A THRUST-STACKED ORIGIN FOR INTER-STRATIFIED TILL SEQUENCES: AN EXAMPLE FROM WEYBOURNE TOWN PIT, NORTH NORFOLK, UK.

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ABSTRACT

Subglacial processes, and their temporal and spatial variations, play a significant role in controlling the behaviour of ice masses. The processes leading to the formation and emplacement of inter-stratified sequences of subglacial tills are, however, particularly poorly understood. Such sequences are relatively widespread, having been found in, for example, the UK, Canada and Germany. Those of the Weybourne area of north Norfolk, UK, are especially interesting in that the majority of the sediment pile is composed of repeated, inter-laminated subglacial till units with very few non-till units present. Many contrasting mechanisms for this highly contorted sequence have been suggested throughout a long history of investigation at the site and even the direction of ice advance that produced the deformation has proved difficult to resolve. In order to address this, the current study combines lithological, structural and palynological techniques to investigate the exposure at Weybourne Town Pit. A re-interpretation of the sequence is presented in which the tills are seen to have been derived initially as subglacial tills from advances of the Middle Pleistocene British Ice Sheet flowing southwards along the east coast of England. A stage of brittle deformation linked to oscillation of the ice margin is identified as occurring after the primary deposition phase. This secondary deformation phase was responsible for localised thrust-stacking of the till blocks and resulted in the inter-stratified sequence seen today.

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INTRODUCTION

Investigation of the dynamics of the major Quaternary ice sheets that existed across northern Europe and North America has revealed a highly significant role for subglacial processes, and their temporal and spatial variations, in controlling the behaviour of ice masses (Evans *et al*., 2006). These findings are important in the context of the likely response of modern ice sheets, especially the Greenland and western Antarctic ice sheets, to perturbation by current and future climate changes (Hughes, 1996; Bentley, 1997).

Sequences composed of inter-stratified subglacial tills are widespread, having been identified in, for example, the UK, Canada and Germany (Fish et al., 2000; Friele and Clague, 2002; Menzies and Ellwanger, 2011). The sequences are composed of stacked, repeated units of two or more till lithofacies most often inter-digitated with units of non-till lithofacies. These units may cross-cut each other, truncating the internal structure of the unit. Exposures range in height between 2 m and 11 m. However, the formation of these sequences is particularly poorly understood and several contrasting mechanisms have been proposed, including: (1) the confluence of ice sheets (Banham and Ranson, 1956; Cox and Nickless, 1972; Ehlers and Gibbard, 1991; Lunkka, 1994), (2) different advances or multiple lobes of the same ice sheet (Straw, 1965; Perrin *et al*., 1979; Ehlers *et al*., 1987, 1991; Hamblin *et al*., 2005), (3) a sedimentary 'melt-out' origin (Haldorsen and Shaw, 1982; Shaw 1982, 1983) and (4) glaciotectonic processes associated with a subglacial deforming bed (Hart et al., 1990; van der Meer *et al*., 2003; Menzies *et al*., 2006).

The Weybourne area of north Norfolk, UK is one region where such inter-stratified tills are exposed. The north Norfolk area, itself, is seen to possess one of the best Early and Middle Pleistocene sedimentary records in north-western Europe (Lee *et al*., 2008; Rose, 2008) and inter-stratified tills are readily visible in a highly contorted sequence at Weybourne Town Pit (National Grid Reference TG 114 430). The sequence here is especially interesting in that the majority of the sediment pile is composed of tills inter-stratified with one another. Very few non-till lithofacies are present. This area has been affected by a number of Early and Middle Pleistocene glaciations (Hamblin *et al*., 2005) and the sediments at the pit are believed to relate to the latter of these glaciations which reached its most southerly limit just to the south of the pit, along the line of the Cromer Ridge.

Despite a long history of investigation, the mechanisms for the emplacement of the inter-stratified facies at Weybourne Town Pit remain enigmatic (Fish *et al*., 2000; Pawley *et al*., 2004; Hart, 2007). Understanding of the direction of ice movement responsible for the inter-stratified tills is also poor, with contrasting interpretations of structural and lithological evidence suggesting numerous different directions (Table 1). For example, structural analysis presented in Fish *et al*. (2000), indicates that ice flow from the southwest was responsible for the chalky and sandy tills exposed in the pit, whilst lithological evidence implies an easterly provenance. Till fabrics examined in Hart (2007), however, imply ice flow directions from the northeast and northwest.

In order to address the controversy surrounding the formation of the inter-stratified sequence and the direction of ice movement responsible for the tills, this paper presents an investigation of the Middle Pleistocene sequence at Weybourne Town Pit, north Norfolk, UK. A suite of structural, lithological and palynological techniques are combined to thoroughly examine the exposure. The inter-stratified sequence is interpreted as comprising a primary stage of till deposition and a

Table 1. Direction of ice advances responsible for the tills of the north Norfolk area, as suggested by some earlier researchers. Study locations: NN= north Norfolk, C= Weybourne Coast and WTP= Weybourne Town Pit. Ice direction: SW-W= ice from between the southwest and south, E&W= ice from the east and west. Lithology: ST=sandy till and CT=chalky till.

Reference	Study Location	Methodology	Direction	
Banham and Ranson (1965)	C & WTP	Clast fabric	NE & NNE	
		Fold orientation	SSW-SW	
Ehlers *et al*. (1987)	NN	Stratigraphy	SW	
		Clast fabric	SW & N	
		Thrust orientation	W & SW	
Fish *et al*. (2000)	C & WTP		ST	CT
		Stratigraphy	W-NW-N	W & NW
		Clast fabric	NNW & SSE	NNW, NE & N
		Fold orientation	SW	SW
		Chalk micropalaeontology	E & W	E & W
Fish and Whiteman (2001)	NN & WTP		ST	CT
		Chalk micropalaeontology	NW	NNW
Pawley *et a*l. (2004)	C		ST	CT
		Clast fabric	NNW	N/A
		Fold orientations	NNW	N/A
		Chalk micropalaeontology	N/A	N
Hart (2007)	WTP		ST	CT
		Clast fabric	NE	NW
		Fold orientation	NNW	NNW

secondary phase of deformation through till remobilisation and emplacement. Flow directions for the ice responsible for depositing the tills are determined, a model for ice-marginal thrust-stacking of till blocks is outlined and the stratigraphic implications of this are discussed.

