Polyphase glacitectonic deformation during possible active retreat, Weybourne Town Pit

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1. Introduction

The significance of the inter-stratified tills exposed in the Weybourne area of North Norfolk has attracted much attention and various scenarios have been proposed for their development (Banham and Ranson, 1965; Bowen *et al*., 1986; Fish *et al*., 2000; Pawley *et al*., 2004; Hart, 2007). This debate highlights the ambiguity of interpreting inter-stratified till sequences where the mechanisms proposed range from: (1) the confluence of different ice sheets (Ehlers and Gibbard, 1991; Lunkka, 1994); a sedimentary 'melt-out' origin (Haldorsen and Shaw, 1982) and glacitectonic processes associated with a subglacial deforming bed (Hart *et al*., 1990; van der Meer *et al*., 2003; Menzies *et al*., 2006).

Despite extensive research, the formation mechanisms of inter-stratified till sequences remain ambiguous and this continues to be the case in the Weybourne area. Additionally, the direction of ice advance at Weybourne has proved contentious with a number of ice flow directions proposed based upon different lithological and structural evidence (see Fish *et al*., 2000 for an overview).

In order to address this, lithological, structural and palynological techniques were combined in the current study to reinterpret the sequence exposed at Weybourne Town Pit, Weybourne. A primary stage of till deposition and secondary phase of deformation through till remobilisation and emplacement are identified. Flow directions for the ice responsible for depositing the tills are determined and a model for thrust-stacking of till blocks associated with an oscillating ice margin is presented.

Site location: Disused brick pit on the eastern edge of Weybourne village. Car parking adjacent on small grassed area (TG 114 430)

2. Geological context

A south-facing exposure of approximately 5 m length and 2 m height on the north wall of the disused Weybourne Town Pit (National Grid Reference TG 114 430) reveals a contorted series of Quaternary sediments. The pit is situated about 600 m south of coastal cliff sections (Pawley *et al*., 2004; Hart, 2007; see Chapter 11), within an area of gently undulating topography (Figure 5.1) which rises southwards to the Cromer Ridge; a major Middle Pleistocene ice marginal push moraine and outwash complex (Hart, 1990; Pawley *et al*., 2005; also see Chapter 13). The Late Pleistocene (Devensian) ice limit is interpreted as lying just to the north of the pit (Pawley *et al*., 2006).

A number of lithostratigraphic schemes have been presented for the area's glacial deposits and the precise number of glaciations these represent is a highly contentious issue (Baden-Powell, 1948; Banham and Ranson, 1956; Perrin *et al*., 1979; Ehlers and Gibbard, 1991; Lunkka, 1994). The recent schemes of Lee *et al*. (2004) and Hamblin *et al*. (2005) are employed here (see Table 5.1; Chapter 5).

3. Methodology

Weybourne Town Pit was visited between 2002 and 2003 (Lee, 2003) with additional work undertaken by the present authors in 2008. Macro-scale features were described from the exposure on the western side of the north quarry wall. Emphasis was placed on recording sediment type, type of bedding, bed geometry and structure. Bulk samples were collected from the till units and the lithology of clasts retained from the 4-8 mm and 8-16 mm fractions (separated by particle size analysis) was examined. Two samples were also collected from each of the till lithofacies for analysis of palynomorph number, age, stratigraphic range and geographic distribution. These samples were processed following the procedures outlined in Wood *et al*. (1996) and prepared using the sodium hexametaphosphate method (Riding and Kyffin-Hughes, 2004; 2006).

4. Structural description and interpretation

4.1 Lithofacies

The exposed sequence at Weybourne Town Pit is divided by the current study into 11 units, attributable to 4 lithofacies (Figure 14.2):

