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A major ice drainage pathway of the last British-Irish Ice Sheet: the Tyne Gap, northern England.

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Abstract:
The Tyne Gap is a wide pass, situated between the Scottish Southern Uplands and the English Pennines that connects western and eastern England. It was a major ice-flow drainage pathway of the last British-Irish Ice Sheet. This study presents new glacial geomorphological and sedimentological data from the Tyne Gap region that has allowed detailed reconstructions of palaeo-ice flow dynamics during the Late Devensian (MIS 2). Mapped lineations reveal a complex palimpsest pattern which shows that ice flow was subject to multiple switches in direction. These are summarised into three major ice flow phases. Stage I was characterised by convergent Lake District and Scottish ice that flowed east through the Tyne Gap, as a topographically controlled ice stream. This ice stream was identified from glacial geomorphological evidence in the form of convergent bedforms, streamlined subglacial bedforms and evidence for deformable bed conditions; Stage II involved northerly migration of the Solway Firth ice divide back into the Southern Uplands, causing the easterly flow of ice to be weakened, and resulting in south-easterly flow of ice down the North Tyne Valley; and Stage III was characterised by strong drawdown of ice into the Irish Sea Ice Basin, thus starving the Tyne Gap of ice and causing progressive ice sheet retreat westwards back across the watershed, prior to ice stagnation.

Introduction:

Ice sheet flow through a glacial cycle is highly dynamic (e.g. Boulton and Clark 1990a, b; Clark, 1997, Clark and Meehan, 2001), as demonstrated by evidence of successive ice flow phases in palimpsest glacial landscapes (Dyke and Morris, 1988; Kleman, 1994). Recent research on glacial palimpsests in the Solway Lowlands, northern England has revealed that, during Late Devensian (Dimlington Stadial) glaciation, the central sector of the last British-Irish Ice Sheet (BIIS) underwent a complex sequence of flow events (Salt, 2001; Salt and Evans, 2004, Clark et al., 2004; Livingstone et al., 2008; Evans et al., 2009), driven by multi-sourced, competing ice dispersal centres in the Southern Uplands, Pennines, Lake District and the Irish Sea (Trotter, 1929; Hollingworth, 1931; Fig. 1). This complexity has implications for: a) ice sheet configuration, stability and dynamics; and b) major ice flow arteries to the margin of the BIIS through the Tyne Gap, Stainmore Gap and Solway Firth.

A partial understanding of the ice flow history in Northern England has accrued through the compilation of erratic trajectories and till provenance (Dwerryhouse 1902; Trotter 1929; Hughes et al., 1998), geomorphological mapping (e.g. Trotter et al, 1929; King, 1976) and ice recessional features (e.g. Yorke et al., 2007). In the Tyne Gap, however, non-systematic and ‘patchy’ mapping of glacial landforms and a poor chronology has resulted in a ‘static’ model of Late Devensian ice flow (Clark, et al., 2004; Evans et al., 2005). This is a significant gap in our knowledge of BIIS dynamics, because the Tyne Gap was the location of an influential ice flow artery (palaeo-ice stream) capable of draining large volumes of ice from the western divide of the BIIS to the North Sea lobe of the east coast (Raistrick 1931; Beaumont 1971; Bouledrou et al. 1988; Catt 1991).

This paper presents new glacial geomorphological and sedimentological data from the Tyne Gap in order to reconstruct the palaeo flow dynamics of this sector of the BIIS and to assess the evidence for a palaeo-ice stream (e.g. Stokes & Clark 1999, 2001). Glacial landform mapping carried out by Livingstone et al., (2008) provides the geomorphological context for this paper. Examples of ice flow switches are provided by Evans et al., (2009) whilst preliminary ice sheet modelling demonstrates how the subglacial streamlining of flow sets was completed over short phases of fast flow activity (Evans et al., 2009). Quantification of subglacial bedform elongation ratios allows the spatial and temporal assessment of relative ice flow velocities in the region, and deglacial features facilitate the reconstruction of ice recession. Field-based assessments of stratigraphy, sedimentology and sediment provenance allow further evaluation of ice flow dynamics and provide information on former subglacial conditions at the ice-bed interface.

Study area:

The Tyne Gap is a wide mountain pass located between the Scottish Southern Uplands to the north and the English Pennines to the south. It extends 80 km eastwards from the Solway Lowlands to the mouth of the River Tyne (Fig. 1). The Tyne Gap is underlain by Carboniferous sedimentary rocks consisting of limestone, shale, sandstone and coal that dip south-southeast towards the edge of the northern Pennines (Fig. 2). Resistant strata, including the Great Whin Sill, result in strong west-east cuestas (Bouledrou et al. 1988). Strata of limestone and sandstone are exposed to the north and south of the Whin Sill, forming a series of scarps (Fig. 2). This strong geologic structure has had a major influence on relief formation.