STUDY SITE AND GEOLOGICAL CONTEXT

Weybourne Town Pit (National Grid Reference TG 114 430), a disused brick pit located to the east of the village of Weybourne in north Norfolk, forms the locality for this study. The pit is approximately 50 m by 20 m in area and 4 m deep. A south-facing exposure of approximately 5 m length and 2 m height reveals a contorted series of Quaternary sediments on the western side of the north quarry wall. The pit lies just to the south of the Late Pleistocene (Devensian) ice limit (Pawley *et al*., 2006) within an area of gently undulating topography (Figure 1). To the south of the pit, the ground rises towards the Cromer Ridge- a major Middle Pleistocene ice marginal push moraine and outwash complex (Hart, 1990; Pawley *et al*., 2005). To the north, the ground slopes gently to the modern coastline, where low cliffs (1-10m) are present.

A number of different lithostratigraphical schemes have been proposed for the area's glacial deposits (Table 2) and the exact number of glaciations the sequences record is contentious. As early as 1877 Geikie suggested that the region had been affected by four glaciations, although this model was largely refuted at the time (Geikie, 1877 in Baden-Powell, 1948). Later, Baden-Powell (1948) advocated the existence of four tills. Following this, two major lithofacies associations were invoked (Banham & Ranson, 1956) and ascribed to a single ice sheet expansion during the Middle Pleistocene (Perrin *et al*., 1979; Bowen *et al*., 1986). Lunkka (1994) expanded the scheme to involve five tills and these became attributed to three separate ice sheet expansions occurring throughout the Pleistocene (Hamblin *et al*., 2000).

However, the published stratigraphies still failed to resolve observed differences in the succession between north Norfolk and the Waveney Valley area to the west. As a result, a reappraisal of the region's stratigraphy was undertaken by Lee *et al*. (2004) and Hamblin *et al*. (2005). They proposed a more robust scheme involving four formations. The stratigraphical nomenclature detailed in Lee *et al*. (2004) and outlined in Hamblin *et al.* (2005) is adopted in this study (Table 3).

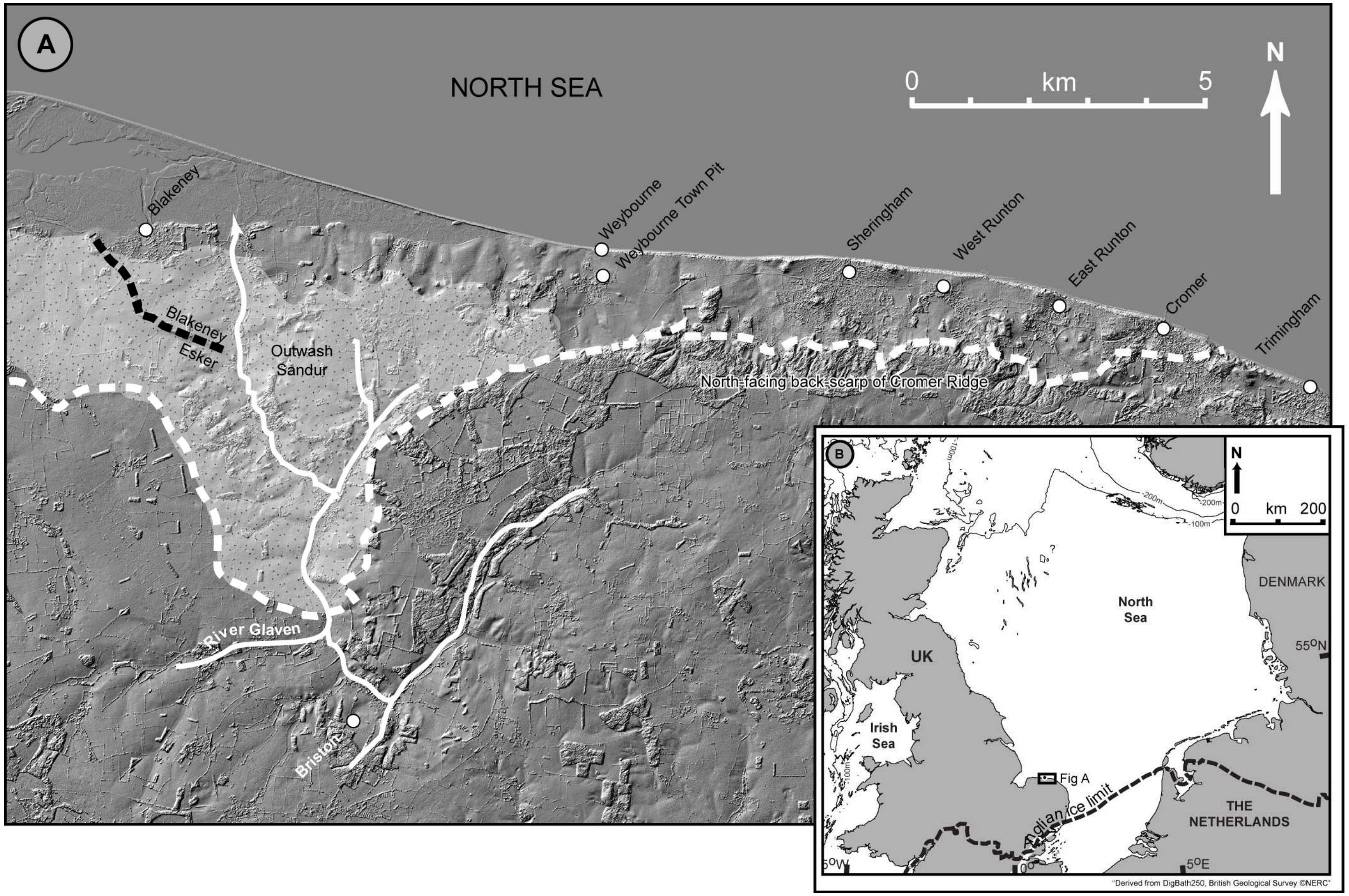

Figure 1. The Weybourne area of Norfolk, UK and location of the Weybourne Town Pit study site. Major glacial geomorphological features (A) and regional context (B) are shown. Middle Pleistocene (Anglian) ice limit after Bowen *et al*. (1986).

Table 2. Previous lithostratigraphical schemes for the glacial deposits of Norfolk.

<table>
<tr><th>Baden-Powell (1948)</th><th>Banham & Ranson (1956)</th><th>Lunkka (1994)</th><th>Lee et al. (2004), Hamblin et al. (2005)</th></tr>
<tr><td></td><td>Briton’s Lane Sand and Gravel</td><td></td><td>Briton’s Lane Formation</td></tr>
<tr><td>Hunstanton Boulder Clay</td><td rowspan="2">Lowestoft Till</td><td rowspan="2">Lowestoft Till Formation
Marly Drift Member</td><td>Sheringham Cliffs Formation</td></tr>
<tr><td>Gipping Boulder Clay
Lowestoft Boulder Clay</td><td rowspan="3">Lowestoft Formation</td></tr>
<tr><td rowspan="3">Cromer Till</td><td>Third Cromer Till</td><td>Cromer Diamicton Member
Mundesley Diamicton Member</td></tr>
<tr><td>Second Cromer Till</td><td>Walcott Diamicton Member</td></tr>
<tr><td>First Cromer Till</td><td>Happisburgh Diamicton Member</td><td>Happisburgh Formation</td></tr>
</table>

Table 3. The pre-Devensian glacial stratigraphy of Norfolk, after Lee *et al*. (2004) and Hamblin *et al*. (2005).

