Interlobate ice sheet dynamics during the Last Glacial Maximum at Whitburn Bay, County Durham, England.

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Abstract

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~~This paper assesses T~~The depositional history of the Devensian glacial tills of Co. Durham was assessed;~~and presents~~ detailed lithostratigraphical and geochemical analysis of clast lithology, particle size, heavy mineralogy and heavy metals analysis is presented. At Whitburn Bay, the lower Blackhall Till is a hybrid subglacial till with a high percentage of locally derived erratics. A boulder pavement at the top of the lower till, points to a switch in ice bed conditions and the production of a meltout lag prior to the deposition of the upper, Horden Till. This is a deformation till, and contains erratics and heavy minerals derived from crystalline bedrock sources in the Cheviot Hills and in the Southern Uplands, including tremolite, andalusite, kyanite, clinopyroxenes and rutile. Within the Horden Till are numerous sand, clay and gravel-filled canals incised downwards into the diamicton, which are attributed to a low energy, subglacially distributed, braided canal drainage system. This evidence, coupled with hydrofractures and the boulder pavement, suggests that the Horden Till was deposited by a surging, fast-flowing ice stream which was decoupled from its bed. The upward, on-land direction of ice movement indicates that the ice stream was confined in the North Sea Basin, possibly by the presence of Scandinavian Ice.

1. Introduction

1.1 Rationale and aims

The behaviour of the British and Irish Ice Sheet (BIIS) along the eastern coast of during the Last Glacial Maximum (LGM) is poorly understood (Carr *et al.* 2006). lobes from both northwest Britain and Scotland overran the area, but the flow lobes, and their dynamic interaction, have only been partially reconstructed. It suggested that ice from the northwest crossed the coast first before ice sourced Cheviot/Tweed area flowed north to south down the coast (Teasdale & Hughes sediments and landforms related to the latter phase of ice flow suggest a surge operated along this coast (Eyles *et al*. 1994; Evans *et al.* 1995), and this late ice has been linked to Heinrich 1 forcing (McCabe *et al*. 2005). The coast- of the ice has also been linked to deflection of the BIIS by Fennoscandian ice in Sea but this remains unproved. During deglaciation it is also apparent that ice from the North Sea lobe resulted in the formation of regionally extensive lakes Wear, Tees, Pickering and Humber (Bateman *et al.* 2007), but the ice their formation are poorly constrained. Furthermore, there is little chronological control on the glacial sediments associated with both the advance phases of the BIIS in this area.

This paper aims to reconstruct the glacial processes operating during the LGM along the Durham coastline. Firstly, it uses macroscale and microscale lithofacies analysis to reconstruct the subglacial and marginal processes occurring during ice sheet advance and recession. Secondly, the paper seeks to determine the patterns and phasing of ice flow in the region using lithological, and heavy mineral and palynological provenancing techniques. Thirdly, the paper considers the glacial landsystem operating along the east coast during the LGM and evaluates the evidence for a surging ice lobe in the North Sea. Finally, the implications of this research for our understanding of regional Quaternary stratigraphic correlation are considered.

1.2 Interlobate Ice Sheet History and Glacial Lake Wear

The pattern of Late Devensian ice movement in Northumberland and Co. Durham involved several interacting ice lobes of fluctuating dominance. Whitburn Bay is located in the area where these ice lobes interacted with each other and with regional proglacial lakes, making it a crucial area for understanding ice sheet flow dynamics and phasing during the LGM.

In eastern Northumberland and county Durham, there is extensive evidence of a first ice lobe passing through the Tyne Gap bearing Lake District erratics and moving in an easterly direction. Drumlin fields in western Northumberland support this (Douglas, 1991). This lobe was confluent with, and later displaced by, ice bearing Cheviot erratics which moved parallel to the coast (Douglas, 1991). This North Sea Lobe surged down the eastern coast of Britain, showing a tendency to move south-westwards, as in the Esk Valley, Robin Hood's Bay, the Vale of Pickering and at Holderness (Catt 1991a).

Trechmann (1915) was the first to suggest the existence of two LGM tills throughout Co. Durham. These tills are well exposed in the coastal cliffs of Co. Durham, where they cap the local Magnesian Limestone bedrock (Smith 1994; Smith & Francis 1967; Bridgland 1999). Within the lower, Blackhall Till (Francis 1972), striations and clast macrofabrics indicate a strong west to east movement (Lunn 1995), with ice moving south-eastwards across eastern Co. Durham from sources in the Pennines, the Lake District and the Southern Uplands (Beaumont 1967). Outlet glaciers entered the Durham area via the Tyne Gap. In the early stages, this Lake District ice coalesced with a Weardale Glacier to form a piedmont lobe glacier in northern Durham (Gaunt 1981). At maximum glaciation, it was probably coalescent with both Scandinavian ice offshore and Tees ice moving over the Stainmore depression in the south (Beaumont 1967).

Francis (1972) correlated the Blackhall Till with the Skipsea Till in the Holderness (Madgett & Catt 1978) the type locality of the LGM in Britain, where it overlies the Silts, dated to 21475-22140 cal. Yr BP (Bateman *et al.* 2007). The glaciofluvial overlie the Blackhall Till, and are overlain by the Horden Till (Francis 1972). A focussed on the genesis of the Horden Till. Catt (1966) proposed a tiered, the Horden and Blackhall tills representing the dirty basal parts of two sheets. However, the Horden Till is more likely to be a basal till from an ice the Blackhall Till after the recession of Lake District ice (Beaumont 1967).

The Horden Till has a very localised distribution, and does not extend much further west than the Durham coastline, supporting the notion that it was probably deposited by a Late Devensian North Sea Lobe, sourced from the Cheviots and the Firth of Forth. It passed the coast of north-east England and extended along the Yorkshire coast, before terminating on the north-eastern fringe of Norfolk (Teasdale & Hughes 1999; Bouton & Hagdorn 2006). This pattern may reflect the presence of Scandinavian ice in the North Sea basin blocking the eastward flow of the North Sea lobe (Carr *et al.* 2006).

The offshore evidence for the North Sea Lobe is extensive. During the deposition of the Bolders Bank and Wee Bankie Formations, ice streams flowed south-eastwards from southern Scotland, piercing the western edge of the Dogger Bank and extending as a lobe across the southern North Sea (Carr 1999). The Bolders Bank till has been correlated with the Skipsea Till of Yorkshire (Cameron *et al*. 1992), and is therefore suggested to be younger than 18 ka BP (Rose 1985).

Glacial Lake Wear (Raistrick 1931) resulted from eastward flowing meltwater being trapped between the North Sea Lobes and the Pennine uplands to the west (Smith 1994; Lunn 1995). It was the largest of a series of ice-dammed lakes (Hughes & Teasdale 1999), and stood at different levels as outlets opened and closed during deglaciation. The lowlands around Sunderland and Newcastle were at one time almost entirely covered by this lake, in which the widespread Tyne-Wear Complex (Smith 1994) deposits were laid down, consisting mostly of laminated clays (Catt 1991b). These were later termed the Durham Member by Thomas (1999). They range from interbedded laminated silty clays and clayey silts up to 55m thick and extending up to 132m OD (Evans *et al.* 2005), to proximal proglacial gravels (Smith & Francis 1967). Finer fractions successively overlap the coarser fractions northwards, marking ice lobe recession. These glaciolacustrine sequences (Evans *et al*. 2005) overlie the Blackhall Till member. Towards the coast, the Horden Till (Catt 2007) overlies this earlier till. Whitburn (Figure 1) is an important site as it exposes both of these members, and was a focal point for ice emanating from the Lake District and from the Southern Uplands and the Cheviots.

2. Methodology

Fieldwork and geochemical analysis of sediments have aided description characterisation of lithofacies. Lithofacies analysis followed standard procedures

Evans and Benn (2004). Clast fabric measurements based on 50 A-axis eigenvector analysis follows Benn (2001).

Particle size, clast lithology, heavy mineral and micromorphological procedures suggested by Gale and Hoare (1992), Mange and Maurer (1992) and Benn (2004). Heavy mineral analysis is utilised for provenance testing and regional ice flow pathways (Gale & Hoare 1992; Mange & Otvos 2005), and is identification of mineral grains with densities greater than 2850 km m^{-3}. ICP-Absorption has also been used to determine the elemental properties of the McClenaghan *et al.* 2000). Micromorphological analysis followed procedures Meer (1993) and Hiemstra and Rijsdijk (2003). Palynomorph analysis was used establish the proportion of dinoflagellate cysts and pollen to aid provenance the ice flow pathway reconstruction (Lee *et al.* 2001; Riding *et al*. 2003c.f. 2000; Smith & Butterworth 1967).

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LEE, J. R., ROSE, J., RIDING, J. B., MOORLOCK, B. S. P. and HAMBLIN, R. Testing the case for a Middle Pleistocene Scandinavian glaciation in Eastern for a Scottish ice source for tills within the Corton Formation of East Anglia, UK. 345-355.

