The Stratigraphy of the Briton's Lane Borehole and Quarry, Beeston Regis, north-east Norfolk

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ABSTRACT

The Cromer Ridge complex in north-east Norfolk has traditionally been recognised as a Scandinavian ice-marginal limit during the Anglian-stage. This interpretation is based upon the presence of glaciotectonised North Sea Drift Formation sediments contained within the Cromer Ridge that reportedly include lithologies eroded from Scandinavia.

Examination of quarry faces and samples from a purpose-drilled borehole at Briton's Lane Quarry on the northern flank of the Cromer Ridge reveal that the ridge, thereabouts, is composed of three lithological units. The lowermost unit, lithofacies A, is a flint-rich gravel equated by clast lithologies to the early-Middle Pleistocene Wroxham Crag Formation. The overlying unit, lithofacies B, comprises a complex sequence of glaciogenic muds, laminated muds, sands, and intercalated diamicton facies. The frequent vertical facies changes and sedimentological evidence of rain-out, mass-movement, and sedimentation from suspension indicate that deposition occurred through glaciogenic sedimentation within a standing water body. Lithofacies B is lithologically equated to the Bacton Green Till Member of the Sheringham Cliffs Formation, with derived-clast lithologies, heavy minerals, and allochthonous palynomorphs indicating an ice-flow path emanating from central Scotland and southwards along the western margin of the North Sea Basin. The absence of Scandinavian-derived clast lithologies within the Bacton Green Till further challenges the view that Scandinavian ice deposited the North Sea Drift Formation. The

uppermost unit, lithofacies C, consists of ice-marginal fan sands and gravels deposited as outwash from a Scandinavian-sourced ice-sheet. This unit, the Briton's Lane Formation, is tentatively associated with the OIS-6 Scandinavian glaciation that deposited the Basement Till of East Yorkshire.

INTRODUCTION

The most prominent glacial landform in northeast Norfolk is the 'Cromer Ridge' which strikes approximately east-west for 14 km between Sheringham and Trimingham (Fig. 1) and which rises to approximately 100 m O.D. The ridge has traditionally been considered a push-moraine complex, composed of North Sea Drift Formation (NSDF) diamictons and outwash sediments (table 1) deposited by multiple advances of a Scandinavian ice-sheet during the Anglian-stage (Mitchell *et al.,* 1973; Perrin *et al.,* 1979; Hart, 1990; Hart & Boulton, 1991; Lunkka, 1994).

Recent investigations have questioned the provenance of these glacial advances with new lithological evidence demonstrating a Scottish rather than Scandinavian ice-source for the diamictons of the NSDF (Lee *et al.,* 2002, 2004a; Pawley *et al*., 2004). The timing and concurrency of these glacial advances has also been questioned by the presence of erratics and armoured till-balls of the basal diamicton member of the NSDF within early Middle Pleistocene Bytham River deposits at Leet Hill [TM 384 926], and strongly suggests the presence of pre-Anglian glaciation within eastern England (Lee *et al.,* 2004b). Furthermore, lithological and field investigations have revealed that one of the tills within the NSDF, the Walcott Diamicton (Lunkka, 1994), is the lateral equivalent of the Lowestoft Formation till, thus rendering the NSDF invalid as a stratigraphical unit (Hamblin *et al.,* 2000; Moorlock *et al.,* 2002; Lee *et al*., 2004a).

An outcome of these radical new findings has been to abandon the NSDF stratigraphical nomenclature in favour of a new quantitative stratigraphical scheme that defines four formations based upon geological mapping and their lithological, structural, geometric and sedimentological properties (Table 1; Lee *et al*., 2004a). Correlation of this new sequence with other local and regional stratigraphies suggests that some of these glacial deposits have been deposited over several Middle

Pleistocene glacial cycles including the Anglian (Hamblin *et al.,* 2000). Consequently, the provenance, timing, and formation of the Cromer Ridge is not adequately defined and can no longer be presumed to represent an Anglian-stage ice marginal position.

PHYSIOGRAPHIC SETTING

Although the south-eastern flank of the ridge is made up of a number of separate ridge elements forming a push-moraine complex (Hart, 1990), sites such as Briton's Lane Quarry and Beeston Hill (Fig. 1) reveal the northern part of the ridge contains thick deposits of sand and gravel with the appearance of an ice-contact slope (Ranson, 1968; Boulton *et al.,* 1984; Hart, 1990).

The present study reports the findings of lithological and sedimentological investigations in the Briton's Lane Quarry [TG 1700 4145] that is situated on the northern flank of the Cromer Ridge 2 km southeast of Sheringham (Fig. 1). The quarry dissects a 40 m-thick sequence of the Briton's Lane Formation that rises to 101 m O.D. These sands and gravels can be traced to the coast at Weybourne (Pawley *et al*., 2004) and Sheringham (Lee, 2003), and crop out extensively around the Cromer district (Moorlock *et al*., 2002) as far south as Hanworth (Lee *et al*., 2004a).