Formation	Members	Characteristics
Briton’s Lane Formation	Briton’s Lane Sand and Gravel Member	Sands and gravels
Sheringham Cliffs Formation	Weybourne Town Till Member	Silt and chalk-rich matrix-supported diamicton
	Runton Till Member	Dark grey (10YR 4/1) to very dark greyish brown (2.5YR 3/2) matrix-supported diamicton.
	Bacton Green Till Member	Dark yellowish sandy brown (10YR 4/4) to dark grey (5Y 5/1) matrix-supported diamicton with sand beds.
Lowestoft Formation	Walcott Till Member	Olive-grey (2.5Y 5/1) to olive-brown (2.5Y 4/3) silt-rich, weakly-stratified matrix-supported diamicton.
	Lowestoft Till Member	Clay-rich, massive matrix-supported diamicton.
Happisburgh Formation	Corton Till Member	Light olive-brown (2.5Y 5/4) to olive-brown (2.5Y 4/4), sandy, generally massive matrix-supported diamicton.
	Happisburgh Till Member	Yellowish grey (2.5Y 4/1) to grey (5Y 4/1), generally massive matrix-supported diamicton.

METHODOLOGY

Weybourne Town Pit was visited between 2002 and 2003 (Lee, 2003) with follow up work by the present authors in 2008. Macro-scale features were described from the exposure on the western side of the north quarry wall. Sediment type, type of bedding, unit geometry and structure were recorded and bulk samples of the diamicton units were collected. These samples were separated into 4-8 mm and 8-16 mm fractions through sieving and the lithology of clasts retained from these fractions was examined in order to determine till provenance. Till provenance was further refined by sampling the diamicton units for palynological analysis. Two samples were taken from each of the diamicton lithofacies identified. These samples were processed following the procedures outlined in Wood *et al*. (1996) and prepared using the sodium hexametaphosphate method of Riding and Kyffin-Hughes (2004; 2006). Palynomorphs were counted and categorised according to age, stratigraphical range and geographical distribution.

DESCRIPTION

Lithofacies

Eleven units, divisible into 4 lithofacies have been identified by the current study at Weybourne Town Pit (Figure 2):

Lithofacies A (Unit 1): Lithofacies A consists of a pale yellow (2.5Y 7/3) to light yellowish brown (2.5Y 6/3), faintly laminated, highly calcareous marl. Within the exposure this lithofacies is restricted to a single unit, Unit 1, which has a maximum observed thickness of 0.58 m.

Lithofacies B (Unit 2): Lithofacies B comprises an olive yellow (2.5Y 7/6) to brownish yellow (10YR 6/8) silty sand which is weakly stratified and exhibits convolute bedding and flame-like contortions. This lithofacies can be traced discontinuously throughout the entire length of the section and is restricted to a single unit, Unit 2, which ranges in observed thickness between 0.15-0.25 m.

Lithofacies C (Units 3, 5, 8 and 10): Lithofacies C consists of a light yellowish brown (2.5Y 6/4) to brownish yellow (10YR 6/6), matrix-supported diamicton with a clayey sand matrix and moderate calcium carbonate content (17-19%). Localised contorted sandy inclusions and discontinuous laminae of more calcareous material are present. This lithofacies occurs as several individual units in the upper 1.5m of the section which range in thickness between 0.1-0.26m. These are the darker horizons seen in the top half of Figure 2.

Lithofacies D (Units 4, 6, 7, 9 and 11): Lithofacies D comprises a light grey (5Y 7/2) to pale yellow (2.5Y 7/4), matrix-supported diamicton, exhibiting a highly calcareous (61-73%) clayey silt matrix. Localised contorted inclusions of sandy material are present. This lithofacies also occurs as several individual units in the upper 1.5 m of the section: the lighter horizons seen in the top half of Figure 2. These range in thickness between 0.1-1.6 m.

Structure

Twelve bounding structures between individual units are identified in the current study. These are typically sharp, 2-3 mm thick and dip at shallow angles towards a general northerly direction. Repetition of units of Lithofacies C and D is evident in the upper 1.5 m of the section. The lower portion of the section, meanwhile, is composed of a single unit of Lithofacies B overlying one unit of Lithofacies A. The bounding structures and geometry of the individual units are described below (Figures 2 & 3):

Structure 1 (Unit 1-2 discontinuity): Structure 1 represents a sharp, sub-horizontal, slightly undulatory boundary separating Units 1 and 2.

Structure 2 (Unit 2-3 discontinuity): Structure 2 is undulatory, rises from east to west by approximately 0.4m and is generally sharp in appearance.

Structure 3: Structure 3 comprises a series of small-scale extensional faults which offsets Structure 2.

Structure 4 (Unit 3-4 discontinuity): Structure 4 is sharp and irregular and dips at shallow angles towards the northwest-northeast.