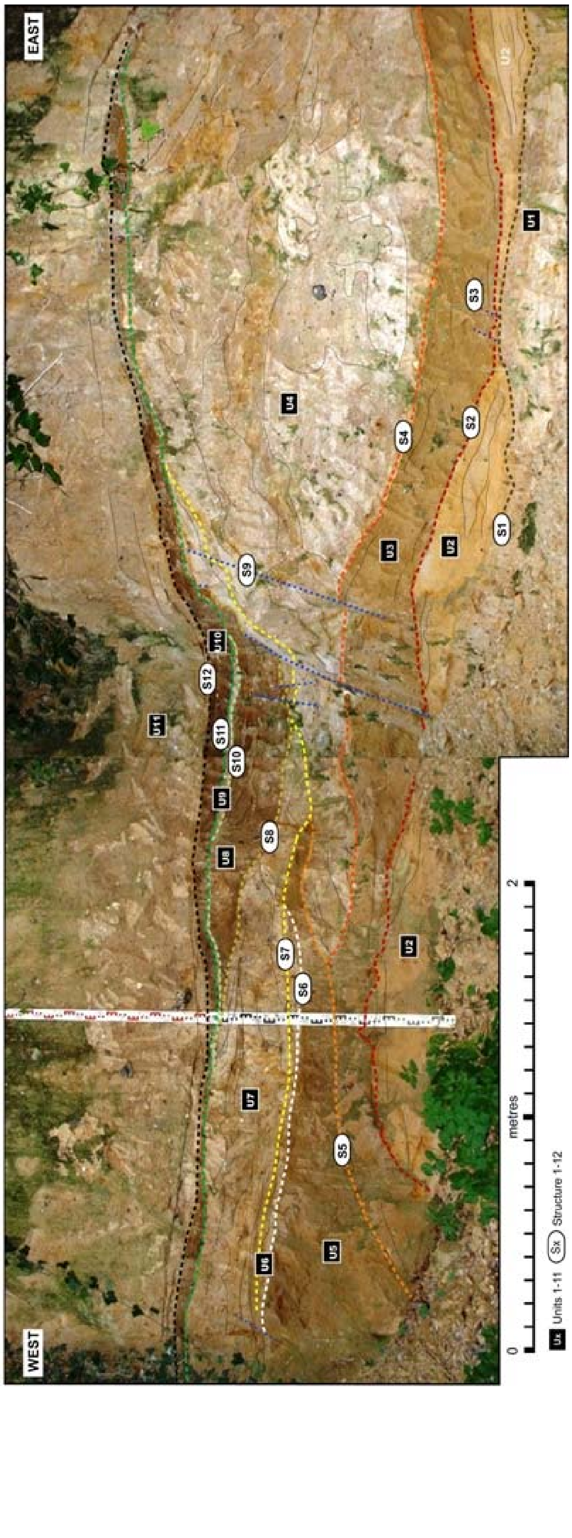

Figure 14.2. Lithological and structural interpretation of the Weybourne Town Pit exposure

Lithofacies A consists of a pale yellow (2.5Y 7/3) to light yellowish brown (2.5Y 6/3) highly calcareous, faintly-stratified marl. This lithofacies occurs as Unit 1 in the exposure and reaches a maximum observed thickness of 0.58 m. The texture and faint stratification are characteristic of deposition within a low energy subaqueous environment and the highly calcareous nature suggests derivation through erosion of a local chalk outcrop.

Lithofacies B comprises a weakly-stratified olive yellow (2.5Y 7/6) to brownish yellow (10YR 6/8) silty sand with convolute bedding. Lithofacies B is restricted to a single unit in the exposure, Unit 2, which ranges in observed thickness between 0.15-0.25 m. Deposition within a low to moderate energy water-lain environment is indicated by the silty-sand texture. Convolute-bedding and syn-sedimentary flame structures imply rapid and high sedimentation rates under conditions of high porewater content.

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. The lithofacies has a moderately low calcium carbonate content (17-19%) but includes localised sandy contortions and discontinuous laminae of more calcareous material. Lithofacies C occurs as a number of individual units in the upper 1.5 m of the section, the darker horizons in Figure 14.2 (Units 3, 5, 8 and 10). These units range in observed thickness between 0.1-0.26m. The colouration, matrix characteristics, clast content and calcium carbonate concentration mirror that of the Bacton Green Till of the Sheringham Cliffs formation (Lee *et al*., 2004).

Lithofacies D comprises a light grey (5Y 7/2) to pale yellow (2.5Y 7/4), highly calcareous (61-73%) clayey silt matrix-supported diamicton. Contorted inclusions of sandy material are present locally. Several individual units of this lithofacies, with a maximum thickness of 1.6 m, occur in the upper 1.5 m of the section: the lighter horizons seen in the top half of Figure 14.2 (Units 4, 6, 7, 9 and 11). The clast content and highly calcareous matrix imply that the parent material is the Weybourne Town Till of the Sheringham Cliffs Formation (Lee *et al*., 2004).