To investigate a continuous sequence through the Cromer Ridge at this location and determine the relationship of the Briton's Lane Formation to underlying deposits, a borehole was drilled through the base of the Briton's Lane Formation at 63 m O.D. At this site, the Briton's Lane Formation rests on a complex series of diamictic sediments, sands and muds that extend from 63 m O.D to 4 m OD.

METHODOLOGY

The borehole was drilled in February 2002, with staff of the British Geological Survey (BSPM, RGC) and members of the Department of Geography at Royal Holloway University of London (SMP, JRL) in attendance. The borehole was drilled using the shell and auger percussion method and its elevation determined. Cohesive sediments were collected as core segments or undisturbed U100 samples, and bulk samples of non-cohesive sands and gravels were collected in polythene bags for later laboratory analysis. Accordingly, sedimentary structures were usually unrecognisable in non-cohesive sediments.

Selected quarry faces were also examined and the texture, structure, and contact relationships of sedimentary units described. Vertical graphic logs were produced with quarry and borehole sections described using a lithofacies scheme (Table 2). The texture of diamicton units was quantitatively established and described according to Moncrieff (1989) and sediment colour defined using Munsell Color charts. Particle-size analysis was performed on the <2 mm fraction through wet and dry sieving of the >63 μm fraction (Gale & Hoare, 1991) and the <63 μm fraction determined using a Micromeritics Sedigraphy 5100 (Coakley & Syvitski, 1991). Calcium carbonate content determination was carried out on the <2 mm size fraction using the gasometric method (Gale & Hoare, 1991).

The clast lithological composition of the 8-16 mm and 4-8 mm size ranges has been quantitatively determined. Heavy minerals have been analysed from the 63-125 μm sand fraction as a provenance and correlation aid (Catt & Penny, 1966; Madgett & Catt, 1978; Perrin *et al.*, 1979; Morton & Hallsworth, 1999) with opaque minerals expressed as a percentage of total mineralogy and non-opaque grains expressed as a percentage of total non-opaques. Allochthonous palynomorphs have also been identified and used as an additional indicator of provenance (Riding *et al.,* 1997; 2000; Moorlock *et al*., 2000a; Lee *et al*., 2002), and these have been categorised into groups of known stratigraphic age.

SEDIMENTARY DESCRIPTIONS

Borehole lithostratigraphical units (lithofacies A and B) and quarry-face stratigraphical sections (lithofacies C) are shown in Figures 2 and 3 respectively.

Lithofacies A (sandy gravel facies)

Rounded to sub-angular large pebble to cobble gravel unit with a fine- to medium-grained sand matrix.

Lithofacies B (diamicton assemblage)

Lithofacies B comprises a thick sequence of alternating diamicton, sand, and mud units that are categorised into several distinct facies-types.

B_1 - Laminated mud facies (Fl, Flc): Laminated muds consist of thickly laminated to thinly bedded very fine-grained sand and mud couplets with either sharp or gradational couplet contacts. Small chalk clasts and granules are commonly embedded within the laminations (Flc) that display bending or rucking of basal contacts and draping of overlying laminae.

B_2 - Massive mud facies (Fm, Fmc): Metre-scale beds of massive muds, sandy muds, or silts (F/Fm) that often contain dispersed clasts (Fc, Fmc) and possess colours ranging from dark grey (5Y 4/1) to dark olive grey (5Y 3/2) and dark greenish black ???(grey 1 2.5/1).

B_3 – Muddy sand and pebbly sand facies (S, Sc, Sg): Medium bedded to thick metre-scale beds of fine-grained sand with dark grey (5Y 4/1) to dark greenish grey ???(grey 1 4/1) colour. Sand units often contain dispersed clasts (Sc) or have occasional gravely beds (Sg).

B_4 - Grey-mud diamicton facies: Comprises metre-scale beds of clast-poor muddy to intermediate diamicton with a grey (5Y 5/1) or very dark grey (5Y 3/1) matrix colour. Matrix structure is largely massive (Dmm) or contains mm-scale chalky stringers with sharp and irregular contacts and a local concentration of chalk grains (Dmm-r). Matrix calcium carbonate content is variable between units and ranges from 6.1-35.4%.

B_5 - Chalky diamicton facies: A highly calcareous (ca. 80%) clast-rich diamicton with a white (2.5Y 8/1) matrix colour and a massive (Dmm, Fm) or thickly laminated (Dml) structure. Matrix particle size distribution shows the diamicton to be mud-rich with a persistent sand component (ca. 10%). The chalky diamicton is intercalated and

stratified with beds of grey-mud diamicton facies, present in m-scale beds or as thick cm-scale sharply bounded and irregular laminations or lenses.