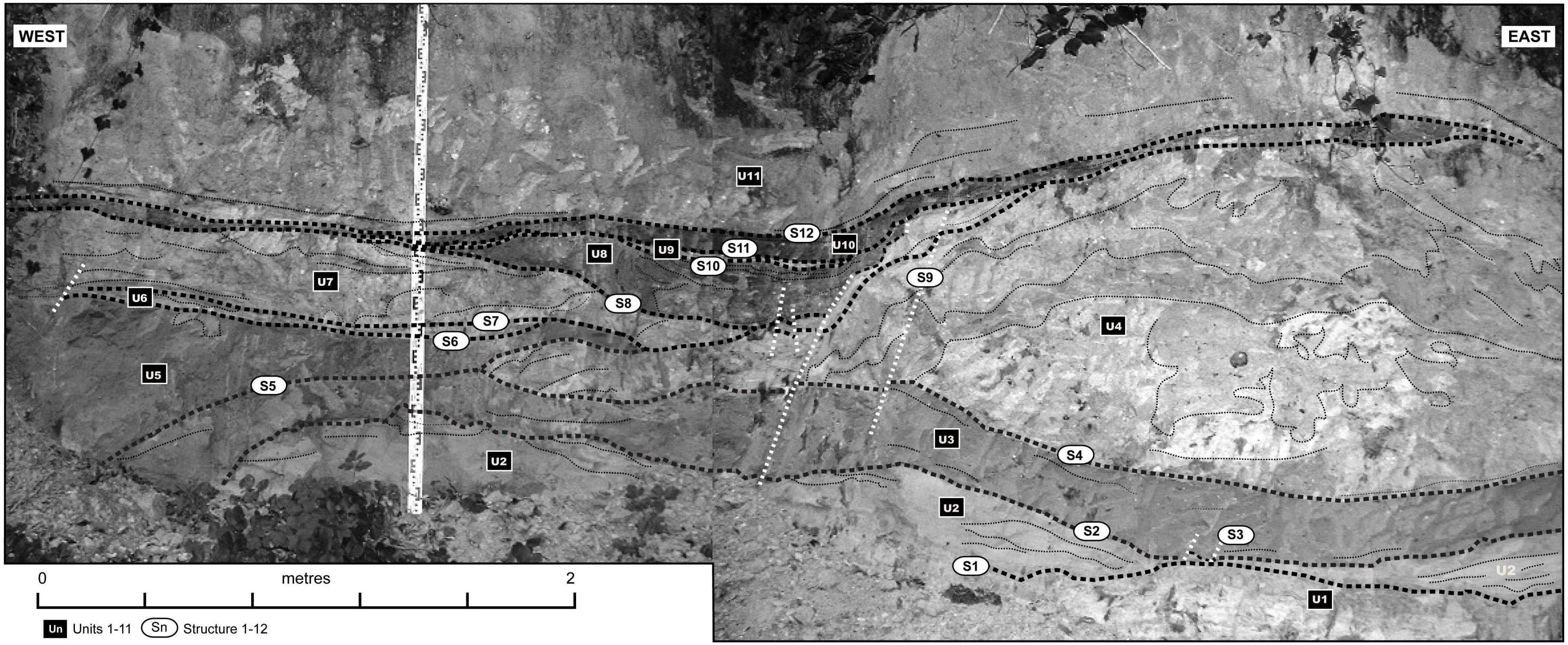

Figure 2. Lithological and structural interpretation of the north quarry wall exposure at Weybourne Town Pit. Repetition of Lithofacies C (Units 3, 5, 8 and 10)) and Lithofacies D (Units 4, 5, 6, 7, 9 and 11) can be seen in the upper 1.5 m of the section, overlying a single unit of Lithofacies B (Unit 2) and a basal unit comprised of Lithofacies A (Unit 1).

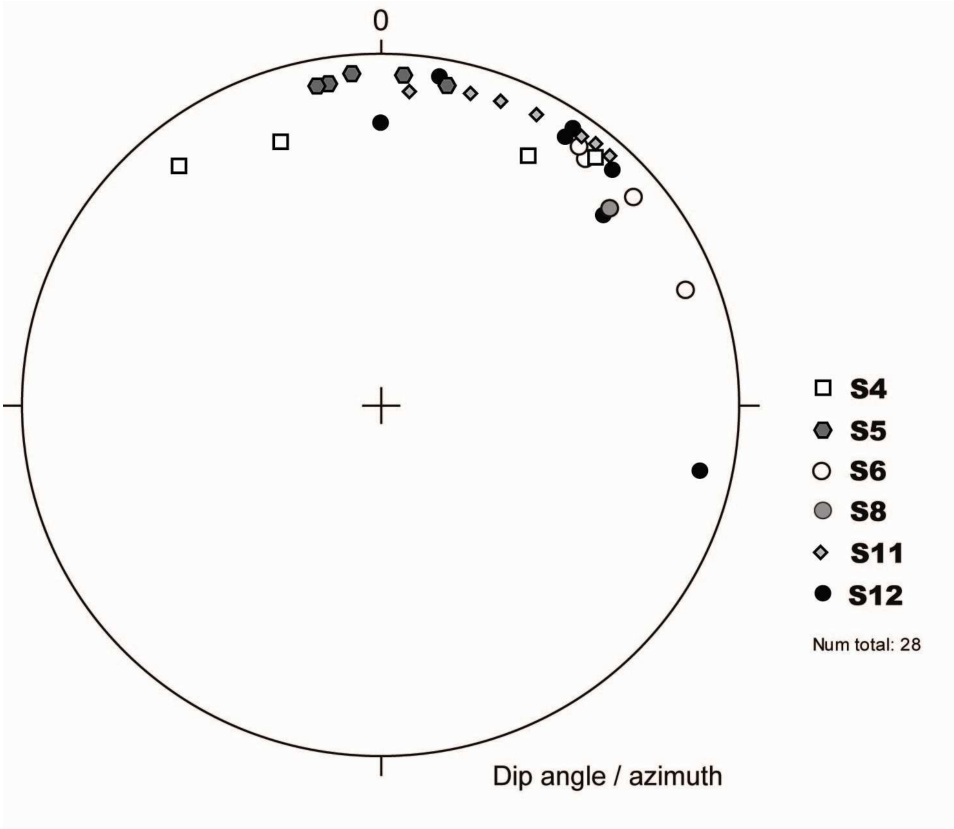

Figure 3. Equal area stereographic projection for planar structures identified within Weybourne Town Pit. Bounding structures, prefix S, as marked on Figure 2 and in the text. A general dip at shallow angels between the northwest and northeast can be seen.

Structure 5 (Unit 4-5 and 3-5 discontinuity): Unit 3 and 4 and Structure 4 are truncated by Structure 5 towards the western half of the section.

Structure 6 (Unit 5-6 discontinuity): Structure 6 dips at a shallow angle to the northeast and east-northeast.

Structure 7 (Unit 6-7, 5-7 and 4-7 discontinuity): Structure 7 is an undulating and sharp discontinuity that can be traced throughout the western and central parts of the section. This feature cross-cuts Units 4, 5 and 6 and Structures 5 and 6.

Structure 8 (Unit 7-8 discontinuity): Structure 8 dips towards the northeast and is generally sharp. In very localised areas the structure has a flame-like appearance.

Structure 9: Structure 9 comprises a series of high-angle extensional faults with a down throw to the west which cross-cuts Unit 4 and impinge upon Units 2, 3, 7 and 8 and structures 2, 4, 7 and 8.

Structure 10 (Unit 8-10 discontinuity): Structure 10 is sharp and slightly irregular and truncates the extensional faults of Structure 9.

Structure 11 (Unit 4-10, 7-10, 8-10 and 9-10 discontinuity): Structure 11 can be traced along the entire length of the section where it truncates Units 4, 7, 8 and 9 and Structures 7, 8 and 10. It is sharp with localised diffuse areas and dips towards the northeast at shallow angles.

Structure 12 (Unit 10-11 discontinuity): Structure 12 forms an undulating discontinuity extending across the whole length of the section, dipping towards the north and northeast at shallow angles.

