and mixing – all common processes associated with thrust tectonics (Twiss and Moores, 1992) – have acted to remobilize and partially mix the upper facies of the *Unio* Bed with adjacent lithologies and this limits its biostratigraphic value. Preservation of delicate floral and faunal remains within the *Unio* Bed (including articulated bones) has been argued by some to preclude glacitectonism (Preece and Parfitt, 2012). However, the described structural evidence implies that preservation occurred because the *Unio* Bed was fluidized limiting the transmission of strain into the delicate fossils (Lee, 2009).

‘Thicker’ (tens of metres) and more variable styles of glacitectonism generally occur relative to the A5 and A6 tectonostratigraphic–parasequence units. The A5 basal contact exhibits a markedly variable geometry and structure. The west of the region is dominated by widespread bedrock erosion, lowering and eastwards migration of the chalk escarpment (Clayton, 2000). Preservation of accreted till is generally confined to topographic lows or around irregularities within the chalk surface. The presence of the continuum of chalk blocks to clasts may indicate early-stage till-generation by detaching, crushing and comminution in an area of enhanced ice-bed traction (Hiemstra *et al.*, 2007). Alternatively, chalk could be derived from the periglacially disrupted chalk head that mantles much of the chalk surface across the region (Williams, 1987; Mortimore *et al.*, 2001; Phillips and Lee, 2013). Erosion and subsequent subglacial entrainment of this head provides an alternative mechanism for incorporating bedrock materials into tills without the requirement for high shear strains beneath glaciers driving comminution.

In the east of the region, the subglacial traction till (Lowestoft Diamicton Member) can be several tens of metres thick with the development of only a thin (metre-scale) underlying glacitectonite. The comparative thickness of subglacial till demonstrates that the east of the region was an area of net till accretion during A5. In north-east Norfolk, by contrast, the A5 tectonostratigraphic assemblage commonly exhibits a thick (tens of metres) glacitectonite with only limited accretion of a subglacial traction till (Weybourne Diamicton Member). Sediment availability within the shear zone was more limited with lower porewater availability leading to enhanced traction and the transmission of strain to deeper structural levels. Although indicating predominantly ‘drier’ modes of glacitectonic deformation, repeated switches between brittle and ductile deformation highlight minor fluctuations within porewater availability and/or substrate rheology that are typical of the *mosaic deforming bed model* (Piotrowski and Kraus, 1997; Piotrowski *et al.*, 2001, 2004; Lee and Phillips, 2008; Tylmann *et al.*, 2013). The resulting glacitectonic melange commonly shows deformation to depths of up to 30 m, encompassing much of the glacial sequence and elements of the preglacial Quaternary and bedrock geology (Hart *et al.*, 1990; Phillips *et al.*, 2008; Burke *et al.*, 2009; Vaughan-Hirsch *et al.*, 2013). Progressive thickening of the shear zone was probably driven by ice-marginal to sub-marginal thrust-stacking of frozen (warm permafrost) sediment slices (Evans and Hiemstra, 2005; Phillips *et al.*, 2008; Waller *et al.*, 2011).

The A6 detachment records a major north–south ice advance (West and Donner, 1956; Ehlers *et al.*, 1987, 1991) followed by active retreat punctuated by several minor ice-marginal readvances (Hart, 1990; Pawley, 2006; Lee *et al.*, 2013). Several different glacitectonic/landform domains have been identified by Lee *et al.* (2013) which have been interpreted as recording multiple phases of:

- Enhanced basal sliding and subglacial deformable bed development (akin to A1–A4) during ice advance (R1, R7) associated with elevated porewater substrate content.
- Sub- to ice-marginal development of ‘long’ low-angle glacitectonic folds (i.e. nappes) and detachments (thrusts) by water-lubricated thrust-gliding (R4, R6) – lateral transmission of stress into the proglacial foreland area to produce large-scale proglacial open folding (R4, R5).