B_6 - Brown-grey diamicton facies: Occurs at the top of lithofacies B and comprises a dark yellowish brown (10YR 3/4) clast-poor intermediate diamicton with a consistent sandy mud matrix. A thick bed of very dark grey (5Y 3/1) diamicton and a 1 m thick unit of bedded sand (Ss) is also present within this sequence. Diamicton structure is largely massive except for the occurrence of chalky streaks in lower parts. Calcium carbonate contents ranges between 13.4 – 16.7%.

Lithofacies C (Briton's Lane Formation)

A thick 39 m sequence of horizontally-bedded sand and gravel overlies lithofacies B and is extensively exposed within the quarry (Fig. 3).

Medium- to coarse-grained sands or pebbly sands are present basally between 62.0-63.5 m O.D. and are horizontally bedded (Sh), type-a rippled (Sr), or locally trough-cross bedded (St) in <10cm sets. Palaeocurrent measurements from Sr units indicate flow towards the south (Fig. 3). Massive gravel sheets (Gs) 10-35 cm thick with poorly sorted small pebble to cobble sized clasts are abundant between 63.5-101.6 m O.D. The gravels are usually matrix-supported but sporadic beds of clast-supported gravels also occur (Gm). Erosional lower contacts are common and normal or reverse grading is occasionally present (Gms). Gs units alternate with horizontally bedded sands (Sh) that form subordinate 4-15 cm-thick beds that pinch out laterally between 62.0–72.0 m O.D. Thicker 3-44 cm Sh units become more common upwards. The Sh units are often normally graded from horizontally bedded medium-grained sand to rippled fine-grained sand (Sr). Thicker beds are occasionally present with cobble size gravel seams. Sand and gravel beds have low <10º dips oriented towards the east or north-east (Fig. 3). Other facies include rare 3 m-wide cross-cutting channels (CH) filled with clast-supported open framework gravels.

LITHOLOGY

Clast lithological results of lithofacies A are summarised in table 4 and lithofacies B-C detailed in table 5. All lithological descriptions within the text are based on the 8-16 mm size fraction with the exception of lithofacies B, described using the 4-8 mm size fraction due to limited sample sizes. A summary of sediment heavy mineralogy and age-diagnostic palynomorphs are shown in tables 3 and 6 respectively.

Lithofacies A (sandy gravel facies)

A flint-rich gravel (83.0%) which includes a significant component of chatter-marked flint (12.9%) and Cenozoic marine shells (4.6%). A small proportion of quartzose material is present (8.4%), comprised predominantly of colourless and white varieties. Other indicator lithologies include a persistent percentage of *Rhaxella* chert (1.1%) and Carboniferous chert (0.5%) with trace amounts of glauconitic sandstone (0.3%), chalk (0.3%), greensand chert (0.1%), and Devonian Upper Old Red Sandstone (0.1%). Trace amounts of volcanic porphyries and basalt (0.5%) and mica-schist (0.1%) are also present.

Lithofacies B (diamicton assemblage)

B_3 - Pebbly sands: The gravel fraction (sample 39) contains large amounts of Cenozoic-derived white/brown flint (35.5%), quartzose (11.0%), and shell/wood material (9.8%) with a secondary proportion of Cretaceous black flint (19.8%). Distinctively high percentages of Jurassic limestone, mudstone, and *Rhaxella* chert (10.5%) demarcate the sands. Other indicator erratics comprise a trace of Permo-Triassic Magnesian Limestone (0.2%), Carboniferous chert (2.4%), and igneous (4.3%) and metamorphic clasts (1.3%) which include basalt, basic and acid porphyry, quartz-mica schist and meta-quartzite.

B_4 - Grey-mud diamicton facies: Two diamicton units analysed (samples 4 and 28/29) contain abundant Cenozoic-derived lithologies including white/brown flint (34.0 ± 7.6%), quartzose material (8.0 ± 3.2%), and a relatively high shell and wood content (5.6 ± 4.2%). Cretaceous chalk (17.7 ± 18.5%) and black flint (20.4 ± 0.6%) also form an important component along with small levels of Jurassic sandstone and limestone (2.5 ± 0.5%) and Carboniferous chert and coal (1.1 ± 0.1%). Trace amounts of

igneous (3.8 ± 1.3%) and metamorphic erratics (1.9 ± 1.3%) comprise porphyritic basic and intermediate volcanic rocks, granodiorite, quartz mica schist, schistose grit, and meta-quartzite.