4.2 Structural relationships

The lower portion of the section is composed of a single unit of Lithofacies B material overlying a unit of Lithofacies A, whilst units of Lithofacies C and D material are repeated throughout the upper 1.5m of the section. A total of 10 bounding planar structures are identified separating these units. The structures are typically sharp, and dip at shallow angles

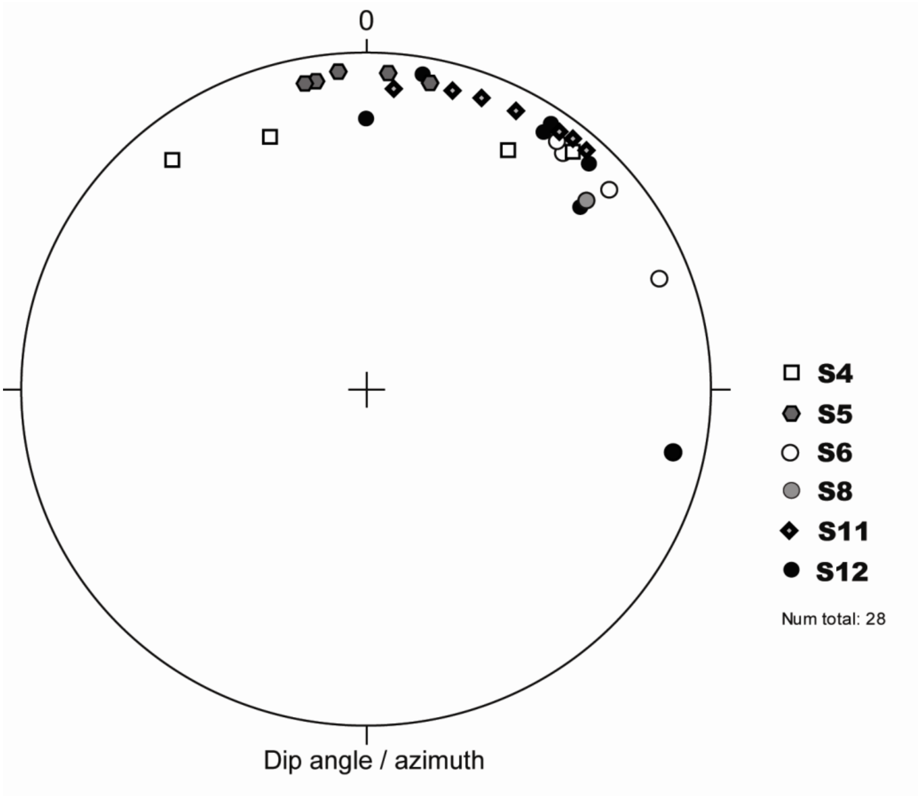

Figure 14.3. Equal-area stereographic projection showing the dip azimuth and dip angle of planar structures (S n) within the northern quarry face at Weybourne Town Pit

towards the northwest-northeast. The bounding structures truncate any internal unit structures (Figure 2) and a number of these structures (structures 5, 7 and 11) cross-cut several units suggesting attenuation of the units prior to and/or during emplacement of the overlying unit. Larger-scale folds are lacking from the sequence and, as such, the juxtaposition of these units is related to brittle rather than ductile deformation. A number of bounding structures (structures S5, S7 and S11) cross-cut several units suggesting truncation of the units prior to and/or during emplacement of the overlying unit. Structurally higher bounding structures (for example S8, S10 and S11) also truncate underlying unit contacts (for example S5 and S7) implying progressive younging upwards throughout the sequence. This phenomenon is typical of the relationships developed in imbricate thrust stacks. Dip angles and azimuth directions support this interpretation of the

Lithofacies	**C**		**D**	
Fraction (mm)	4-8	8-16	4-8	8-16
Sedimentary lithologies				
Pleistocene (%)				
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 (%)				
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 (%)				
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 (%)				
Red sandstone, evaporate	0.0	0.0	0.6	0.0

Crystalline lithologies				
Scotland (%)				
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 (%)				
Quartz dolerite / basalt	0.1	0.0	0.0	0.0