Clast lithology

The clast population of Lithofacies C is dominated by lithologies derived from older Pleistocene deposits (93.0-93.6%), including: white, brown and chatter-marked flint, quartzite and shell and wood fragments (Table 4). A smaller Cretaceous component, including black flint (4.4-5.9%) and sparse chalk pebbles (0.2-0.6%), is also present. Jurassic ironstone was represented in the 4-8 mm fraction and crystalline clasts included quartz- and micaceous schists. In contrast, the clast composition of Lithofacies D is dominated by Cretaceous lithologies including chalk (59.9-79.5%) and black flint (4.1-6.5%) (Table 4). Clasts derived from Pleistocene deposits occur to a lesser extent and include white, brown and chatter-marked flint (12.6-28.3%) and quartzite (2.0-4.0%). Minor Jurassic (oolitic limestone 0.1%) and Permo-Triass (red sandstone 0.6%) components were also noted.

Table 4. Clast lithological composition of Lithofacies C and D.

Lithofacies	**C**		**D**	
Unit	3,5 and 8		4 and 11	
Fraction (mm)	4-8	8-16	4-8	8-16
Number of clasts	862	158	1009	202
Sedimentary lithologies				
Pleistocene (%)				
Total	93.0	93.6	15.3	33.3
Chatter-marked, white/ brown flint	70.4	86.7	12.6	28.3
Vein quartz, quartzite, schorl	10.4	5.0	2.0	4.0
Rhaxella and greensand chert	0.8	0.6	0.1	1.0
Shell, wood	11.4	1.3	0.6	0.0
Cretaceous (%)				
Total	6.2	5.0	83.6	65.8
Chalk	0.2	0.6	79.5	59.9
Black flint	5.9	4.4	4.1	6.5
Carstone, glauconitic sandstone	0.1	0.0	0.0	0.0
Jurassic (%)				
Total	0.0	1.3	0.1	0.1
Sandstone, limestone, ironstone, shell	0.0	1.3	0.0	0.1
Oolitic sandstone, limestone, chert	0.0	0.0	0.1	0.0
Permo-Triassic (%)				
Total	0.0	0.0	0.6	0.0
Red sandstone, evaporate	0.0	0.0	0.6	0.0
Crystalline lithologies				
Scotland (%)				
Total	0.6	0.0	0.4	0.0
Dalradian, gabbro	0.6	0.0	0.1	0.0
Granite, granodiorite, quartzporphyry	0.0	0.0	0.1	0.0
Acid porphyry	0.0	0.0	0.2	0.0
Scotland/ northern England (%)				
Total	0.1	0.0	0.0	0.0
Quartz dolerite / basalt	0.1	0.0	0.0	0.0
Unknown lithology (%)	0.1	0.0	0.2	0.0

Table 5. The sampled palynomorph content of Lithofacies C and D.

Lithofacies	C		D	
Unit	3	8	4	11
Grains per slide	716	295	1155	1210
Quaternary forms (%)	1.7	9.8	7.8	12.6
Palaeogene (%)				
Dinoflagellate cysts	0.4	1.0	2.9	10.6
Cretaceous (%)				
miospores	1.8	0.3	1.4	0.9
Dinoflagellate cysts	1.2	1.4	3.2	4.5
Jurassic (%)				
miospores	12.8	17.9	14.5	26.7
microplankton	1.8	1.4	2.5	7.3
Carboniferous (%)				
miospores	29.9	2.7	3.8	4.0
Non-age diagnostic forms (%)	51.3	65.5	63.9	43.4

Palynology

Palynomorph assemblages from Lithofacies C (samples from Units 3 and 8 in Figure 2) are dominated by Carboniferous forms (Table 5). Westphalian (*Cirratriradites saturni*) and Viséan/Namurian (*Tripartites trilinguis*) markers are also present. Long-ranging Mid-Late Jurassic miospores are relatively common, including *Callialasporites* spp., *Classopollis* spp. and *Cyathidites* spp. Jurassic microplankton are relatively scarce but both *Halosphaeropsis liassica* derived from the Lower Toarcian (Bucefalo Palliani and Riding, 2003) and *Cribroperidinium globatum*, a key Kimmeridgian marker, are present. Cretaceous material is rare but includes the Lower Cretaceous spores *Appendicisporites* and *Cicatricosporites* and the Upper Cretaceous dinoflagellate cyst *Spongodinium delitiense*. A sparse Palaeogene input including *Cordosphaeridium gracile* and *Dracodinium*-the latter genus derived from the early-mid Miocene (Powell, 1992)-is also recognised. Somewhat variable levels of Quaternary pollen are present.

Samples from Lithofacies D (taken from units 4 and 11 in Figure 2) are significantly richer in organic palynomorphs than those from Lithofacies C (Table 5). The Carboniferous content is of low quantity and diversity, with only *Densosporites* spp. and *Lycosphora pusilla* recovered. Conversely, the number of Middle Jurassic miospores is relatively high and includes *Callialasporites* spp., *Classopollis* spp. and *Cyathidites* spp. Jurassic microplankton are also evident in higher percentages than in Lithofacies C, with Lower Toarcian (*Halosphaeropsis liassica* and *Nannoceratopsis gracilis*) markers identified. *Cribroperidinium globatum* and *Cribroperidinium longicorne*, which are strongly indicative of the Kimmeridgian (Riding and Thomas, 1992), were also found. Lower Cretaceous spores are rare but Cretaceous dinoflagellate cysts are present in significant proportions, with the Santonian-Campanian form *Senoniasphaera protrusa* and *Xenascus wetzelii* from the Campanian/Early Maastrichtian observed. No stratigraphically significant Palaeogene dinoflagellate cysts were observed.

INTERPRETATION

Palaeoenvironmental interpretation

Lithofacies A

The fine-grained texture and faint stratification of Lithofacies A suggest deposition within a very low energy subaqueous environment. Derivation from erosion of a local Chalk outcrop is implied by the highly calcareous nature of the lithofacies.

Lithofacies B

Lithofacies B posses a silty-sand texture which is indicative of deposition within a low to moderate energy subaqueous environment. Faint stratification implies minor changes in flow regime or sediment source. Synsedimentary flame structures and convolute-bedding provide evidence for dewatering and indicate rapid and high sedimentation rates, coupled with an elevated porewater content.