RIDING, J. B., ROSE, J. and BOOTH, S. J. 2003. Allochthonous and indigenous palynomorphs from the Devensian of the Warham Borehole, Stiffkey, north Norfolk, England; evidence for sediment provenance. *Proceedings of the Yorkshire Geological Society*, **54**, 223-235.

3. Sedimentology and Stratigraphy

3.1 Site location and general description

At Whitburn Bay, on the north-east coast of Co. Durham, south of South Shields (Figure 1), glacigenic sediments are well exposed above the Magnesian Limestone bedrock (Figure 3). Lithofacies Associations 1 and 2 are superimposed lower and upper diamictons. Incised into Lithofacies Association 2 are units of laminated sand and clay, rippled sand, and bedded coarse sand and gravel, which constitute Lithofacies Association 3.

3.2 Lithofacies Association 1: A massive, matrix supported diamicton.

Lithofacies Association 1 (LFa 1), the lower diamicton, is inconsistently Bay, but is well exposed in Sections 1, 2, 3 and 6 (Figures 3, 4, 5). It is a brown, consolidated, gravel-rich diamicton capped with a boulder or cobble pavement directly on Magnesian Limestone bedrock. Contacts are sharp, unconformable The diamict contains faceted, striated pebbles, and erratic materal (e.g. coal and pebbles). The clast fabric has low dip angles and a moderately strong clustering from NW to SE (Figure 5).

3.2.1 Lithofacies Association 1 Thin Section Analysis

Three samples of LFa 1 were taken from Section 1. Sample 1-1 was from the base of LFa 1, and 1-2 is from the middle of LFa 1. In thin section, Sample 1-1 is a light brown, matrix-supported, massive diamicton of even density (Table 1). Rotations and Type II Pebbles are common, and there is a strong skelsepic plasmic fabric. Sample 1-2 has a massive, brown, diamict matrix. The skeleton grains are matrix supported and poorly sorted. Larger skeleton grains within matrix exhibit edge-rounding; smaller grains are generally angular. Elongated grains are commonly lineated and aligned. The plasmic fabric (Table 1) is very localised and patchy, with a strong skelsepic plasmic fabric around larger skeleton grains.

Sample 1-3 was taken from the boundary between LFa1 and LFa 2 (Table 1) at Section 1. On macroscopic inspection, the slide is a brown, silty, matrix-supported diamicton. It has many rounded or sub-rounded skeleton grains. A band of lighter coloured, less dense matrix divides the slide into three distinct areas, and the matrix material here is folded and deformed. The contacts between the three zones are sharp. There are rare microfossils, possibly associated with the limestone clasts present. Convoluted, swirling structures are apparent, and are associated with boudinage structures. The top and bottom zones contain strong rotational structures with associated pressure shadows, lineations, and Type II and III pebbles. Small numbers of crushed grains are also present. Necking structures between grains are apparent. FIGURE?

3.2.2 The Boulder Pavement

A boulder pavement occurs consistently at the top of LFa 1 and is laterally extensive across Whitburn Bay. At Section 1 it consists of well faceted, striated boulders up to 50cm across, and extends for 20m (Figure 5). The spacing between the boulders here ranges from a few centimetres up to 60 cm~~entimetres~~. The boulders are flat and polished on their upper surfaces and are either horizontally orientated or dip to the NNW. The mean dip direction of the boulders is 141° and the mean dip is 8.5°. The upper surfaces of the boulders are predominantly striated in a NNE to SSW direction. Some boulders exhibit multiple striae directions, with a dominant upper set and a fainter lower set. The lower set are striated in a NW to SE direction. Lithologically, the boulder pavement consists of Pennine and local rocks, including Carboniferous limestone, sandstone and Magnesian limestone. Between, above and around the boulders at Section 1 there are some channelised, massive, poorly sorted gravels with a sharp, undulating lower contact.

3.3 Lithofacies Association 2: A massive, matrix-supported diamicton

LFa 2 is a dark brown, over-consolidated, matrix-supported, gravel-poor diamicton. Its rare gravel clasts range from subangular to angular, and are faceted and striated. Clast fabrics indicate a moderate orientation from the NNE to SSW. At Section 10, LFa 2 overlies a localised, massive, poorly sorted coarse sand (Unit 1) containing common angular fine to coarse gravel and cobbles (Figures 6 and 7). It has an erosive, undulating lower contact and a scoured upper contact. LFa 2 contains far-travelled, striated clasts with faceted sides, ranging from fine gravel to cobble size. The erratic suite includes Cheviot porphyries and granites, Old Red Sandstone, Carboniferous Limestone; and Greywacke, schist, rhyolite and arkose sandstone from the Southern Uplands.

At Section 2a, 20m north of Section 1, LFa 1 and LFa 2 are exposed in superposition, with LFa 2 exhibiting a number of overturned pipe structures (Figure 8). LFa 2 is then unconformably overlain by a fine, well sorted, thinly bedded sand with a convex base.

3.3.1 Lithofacies Association 2: Thin Section Analysis.

Sample 1-4 was taken from the upper diamicton (LFa 2) at Section 1. It is a dense, dark brown diamicton, with a small number of sub-rounded to rounded, matrix-supported skeleton grains, predominantly in the fine sand to silt size fraction (Table 1). Numerous smaller angular flakes and coal grains are evenly distributed across the slide.

At Section 10 LFa 2 directly overlies bedrock, and sample 10-1 along this interface shows a highly variable structure (Table 1). The limestone bedrock is clearly seen to be drawn up into the diamicton, and matrix material has also been injected downwards into the limestone (Figure 9). Aligned clay particles along the boundary indicate shearing. The diamicton is weakly stratified, and contains numerous rotational structures, Type II Pebbles, and is strongly birefringent. Skeleton grains include coal, siltstone, sandstone and limestone lithologies. Aligned skeleton grains are common.

3.4 Lithofacies Association 3: Stratified gravels, sands and fines.

A number of units of sand and gravel, and of bedded sand, silt and clay, are persistently exposed in Whitburn Bay. These units occur at various heights throughout the section.

3.4.1 Lithofacies Association 3: Coarse sand and Gravel

At Section 5, LFa 2 is vertically dissected by medium to coarse rudaceous understood that 'rudaceous' is a rather outmoded term) clast-supported gravel erosive contacts (LFa 3) (Figure 10). Smaller dykes occur as offshoots from the The clastic dykes have clear-cut, sharply erosive boundaries. In the middle of gravels, there is an infill of fine, thinly bedded sands (Unit 3, LFa 3), which are and contorted. Above the dykes, rudaceous gravels fan up and out into the unit and into coarsely bedded gravels (Unit 4, LFa 3). The lithologies of the those of the underlying diamicton, with Magnesian limestone the most abundant Intraclasts of diamicton occur commonly within the gravels.

At Section 6, a coarse, poorly sorted, bedded sand and gravel is also well exposed, and displays a channelised form. They have a sharp, erosive, undulating bottom contact and a flat, sharp, upper contact.

3.4.2. Lithofacies Association 3: Rippled sands and laminated sand and clay.

At many locations, laminated and draped-rippled sands and clays are incised into LFa 2, and outcrop in cross-section as nested channel forms with concave basal contacts and flat tops (Figure 11). At Section 9a 20 cm of coarse, poorly sorted sand and gravel rest directly on bedrock, and are overlain by 0.75m of planar laminated, well sorted fine sand with a sharp lower contact. Above this is a yellowish-brown, well sorted fine sand with Type A climbing ripples and gradational lower contacts (Unit 2, LFa 3). Next in the sequence are 60 cm of rippled sands with preserved stoss-side laminations and planar bedded sand and clay (Unit 5, LFa 3). The repeated change between planar bedded sands and Type B climbing ripples represents fluctuating flow, with the Type B ripples indicating slowly migrating ripples with high vertical aggradation rates (c.f. Ashley 1995). A dark brown diamicton with sheared and sharp, erosive lower contacts (LFa 2), caps the sequence.

At Section 9d (Figure 11), LFa 1 is overlain by one metre of heavily deformed sand with recumbent folds, overfolds, and convolute lamination (Unit 2; LFa 3). The sand unit has a sharp, scoured lower contact with a pebble lag near the base and a thick planar bed of clay half way up Unit 2, which is overlain by Type A climbing ripples. The lower contact with Unit 1 is sharp, but the upper contacts are gradational. This unit is overlain by massive fine sand with occasional coal planar laminations (Unit 3; LFa 3). In Unit 4 (LFa 3), clay and sand laminations are strongly folded and anastomosed into overfolds and recumbent folds. There are also massive, homogenised clay inclusions. Above this is 50cm of alternating sand and clay planar laminations with a sharp, erosive lower contact (Unit 5). A 200cm thick, dark yellowish brown (10YR 4/4), massive, gravel-poor diamicton caps Section 9d (Unit 6; LFa 2).