Table 14.1. Clast lithological composition of Lithofacies C and D

bounding surfaces as thrusts, dipping consistently at shallow angles towards the northwest, north and northeast (Figure 14.3). The sense of movement along these thrust planes is, therefore, towards the south, implying that the stress responsible for this brittle deformation was applied from a northerly direction. The similar geometry of the bounding structures and repeated stacking of units of two lithofacies (Lithofacies C and D) implies formation during the same deformation event, rather than several discrete phases of deformation separated by large time-spans. The inter-stratified sequence is, therefore, consistent with a secondary reworking phase of repeated thrust formation, shearing of pre-existing material along these thrusts and stacking of the resulting units. In places, individual thrust surfaces are cross-cut by small-scale high-angle extensional faults (e.g. structures 3 and 9) which probably occurred either as loading during repeated stacking, or by drying out of the stacked sequence.

5. Provenance of Lithofacies C and D

It was established within the previous section that the geometric arrangement of the units within Weybourne Town Pit are related to a secondary deformation phase. The lack of mixing of Lithofacies C and D material within individual units indicates that their primary provenance – namely the provenance of the parent material, can be determined.

Lithofacies	C	D
Carboniferous (%)		
miospores	16.3	3.9
Jurassic (%)		
miospores	15.35	20.6
microplankton	1.6	4.9
Cretaceous (%)		
miospores	1.05	1.15
dinoflagellates	1.3	3.85
Palaeogene (%)		
dinoflagellates	0.7	6.7
Quaternary forms (%)	5.75	10.2

Table 14.2. Sampled palynomorph contents of Lithofacies C and D. Percentage contents are the average of two samples per lithofacies

Clast lithological analysis reveals that lithologies derived from older Pleistocene deposits, such as white, brown and chatter-marked flint; quartzite and shell and wood fragments, dominate in Lithofacies C (Table 14.1). A Cretaceous component, including black flint and sparse chalk pebbles is present in smaller quantities and Jurassic ironstone was represented in the 4-8 mm fraction. This suggests a dominance of locally-sourced clast lithologies derived from the reworking of pre-existing Pleistocene outcrops. Schists and quartz dolerite from northern Britain and ironstones hailing from the Early Jurassic Redcar Mudstone Formation and/or Cleveland Ironstone Formation are also present.

Palynological analysis of Lithofacies C (samples derived from units 3 and 8 in Figure 14.2) highlights a dominance of Carboniferous forms, especially the long-ranging taxa *Densosporites* spp (Table 14.2). Westphalian (*Cirratriradites saturni*). Viséan/Namurian (*Tripartites trilinguis*) markers are also present and long-ranging mid-late Jurassic miospores are relatively common. Although levels of Jurassic microplankton are low, both *Halosphaeropsis liassica* derived from the Lower Toarcian (Bucefalo Palliani and Riding, 2003) and *Cribroperidinium globatum*, a key Kimmeridgian marker, are evident. These findings support a provenance from northern Britain as suggested by the clast lithological analysis. Indeed, Jurassic forms from the Yorkshire Basin and occasional Lower Cretaceous palynomorphs from East Yorkshire and/or Lincolnshire are evident.

Clast lithological analysis of Lithofacies D material reveals a dominance of Cretaceous clast lithologies including chalk and black flint (Table 14.1). These hail from the Santonian-Campanian and Campanian-Maastrichtian Chalk zones of Lincolnshire and the western margin of the North Sea Basin. Clasts derived from older Pleistocene deposits occur to a lesser extent and include white, brown and chatter-marked flint and quartzite. The presence of clasts from Carboniferous strata which are absent at the surface within the North Sea area precludes derivation of the till from the northeast (Lee *et al*., 2002; Riding *et al*., 2003). An ice source from northwest Britain is also untenable due to the presence of a significant Mesozoic and Cenozoic input.

Palynological evidence reveals that samples from Lithofacies D (derived from units 4 and 11 in Figure 14.2) are richer in organic residues than those from Lithofacies C (Table 14.2). The Carboniferous content is of low quantity and diversity yet characteristic of that in Northumberland, Durham and the Midland Valley of Scotland. Conversely, the level of Middle Jurassic miospores is high whilst Jurassic Microplankton are also evident in higher percentages than in Lithofacies C, with Lower Toarcian (*Halosphaeropsis Liassica* and *Nannoceratopsis gracilis*) markers identified. Markers strongly indicative of Kimmeridgian sediment (*Cribroperidinium globatum* and *Cribroperidinium longicorne)* (Riding and Thomas, 1992), are also found.