Heavy mineral analysis (samples 19, 20, 29, 35) produced a moderate opaque mineral content (26.6 ± 8.6) with relatively high proportions of epidote (31.1 ± 4.4%), amphibole (29.6 ± 2.2%), and garnet (15.1 ± 2.4%). These samples also produced an abundant palynomorph, wood, and plant tissue content with Quaternary (19.2-29.3%) and Jurassic forms (1.0-15.3%) dominating the palynomorph assemblage. However, small proportions (0.7-5.1%) of Carboniferous spores are also present and include the long-ranging *Densosporites* spp. and *Lycospora pusilla*.

The Jurassic palynomorph content consists of Mid Jurassic miospores (1.0-13.6%) and a sparse dinoflagellate cyst assemblage (0.0-1.7%) indicative of the Kimmeridgian Stage. Small levels of Late Cretaceous dinoflagellate cysts (0.5-1.2%) include *Cribroperidinium reticulatum*, *Cribroperidinium wetzelii*, *Hystrichosphaeropsis quasicribrata* and *Spongodinium delitiense*, that are indicative of the Campanian-Maastrictian transition (Herngreen *et al*., 1996; Stover *et al*., 1996; Roncaglia & Corradini, 1997; Schiøler *et al*., 1997). Similarly small proportions of Palaeogene dinoflagellate cysts (0.0-3.6%) include species predominately of Ypresian (Early Eocene) age. Quaternary pollen and spores represent the most abundant taxa (19.2-27.9%) although Quaternary dinoflagellate cysts are present only in low levels (0.0-1.4%).

B_5 - Chalky diamicton facies: The clast-rich chalky diamicton is dominated by Cretaceous chalk (79.5 ± 7.2%) and black flint (9.6 ± 3.4%) with a small amount of Cenozoic-derived white/brown flint (7.2 ± 0.8%) and quartzose material (2.3 ± 1.8%). A high opaque mineral content (94.0 ± 3.0%) and apatite (11.9 ± 13.5%) distinguish the facies.

Three samples (30,31,36) produced extremely rich palynofloras that are dominated by Late Cretaceous dinoflagellate cysts (44.1-99.3%). Key species comprise *Alisocysta circumtabulata*, *Cladopyxidium paucireticulatum*, *Isabelidinium* *cooksoniae*, *Neoeurysphaeridium glabrum*, *Palaeotetradinium maastrichtiense*, and *Xenascus wetzelii* that are indicative of the Campanian-Maastrictian transition.

B_6 - Brown-grey diamicton facies: The diamicton produced a small gravel fraction (sample 44) that is mostly composed of Cenozoic- (32.4%) and Cretaceous-derived lithologies (55.0%) including a relatively high chalk content (35.6%). Other lithologies include small levels of Jurassic *Rhaxella* chert, sandstone, and limestone (2.7%), Carboniferous chert and limestone (4.1%), and a trace amount of Devonian Upper Old Red Sandstone in the 8-16 mm size fraction. Granite (0.9%) and acid porphyry (1.4%) comprise the igneous assemblage and metamorphic erratics (1.8%) include schistose lithologies and meta-quartzite. A moderately high opaque content (34.8 ± 3.2%) with relatively high levels of amphibole (33.5 ± 2.9%), epidote (29.3 ± 2.7%), and garnet (14.8 ± 2.1%) represent the most important heavy minerals.

Three diamicton samples analysed (samples 44, 47, 48) produced a diverse palynomorph assemblage characterised by abundant Carboniferous (11.9-20.1%) and Jurassic forms (22.2-36.9%). The Carboniferous spores are dominated by the long-ranging *Densosporites* spp. but also include *Tripartites trilinguis* that is characteristic of the Viséan-Namurian transition (Owens *et al*., 1977). *Punctatisporites sinuatus* and *Radiizonates* spp. range throughout the Namurian to Westphalian and *Reticulatisporites reticulates* is typical of the Westphalian (Clayton *et al*., 1977; Clayton & Butterworth, 1984).

Jurassic miospores (20.2-26.8%) are indicative of the Mid-Late Jurassic (Riding *et al*., 1991) and Jurassic microplankton (2.0-10.4%) include key species such as *Halosphaeropsis liassica*., *Mancodinium semitabulatum*, *Nannoceratopsis deflandrei* subsp. *deflandrei* and *Nannoceratopsis deflandrei* subsp. *senex*. This association is indicative of the Early Jurassic (early Toarcian) (Riding *et al*., 1999; Bucefalo Palliani & Riding, 2000). Small numbers of *Liasidium variabile* are indicative of input from the Upper Sinemurian (Bucefalo Palliani & Riding, 2000) and small proportions of Kimmeridgian Stage dinoflagellate cysts are also present.