- (c) Rapid vertical expulsion of porewater from the substrate (R8, R10) due to loading of the sediment pile.
- (d) Moderate- to variable-angle thrust-stack imbrication related to ice- to sub-marginal thrusting with varying substrate porewater content (R2?, R6, R9–11).
- (e) Ice-marginal development of steeply inclined 'short' thrust complexes including rafting associated with dry bed conditions (R3, R12).

Glacitectonic styles and geometry – controls and implications

Structural evidence presented above highlights the significance of substrate rheology on glacitectonic style and geometry, specifically that shorter and higher-angle glacitectonic structures, coupled with enhanced ice-bed traction and rafting, generally form in more cohesive strata. By contrast, longer and shallower glacitectonic structures including low-angle thrusting, isoclinal folding and long thrust blocks indicative of thrust gliding form in generally less cohesive materials. These observations are supported by basic rheological theory (Twiss and Moores, 1992; Jones, 1994), theoretical and sand-box modelling experiments (Dahlen *et al.*, 1984; Nieuwland *et al.*, 2000) and practical application to Quaternary sediments (Mackay, 1959; Mackay and Mathews, 1964; Mooers, 1990; Harris *et al.*, 1997; Williams *et al.*, 2001).

Data indicate that the rheological properties of the substrate have changed both temporally and spatially and that this reflects variability in substrate lithology (controlling porosity and permeability) and meltwater/groundwater flux (controlling porewater availability) (Boulton and Caban, 1995). Several studies have also drawn attention to the role of permafrost in ice-marginal environments adding a temporal and, to a lesser extent, spatial influence on porewater state (solid or liquid) and the thermo-mechanical properties of the substrate (Krüger, 1996; Evans and Hiemstra, 2005; Robinson *et al.*, 2008; Szuman *et al.*, 2013; Waller *et al.*, 2009). Indeed, a growing body of literature reports such glacier-permafrost mechanisms from both relict (e.g. Szuman *et al.*, 2013) and modern glacial environments (e.g. Mackay, 1959; Kupsch, 1962; Mackay and Mathews, 1964; Mooers, 1990; Vaughan *et al.*, 2014).

In East Anglia, the existence of regionally extensive permafrost during the onset of glaciation is well established

(Gardner and West, 1975; Rose *et al.*, 1985; Lee *et al.*, 2003; Rose and Allen, 1977; Kemp *et al.*, 1993; Murton *et al.*, 1995; Candy *et al.*, 2011, and references therein). Indeed, several studies from the region suggest glacier-permafrost interactions in relation to glacitectonic raft detachment (Banham, 1975; Burke *et al.*, 2009) and melange development (Waller *et al.*, 2011). However, the recognition of glacitectonic structures that are genetically related to permafrost (rather than drier or wetter substrate conditions) in a more generic ice advance context is challenging because geological evidence for frozen ground is often subtle (if present) and seldom unequivocal (Waller *et al.*, 2011). Nevertheless, due to the known presence of extensive permafrost in East Anglia during glaciation, it is considered that glacier-permafrost interaction may have played a significant role in controlling glacitectonic processes within the lower parts of the structural sequence (A1–A4, part of A5) as indicated by two local studies (Richards, 2000; Whiteman, 2002). Within this scenario, proglacial or ice-marginal thrusting of permafrost could have led to the repeated thrust-stacking of frozen preglacial sediment that formed the lower glacitectonite within the shear zones. Thrust detachment is likely to have occurred along localized rheological boundaries relating to either (or both) lithology or the thermo-mechanical properties of the substrate. Contemporaneous folding and dewatering during thrust-stacking could indicate ductile deformation of warm permafrost and localized pressure-melting. In contrast, the development of laterally persistent sub-horizontal décollement surfaces during subsequent subglacial overriding implies a rheological discontinuity developed regionally that was not purely lithology-controlled – for instance, the base of the permafrost active layer.

Regional-scale correlation of till units: myth or reality?