6. Discussion

6.1 Till provenance and primary deposition phase

A complex origin for the inter-stratified sequence at Weybourne Town Pit is demonstrated by the lithological, structural and palynological evidence outlined above. The Bacton Green and Weybourne Town tills are identified as the parent materials for the units derived from Lithofacies C and D, based upon particle size, colour, relative carbonate content and clast content. These overlie individual units of a basal marl and silty sand (Lithofacies A and B, respectively). The tills were originally derived from northern Britain and the western margin of the North Sea Basin, most likely as subglacial tills

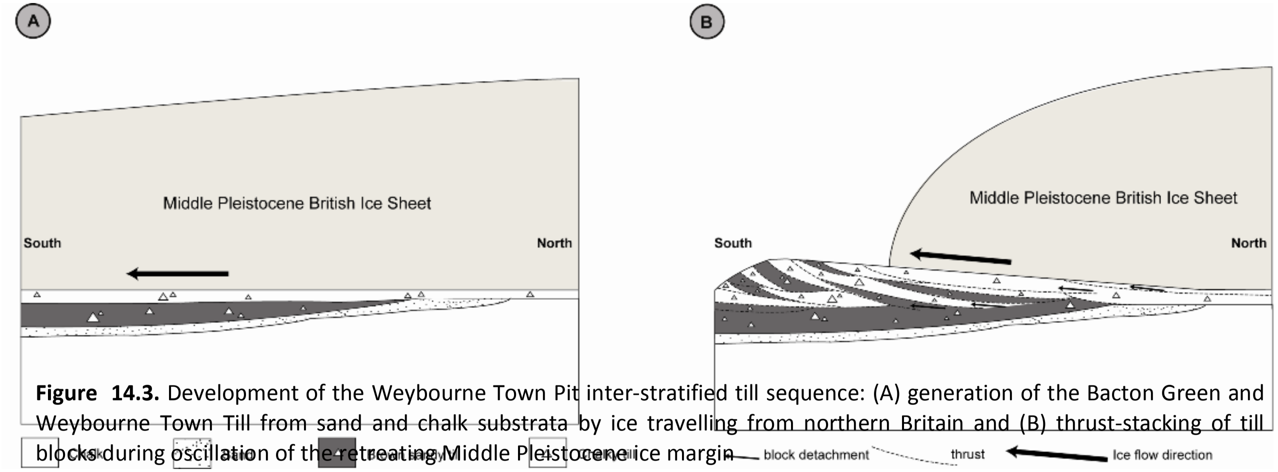

Figure 14.3. Development of the Weybourne Town Pit inter-stratified till sequence: (A) generation of the Bacton Green and Weybourne Town Till from sand and chalk substrata by ice travelling from northern Britain and (B) thrust-stacking of till blocks during oscillation of the retreating Middle Pleistocene ice margin

of the British Ice Sheet. Lithological differences between the two tills reflect differential incorporation of locally-derived chalk and sand substrata.

Structural evidence presented in Fish *et al*. (2000) and in Hart (2007) implies a southwesterly origin for both tills. However, within these studies the inter-stratified units are interpreted as folds and laminations which is considered unlikely by the current authors given the pre-dominance of brittle deformation structures demonstrated above. The northerly origin for the ice responsible for the initial deposition of the Bacton Green and Weybourne Town tills demonstrated in the current study is consistent with lithological and clast fabric analysis presented in Fish *et al*. (2000) as well as the findings of Perrin *et al*. (1979), Fish and Whiteman (2001), Pawley *et al*. (2004) and Scheib *et al*. (2011) who investigated Middle Pleistocene chalky tills in north Norfolk.

The suggestion that coeval British and Scandinavian ice sheets were responsible for the deposition of the Bacton Green Till and Weybourne Town Till members (Perrin *et al*., 1979; Bowen *et al*., 1986; Ehlers and Gibbard, 1991; Lunkka, 1994) is unsupported by the current study due to the dominance of diagnostic lithologies from northern and eastern Britain and the absence of Scandinavian lithologies. Deposition by the British Ice Sheet only is inferred.