Three micromorphology samples were taken from Section 9a, which are Table 1. Samples 9a-1 and 9a-2 (from units 1 and 2, LFa 3) are similar in predominantly show thinly bedded sands. The grains are well sorted fine sand, occasional larger coal grains. The skeleton grains are mostly clast supported, angular to angular. Matrix material is largely absent apart from in small, localised distributed across the slides. Elongate grains are aligned sub-parallel with each patches of skelsepic plasmic fabric have a moderate birefringence. Sample 9a-

(LFa 3), is macroscopically strongly laminated; with deformed, normally faulted folded structures (Figure 12). The bedding is graded, with coarser sand and finer coarse sand laminations are clast supported, with sub-rounded to sub-angular moderately sorted, with rare larger grains including sandstone, limestone, and The coarse laminations coarsen upwards, have sharp contacts, and contain masepic plasmic fabric. In contrast, the fine sand and silt laminations are finer mostly matrix supported. The basal contacts are graded. Within the fine clay are rip-up clasts, boudinage structures, and numerous water-escape structures

4. Geochemical Analysis

4.1 Lithofacies Association 1

Five bulk and gravel samples were analysed from LFa 1. The samples reacted vigorously to 10% hydrochloric acid. Metals analysis reveals it is high in sodium, magnesium, aluminium, potassium, calcium, iron, manganese and titanium.

Magnesian Limestone dominates LFa 1, with Carboniferous limestone present in small amounts. There are also relatively low amounts of Whin Sill dolerite erratics, and very low amounts of quartz and other igneous material. Other rare erratic clasts within LFa 1 include Old Red Sandstone, greywackes, and coal (Table 5). Old Red Sandstone outcrops in the northern and western Lake District and in the Southern Uplands (Johnson 1995). The Carboniferous Coal Measures, sourcing sandstones and coal, are located immediately to the west and north east.

The most prominent heavy mineral is dolomite. The far travelled suite contains an abundance of medium-grade metamorphic minerals such as clinozoisite, andalusite, kyanite, garnet and olivine. Biotite and tourmaline, common in many igneous rocks, are also present.

4.2 Lithofacies Association 2

Seven bulk and clast samples were taken from LFa 2 (Table 2). This lithofacies has a weak to moderate reaction to hydrochloric acid. It is poorer in Magnesian limestone and richer in Carboniferous limestone than LFa 1 (Table 5). There are substantially higher percentages of igneous clasts present, including pink porphyries, rhyolites and granites, together with Whin Sill dolerite. The pink rhyolites are typical of the Cheviots region.

LFa 2 has significant amounts of kyanite, rutile, clinopyroxenes, and baryte (Table 4). Detrital rutile is sourced from high grade, regionally metamorphosed terrains. Amphiboles and hornblendes are also likely to be sourced from crystalline bedrock.

Palynological analysis indicates thatshows abundant kerogen, wood preserved palynomorphs awere present, with lower proportions of non-woody palynomorphs, entirely of Carboniferous age, are dominated by the long-ranging *Densosporites* and *Lycospora pusilla*. -Lower numbers of *Endosporites* spp., *Radii~~z~~zonates* spp., *Tripartites trilinguis* and *Tripartites ve~~s~~tustus* were also 2007). *Endosporites globiformis, Florinites* spp., and *Ra~~i~~di~~i~~izonates* spp. (note: *Radiizonates* spp.) are~~is~~ indicative of the Westphalian (Smith & Butterworth indicates that some Namurian input is possible. This indicates a likely derivation Newcastle coalfield to the north.

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4.3 Lithofacies Association 3

The fine, laminated sand facies of LFa 3 was sampled at Section 9a. It is a yellowish brown well sorted sand (Table 2), which reacts vigorously to hydrochloric acid. The sand facies is rich in high grade metamorphic minerals, such as rutile, clinopyroxenes and amphiboles (Tables 4 and 5).

5. Interpretation

5.1 Lithofacies Association 1: massive, matrix-supported diamicton.

Lithofacies Association 1 has the macro-scale characteristics of a subglacial till (Carr 2001). These include striated, far-travelled, faceted clasts, far-travelled heavy minerals, an over-consolidated, matrix-supported diamicton, and well-orientated, clustered clast fabrics (Evans *et al*. 2006; Benn & Evans 1998). A comparison of LFa 1 and LFa 2 shows that locally sourced, non-durable clasts dominate LFa 1. LFa 2 has a more significant component of far travelled clasts, including igneous erratics (Figure 13).

The micromorphological analysis supports a genesis as a subglacial till. Rotational structures, rounded Type II and III Pebbles, and skelsepic plasmic fabrics denote ductile deformation (van der Meer 1997) and grain rotation in a till matrix (van der Meer 1997; Nelson *et al.* 2005). The rotation of skeleton grains has caused preferential alignment of clay particles (Roberts & Hart 2005), through the transmission of stress perpendicular to the particle edges. Masepic plasmic fabrics, lineations of grains and crushed grains imply high strain and pressure in a brittle environment (Menzies 2000). The combination of both brittle and ductile deformation structures suggests polyphase deformation. The common turbate structures, and the lack of flow structures, marbling and tile structures, precludes a genesis as a mass movement or debris flow (Carr 2001; Menzies & Zaniewski 2003).

Sample 1-3, from the junction between LFa 1 and LFa 2 at Section 1, could show décollement plane, where the upper till has slid over the lower till in the environment (as demonstrated by van der Meer *et al.* 2003). It contains micro-escape structures that have been subsequently deformed. The two varieties of (bimasepic) plasmic fabric indicates strong shear in two directions. The coherent, and well shaped, with no inter-granular disintegration or stringers, and character to the till matrix. These soft sediment clasts could indicate existing sediments.

LFa 1 is interpreted as a terrestrial subglacial hybrid till, or traction till (Evans *et al.* 2006); with evidence for both lodgement and deformation, which varied spatially throughout Whitburn Bay (as also noted by Lunkka in Norfolk in 1994; Nelson *et al.* 2005). The striated, lodged clasts with well defined stoss and lee ends, and the lodged boulder pavement, are indicative of lodgement. In contrast, many other sections demonstrate structures indicative of extensional deformation, such as stringer initiation, low clast fabrics, massive, homogenous sections, and micromorphological evidence of extensive ductile deformation.

5.2 The Boulder Pavement

The boulder pavement occurs at the top of the lower till. Striations and clast fabrics are consistent with LFa 2, indicating that the boulders were overridden by the second phase of ice flow. There are several theories of boulder pavement formation, ranging from lodgement, deformation and a continuum between them. Boulton and Paul (1976) propose a 'traffic jam' mechanism for boulder pavement formation, where boulders build up behind lodged clasts. These stones form a nucleation point behind which other stones cluster. The lodgement of clasts on a soft bed involves the ploughing up of the deformable substrate so that it forms a prow, which arrests the forward movement of the clast. Large clasts are preferentially lodged, forming an obstacle to the further movement of such clasts, and creating clusters or pavements (Evans *et al.* 2006). After lodgement, the boulders are extensively abraded, which truncates and striates the upper surfaces. The presence of the boulder pavement may aid sliding and fast flow.

Clark (1991), van der Wateren (1999) and Glasser *et al* (2001) argue that striated boulder pavements form when boulders settle to the base of a weak deforming sediment. The overriding deforming sediment then abrades them.

Jørgensen and Piotrowski (2003) counter-argue that a boulder pavement is an erosional surface, which can indicate truncation and removal of lower sediments. Boulder pavements typically have flat, polished upper surfaces with unidirectional striations, and are strongly faceted. Lodgement and extensive abrasion by the sole of the ice sheet truncates, orientates and striates the upper surfaces of the boulder pavements (Jørgensen & Piotrowski 2003).

Hicock (1991) favours a combination of lodgement, deformation, melt-out and erosion. He proposes a continuum of pavement-forming processes, from deformation-dominated to lodgement-dominated pavements. Boulton (1996) maintains that during erosion of the till down to the A/B interface, dense clasts, on being exposed, resist being drawn into glacier flow and remain immediately above the 'descending A/B interface, thus concentrating larger clasts from the mobilised till at the A/B interface'.

The pavement at Whitburn may represent an erosional lag formed within a deforming bed (Figure 14). As the boulders are orientated and striated strongly in one direction, it is unlikely that they have sunk through the deforming layer, as this would lead to multiple striae directions and to rotation of clasts (Jørgensen & Piotrowski 2003). It is more likely that the boulders melted out from the base of the ice sheet, possibly during a phase of ice quiescence related to a switch in ice flow direction, and where then lodged into the deforming substrate as ice movement was reactivated, causing striation and faceting before eventual burial by till deposition (LFa 2).