Lithofacies C

Lithofacies C occurs as several individual units exposed within the upper portion of the section. The brown coloration, clayey sand matrix, flint-dominated clast content and moderate calcium carbonate concentration of Lithofacies C mirror that of the Bacton Green Till Member of the Sheringham Cliffs Formation (Lee *et al*., 2004). Internal ductile deformation structures suggest deposition under conditions of high pore-water content, most likely as a subglacial till. Clast lithological analysis reveals that Lithofacies C is dominated by locally-sourced lithologies derived from the reworking of pre-existing Pleistocene outcrops. Further travelled clast lithologies include schists and quartz dolerite from northern Britain and ironstones hailing from the Lower Jurassic Redcar Mudstone and/or Cleveland Ironstone formations. Furthermore, palynomorph contents include Jurassic forms from the Yorkshire Basin and sparse Lower Cretaceous palynomorphs from East Yorkshire and/or Lincolnshire. As such, the ice originally responsible for the deposition of Lithofacies C is interpreted to have travelled from northern Britain.

Lithofacies D

The distinctive coloration, highly calcareous matrix and high chalk clast content indicate that the parent material of Lithofacies D is the Weybourne Town Till Member of the Sheringham Cliffs Formation (Lee *et al*., 2004). Evidence for internal ductile deformation structures implies that this till was deposited under conditions of high pore-water content, most likely as a subglacial till. Clast lithological analysis provides evidence for Cretaceous clasts derived from the Santonian-Campanian and Campanian-Maastrichtian Chalk zones of Lincolnshire and the western margin of the North Sea Basin.

Allochthonous palynomorph contents also demonstrate derivation from northern Britain. Indeed, a Carboniferous component characteristic of that in Northumberland, Durham and the Midland Valley of Scotland is present. Such content precludes derivation of this till from the northeast, across the North Sea, as Carboniferous strata are absent at the surface within this area (Lee *et al*., 2002; Riding *et al*., 2003).

Structural relationships

Each of the unit contacts (Structure 1, 2, 4, 5, 6, 7, 8, 10, 11 and 12) identified in Figure 2 is sharp and irregular. They all truncate the internal fabric of the underlying unit and Structures 5, 7 and 11 each truncate a number of units. This suggests attenuation of these units prior to and/or during emplacement of the overlying unit and implies a stage of brittle deformation occurring after the initial deposition of Lithofacies A, B, C and D material.

The internal structure of units 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 is also orientated sub-obliquely to their respective underlying unit contact and so a tectonic rather than sedimentary mechanism for the emplacement of these units may be inferred. No meso-scale folds have been recognised within the sequence, indicating that the tectonic deformation leading to the juxtaposition of these units was predominantly brittle in nature. Consequently, the brittle deformation stage which truncated the upper portions of each of these units may have been contemporaneous with the tectonic emplacement of each of the overlying units.

Synsedimentary flame structures and convolute-bedding contained within the internal fabric of units of Lithofacies B, C and D material, provide evidence for ductile deformation. In light of the above interpretation, this ductile deformation must have occurred prior to the emplacement of these units in their current positions. The onset of brittle deformation is facilitated either by a sufficient time-period having elapsed between the initial ductile deformation of the units of Lithofacies B, C and D material and the subsequent brittle deformation stage for drying of the sediments or by dewatering of the sediments during the subsequent brittle deformation stage itself. Brittle deformation resulting from freezing of the sediments is unlikely given the tendency towards pressure melting found in subglacial and ice-marginal environments.

The unit contacts are clearly cross-cutting with structurally higher discontinuities (for example S8, 10 and 11) in many cases truncating underlying structures (for example S5 and 7). These cross-cutting relationships imply that the relative age of emplacement of these units get generally younger upwards throughout the sequence. Whilst this is the simplest explanation, the entrainment of more than one thrusted unit during subsequent thrusting stages is not impossible and as such deviation from the relative younging upwards model may occur.

The similar geometry and orientation of these structures means that they probably formed during the same deformation event, rather then several discrete phases of deformation separated by large time-spans. Indeed, the repeated stacking of units of two lithofacies (Lithofacies C and D) implies the reworking of pre-existing material during one deformation event. The inter-stratified nature of the units is, therefore, consistent with a reworking phase of repeated thrust formation, shearing of pre-existing material along these thrusts and stacking of the resulting units which post-dates the initial formation of the Lithofacies B, C and D and given its lithostratigraphical position, Lithofacies A.

Dip angles and azimuth directions obtained from the contacts between the till units (Structures 2, 4, 5, 6, 7, 8, 10 and 11) reveal a dip at shallow angles towards the northwest, north and northeast. The sense of movement along these thrust shear planes is, therefore, towards the south, implying that the stress responsible for this brittle deformation was applied from a northerly direction.

The base of Unit 1 lies below that of the exposure and so little inference can be made as to the mechanism of emplacement for this unit. Nearby borehole logs reveal the occurrence of similar units at National Grid Reference TG 110 433, 115 431 and 110 430. The elevation of these units varies (units tops at +5.39 mOD, +14.6 mOD and +9.86 mOD, respectively), as does the unit thickness (8.84 m, 2.05 m and 12.2 m, respectively). It is not known whether these units are in situ or have been subjected to thrusting processes, as seen for Units 2-11 at the pit.

DISCUSSION

Lithostratigraphy and till provenance

The lithological, structural and palynological evidence presented above indicates a complex origin for the inter-stratified sequence at Weybourne Town Pit. Of the 11 units identified, 9 are diamictons and these are attributable to 2 lithofacies: Lithofacies C and D. The parent materials of these lithofacies are the Middle Pleistocene Bacton Green and Weybourne Town Till members of Hamblin *et al*. (2005), respectively. The remaining 2 units are represented by 2 lithofacies: a basal marl and silty sand.

Clast lithological analysis and palynomorph contents of the till lithofacies suggest that the ice responsible for the initial derivation of these tills flowed southwards from northern Britain along the east coast of England and the western margin of the North Sea (Figure 4) before entering the Weybourne region of north Norfolk. Lithological differences between the two tills reflect differential incorporation of locally-derived chalk and sand substrata.

A northerly origin for the ice responsible for the initial deposition of the Bacton Green and Weybourne Town Till members is consistent with the findings of Perrin *et al*. (1979), Fish and Whiteman (2001), Pawley *et al*. (2004) and Scheib *et al*. (in press) who investigated the Middle Pleistocene chalky tills seen in north Norfolk. Structural evidence presented in Fish *et al*. (2000) and in Hart (2007) implies a southwesterly origin for both tills. However, this relies upon the interpretation of the inter-stratified units as folds and laminations which is unlikely given the pre-dominance of brittle deformation structures. The provenance gained from this structural evidence also contrasts with a northerly provenance demonstrated by lithological and clast fabric analysis in Fish *et al*. (2000).