In Britain, lithostratigraphy is a widely employed technique within lowland glaciated terrains. However, even in classic glacial sequences such as East Yorkshire and East Anglia, scientific opinion is divided as to whether lithostratigraphy can (Banham, 1968; Madgett and Catt, 1978; Ehlers and Gibbard, 1991; Lunkka, 1994; Lee *et al.*, 2004a; Catt, 2007; Rose, 2009) or cannot be robustly applied (Hart, 1987; Hart and Boulton, 1991a; Roberts and Hart, 2005; Boston *et al.*,

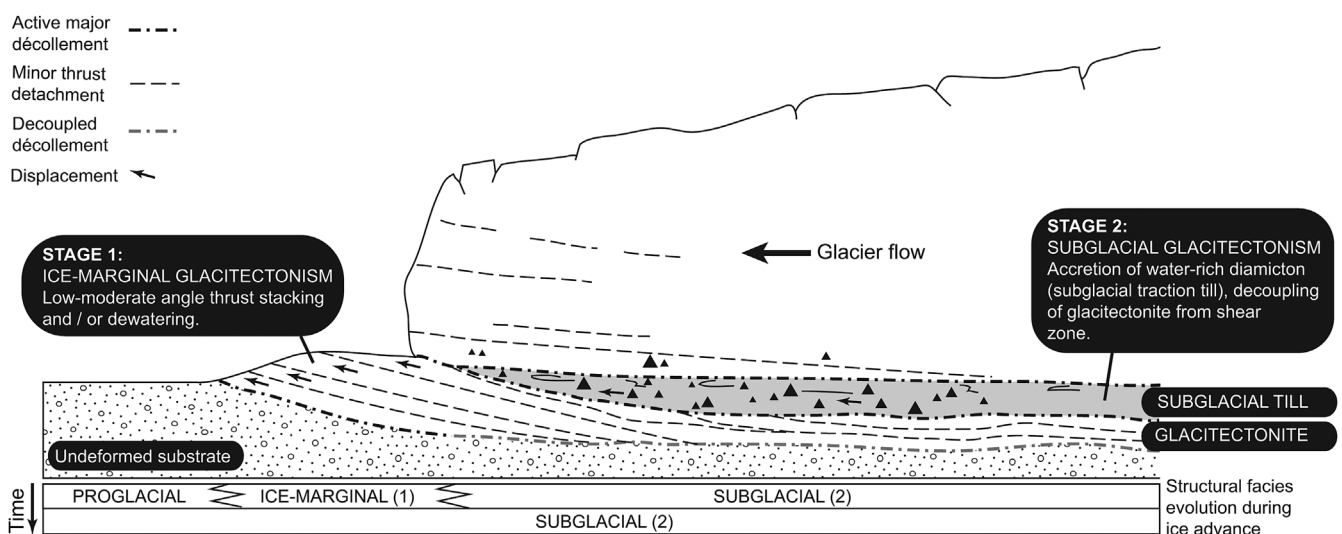


Figure 13. A schematic model showing the development of glacitectonites and subglacial tills by ice-marginal thrusting and subglacial overriding during ice advance. During Stage 1, ice-marginal thrust stacking and dewatering of pre-existing substrate materials predominate. Subsequent overriding during ice advance and rapid till accretion causes the glacitectonite to be decoupled with strain accommodated within the till.

2010; Evans and Thomson, 2010). A wide range of factors that may limit the development of laterally extensive glacial sequences/units include: (i) the dynamic range of processes that control the spatial character of units, (ii) the facies complexity of glacial sequences, (iii) facies repetition at multiple stratigraphic levels and (iv) glaciectonic deformation and structural re-ordering of strata (Rose and Menzies, 1996). However, despite these factors, in certain glaciological situations some glacial units – especially diamicton units – do form distinctive and spatially extensive lithological horizons.

The glacial sequence of northern East Anglia provides a good example of where diamictons (A1–A4 tectonostratigraphic assemblages) form regionally mappable units that possess remarkably consistent lithological properties (Rose, 2009). Key controls on the development of lithologically persistent diamicton units appear to be limiting ice-bed traction, thereby reducing local erosion and entrainment of new lithologies, coupled with relatively homogenous substrate geology. Despite these ‘exceptions to the rules’, glaciogenic diamictons simply form a single and frequently discontinuous component of more complex and extensive glaciogenic/tectonostratigraphic units. These can be highly variable in lithology, composition, structure and thickness but form regionally extensive and mappable surfaces or zones that constrain discrete glaciogenic packages that record phases of glacial landsystem development (van der Wateren, 2005; Pedersen, 2012, 2014). Regional correlation of these detachments enables a more dynamic process-based stratigraphic approach with the potential to deploy specific techniques (e. g. seismic) that enable simpler correlation of onshore and offshore sequences.