5.3 Lithofacies Association 2: massive, matrix-supported diamicton.

Faceted, striated, far travelled clasts, and the over-consolidated nature of the diamicton, indicate that LFa 2 is also a subglacial till. The variable presence of LFa 1 indicates that either extensive deformation has homogenised the two tills, or the later ice advance has eroded the lower lithofacies. Clast fabrics and striations indicate general ice movement from the north-west to south east. The low and variable S_1 values from the clast fabrics suggest extensive deformation (c.f. Evans *et al.* 2006). Hart (2007) argues that weak clast fabric strengths reflect clast interaction and a dominance of deformation and rotation, and furthermore that high grain size and low sorting emphases rotation, leading to low clast fabric strength in subglacial diamicts.

At Section 2a, the overturned pipe structures are evidence of the squeezing of the soft, saturated LFa 1 into LFa 2 under a high ice overburden pressure (Figure 15). They are overturned to the south east, supporting this direction of ice flow. The preservation of these features is indicative of lower strain rates at this point.

Micromorphological analysis of LFa 2 reveals numerous micro-scale deformational structures, such as circular structures with associated skelsepic fabrics, aligned grains and grain lineations (Figure 9). Elongate grains near the shear plane have rotated until they are aligned plane-parallel. Crushed grains and strong masepic plasmic fabrics indicate pervasive strain and high pressure. These features are indicative of subglacial deposition and deformation (van der Meer 1997; Carr 2001). Sample 10-1 shows in detail the junction of the LFa 2 diamicton with the underlying bedrock, and further supports a subglacial till interpretation, based on the strong presence of circular structures, crushed grains, Type II pebbles, and a strong plasmic fabric. At a macroscale, the Magnesian Limestone bedrock has been entrained into the till with evidence of stringer formation and cannibalisation of the lower soft, dolomitic bedrock.

The erosion or incorporation of LFa 1 into LFa 2, for example at Sections 5 and 10, suggests that LFa 2 is a subglacial traction till (Evans *et al.* 2006), but the highly variable and often low clast fabric strengths, as well as the preservation of the pipe structures and canal fills suggest a low strain deformation signature. These features have a low preservation potential, and are unlikely to have survived the process of lodgement (Nelson *et al.* 2005).

The localised lense of chaotically sorted sand and gravel at the base of the diamicton at Section 10 represents a narrow channel. The deposition of this waterlain deposit at the bedrock/till interface may relate to the separation of the till and bedrock.

Ultimately, LFa 1 and LFa 2 represent a mosaic of processes operating subglacially at the time of sediment deposition, at both the macro- and the micro-scale (c.f. Piotrowski *et al*. 2004). The location of deforming spots could be controlled by the capacity of the bed to evacuate pore water (c.f. Boulton *et al.* 2001). Areas of low permeability and high water pressure will deform first (Piotrowski *et al*. 2004). Multiple switches in different modes of deposition and deformation resulted in the variable appearance of the two tills and the boulder pavement at Whitburn Bay (c.f. Piotrowski *et al*. 2004; Piotrowski *et al.* 2006).

5.4 Lithofacies Association 3: Sand and gravel facies.

The gravel dykes at Section 5 are interpreted as the result of high-pressure fluid escape beneath the ice sheet; i.e., as hydrofracture fills. These sub-vertical clastic dykes are traditionally interpreted as the product of the escape of pressurised groundwater (Evans *et al.* 2006). Tensional cracks are infilled by sediment fluidised by the escaping water (Figure 16). These hydrofractures occur where fluid pressure exceeds the tensile strength of the sediment and the smallest component of the ice overburden pressure (Rijsdijk *et al*. 1999). Juxtaposed thinly bedded, calcreted sands, and coarse, well sorted gravel indicates variable flow regimes.

At Whitburn Bay, subglacial meltwater would have discharged into the Magnesian Limestone aquifer. The overlying tills acted as aquiludes, hydraulically confining the bedrock (as also observed by Rijsdijk *et al*. 1999 at Killiney Bay, Ireland). When the supply of meltwater exceeded the capacity of the bedrock aquifer, water pressures rose beneath the overlying till. When the water pressure exceeded the tensile strength of the till, it caused tensile fracturing, which enabled hydrofracturing (Figure 16). The discharge of water was sufficient to fluidise the sands and gravels, transport them through the hydrofracture and inject them into the overlying sediments. Subsequent glaciotectonism further deformed these contorted beds. A high percentage of calcium carbonate in the ground water, derived from the Magnesian limestone bedrock, resulted in calcretion of the gravels.

The gravel channel at Section 7 is a high energy subglacial Nye channel. The well sorted cobble gravel, with an undulating lower contact and a flat, eroded upper contact, lacks the internal structures associated with subaerial fluvial systems (c.f. Lunkka 1994). These channels were discreet, hydraulically efficient, channelised systems which were effective at evacuating subglacial meltwater. They are highly erosive and incised into the deforming layer.

5.5 Lithofacies Association 3: Laminated sand and clay facies.

The sand and clay bed at Section 2b contains laminated and thinly bedded well sorted sand and clay, indicating deposition in a low energy fluvial environment. The laminated sand and clay beds have closed edges, flat tops, and undulating, convex bottom contacts, indicating that they were incised into the diamicton, perhaps in a period of higher energy flow (van der Meer *et al.* 2003). The laminations are locally strongly deformed and contain water escape structures. Load and flame structures can indicate deformation and remobilisation of water-saturated beds, and can suggest rapid deposition (Glasser *et al*. 2001) or a high overburden pressure. The recumbent folds and overfolds are indicative of secondary glaciotectonism.

Section 9a exhibits Type A climbing ripples, indicating fast flowing water and rapidly migrating ripples. These are overlain by alternating sand and clay planar laminations, representing periods of fast flowing water and periods of suspension settling under low- or no-flow conditions, indicating periodical quiescence of the channel and little sediment input (c.f. Ashley & Smith 1985; Ashley *et al*. 1982).

Micromorphological analysis of the thin section samples obtained at Section 9a supports a fluvial genesis for the sands, followed by glaciotectonism. Samples 9a-1 and 9a-2 are crudely bedded with numerous grain lineations and contain climbing ripples. The presence of a masepic plasmic fabric could be a primary depositional feature. The extensive deformation of the primary bedding in Sample 9a-4 indicates pervasive shear, and the erosion and incorporation of bed material; with structures such as rip-up clasts, boudins and strong plasmic fabrics commonly seen. In times of very low or no flow the clay laminae were deposited, reflecting quiescence and ponding events. The presence of sand grains in the clay laminae suggests that these are micro-dropstones formed in a glaciolacustrine environment, by melt-out from the overlying ice.

These isolated channelised forms, with concave-up bases and flat tops, and the strong variation in height of these channels, argues against a proglacial origin. Distal proglacial sandur systems are characterised by trough cross-bedded, cyclic fining-upward sequences of gravels, sands and silts with slip face migration of longitudinal and linguoid braid bars. This gives rise to planar cross-beds, with abundant ripple-drift and cross-lamination (Maizels 1995). Distal proglacial outwash sediments typically exhibit megaripple migration on point-bar surfaces, producing large scale trough cross-beds. The lack of bars, dunes and tabular bedding in the Whitburn channels systems suggests that they are subglacial glaciofluvial sediments (Collinson 1996). We interpret them as a low energy subglacial braided canal network, as defined by Walder & Fowler (1994), which was active beneath the ice sheet that formed the traction tills.

This type of distributed subglacial drainage system is inefficient, and can result in flows and ponding beneath the ice sheet. Braided canal systems are effective flow cannot evacuate all the excess water in the system (Benn & Evans 1996). have long been recognised in the geological record as broad lenses of sorted tills with concave-up lower contacts and nearly planar upper contacts (for *al.* 1986; Lunkka 1994; Shaw 1987). Englacial conduits are recognised to rarely than 200m into the ice sheet (Piotrowski *et al.* 2006), indicating that Whitburn ice marginal environment. Ductile deformation, despite the high drainage would therefore have occurred close to the ice margin under low cryostatic

Swift *et al.* (2002) argued that seasonal reorganisation of subglacial drainage can occur beneath many temperate and polythermal glaciers, resulting in distributed and channelised configurations, with the development of a hydraulically efficient, channelised subglacial drainage system during the ablation season. This would involve higher pressure, channelised, faster flowing canals (such as Section 7) and slower moving, lower energy, distributed drainage systems (such as Section 9) evolving throughout the year. These lower energy channels also demonstrate flow variability at smaller scales, with evidence of periodic quiescence and ponding, as well as periods of faster flow, demonstrated by Type A and B climbing ripples and planar lamination.

High porewater pressure, as evidenced by hydrofracturing and extensive till deformation results in an excess of water at the ice sole, and may induce basal decoupling and the formation of englacial canals. These drain porewater, raising of the shear strength of the surrounding sediments (Piotrowski *et al.* 2006). This can contribute to 'sticky spot' development, of areas of both high and low deformation, changing through space and time.