Two divisions of chalky till, believed to be equivalent to the Weybourne Town Till have been identified in northern Norfolk by Ehlers *et al.* (1987) and Fish and Whiteman (2001). The sedimentology and provenance of the younger of these units correspond closely with that presented in this study. As Weybourne Town Pit is regarded as the stratotype for the Weybourne Town Till Member, and there is no evidence for the older unit at the pit, this older unit should not be regarded as equivalent to the Weybourne Town Till. Further investigation of the older chalky till is required before a stratigraphical unit can be assigned.

6.2 Thrust-stacking of inter-stratified till blocks during secondary deformation phase

The cross-cutting unit relationships and truncation of the internal fabric by adjacent disconformities combined with the repetitive stratigraphy of the sequence indicate a tectonic origin by thrusting. A sedimentary melt-out origin for the inter-stratified till sequence, as proposed by Haldorsen and Shaw (1982; 1983) for similar sequences elsewhere, is therefore considered unviable in this instance.

The presence of brittle deformation structures along unit contacts, meanwhile, suggests that the ductile subglacial deforming bed model (i.e. Hart and Boulton (1991a); van der Meer *et al*. (2003); Menzies *et al*. (2006) is not applicable in the context of Weybourne Town Pit (cf. Fish *et al*., 2000; Hart, 2007). As these brittle deformation structures truncate the internal ductile fabric of the units it is considered that the inter-digitated nature of the sequence relates to a secondary phase of glacitectonics which postdates the initial deposition of the sediments perhaps as subglacial tills. Indeed, the geometry of the unit discontinuities is typical of low-angle thrust planes and the individual units are interpreted as thrusted blocks formed during a series of events introducing alternate slices of Bacton Green Till and Weybourne Town Till. Ice movement from a northerly direction provided the stress responsible for this thrusting. As the Weybourne Town Pit area lies to the south of the Late Pleistocene (Devensian) ice limit, thrusting during the latter stages of Middle Pleistocene glaciation is inferred.

The low preservation potential of till blocks formed up-ice of the maximum ice sheet extent during the advance phase of the ice sheet means that the emplacement of the inter-stratified sequence at Weybourne Town Pit by different advances or multiple lobes of the same ice sheet (cf. Straw, 1965; Perrin *et al*., 1979; Ehlers *et al*., 1987, 1991; Hamblin *et al*., 2005) is unlikely. Instead, the thrust features are more likely to be ice marginal features, a situation where their preservation potential is likely to be increased. Short-term oscillations of the ice margin during active retreat of the ice sheet (Figure 14.3) are therefore inferred. 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).

The absence of similar inter-stratified sequences in the nearby Weybourne coastal sections (Phillips *et al*., 2008) implies that the effects of the reworking stage were relatively localised. This further supports an ice marginal situation of the Weybourne Town Pit area during the formation of the thrust slices. The palaeoenvironment of the Weybourne Town Pit sediments is, therefore, reinterpreted as follows:

1. Lithofacies A marl is deposited within a shallow lacustrine basin.
2. Subaqueous deposition of Lithofacies B sands.
3. Deposition of Lithofacies C and D subglacial tills by Middle Pleistocene British ice travelling southwards from northern Britain along the east coast of England and western margin of the North Sea (Primary deposition phase).
4. Over-riding and re-mobilisation of blocks of Lithofacies B, C and D along thrust planes during active retreat of the Middle Pleistocene British Ice Sheet from its maximum extent against the Cromer Ridge (Secondary deformation phase).

7. Conclusions

The interpretation of facies composed of inter-stratified subglacial tills is an aspect of glacial geology that remains particularly poorly understood. Despite a long history of investigation the formation mechanisms and direction of ice advance responsible for the highly contorted sequence at Weybourne Town Pit, north Norfolk, remain enigmatic. In order to address this, lithological, structural and palynological techniques were applied to present a reinterpretation of the sequence. Four lithofacies were identified: a basal marl (A), silty sand (B) and two subglacial tills (C and D) of the Middle Pleistocene British Ice Sheet. Lithological and palynological evidence indicates that these tills were derived by ice flowing along the east coast of England from northern Britain. Structural relationships between the units imply a reworking stage of repeated, brittle deformation which occurred after the initial formation of the lithofacies. The style and trend of this secondary phase is consistent with accretion by a series of thrust-stacking events. The absence of similar structures at nearby coastal sections suggests that the effects of this glaciotectonism are 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.