Middle Pleistocene glacial history of northern East Anglia

Palaeogeographical evolution

The Middle Pleistocene glacial history of northern East Anglia can be linked to six major oscillations of British North Sea and Pennine ice into the region (Fig. 14). Each oscillation led to the development of a tectonic detachment and/or major sedimentary bounding contact (A1–A6) that can be traced regionally where they bound packages of glaciogenic sediment forming individual *glaciogenic parasequences* (or formations).

The geometry of these detachments reveals three separate ice sheet configurations. The first corresponds to the A1 and A2 tectonostratigraphic assemblages and accretion/deposition of the Happisburgh and Corton formations, respectively. An initial advance of British North Sea ice into north-east Norfolk, possibly over an extensive area of permafrost, led to the development of the A1 detachment and accretion of the Happisburgh Diamicton Member (Fig. 14a). Northwards retreat of the ice margin led to the establishment of several shallow but progressively enlarging glacial lake basins (Ostend Clay Member) with localized deltaic input (Happisburgh Sand Member) (Lunkka, 1994; Hart, 1999; Lee *et al.*, 2008). A more extensive readvance from the north and north-west led to the development of the A2 detachment with deposition of the Starston and Corton Diamicton members in areas of chalk (dominantly) and Quaternary substrate, respectively (Fig. 14b). This ice advance reached the Bytham River valley causing localized drainage diversion (Rose *et al.*, 1999b; Lee, 2001) and ice-damming (Mathers *et al.*, 1987). Preservation of the Corton Formation to the west of Diss is restricted to depressions within the rockhead surface. It implies that ice extended further westwards, but glacial deposits have been largely removed during the A5 advance. Deposition of the Leet Hill Sand and Gravel and Corton Sand members

occurred as the ice margin retreated northwards, forming a thick drape that infilled the pre-existing topography. A distinctive angular unconformity and period (of unknown duration) of widespread landscape modification occurs between the top of the Corton Formation and the development of the A5 detachment in the Waveney Valley (Fig. 15) extending west towards Norwich. This interval includes evidence for widespread fluvial erosion (Lee *et al.*, 2004b), marine transgression (Lee *et al.*, 2006; Read *et al.*, 2007), landscape stabilization including the development of boreal (Candy, 2002) and then arctic soils (Bridge and Hopson, 1985; Arthurton *et al.*, 1994; Rose *et al.*, 1999b) before the main Anglian Glaciation.

The second ice sheet configuration corresponds to the development of the A3, A4 and A5 tectonostratigraphic assemblages associated with contemporaneous glaciation of the region by British North Sea and Pennine ice lobes. In north-east Norfolk, the A3 detachment truncates underlying deposits and was formed during the south-eastwards advance of British North Sea ice (Fig. 14c). It resulted in the accretion of a subglacial traction till, the Walcott Diamicton Member, and during ice-marginal retreat, deposition of deltaic (Mundesley Sand Member) and ice-distal glaciolacustrine deposits (Ivy Farm Silt Member). Collectively these units form the Mundesley Formation. The A3 and A5 detachments exhibit a mapping continuity in the Eccles–Stalham and Fakenham areas implying broadly contemporaneous accretion of the Walcott Diamicton Member (Mundesley Formation) and the Lowestoft Diamicton Member (Lowestoft Formation) possibly over an extensive area of permafrost. The A5 detachment can be traced westwards across East Anglia, the Fen Basin and the Midlands (West and Donner, 1956; Rice, 1968; Perrin *et al.*, 1979; Rose, 1992; Fish and Whiteman, 2001; Scheib *et al.*, 2011). It records the eastwards flow of the Pennine ice lobe across central and eastern England entraining successive lithologies resulting in the Thrussington–Bozeat–Lowestoft ‘till sheet’ (Scheib *et al.*, 2011). Subglacial erosion of Jurassic and Cretaceous strata destroyed preglacial drainage forming the Fen Basin and lowering the chalk escarpment (Clayton, 2000). In the west, accretion of the Lowestoft Diamicton Member was largely restricted to ‘smears’ within topographic lows and around bedrock obstacles. Further eastwards, possibly in an area characterized by permafrost, the ice became largely decoupled from its bed, resulting in the accretion of a thick till sheet that infilled the pre-existing topography.