Lithofacies Association 3 therefore demonstrates fluctuations of meltwater discharge at multiple scales. Seasonal changes in meltwater discharge are capable of driving the sedimentological signal. An alternative explanation for the laminated clay and sand facies at Whitburn Bay could be backfilling of the canals during times of low or no flow, related to ice marginal lake level fluctuations. There is extensive evidence of proglacial lakes in Co. Durham and Yorkshire (Gaunt 1981). During periods of low lake levels, high submarginal discharge in these channels would have resulted in the deposition of rippled and bedded sands, but during periods of high ice marginal lake levels, backfilling of the channels will have caused ponding and clay drape lamination. The canal fills could thus be related to the activity of local lakes such as Glacial Lake Wear. Indeed, episodic changing lake levels, related to both seasonal variations in meltwater and the movement of ice lobes, have been suggested in Glacial Lake Wear (Gaunt 1981). Fluctuating lake levels could also explain why this signal is repeated in all channels at variable heights along the Whitburn site.

6. Provenance of the Whitburn Bay tills

Old Red Sandstone is perhaps the most useful lithology for provenance testing it outcrops in the northern and western Lake District and in the Southern Uplands 1995). Carboniferous Limestone outcrops in the north and south Lake District, in Northumberland Basin between the Alston Block, and in the Southern Uplands

Sill dolerite is a local Permian intrusive igneous rock, which outcrops to the north area. The Carboniferous Coal Measures immediately to the west and north of are sources for the coal and sandstones of LFa 1 (Figure 2). The assemblage of Carboniferous and Permian erratics indicates a locally derived till. Clast fabric orientations support an east-west direction of ice movement.

LFa 1 is high in clinozoisite, andalusite, kyanite, garnet and olivine. Clinozoisite is a product of low to medium grade metamorphism, and is common in some schists. Some basic igneous rocks may also contain clinozoisite. Andalusite and kyanite are metamorphic minerals, common in contact aureoloes around igneous intrusions and in gneisses and schists. Olivines are the principle components of many basic igneous rocks (Mange & Maurer 1992). The presence of metamorphic and igneous-derived minerals in LFa 1 suggests that the matrix was sourced from further afield, and perhaps from igneous and lower grade metamorphic complexes in the Lake District.

Ratios of apatite to tourmaline, garnet to zircon, rutile to zircon, and spinel to zircon are also useful in reflecting source characteristics. These data indicate that the two tills at Whitburn Bay have distinctly different sources, as all the indices show differences (Figure 17; Morton & Hallsworth 1994). LFa 1 contains a number of far-travelled heavy minerals, but few far-travelled igneous clasts. The clast fabrics and presence of crystalline minerals indicates a source from northwestern England and the Lake District. Hence, this first phase of ice movement crossed the Pennines and deposited the lower till.

A greater proportion of Carboniferous Limestone in LFa 2 compared to LFa 1 indicates that LFa 2 has been isolated from the local Permian bedrock by a mantle of earlier till (LFa 1), which is widespread in the Durham region (Beaumont 1967). The pink granites, rhyolites and porphyries are distinctive and are from the Cheviots. Greywackes are common in the Southern Uplands, and Whin Sill dolerite is located to the west and north of the study area.

LFa 2 is rich in muscovite, andalusite and kyanite, which are common in schists and metamorphic rocks. Zoisite is generated by medium-grade regional metamorphism, and is a characteristic component of silicate granulites and micaschists. Regionally metamorphosed terrains are the most common source of detrital rutile. Amphiboles such as horneblende and tremolite are present in small quantities. These are chemically unstable minerals, derived from crystalline bedrock sources (Lee *et al.* 2004). Augitic and diopsidic clinopyroxenes are widespread in ultramafic and intermediate igneous rocks, and are common in gabbros, dolerites, andesites and basalts, indicating a likely source from eastern Scotland.

The palynomorph~~logical~~ assemblages indicate~~s~~ a likely derivation from the coalfield, to the north. There was no palynological evidence for~~xpression of~~ the Limestone, supporting the interpretations of LFa 2 overriding LFa 1, and having the local Magnesian Limestone bedrock. However, it should be borne in mind

Magnesian Limestone is a relatively organic-poor unit. Collectively, this evidence indicate a source in the Cheviots and Southern Uplands. A clast fabric indicative SSE flow direction supports this.

7. Discussion

7.1 Evolution of the glacigenic sequence at Whitburn Bay

Recent research has highlighted the fact that there is large spatial variability in basal friction below ice sheets, and that glacier beds generally comprise mosaics of sliding, deformation, lodgement and ploughing (Nelson *et al.* 2005; Evans *et al.* 2006; Piotrowski *et al*. 2004). Whitburn Bay demonstrates this well, with evidence for lodgement in the form of the clast pavements, juxtaposed with extensive evidence for deformation and hydrofracturing.

A multiphase model of land-system development (Figure 18) can be deduced from glacigenic sediments at Whitburn Bay. The first phase (Figure 19) involved the arrival of an ice lobe from the west, which deposited LFa 1. This ice originated in the Lake District and entered eastern England via the Tyne Gap.

The second ice lobe (Figure 19) flowed down the eastern coast of Britain and deflected or obstructed the first. This North Sea Lobe deposited the Horden Till in Co. Durham. In the offshore area, the Bolders Bank till was deposited. As it continued southwards over the varying lithologies in Yorkshire, the North Sea Lobe entrained local lithologies such as chalk and shale. This formation is younger than 21475-22140 cal. Yr BP (Cameron *et al.* 1992; Bateman *et al.* 2007).

The North Sea Lobe overrode the lower till. The initiation of the boulder have been triggered by a period of basal ice melting as flow from the west lodged and abraded by ice flowing from the north which deposited LFa 2 (Figure distributed subglacial drainage system of braided canals developed beneath the have changed, possibly seasonally, to a discrete, higher pressure drainage efficient Nye channels. Björnsson (1998) argued that glacial surges and fast ice associated with subglacial distributed drainage systems, because an increase in pressure, as evidenced by the extensive existence of subglacial canals, can lead decoupling of the ice from its bed (Björnsson 1998; Evans *et al.* 2006). The the shear stress is translated to underlying sediments and results in the dilation when the critical water pressure for failure is reached, sliding can occur (Boulton Additionally, when ice overrides a wet subglacial till, enhanced flow velocities from till deformation and sliding at the ice / bed interface (Ng 2000; Boulton *et al*. sedimentary signal within the canals may be controlled by a fluctuating internal with alternating periods of current flow and ponding pointing to an inefficient often typical of surging glaciers (Björnsson 1998; Evans *et al.* 2006), but it is also fluctuating local lake levels influenced the hydraulic efficiency in these environments.

Surging ice streams related to Heinrich 1 have been considered since the mid 1990s (Eyles *et al.* 1994; McCabe and Clark 1998). Boulton & Hagdorn (2006) argue that model simulations show a powerful ice stream flowing down the eastern coast of Britain, which bifurcates at its head and pierces the Dogger Bank as well as one lobe penetrating the Wash embayment. This damming of the Wash embayment created Glacial Lake Humber. Recent OSL dates on the high stand of this lake (Bateman *et al.* 2007) of 16.6 ± 1.2kyr suggest that the BIIS was surging at the western edge of the North Sea Basin during Heinrich 1, depositing the Skipsea Till and the Bolders Bank Formation. Eyles *et al*. (1994) argue that this east coast ice stream experienced recurrent onshore surging against the rising bedrock surface of Holderness and Lincolnshire. Drumlin swarms in the valleys of northern England record accelerated ice flow from the reservoir regions, and may have been integral parts of the surging system (Eyles *et al.* 1994).

Other ice streams associated with Heinrich 1 are gradually being recognised in Britain (McCabe *et al*. 2005), and it is now proposed by several researchers that the BIIS was very sensitive to abrupt climate changes in the North Atlantic Ocean. A dynamic BIIS was thus characterised by large and rapid fluctuations. Climatic change in the North Atlantic may also have contributed to ice sheet reorganisations, with changes in ice flow pathways and centres of ice dispersion.

7.2 Implications for Quaternary Stratigraphy of Eastern England

The locally derived Blackhall Till (LFa 1) at Whitburn Bay was previously correlated with the Skipsea Till of Holderness (Francis 1972) due to its stratigraphical position, but this is disputed on the basis of the provenance data presented here. We favour an origin from ice flowing from the Lake District and across the Pennines through the Tyne Gap. The Blackhall Till shows a distinct west to east movement, and comprises mainly local clasts. Previous workers (Beaumont 1967) have suggested that it is limited in extent, and there seems to be no equivalent further south.