Relatively low proportions of Late Cretaceous dinoflagellate cysts (1.2-4.4%) includes species indicative of the Campanian-Maastrictian transition based on the occurrences of *Hystrichosphaeropsis quasiscribrata*, *Microdinium* spp., and *Spongodinium delitiense*. Palaeogene (0.5-1.4%) dinoflagellate cysts are present and indicate input from the Early-Mid Eocene (Ypresian to Luteian). Small proportions of Quaternary miospores (1.3-3.4%) and dinoflagellate cysts (0.5-2.8%) are also present.

Lithofacies C (Briton's Lane Formation)

The Briton's Lane Formation is flint-rich (85.6 ± 2.1%) and largely composed of Cenozoic derived brown/white flint (69.4 ± 6.6%) and chattermarked flint (8.5% ± 3.2%) with a smaller amount of quartzose material (10.3 ± 1.6%). Other indicator lithologies include Cretaceous black flint (7.7 ± 2.9%) with a small amount of Jurassic *Rhaxella* chert and sandstone (1.1 ± 0.5%), Permo-Triassic red sandstone (0.1% ± 0.0%), Carboniferous chert (0.2 ± 0.2%), and Devonian Old Red Sandstone (0.1 ± 0.1%). An igneous (1.0 ± 0.4%) and metamorphic suite (0.9 ± 0.5%) includes porphyritic volcanics, granite, basalt, quartz dolerite, schist, mica schist, garnet-mica schist and rare traces of meta-quartzite, baked sandstone, and schistose grit. Heavy mineral counts show a variable assemblage but with a generally high opaque, (57.6 ± 15.6%), zircon (19.7 ± 7.6%), and garnet (19.8 ± 10.4%) content.

SEDIMENTOLOGICAL INTERPRETATION

Lithofacies A (sandy gravel facies)

Although disturbed material was collected, the sandy gravel texture with high proportions of chatter-marked flint and marine shell indicate that deposition probably occurred in a high-energy shallow-marine environment.

Lithofacies B (diamicton assemblage)

Lithofacies B comprises a complex series of interbedded and frequently alternating mud, sand, and diamicton facies. B_1 Laminated mud facies (Fl, Flc) possessing some gradational couplet contacts form typical rhythmite structures reflecting subaqueous deposition (Smith & Ashley, 1985). The presence of dropstone structures and laminae-clast drapes demonstrate the delivery of ice-rafted debris and rain-out of suspended mud (Gilbert, 1990). The associated and intercalated B_2 massive mud units (Fm) are also likely to be deposited from suspension.

The B_3 muddy and pebbly sands (S, Ss, Sc, Sg) are commonly intercalated with the laminated (Fl) or massive mud facies (Fm, Fm) and could be deposited from underflows, turbidity currents (Lowe, 1979, 1982, Nardin, 1979; Walker, 1992), or sediment gravity flow (Middleton & Hampton, 1976). The common inter-bedding of the muddy sands suggests that cyclical operation of underflow current or downslope movement processes has been superimposed on background sedimentation from suspension forming the laminated or massive muds during periods of quiescence.

The association of the B_4 grey-mud diamicton facies with laminated and massive muds suggests deposition also occurred subaqueously. The absence of stratified debris flow facies and incorporated sediment lenses (Eyles *et* al., 1985; Eyles & Lagoe, 1990) suggests that rapid rain-out of suspended sediment and ice-rafted debris is a likely depositional mechanism (Visser, 1983; 1997; Eyles *et al.,* 1985; Eyles & Lagoe, 1990; Eyles & Eyles, 1992).

The B_5 chalky diamicton facies (Dmm, Dml, Dms) displays evidence of waterlain processes depositing the laminated chalky fines (Dmm and Dml units) with deformational and shearing processes accounting for the irregular and sharply bounded stratification and lenses of contrasting chalky and grey-mud diamicton lithologies (Dms units). The chalky diamicton contains a small but significant percentage of sand signifying the mixing of chalk with other sediment and the fine-grained composition generally precludes an ice-proximal subaqueous setting (Powell, 1990). It is proposed that the chalky fines were deposited from suspension in an ice-distal setting and were periodically deformed by cohesive debris flows producing the stratified Dms units.

The borehole sequence is capped by the B_6 brown-grey diamicton facies with relatively uniform particle size, heavy mineral, and calcium carbonate properties in contrast to other facies within the borehole. This facies could have been deposited by either subaqueous or subglacial processes.

Lithofacies C (Briton's Lane Formation)

The rippled sand facies (Sr, Sh, St) reflect initial glaciofluvial outwash with intervals of plane-flow (Sh units) and the migration of sandy (Sr, St) bedforms (Miall, 1977; 1985; Dawson & Bryant, 1987).