A subsequent readvance of British North Sea ice into north Norfolk led to the development of the A4 Tectonostratigraphic Assemblage and the accretion of diamicton, outwash and glaciolacustrine deposits (Sheringham Cliffs Formation) (Fig. 14d). Accretion of diamicton occurred both subglacially (Bacton Green Diamicton Member) and subaquatically as rain-out, turbidite and mass-flow deposits (Banham, 1968; Lunkka, 1994; Pawley, 2006; Lee and Phillips, 2008). As the ice margin retreated northwards, the sediment pile in north Norfolk was progressively overridden by the British Pennine Ice lobe from the south-west (Lee and Phillips, 2008; Phillips *et al.*, 2008; Fleming *et al.*, 2013). This caused the A5 detachment to extend across north Norfolk forming a variably pervasive glaciectonite (West Runton Melange Member) and a discontinuous chalky till (Weybourne Diamicton Member) (Fig. 14e).

The third ice sheet configuration relates to the development of the A6 Tectonostratigraphic Assemblage and deposition/accretion of till and outwash deposits (Britons Lane Formation) during an advance of British North Sea ice from the north and north-west (Fig. 14f). In north-west Norfolk, this led

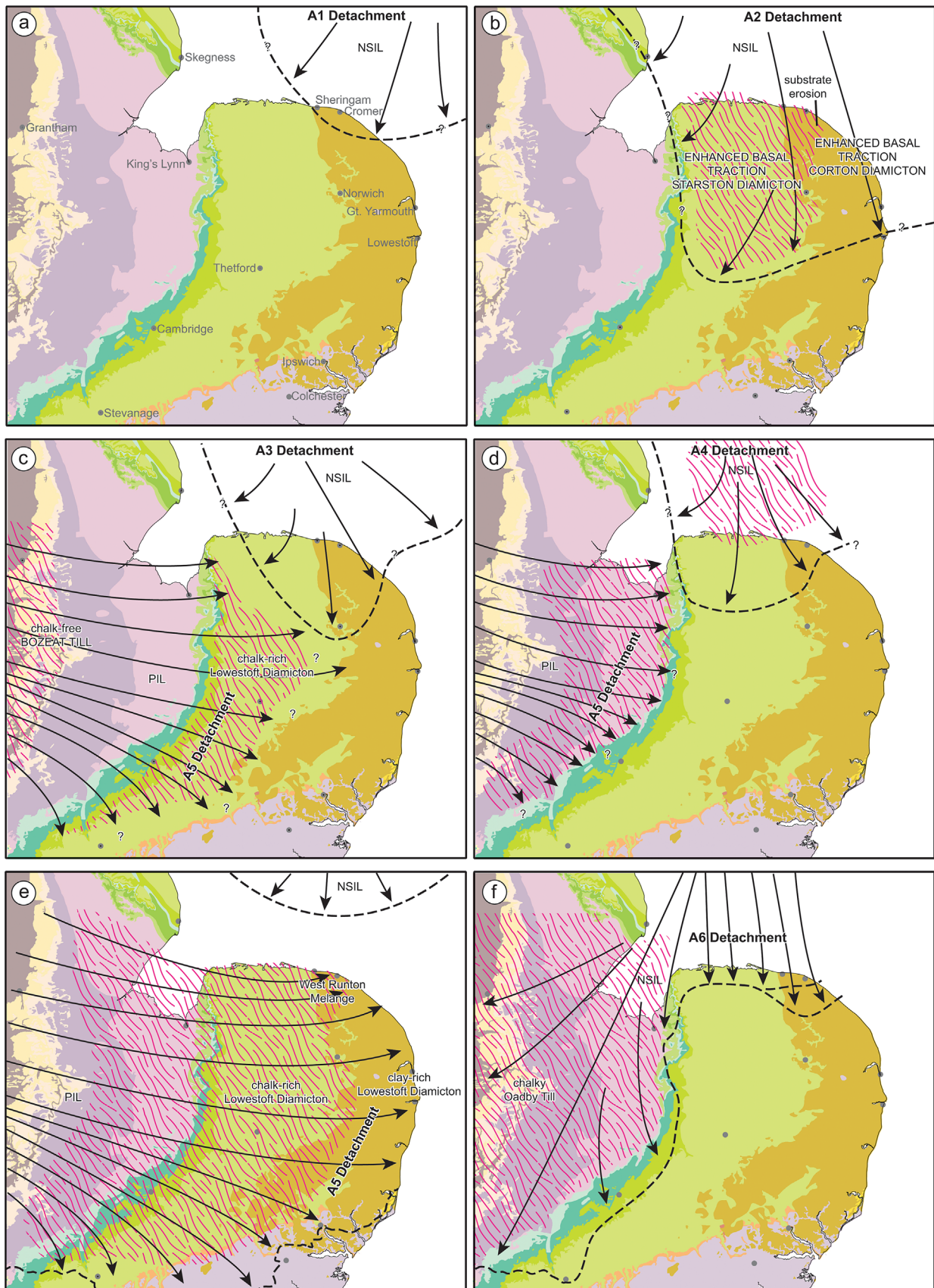