There has been little detailed geochemical data published on the Skipsea Till. It has been described as a very dark greyish brown till, containing 32.8-42.4% silt (Madgett & Catt 1978). The Skipsea Till contains chalk, shale, Cheviot porphyries, granites, Whin Sill dolerite, Carboniferous and Magnesian limestone, coal and greywackes. The Skipsea Till is rich in the amphibole and epidote heavy minerals, but low in chlorite and biotite heavy minerals. Thus, the clast lithology and the fine sand mineralogy of the Skipsea Till (Madgett & Catt 1978) suggests correlation to the Horden Till (LFa 2).

The macrofabric of LFa 2 at Whitburn Bay and of the Skipsea Till at Holderness deposition by ice moving inland from the North Sea basin. Ice originated from Uplands, streamed down the eastern coast of Britain (Eyles *et al*. 1994), invaded

Basin and deposited the Skipsea Till and the Bolders Bank Till (Cameron *et al*. 2006). The movement inland could be due to coalescence of British ice with offshore in the North Sea, although it should be noted that Carr *et al*. (2006) and Fennoscandian ice sheets had decoupled by this stage. Hence, this work North Sea Lobe flowing south was the second ice lobe to transgress the Durham first ice body to reach the Holderness coast during the LGM.

8. Conclusions

This research at Whitburn Bay clearly supports the existence of a complex, interlobate, late Devensian BIIS along the coast of Britain. LFa 1 and 2 represent ice flow from two different directions within the same glaciation. The Blackhall Till (LFa 1) originated in north-western England, mainly sourced in the Lake District. It is interpreted as a traction till, demonstrating both lodgement and deformation. The Horden Till (LFa 2) originated in the Southern Uplands and the Cheviots, and represents an ice lobe flowing down the eastern coast of Britain. The boulder pavement between the two tills was deposited initially by basal meltout as ice flow from the west waned, and was later lodged and abraded by ice moving southwards.

The braided canal system preserved in the Horden Till suggests a low-flow subglacial drainage system, juxtaposed with high energy gravel channels, reflecting periodical changes in the subglacial drainage hydraulic regime. Extreme changes in subglacial drainage pressure are also supported by the existence of hydrofractures, which may have triggered the development of high energy channels at the ice-bed interface. The episodic changes from water flow to quiescence in these submarginal channels indicates periodic ponding events. This sedimentological signal could be driven by periodically fluctuating lake levels in the proglacial Glacial Lake Wear. High lake levels would result in backfilling of the channels, quiescence, and the formation of draped lamination. An increase in meltwater or a drop in the lake level would result in the channels 'switching on' and discharging into the lake. Seasonal re-organisations of the subglacial drainage system could result in the juxtaposition of sand and very high energy gravel channels.

The Horden Till may be correlative with the Dimlington Stadial Skipsea Till and Bolders Bank Tills in Yorkshire and offshore respectively. This may suggest that the North Sea ice lobe flowing south was the second ice lobe to transgress the Durham area, but the first ice mass to cross the Holderness coast during the LGM.

Evidence is mounting for a surging ice stream located on the eastern coast of Britain (Boulton & Hagdorn 2006; Eyles *et al*. 1994). Fast ice flow at Whitburn Bay is supported by evidence for basal decoupling, extreme fluctuations in subglacial porewater pressure, and the presence of wet, slippy, deforming beds.

INTERLOBATE ICE SHEET DYNAMICS DURING THE LAST GLACIAL MAXIMUM AT WHITBURN BAY.
WHITBURN BAY.

Glossary of Micromorphology terms

- *Plasmic fabric:* the arrangement of clay and silt-sized particles in a sample.
- *Domain:* a localized zone displaying a characteristic plasmic fabric.
- *Skelsepic:* preferred orientation of plasmic fabric around the surfaces of larger grains: indicates rolling of larger grains.
- *Lattisepic:* preferred orientation of plasmic fabric in two perpendicular orientations: commonly associated with skelsepic plasmic fabric.
- *Masepic:* preferred orientation of plasmic fabric in diffuse domains of parallel orientation: indicative of pervasive shearing.
- *Unistrial:* preferred orientation of plasmic fabric in discrete parallel domains; indicative of discrete shear.
- *Galaxy / rotation structures / turbate structures:* circular alignments of grains around cores of consolidated sediment or larger grains; indicative of rotation.
- *Pressure shadows:* symmetric or asymmetric tails of material on the stoss and lee of large grains. Indicative of planar shearing (symmetric) or rotation (asymmetric).
- *Pebble type I:* arrangement of brecciated sediment such that it appears to form a series of rounded intraclasts delineated by packing voids.
- *Pebble type II:* soft sediment intraclasts of material similar in nature to the surrounding sample, but with a clearly defined discrete internal plasmic fabric.
- *Pebble type III:* soft sediment intraclasts of material different in nature to the surrounding sample: evidence of reworking of pre-existing sediments.

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References

Allen, J.R.L., 1963: The classification of cross-stratified units, with notes on their origin. *Sedimentology 2*, 93-114.

Ashley, G.M., 1995: Glaciolacustrine Environments. In: Menzies, J., (ed) 1995: *Modern Glacial Environments. Processes, dynamics and sediments.* Glacial Environments Volume 1. Butterworth-Heinemann.

Ashley, G.M., & Smith, N.D., 1985: Proglacial lacustrine environment. In: Ashley, G.M., Shaw, J., and Smith, N.D., (eds): *Glacial Sedimentary Environments.* Society of Economic Paleontologists and Mineralogists. Short Course No. 16.

Ashley, G.M., Southard, J.B., & Boothroyd, J.C., 1982: Deposition of climbing-ripple beds: a flume simulation. *Sedimentology 29*, 67-79.

Ashley, G.M., & Warren, W. P., 1997: The Ice Contact Environment. *Quaternary Science Reviews 16*, 629-634.

Bateman, M.D., Buckland, P.C., Chase, B., Frederick, C.D., and Gaunt, G.D., 2007. The Late-Devensian proglacial Lake Humber: new evidence from littoral deposits at Ferrybridge, Yorkshire, England. *Boreas* in press.

Beaumont, P., 1967: *The glacial deposits of Eastern Durham.* Unpubl. PhD thesis, Durham University.

Benn, D.I., 2001: Random variation of fabric eigenvalues: Implications for the use data to differentiate till facies. *Earth-Surface Processes and Landforms 26*, 295-

Benn, D.I., & Evans, D.J.A., 1996: The interpretation and classification of subglacially deformed materials. *Quaternary Science Reviews 15*, 23-52.

Benn, D.I., & Evans, D.J.A., 1998: *Glaciers and Glaciation.* Arnold, London.

Björnsson, H., 1998: Hydrological characteristics of the drainage system beneath a surging glacier. *Nature 395*, 771-774.

Boulton, G.S., 1996: Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. *Journal of glaciology 42*, 43-62.

Boulton, G.S., & Hagdorn, M., 2006. Glaciology of the British Isles Ice Sheet during the last glacial cycle: form, flow, streams and lobes. *Quaternary Science Reviews 25*, 3359-3390

Boulton, G.S., & Paul, M.A., 1976: The influence of genetic processes on some geotechnical properties of glacial tills. *Quarterly Journal of Geological Engineering 9*, 159-194.

Boulton, G.S., Dobbie, K.E., & Zatsepin, S., 2001: Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quaternary International 86*, 3-28.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery D.H., Lott, G. K., Bulat, J., & Harrison, D.J., 1992: *United Kingdom offshore regional report: The geology of the Southern North Sea.* HMSO: London; 153pp.

Carr, S.J., 1999: The micromorphology of Last Glacial Maximum sediments in the Southern North Sea. *Catena 35*, 123-145.

Carr, S.J., 2000: Micromorphological evidence supporting Late Weichselian glaciation of the Northern North Sea. *Boreas 29*, 315-328.

Carr, S.J., 2001: Micromorphological criteria for discriminating subglacial and glacimarine sediments: evidence from a contemporary tidewater glacier, Spitsbergen. *Quaternary International 86*, 71-79.

Carr, S.J., 2004: Micro-scale features and structures. In: Evans, D.J.A, & Benn, *practical guide to the study of glacial sediments.* Arnold, London.

Carr, S.J., Holmes, R., van der Meer, J.J.M, & Rose, J., 2006: The Last Glacial Maximum in the North Sea: Micromorphological evidence of extensive glaciation. *Journal of Quaternary Science 21,* 131-153.

Catt, J.A., & Penny, L.F., 1966: The Pleistocene deposits of Holderness, east Yorkshire. *Proceedings of the Yorkshire Geological Society 35*, 375-420

Catt, J.A., 1991a: Late Devensian glacial deposits and glaciations in eastern England and the adjoining offshore region. In: Ehlers, J., Gibbard, P.L., & Rose, J., (eds) 1991: *Glacial deposits in Great Britain and Ireland,* 61-68. A.A. Balkema, Rotterdam.