The overlying Gs matrix-supported gravel sheets with erosive lower contacts are produced by high-energy sheet-flow (Nemec & Steel, 1984; Krzyszkowski & Zielinski, 2002) whereas the interbedded Sh units signify deposition during the waning flood stage (Miall, 1977; 1985; Smith, 1985; Maizels, 1993). The fining-up tendencies and occasional transitions from Sh into Sr units indicate declining flow velocities (Leeder, 1999). Sh units sometimes pinch-out laterally and these beds probably represent the margins of individual sandy flood sheets (Miall, 1985).

The absence of cross-stratification (Gp, Gt) indicates that water depths remained generally shallow. Deeper flow would therefore have been confined to a few main channels (CH) with crosscutting relationships produced during channel abandonment, migration, and reactivation (Miall, 1985).

DEPOSITIONAL ENVIRONMENT

In summary, Lithofacies A (sandy gravel facies) probablyy reflects deposition within a high-energy shallow-marine environment. By contrast, Lithofacies B (diamicton assemblage) comprises a complex series of alternating muddy sands, laminated or massive muds and intercalated diamictons. These rapid and frequent vertical facies changes are typical of glaciomarine and glaciolacustrine sequences (Eyles *et al.*, 1985).

The fine-grained nature of the lithofacies B muds and diamictons indicates deposition occurred in an ice-???distil subaqueous environment where suspension deposition or rapid rain-out of pelagic muds operated with an input of ice-rafting debris. These processes are superimposed by cyclically occurring periods of mass-movement or underflow current sedimentation producing the muddy and pebbly sand facies. Due to the limited availability of undisturbed sediments, the sequence cannot provide direct evidence of whether the standing water body was a glaciomarine or glaciolacustrine basin.

The coarse gravel and poorly sorted texture of the Lithofacies C Briton's Lane Formation with evidence of high-energy sheet-flow suggests deposition occurred as ice-proximal outwash with generally shallow water depths or deeper flow confined within a few main channels (Boothroyd & Ashley, 1975). As there is little evidence of widespread lateral accretion processes, it is suggested that deposition was controlled by high sediment supply, recurring floods and discharge variations rather than by repeated channel aggradation and reoccupation characteristic of the braided river environment (Miall, 1977; 1985; Smith, 1985). Consequently, this style of sedimentation shows more similarity to a waterlain deposit-dominated ice marginal fan (Krzyszkowski & Zielinski, 2002) rather than a braided river or sandur environment.

SEDIMENTARY PROVENANCE AND LITHOSTRATIGRAPHY

Lithofacies A – Wroxham Crag Formation

Lithofacies A shows a lithological similarity to the Mundesley Member of the Wroxham Crag Formation (Rose *et al*., 2001) on the basis of a high flint, chatter-marked flint, and shell content with subordinate amounts of quartzose lithologies. This formation has been attributed to an early-Middle Pleistocene shallow-marine environment influenced by input from the Thames and Ancaster River systems. The trace amounts of igneous and metamorphic clasts are tentatively suggested to reflect early-Middle Pleistocene upland glaciation and an input of erratics into lowland river systems.

Lithofacies B - Bacton Green Till Member (Sheringham Cliffs Formation)

In summary, the grey-mud diamicton units are distinctive, with a high percentage of Cenozoic-derived clast lithologies including shell and wood, abundant Quaternary-derived palynomorphs, secondary proportions of Cretaceous-derived lithologies, and small levels of Jurassic and Carboniferous lithologies with igneous and metamorphic erratics. The chalky diamicton facies is characterised by its extremely high Cretaceous chalk content, abundant Campanian-Maastrictian palynomorphs, and a high opaque heavy mineral content. The brown-grey diamicton facies contains significant levels of Pleistocene, Palaeogene and Cretaceous clast lithologies with relatively high percentages of Jurassic and Carboniferous clasts. The palynomorph content is also Carboniferous and Jurassic-rich, and opaque heavy minerals are moderately high.

These lithological properties are contrasted to the lithological characteristics of several eastern England till lithofacies (Table 7). The Briton's Lane diamicton facies can be correlated with the Bacton Green Till Member (Sheringham Cliffs Formation) (Perrin *et al*., 1979; Lunkka, 1994; Moorlock *et al*., 2002; Pawley *et al*., 2004; Lee *et al*., 2004a) on the basis of similar brown-grey matrix colour, variable sand-rich particle size distribution (Fig. 4), low calcium carbonate content, and similar heavy mineral content. The diamictic sediments are lithologically unlike the Happisburgh, Walcott, and Lowestoft tills, and the waterlain generated facies variability is characteristic of the Bacton Green Till (Lunkka, 1994; Moorlock *et al*., 2002; Lee, 2003; Lee *et al*., 2004a).