Figure 14. Schematic palaeogeographical maps showing the glacial history of northern East Anglia and adjoining areas relative to A1–A6. (a) A1 Detachment including the Happisburgh Diamicton Member. (b) A2 Detachment including accretion of the Starston and Corton Diamicton members of the Corton Formation. (c) A3 and A5 Detachments – accretion of the Walcott Diamicton Member in north-east Norfolk, lowering of the chalk escarpment and accretion of the Lowestoft Diamicton Member in the west of the region. (d) A4 and A5 Detachments – accretion of the Bacton Green Diamicton Member in north Norfolk, erosion of Jurassic mudstones in the Fen Basin and accretion of the Lowestoft Diamicton Member. (e) Main A5 Detachment – widespread erosion of Jurassic mudstones (Fen Basin) and chalk bedrock; localized accretion of chalk-rich Lowestoft Diamicton (west) and Weybourne Diamicton members (north) and clay-rich Lowestoft Diamicton Member in the east as an extensive till sheet; pervasive glaciectonic deformation in north-east Norfolk and accretion of the West Runton Melange Member. (f) Detachment A6 – glaciectonism and outwash sedimentation relative to a dynamic and oscillating margin in north Norfolk, breaching and erosion of The Wash and accretion of the Oadby Till in the Midlands.