Catt, J.A., 1991b: The Quaternary history and glacial deposit in east Yorkshire. In: Ehlers, J., Gibbard, P.L., & Rose, J., (eds) 1991: *Glacial deposits in Great Britain and Ireland,* 181-191. A.A. Balkema, Rotterdam.

Catt, J.A., 2007: The Pleistocene Glaciations of eastern Yorkshire: A Review. *Proceedings of the Yorkshire Geological Society 56*, 177-207.

Clark, P.U., 1991: Striated clast pavements: Products of deforming subglacial sediment? *Geology 19*, 530-533

Collinson, J., 1996: Alluvial Sediments. In: Reading, H., 1996: *Sedimentary environments: Processes, facies and stratigraphy. 3rd edition*. Blackwell Science, UK

Douglas, T., 1991: Glacial deposits of Northumbria. In: Ehlers, J., Gibbard, P.L., & Rose, J., (eds) 1991: *Glacial deposits in Great Britain and Ireland.* P. 169-174. A.A. Balkema, Rotterdam.

Dreimanis, A., Hamilton, J.P., & Kelly, P.E., 1986: Complex subglacial sedimentation of Catfish Creek till at Bradtville, Ontario, Canada. In: van der Meer, J.J., (ed), *Tills and Glaciotectonics.* Proceedings on an INQUA symposium on genesis and lithology of glacial deposits. Amsterdam.

Evans, D. J. A., Owen, L. A., & Roberts, D.H., 1995: Stratigraphy and Sedimentology of Devensian (Dimlington Stadial) glacial deposits, east Yorkshire, England. *Journal of Quaternary Science 10*, 241-265.

Evans, D.J.A., & Benn, D.I., 2004: *A practical guide to the study of glacial sediments.* Arnold, London.

Evans, D.J.A., Clark, C.D., & Mitchell, W.A., 2005: The last British Ice Sheet: A review of the evidence utilised in the compilation of the Glacial Map of Britain. *Earth Science Reviews 70*, 253-312.

Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., & Auton, C.A., 2006: Subglacial till: Formation, sedimentary characteristics and classification. *Earth-Science Reviews 78*, 115-176.

Eyles, N., McCabe, A.M., & Bowen, D.Q., 1994: The stratigraphic and sedimentological significance of Late Devensian ice sheet surging in Holderness, Yorkshire, UK. *Quaternary Science Reviews 13*, 727-759.

Francis, E. A., 1972: Quaternary. In: Johnson, G.A.L., & Hickling, G., *Geology of Durham County.* Transactions of the Natural History Society of Northumberland, Durham and Newcastle Upon Tyne.

Gale, S. J., & Hoare, P. G., 1992: *Quaternary Sediments: Petrographic Methods for the study of unlithified rocks.* John Wiley and Sons, New York.

Gaunt, G.D., 1981: Quaternary history of the southern part of the Vale of York. In: Neale, J., & Flenley, J., (eds) 1981: *The Quaternary in Britain*, 82-97. Pergamon Press, Oxford.

Glasser, N.F., Hambrey, M.J., Huddart, D., Gonzalez, S., Crawford, K.R., & Maltman, A.J., 2001: Terrestrial glacial sedimentation on the eastern margin of the Irish Sea Basin: Thursaston, Wirral. *Proceedings of the Geologists' Association 112*, 131-146.

Hart, J.K., 2007: An investigation of subglacial shear zone processes from Weybourne, Norfolk, UK. *Quaternary Science Reviews* 26, 2354-2374.

Hicock, S.R., 1991: On subglacial stone pavements in till. *Journal of Geology 99*, 607-619.

Hiemstra, J.F., & Rijsdijk, K.F., 2003: Observing artificially induced strain: implications for subglacial deformation. *Journal of Quaternary Science 18*, 373-383.

Hughes, D.B. & Teasdale, D.A., 1999: Herrington Colliery opencast coal site (NZ 335 540). In: Bridgland, D.R., Horton, B.P., & Innes, J.B., 1999. *The Quaternary of north-east England field guide.* Quaternary Research Association, 137-146,

Johnson, G., 1995: *Robson's Geology of North East England.* Transactions of the Natural History Society of Northumbria *56*, part 5.

Jørgensen, F., & Piotrowski, J.A., 2003: Signature of the Baltic Ice Stream on Funen Island, Denmark, during the Weichselian glaciation. *Boreas 32*, 242-255.

Lunn, A., 1995: Quaternary. In: Johnson, G., 1995 (ed): *Robson's Geology of North East England.* Transactions of the Natural History Society of Northumbria *56*, part 5, 297-312.

Lee, J. R., Rose, J., Hamblin, R.J.O., & Moorlock, B.S.P., 2004: Dating the earliest lowland glaciation of eastern England: a pre-MIS 12 early Middle Pleistocene Happisburgh glaciation. *Quaternary Science Reviews 23*, 1551-1566.

Lunkka, J.P., 1994: Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of northeast Norfolk, England. *Journal of Quaternary Science 9*, 209-233.

Madgett, P.A., & Catt, J.A., 1978: Petrography, stratigraphy and weathering of Late Pleistocene tills in East Yorkshire, Lincolnshire and North Norfolk. *Proceedings of the Yorkshire Geological Society 42*, 55-108.

Mange, M.A., & Maurer, H.F.W., 1992: *Heavy Minerals in Colour.* Chapman and Hall, London.

Mange, M.A., & Otvos, E.G., 2005: Gulf coastal plain evolution in West Louisiana: Heavy mineral provenance and Pleistocene alluvial chronology. *Sedimentary Geology 182*, 29-57.

McCabe, A.M., Clark, P.U., & Clark, J., 2005: AMS C^{14} data of deglacial events in the Irish Sea Basin and other sectors of the British-Irish Ice Sheet. *Quaternary Science Reviews 24*, 1673-1690

McCabe, A.M., & Clark, P.U., 1998: Ice Sheet Variability around the North Atlantic Ocean during the last deglaciation. *Nature 392*, 373-377.

McClenaghan, M.B., Thorleifson, L.H., & DiLabio, R.N.W., 2000: Till geochemical and indicator methods in mineral exploration. *Ore Geology Reviews* 16, 145-166.

Should now be deleted? = check

Menzies, J., 2000: Micromorphological analyses of microfabrics and microstructures, indicative of deformation processes, in glacial sediments. In: Maltman, A.J., Hubbard, B., Hambrey, M.J., (eds), *Deformation of Glacial Materials.* Geological Society Special Publication 176, London, 245-257.

Menzies, J., & Zaniewski, K., 2003: Microstructures within a modern debris flow deposit derived from Quaternary glacial diamicton – a comparative micromorphological study. *Sedimentary Geology 157*, 31-48.

Morton, A.C., & Hallsworth, C., 1994: Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. *Sedimentary Geology 90*, 241-256.

Nelson, A.E., Willis, I. C., & Ó Cofaigh, C., 2005: Till genesis and glacier motion inferred from sedimentological evidence associated with the surge-type glacier, Brúarjökull, Iceland. *Annals of Glaciology 42*, pp. 14-22.

Ng, F.S.L., 2000: Canals under sediment-based ice sheets. *Annals of Glaciology 30*, 146-152.

Piotrowski J.A., Larsen, N.J., & Junge, F.W., 2004: Reflections on soft subglacial beds as a mosaic of deforming and stable spots. *Quaternary Science Reviews* 23, 993-1000.

Piotrowski, J.A., Larsen, N.K., Menzies, J., & Wysota, W., 2006: Formation of subglacial till under transient bed conditions: deposition, deformation, and basal decoupling under a Weichselian ice sheet lobe, central Poland. *Sedimentology 53,* 83-106.

Raistrick, A., 1931: The glaciation of Northumberland and Durham. *Proceedings of the Geologists' Association 42*, 281-291

Riding, J. B., 2007: A palynological investigation of diamictons and tills from northeast England. *British Geological Survey Internal Report,* IR/07/021R.

Rijsdijk, K.F., Owen, G., Warren, W.P., McCarroll, D., & van der Meer, J.J.M., in over-consolidated tills: evidence for subglacial hydrofracturing at Killiney Bay, *Sedimentary Geology 129,* 111-126.

Roberts, D.H., and Hart, J.K., 2005: The deforming bed characteristics of a stratified till assemblage in north East Anglia, UK: investigating controls on sediment rheology and strain signatures. *Quaternary Science Reviews 24*, 123-140.

Rose, J., 1985: The Dimlington Stadial / Dimlington Chronozone: A proposal for naming the main glacial episode of the Late Devensian in Britain. *Boreas 14*, 225-230.

Sejrup, H.P., Haflidason, A., Aarseth, I., King, E., Forsberg, C.F., Long, D., & Rokoengen, K., 1994: Late Weichselian glaciation history of the northern North Sea. *Boreas 23*, 1-13.

Shaw, J., 1987: Glacial sedimentary processes and environmental reconstruction based on lithofacies. *Sedimentology 34*, 103-116.