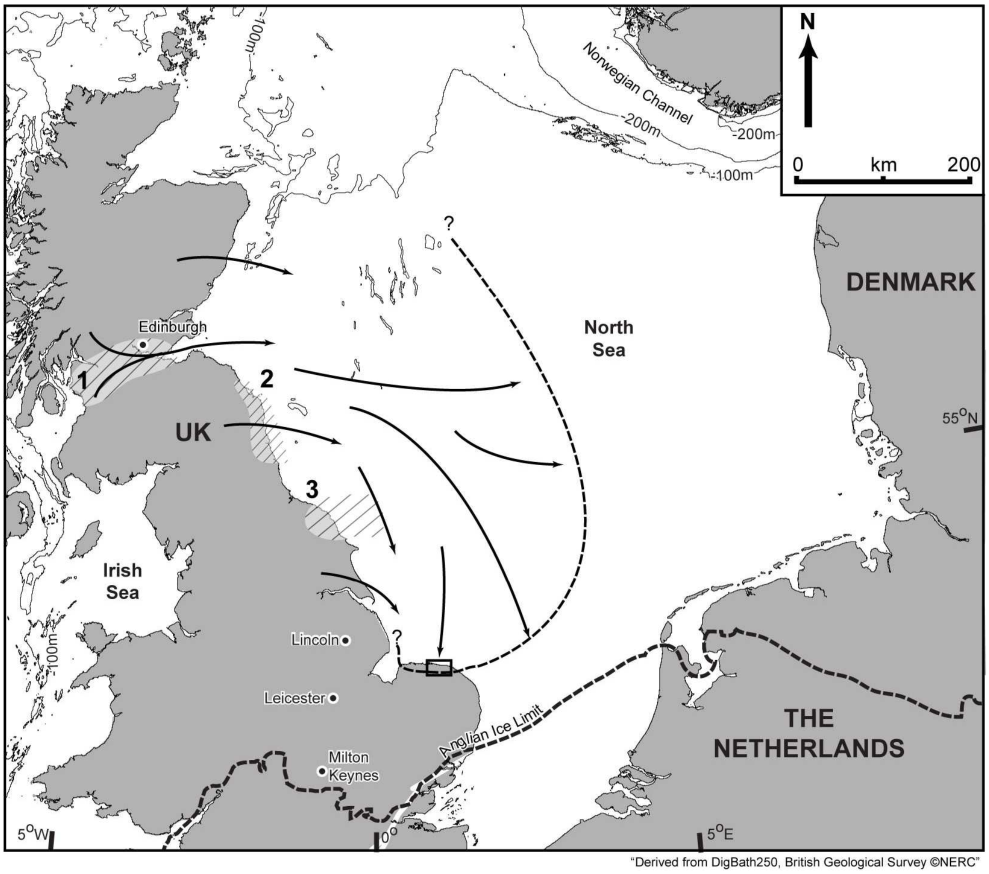

Figure 4. Ice flow model for the British Ice Sheet during accretion of the Weybourne Town Pit sequence. Source areas: 1=Midland Valley of Scotland, 2=County Durham and 3=Yorkshire Basin. Middle Pleistocene (Anglian) ice limit after Bowen *et al*. (1986) and ice lobe limit from Lee *et al*. (2002).

Interestingly, Ehlers *et al*.(1987) and Fish and Whiteman (2001) identify two divisions of chalky till within North Norfolk and suggest that these are equivalent to the Weybourne Town Till Member of Hamblin *et al*. (2005). The older of these units is believed to have been derived from a more westerly direction, whilst the sedimentology and provenance of the younger correspond closely with that of the Weybourne Town Till Member at Weybourne Town Pit presented in this study. As there is no evidence for the older unit at the pit and the pit is regarded as the type site for the Weybourne Town Till Member, the older unit should not be regarded as part of this member. This should be the case even if the entire sequence exposed at the pit (including Unit 1) has been thrust-stacked and the possibility, therefore, that the older chalky till exists at this site but below the base of the exposure.

Instead, the older unit may well correspond to the Bacton Green Till Mélange Member of Phillips *et al*. (2008). This contains material derived from the sandy Bacton Green Till Member as well as a significant proportion of glaciotectonised pre-existing sediments, including the Chalk-rich Walcott and Happisburgh Till Members (Lowestoft and Happisburgh formations, respectively) which can give the unit a Chalk-rich character. Further investigation is required before the unit can be assigned to the Bacton Green Till Mélange Member or a separate chalk-rich formation.

The presence of distinctive British clast lithologies within Lithofacies C and D and the absence of diagnostic Scandinavian erratics suggests that the Bacton Green and Weybourne Town Till members were deposited by the British Ice Sheet only. This contrasts with the view that coeval British and Scandinavian ice sheets were responsible for the deposition of the chalky and sandy tills within the area (Perrin *et al*., 1979; Bowen *et al*., 1986; Ehlers & Gibbard, 1991; Lunkka, 1994).

Thrust-stacking, polyphase glaciotectonic deformation and inter-stratified till sequences

The cross-cutting relationships between units 2-11, truncation of the internal fabric by adjacent disconformities and repetitive stratigraphy indicate a tectonic rather than sedimentary origin for the geometric arrangement of the silty sand and Bacton Green and Weybourne Town Till member units exposed at Weybourne Town Pit. This suggests that a sedimentary melt-out origin for inter-stratified till sequences (Haldorsen and Shaw, 1982; 1983) is not relevant in the context of Weybourne Town Pit.

Hart (2007) and Fish *et al.* (2000) interpreted the contorted Weybourne Town Pit sequence as a series of drag folds and boudins originating from ductile deforming bed conditions. However, the sharp, cross-cutting nature of the unit contacts implies that these structures are, in fact, related to brittle deformation. In addition, these brittle deformation structures truncate the internal ductile fabric of the units. The inter-stratified nature of the sequence, therefore, results from a phase of glacitectonics which postdates the primary deposition of the sediments as subaqueous sand and subglacial tills.

Dip angles and azimuth directions obtained from the sharp, persistent unit discontinuities reveal a dip at shallow angles towards the northwest, north and northeast. The geometry and structure of these discontinuities is typical of low-angle thrust planes. The individual units are, therefore, interpreted as thrusted blocks and are seen to have formed during a series of thrusting events which stacked a unit of silty sand and alternate units of the Bacton Green Till and Weybourne Town Till members. The stress responsible for this thrust-stacking relates to ice movement from a northerly direction.

The emplacement of these inter-stratified units by different advances or multiple lobes of the same ice sheet (Straw, 1965; Perrin *et al*., 1979; Ehlers *et al*., 1987, 1991; Hamblin *et al*., 2005) is unlikely. This is due to the low preservation potential of such features when formed up-ice of the maximum ice sheet extent during the advance phase of the ice sheet. The inter-stratified nature of units 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11 is, therefore, more likely to be related to short-lived oscillations of the ice margin (Fig 5) as the Middle Pleistocene ice sheet retreated from its maximum extent, marked by the Cromer Ridge. Indeed, similar glacitectonic features identified at Drymen, Scotland have been attributed to polyphase deformation resulting from an oscillating ice margin following the Loch Lomond Re-advance (Phillips *et al.,* 2002).