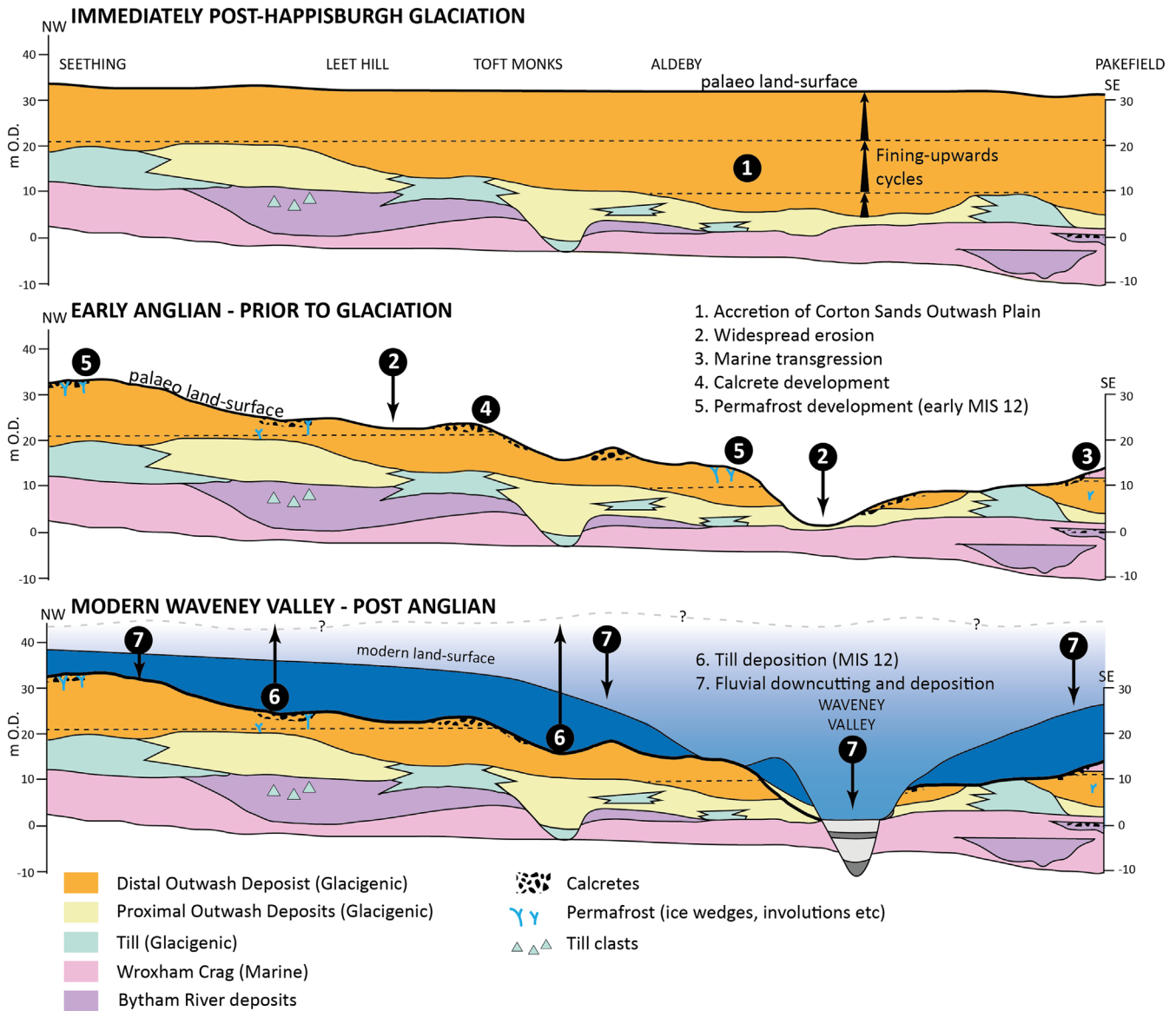


Figure 15. Schematic cross-section through the Lower Waveney Valley (adapted from Hopson & Bridge, 1987) showing a marked angular unconformity and phase of landscape change between the accumulation of the Corton Sand Member (A2 parasequence) and the accretion of the Lowestoft Diamicton Member (A5 Detachment).

to the development of the A6 detachment as a thin subglacial shear zone comprising highly chalky comminution tills (Stody Diamicton Member) and outwash deposits (Table 2; Ehlers *et al.*, 1987; Fish and Whiteman, 2001; Pawley, 2006). In north-east Norfolk a 12-stage ice-marginal retreat sequence developed with the maximum known southwards ice extent occurring between Aylsham, Aldborough and Mundesley (Lee *et al.*, 2013). The Cromer Ridge (*sensu stricto*) forms a temporary sill-stand position during ice-marginal retreat (Lee *et al.*, 2013). Subsequent thinning of the glacier margin, coupled with changes in substrate drainage and slope, caused repetitive thrust-stacking and the generation of an over-sized morainic landform (Lee *et al.*, 2013). Outwash deposits capping the landform have been dated by optically stimulated luminescence to MIS 12 (Pawley *et al.*, 2008) and at Sidestrand contain an organic kettle-hole fill attributed to the early Hoxnian (Hart and Peglar, 1990; Preece *et al.*, 2009).