Smith, A.H.V., & Butterworth, M.A., 1967: Miospores in the coal seams of the Carboniferous of Great Britain. *Special Papers in Palaeontology~~Palynology~~ 1*, 324 p.

Smith, D.B., & Francis, E.A., 1967. *Geology of the Country between Durham and West Hartlepool.* Memoirs of the Geological Survey of Great Britain.

Smith, D.B., 1994. *Geology of the county around Sunderland.* Memoir of the British Geological Survey.

Swift, D.A., Nienow, P.W., Spedding, N., & Hoey, T.B., 2002: Geomorphic implications of subglacial drainage configuration: rates of basal sediment evacuation controlled by seasonal drainage system evolution. *Sedimentary Geology 149*, 5-19.

Teesdale, D., & Hughes, D., 1999: The glacial history of north-east England. In: Bridgland, D.R., Horton, B.P., and Innes, J.B., (eds) 1999. *The Quaternary of north-east England.* QRA Field Guide.

Thomas, G.S.P., 1999. Northern England. In: Bowen, D.Q., (eds), 1999: *A revised correlation of Quaternary deposits in the British Isles,* 91-98. The Geological Society Special Report No. 23.

Van der Meer, J.J.M., 1993: Microscopic evidence of subglacial deformation. *Quaternary Science Reviews 12*, 553-587.

Van der Meer, J.J.M., 1997: Particle and aggregate mobility in till: microscopic evidence for subglacial processes. *Quaternary Science Reviews 16*, 827-831.

Van der Meer, J.J.M., Menzies, J., & Rose, J., 2003: Subglacial till: the deforming glacier bed. *Quaternary Science Reviews 22*, 1659-1685.

Van der Wateren, F.M., 1999: Structural geology and Sedimentology of the Heiligenhafen till section, Northern Germany. *Quaternary Science Reviews 18*, 1625-1639.

Walder, J.S., and Fowler, A., 1994. Channelised subglacial drainage over a deformable bed. *Journal of Glaciology 40 (134),* 3-15

Weltje, G.J., & von Eynatten, H., 2004: Quantitative provenance analysis of sediments: review and outlook. *Sedimentary Geology 171*, 1-11.

Whitburn Bay Tables

		Lithofacies 1		Pipes	Lithofacies 2			Lithofacies 3			
	Sample	1-1	1-2	2-1	10-1	1-3	1-4	2-2	9a-1	9a-2	9a-4
Skeleton	Shape <500 um	SR	SR	SR	SR/SA	SR	SR	SR/SA			SR/SA
	Shape >500 um	SA	SA	SR	SR/SA	SA	SA	A	SA/A	SA/A	SR/SA
Texture	Texture	F	F	F/M/C		F/C	F	F	M	M	M/C
Voids	Voids	•	•	••		•	•	•			•
	Void Type	L	L	L		L/P	P	L/P			L
Deformation structures	Section Elements			S; Be		Ba		F	Be	Be	Be; Bo
	Rotation	•••	•••		•••	•••	••	•••	•		•
	Pressure shadow		•								
	Crushed grains	••	•			••	•				
	Pebble I				•						
	Pebble II	•••	••		••	•••	••				
	Pebble III										
	Water escape			••	•						
	Lineations		••	•••		••	••	•••		••	•
	Folds			•••							••
Fluvial / marine features	Dropstones										••
	Micofossils					•					
	Laminae			•••							•••
Plasmic Fabric	Lattisepic							••			
	Skelsepic	•••	•••	•••	•••	•••	•••	•	•	•	•
	Omnisepic										
	Masepic		••		•••	•••	••	•••			•
	Kinking			•							

Table 1. Summary diagram of Micromorphological analysis, Whitburn Bay. One dot indicates that a feature is present. Two or three dots indicates that it is more common.
Voids: L – Laboratory induced; P – Packing induced.

Shape: SR – sub-rounded; SA – sub-angular; R – rounded; A – angular.

Texture: C – coarse; M – Medium; F – Fine.

Section elements: Be – bedding; Ba – banding, S – shear; Bo – boudinage.

	Lithofacies 1	Lithofacies 2	Lithofacies 3
% Gravel	11.82	11.76	0
% Sand	18.36	17.37	17.6
% Silt	39.1	38.88	72.5
% Clay	30.7	33.99	9.9

Table 2. Average particle size distribution

	Concentration (mg/kg)							
Lithofacies	**Li7**	**Be9**	**B11**	**Na23**	**Mg24**	**Al27**	**K39**	**Ca44**
LF1	58.75	1.5	50.5	3822.5	1707.5	29600	11550	17475
LF2	67.75	2	67.25	4375	1525	32475	11725	15800
LF3	41	1	41	3650	3400	18900	13100	30600

Lithofacies	Ti48	V51	Cr52	Fe57	Mn55	Co59	Ni60	Cu63
LF1	3762.5	76.25	75	31775	389	13.75	39.25	22
LF2	4365	88.25	87.25	35200	529	15	44.75	25.5
LF3	3070	53	50	24800	595	10	28	17

Lithofacies	Zn66	As75	Mo98	Ag107	Sb123	Ba137	Pb206	Si14
LF1	62.25	8.25	4.75	1	0	337	19.25	278688
LF2	51	8.25	7.25	1.5	0.25	350.5	22.75	301196.3
LF3	44	8	2	1	0	404	23	30.67

Table 3. Average Heavy Metals results at Whitburn Bay

			Lithofacies 1	Lithofacies 2	Lithofacies 3
		% Opaques	71.18	57.36	83.70
		% Non Opaques	28.82	42.64	16.30
		% Heavy Minerals	*2.37*	*8.28*	*13.82*
Silicates	*Silicate GP*	*Olivine GP*	4.75	2.92	4.82
		Zircon	3.00	3.14	9.24
		Sphene	1.52	0.80	1.61
		Garnet GP	13.63	13.76	24.50
		Sillimanite	0.44	1.49	0.00
		Andalusite	8.79	6.11	3.21
		Kyanite	8.11	5.60	4.02
		Staurolite	1.69	1.41	0.40
		Chloritoid	0.22	0.46	0.00
	Epidote GP	*Zoisite*	5.51	3.23	3.61
		Clinozoisite	7.33	2.24	2.01
		Epidote	2.10	1.41	0.80
		Tourmaline GP	2.86	2.12	8.03
	Pyroxene GP	*Enstatite*	2.21	0.98	2.41
		Hypersthene	0.20	0.09	1.20
		Diopsidic Clinopyroxene	1.18	2.36	4.02
		Augitic Clinopyroxene	0.67	1.35	1.61
	Ampbibole GP	*Tremolite*	0.53	0.00	0.00
		Horneblende	0.44	0.39	2.01
		Diallage	0.30	0.00	0.00
		Amphibole	0.11	0.18	0.80
	Mica GP	*Muscovite*	6.79	7.27	5.22
		Biotite	1.72	1.56	0.80
		Chlorite GP	4.83	2.09	4.82
Oxides		*Rutile*	0.35	1.74	2.81
		Brookite	0.54	0.55	1.61
		Spinel GP	0.22	0.30	0.00
		Anatase	0.08	0.19	0.00
Carbonates		*Dolomite*	15.54	32.98	4.02
Sulphides		*Baryte*	0.30	0.18	0.00
		Sphalerite	0.00	0.00	0.40
Phosphates		*Apatite*	4.06	3.09	6.02

Table 4. Average Heavy Minerals at Whitburn Bay.

	Clast Lithology	Lithofacies 1 Average %	Lithofacies 2 Average %
Igneous	Diorite	0.00	0.20
	Granite	0.00	0.21
	Gabbro	0.00	0.20
	Rhyolite	0.00	0.82
	Andesite	0.51	0.72
	Porphyry	0.17	0.83
	Felsite	0.00	0.17
	Slate	0.00	0.49
	Schist	0.00	0.75
Sandstone	Sandstone	10.59	12.09
	Arenite Sandstone	0.68	1.55
	Quartzitic Sandstone	8.05	6.11
	Siltstone	0.16	0.70
	Breccia	0.16	0.00
Jurassic	Ironstone	1.57	1.76
	Mudstone	0.80	2.11
Triassic	Brown Quartzite	1.05	0.61
	Red Quartzite	0.17	0.74
	White Quartzite	0.35	0.37
	White Vein Quartz	0.00	0.43
Permian	Magnesian Limestone	48.46	33.10
	Yellow Sands	1.54	2.79
Carboniferous	Old Red Sandstone	0.67	0.66
	Whin Sill Dolerite	0.83	1.97
	Carboniferous Limestone	12.55	18.12
	Coal	1.63	1.72
Devonian	Chert	0.19	0.57
	Shale	0.00	0.17
Precambrian	Arkose Sandstone	2.25	2.36
	Greywacke	7.61	5.63

Table 5. Average Clast lithology results from Whitburn Bay