Cenozoic material (weathered flint, quartzose material), epidote-amphibole-garnet-rich heavy mineral assemblages, and Quaternary or Palaeogene dinoflagellate cysts indicate the reworking of Pleistocene sediments in north Norfolk or Palaeogene sediments from the adjacent North Sea Basin (Boswell, 1916; Soloman, 1932; Perrin *et al.,* 1979; Rose *et al*., 2001; Lee *et al*., 2002, 2004a,b). Specifically, persistent levels of Palaeogene dinoflagellate cysts of mainly Early Eocene age are reworked from the western North Sea Basin. The abundance of these properties in the grey-mud diamicton facies demonstrates these units largely consist of subaqueously deposited local Pleistocene or Palaeogene material.

The significant proportions of Cretaceous-derived black flint and chalk together with palynomorphs of Campanian to Maastrictian age denote the erosion of local Cretaceous Upper Chalk in north-east Norfolk with no significant mixing of more far-travelled Chalk Group material. The prevalence of Late Cretaceous material in the chalky diamicton facies reflects a major input of Late Cretaceous material into the water column. The high apatite content of this facies is derived either from a carbonate rock source (Mange & Maurier, 1992), or from phosphatic nodular horizons within Mesozoic mudstones (Lee *et al*., 2004b).

The percentages of Jurassic sandstone, limestone, and *Rhaxella* chert are higher than recorded in Early to Middle Pleistocene fluvial and shallow marine sediments (Rose *et al.,* 2001) indicating the erosion of Jurassic bedrock outcrops distributed around East Yorkshire (Cameron *et al*., 1992). Jurassic palynomorphs are present in persistent to abundant levels with terrestrial miospores of mostly Early to Mid-Late Jurassic age and smaller proportions of marine dinoflagellate cysts of early Toarcian and Kimmeridgian age. The Yorkshire Basin or East Midlands Shelf is the probable source of the miospores and early Toarcian marine microplankton . The Kimmeridgian dinoflagellate cysts are sourced from the Kimmeridge Clay Formation which crops out extensively in and around the Wash area (Cox & Gallois, 1981). Specifically, Sinemurian marine microplankton within the B_6 brown-grey diamicton facies are derived from the Redcar Mudstone Formation of north-east England (Bucefalo Palliani & Riding, 2000) or the Brant Mudstone Formation of the East Midlands Shelf.

The presence of Permo-Triassic Magnesian Limestone indicates ice flow over outcrops in north-east England and the Carboniferous chert and limestone can only have been derived from either north-east England or central Scotland (Cameron & Stephenson, 1985). Persistent to abundant Carboniferous palynomorphs indicate the erosion of a range of Carboniferous strata and could only be derived from the Northumberland-Durham area of north-east England or from southern Scotland. Devonian Upper Old Red Sandstone may have been derived from the Midland Valley of Scotland (Cameron & Stephenson, 1985) or possibly from outcrops in southern Norway.

The crystalline erratic suite could have been derived from southern Norway or from northern England and central Scotland. However, the lithological and palynomorph assemblages document successive ice-flow over Carboniferous to Pleistocene strata from central Scotland to north-east and eastern England. This ice-flow path and the absence of diagnostically Scandinavian material (rhomb porphyry, larvikite, nordmarkite) is better explained by a Scottish-based ice sheet emanating from central Scotland and flowing southwards along the western margin of the North Sea Basin.

Lithofacies C - Briton's Lane Formation

The abundant levels of weathered white/brown and chatter-marked flint with smaller proportions of quartzose material indicate substantial reworking of Cenozoic sediments in north Norfolk or the North Sea Basin. The small amounts of Jurassic *Rhaxella* chert and sandstone may be derived from the East Midlands Shelf or reworked from Pleistocene sediments. The trace amounts of Permo-Triassic red sandstone, Carboniferous chert, and Devonian Old Red Sandstone are likely to be derived from bedrock sources within northern England and central Scotland although reworking from older glacigenic sediments cannot be discounted. A feature of these deposits, are the relatively abundant crystalline erratic content which includes species of British and, perhaps most significantly, Scandinavian provenance. These Scandinavian lithologies include the rhomb porphyry recorded here and at Weybourne (Moorlock *et al*., 2000; Pawley *et al*., 2004), and gneisses, migmatites and quartz pegmatites recorded from several localities (Moorlock *et al*., 2000; Lee *et al*., 2004a). These may have been reworked from older glacigenic sequences. However, on the basis of the relatively abundant crystalline erratic content and Oslofjord-derived rhomb porphyry clasts found at Briton's Lane and Weybourne (Moorlock *et al*., 2000; Pawley *et al*., 2004), the Briton's Lane Formation is attributed to a Scandinavian ice-source.