Further ice-contact and outwash sequences occur at lower elevations situated to the north of the Cromer Ridge. These include a series of S-directed small ice-marginal thrust features (Lee *et al.*, 2013) at Weybourne Town Pit (Fish *et al.*, 2000; Evans *et al.*, 2011), Stody (Pawley, 2006) and several other sites regionally (Ehlers *et al.*, 1987; Pawley *et al.*, 2008).

Further evidence includes the development of the Kelling and Salthouse sandurs (West, 1957; Straw, 1960; Straw and Clayton, 1979; Pawley, 2006), the Blakeney Esker (Sparks and West, 1964; Gray, 1997; Gale and Hoare, 2007), reported kame terraces flanking the Glaven Valley (Sparks and West, 1964) and mounds of glaciifluvial gravel further west towards Stiffkey (Moorlock *et al.*, 2008). The most northern glacigenic remnants are the steep-sided glacitectonic hillocks between Overstrand and Weybourne that form a heavily dissected thrust-block moraine (Lee *et al.*, 2013) and thrust complexes recognized offshore beneath Dudgeon Shoal (C. Mellett, pers. comm., 2014). Currently, none of these lower elevation landforms or deposits has been successfully dated and the simplest interpretation is that they simply record a phase of glacier-downsizing (i.e. thinning) from the main Cromer Ridge forming phase (Lee *et al.*, 2013). However, an alternative scenario is that some or all of these lower-elevation features may have formed during a younger pre-Devensian glacial episode(s) (Lee *et al.*, 2013; Westaway *et al.*, 2015).

Correlation of the A6 Detachment with sequences to the west is speculative but it is tentatively correlated to the Oadby Till Member within the Midlands. Previously, the Oadby Till

Member was correlated with the A4 Detachment (Bacton Green Diamicton Member), with both overlying the Thrussington–Bozeat–Lowestoft Till Sheet (Hamblin *et al.*, 2005; Rose, 2009; Lee *et al.*, 2011). However, the recognition that the A5 Detachment (Thrussington–Bozeat–Lowestoft Till Sheet) overlies the A4 Detachment (Bacton Green Till Member) in northern East Anglia precludes this possibility.

Conclusions

- Within this paper a tectonostratigraphic–parasequence approach is applied to the Middle Pleistocene glacigenic succession of northern East Anglia. Individual stratigraphic assemblages ('Formations') are bound by lower and upper boundaries defined by glacitectonic detachments or sedimentary contacts that record the first influence/sediment input by glacial processes.
- Six separate tectonostratigraphic–parasequence assemblages (A1–A6) are defined in northern East Anglia and characterized by glacitectonic, sedimentological, lithological, kinematic and genetic properties. They relate to repeated oscillations of British North Sea and Pennine ice lobes into the region. A regional-scale post-A2 angular unconformity of unknown duration that encompasses a period of widespread landscape erosion and stabilization (soil development) is recognized.
- The style of glacitectonism generally becomes variable and more pervasive within higher parts (A5 and A6) of the structural sequence. Differences in the geometry and style of glacitectonic deformation are strongly controlled by substrate rheology (lithology, porosity and permeability), porewater availability and the presence or absence of permafrost.
- Field evidence (A1–A4, part of A5) demonstrates that during ice advances, the substrate (i.e. the pre-glacial land surface) was largely decoupled from the subglacial shear zone during rapid till accretion. This limited the transmission of strain downwards into the substrate acting to preserve pre-existing sediments and structures. This mechanism can explain why archaeology (the oldest in northern Europe) has been so well preserved beneath glacial deposits in Eastern England.
- Key controls on the bulk lithology of a subglacial traction till are the lithological complexity of the substrate and the degree of ice-bed coupling (i.e. traction). In areas of relatively simple substrate geology and limited ice-bed coupling, the lithological character of tills can remain comparatively uniform over wide areas.

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