An ice marginal situation of the Weybourne Town Pit site during the formation of the till units is further supported by the fact that the inter-stratified sequence is relatively localised. Indeed, similar structures are absent from coastal sections between West Runton and Weybourne (Phillips *et al*., 2008). In this context, the thrusted sequence forms part of a localised sediment stack constructed during temporary re-advances of the ice margin. In contrast, the coastal sections at West Runton and Weybourne were not subjected to glacitectonic deformation during short-lived ice marginal oscillation: instead the Middle Pleistocene ice sheet retreated relatively uniformly over these coastal locations.

The inter-stratified nature of the sequence at Weybourne Town Pit, therefore, relates to a secondary phase of deformation which post-dates the initial deposition of the Bacton Green and Weybourne Town Till members as subglacial tills of the British Ice Sheet. Active retreat of the Middle Pleistocene ice sheet would provide a possible mechanism for such localised, repetitive oscillation of the ice margin. Comparable repeated ice marginal oscillation has been noted for the retreat phase of the Late Devensian Irish Sea Ice Stream (Thomas and Chiverrell, 2007).

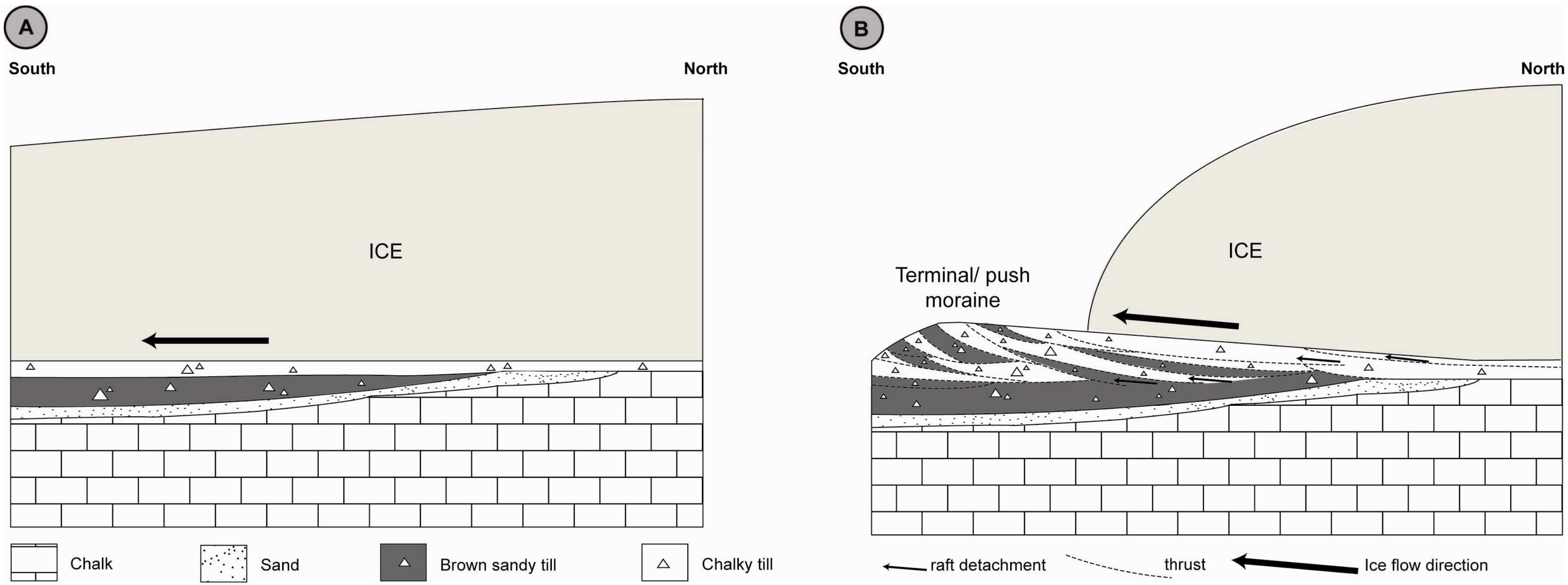

Figure 5. A thrust-stacked origin for the inter-stratified sequence at Weybourn Town Pit, North Norfolk, UK. (A) generation of the Bacton Green and Weybourn Town Till members from sand and Chalk substrata, respectively and (B) detachment, transport and emplacement of till blocks along low-angle thrust planes during active retreat of the Middle Pleistocene (Anglian) ice margin.

The palaeoenvironment of the Weybourne Town Pit sediments is, therefore, reconstructed as follows:

1. Deposition of Lithofacies A marl within a shallow lacustrine basin.
2. Deposition of Lithofacies B sand subaqueously.
3. Deposition of Lithofacies C and D subglacial tills by the Middle Pleistocene British Ice Sheet (primary deposition phase). These tills were derived by ice travelling southwards from northern Britain along the east coast of England and western margin of the North Sea.
4. Over-riding and re-mobilisation of blocks of Lithofacies B, C and D along thrust planes during short-lived, repeated oscillations of the southeast margin of the Middle Pleistocene British Ice Sheet (secondary reworking phase). This occurred during active retreat of the ice sheet from its maximum extent against the Cromer Ridge.

CONCLUSIONS

Subglacial processes play a highly significant role in controlling the behaviour of ice masses. Despite this, the processes leading to the formation and emplacement of inter-stratified sequences of subglacial tills remain particularly poorly understood. Those of the Weybourne area of north Norfolk, UK have a long history of investigation but the mechanism for the formation of the inter-stratified till sequence at Weybourne Town Pit and the direction of ice advance responsible remain particularly enigmatic. In order to address this, the current study combined lithological, structural and palynological evidence to present a re-interpretation of the sequence. Eleven units, divisible into four lithofacies were identified. These lithofacies correspond to a basal marl, silty sand and two subglacial tills of the Middle Pleistocene British Ice Sheet: the Bacton Green Till and the Weybourne Town Till members. These tills were originally derived from northern Britain by ice flowing along the east coast of England. Structural relationships between the units imply that the inter-stratified nature of the till and silty sand units results from repeated, brittle glacitectonic deformation occurring after the initial formation of these lithofacies. The style and trend of this deformation phase is consistent with accretion by a complex series of thrust-stacking events. The absence of similar structures at nearby coastal sections suggests that the effects of this glaciotectonism were highly localised, with the contorted sequence at Weybourne Town Pit related to repeated ice-marginal oscillation during the active retreat of the Middle Pleistocene British Ice Sheet from its maximum extent against the Cromer Ridge.

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