DISCUSSION

The sedimentary succession of Briton's Lane provides direct evidence of 2 glacial advances entering north Norfolk, firstly by a Scottish-based ice sheet terminating in a standing water body and depositing the Bacton Green Till Member, and secondly by an advance of Scandinavian-based ice depositing the Briton's Lane Formation as ice-marginal outwash towards the east or northeast.

The available lithological evidence challenges the view that Scandinavian ice deposited the former-NSDF tills (Ehlers & Gibbard, 1991) as no erratics of

Scandinavian provenance have been found *in situ* within them (Lee *et al*., 2002, 2004a; Pawley *et al*., 2004).

For this reason, the Briton's Lane Formation is correlated with the Basement Till in east Yorkshire and Welton Till in Lincolnshire (Catt & Penny, 1966; Alabaster & Straw, 1976; Madgett & Catt, 1978) as these deposits record the first introduction of Scandinavian material (Hamblin *et al*., 2000). The Basement Till is generally accepted as evidence for an OIS-6 glaciation as it underlies the Ipswichian (OIS-5e) raised beach at Sewerby (Catt & Penny, 1966; Madgett & Catt, 1978; Bateman & Catt, 1996) although other workers have argued a late-Devensian age based on amino-acid razimisation dating (Eyles *et al*., 1994).

If the correlation of the Briton's Lane Formation with the OIS-6 Basement Till is valid (Hamblin *et al*., 2000), the timing of the formation of the Cromer Ridge can be questioned. The Bacton Green Till can be traced to within the southern flank of the Cromer Ridge where it is pro-glacially deformed along with the Happisburgh and Walcott tills at Trimingham (Hart 1990; Hart & Boulton, 1991; Lunkka, 1994). As these till members are lithologically unrelated to the Briton's Lane Formation, this proglacial deformation must have occurred prior to the deposition of the Briton's Lane Formation (OIS-6). This deformation could have occurred during an OIS-6 Scandinavian ice advance (Hamblin *et al*., 2000). A second alternative is the Cromer Ridge was produced during the Anglian OIS-12 with the OIS-6 Briton's Lane Formation draped over the topography.

CONCLUSIONS

Complexly intercalated diamictons, muds, and sands reflect glacial deposition in a standing water body and are correlated with the Bacton Green Till Member of the Sheringham Cliffs Formation on the basis of clast lithology, heavy mineral content, ??palynomorphs, particle size, and calcium carbonate content. From these properties, a flow-path from central Scotland to north-east Norfolk can be constructed. Furthermore, the absence of diagnostically Scandinavian material confirms that all three diamicton-members of the former NSDF were deposited by Scottish-based ice.

The Briton's Lane Formation, therefore, currently provides the only evidence for Scandinavian glaciation in East Anglia.

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Table 1 – Correlation of stratigraphic schemes.

Table 2 – Lithofacies code terminology used within the present study. Modified from Miall (1977) and Eyles *et al* (1983).

Table 3 – Heavy mineralogy of the Briton's Lane Quarry sedimentary facies. Analysis was performed on the 63-125μm fraction. Opaque minerals are expresses as percentage of total mineralogy whereas non-opaque minerals are expressed as a percentage of total non-opaques.

Table 4 – Clast lithological analysis of lithofacies A (4-8 mm and 8-16 mm fraction).

Table 5 – Clast lithological analysis (8-16 mm) of lithofacies B and C.

Table 6 – Age-diagnostic palynomorph species levels within analysed diamicton samples. Species are grouped into categories of known stratigraphical age.

Table 7 – A) Summary of the quantified lithological characteristics of several major till lithofacies present in eastern England and comparative lithological summary of lithofacies B.

Figure 1 – A) Map of Norfolk showing the approximate distribution of the Cromer Ridge, North Sea Drift, Marly Drift, and Lowestoft Till (white area). Scale given by 20 km national grid squares. B) Expanded map of study area showing the position of Briton's Lane Quarry on a 1km grid square map.

Figure 2 – Lithostratigraphic log of lithofacies A and B (borehole sediments) with a graphical summary of particle size, calcium carbonate content, percentage opaque heavy minerals, and 4-8 mm clast lithology presented adjacent to the corresponding sample number.

Figure 3 – Sedimentary log of lithofacies C (Briton's Lane Formation) with results of palaeocurrent measurements from bedding planes.

Figure 4 – Ternary diagram summarising the particle size distribution of the Briton's Lane diamictons and compared to the major till lithofacies of eastern England (Madgett & Catt, 1978, Perrin *et al*., 1979, Lee *et al.,* 2004; Pawley et al., 2004).