Methods

Subglacial bedform mapping:

Mapping of subglacial bedforms involved the compilation of lineations, meltwater channels, eskers, ribbed moraine, hummocky terrain, glaciofluvial sediment accumulations and transverse ridges from NEXTMap 5m resolution airborne Interferometric Synthetic Aperture Radar (IFSAR) imagery (cf. Livingstone et al., 2008). The method follows the criteria of Clark (1997, 1999), Kleman et al., (2006) and Livingstone et al., (2008) in identifying discrete ‘flow sets’, or a collection of glacial features formed during the same flow phase. Flow sets are defined on the basis of conformity, length, parallelism and morphology (Clark, 1999). Cross-cutting relationships and superimposed bedforms are used to construct a relative chronology, with flow sets assigned to distinct ice ‘flow phases’ (Boulton & Clark, 1990a,b; Clark, 1993, 1999; Kleman et al., 2006). Six flow phases (phase 6 = oldest) were identified. A further two sub-groups did not exhibit cross-cutting relationships (cf. Livingstone et al., 2008). The assumptions of Kleman and Borgström (1996) were applied: i) basal sliding requires a thawed bed; ii) lineations only form if basal sliding occurs; iii) lineations are aligned parallel to flow and perpendicular to ice-surface contours; and iv) frozen bed conditions inhibit re-arrangement of the subglacial landscape.

Flow direction was determined by drumlin stoss and lee forms and till provenance. Subglacial bedform length was quantified by calculating elongation ratios (length/width). Superficial (DiGMapGB-625; BGS website) and bedrock geology maps were overlaid on NEXTMap data to depict areas of bedrock moulded lineation and structural lithological influences. Bedform "fan" delineation was undertaken using the method of Kleman and Borgström (1996), allowing the assessment of internal age chronologies, relative velocities, subglacial thermal regimes, stillstands, ice sheet configurations and potential ice streams. These were derived by combing 'flowsets' with other glacial landform assemblages, such as moraines, meltwater channels, glacial lakes and eskers.

Sedimentology and Stratigraphy:
Borehole information and field exposures at Hayden Bridge, Haltwhistle, Hexham and Willowford in the Tyne Gap (Fig. 1) supplement the geomorphological mapping and allow stratigraphic correlation of ice flow events. Stratigraphy and sedimentological investigations included analysis of sediment texture, structure and architecture, colour and lithofacies classification, together with clast A-axis macrofabric measurements, clast lithological analysis and thin section sampling for micromorphology. Borehole logs (at Haltwhistle and Hexham) provide a wider coverage for detailed stratigraphic correlation, even though they were not available for sampling.

Results and Interpretation:

1. Glacial Geomorphology

Streamlined subglacial bedforms:
Subglacial lineations (Fig. 3a,b) are ubiquitous below the 400 m contour, are ≤1500 m long and comprise both bedrock and till. Mapping (Fig. 3) indicates that ice flow in the Tyne Gap during the last glaciation was predominantly towards the east. Flow set differentiation reveals overprinting of subglacial bedforms due to a series of ice flow shifts (cf. Evans et al., 2009). Several features typify the general ice flow pattern through the Tyne Gap, including a central trunk zone, marked by a smooth corridor of streamlined terrain, and evidence of flow convergence from the Lake District and Southern Uplands (Fig. 3b). A major 'set' of lineations stretching SE down the North Tyne valley and sourced from the central Southern Uplands is also apparent (Fig. 3). Towards the east coast the lineations become more subdued and eventually disappear with the exception of a small, isolated, N-S orientated set (Fig. 3b). Lineations are also scarce in the Solway Lowlands. The few bedforms present are subdued and hummocky and typical of Smith and Clark's (2005) "ovoid forms".

Subglacial bedforms in the Tyne Gap are influenced by the Whin Sill dolerite, and south-easterly dipping, interbedded sandstone and limestone strata (Fig. 2). This gives rise to a visually striking streamlined terrain trending along the exposed bedrock (Fig. 3a), which has previously been mapped (Livingstone et al., 2008) as subglacial bedforms pertaining to different flow sets. However, we acknowledge that preferential erosion along bedrock structures could produce two obliquely angled sets of structures during a single ice flow phase. Superficial and bedrock geology maps were used to assess which lineations were formed along exposed bedrock structures. These lineations, although recognised as subglacial bedforms, are not included in the construction of flow sets here because of their relative age ambiguity.

Relative chronology of flow sets:

When organised into flow phases (Fig. 3c) based on cross-cutting relationships, initial ice flow is seen to originate from the south-west, i.e. the Lake District and northern Pennine tributaries (phase 6). This was followed by a progressive shift in flow towards the east (phases 5 and 4, Fig. 3c) as Scottish ice became increasingly influential. During this phase, valleys in the north Pennines continued to act as important secondary arteries (flow group B1 and B2, Fig 3c). This period of ice movement is characterised by significant convergence of flow from the Lake District and Southern Uplands through the Solway Lowlands into the Tyne Gap. The increasing Scottish dominance resulted in the northern margin of the Tyne Gap ice flow being supplanted by ice flow down the North Tyne Valley (phase 3, Fig. 3c) and Scottish ice flowing SE into the Solway Lowlands. The final phases (phases 2 and 1, Fig. 3c) record a flow switch to a south-westerly direction, across the Tyne into the Solway Lowlands and into the Irish Sea. These later flow phases are topographically constrained, suggesting significant ice surface lowering and deglaciation. The north-south orientated, east coast lineations (Fig. 3c) are related to a separate flow within the ice sheet. This, combined with their isolated position, makes it difficult to assign a flow phase to these features. However, as the Tyne Gap lineations of phases 6 and 5 wane towards the east coast (Fig. 3c) it can be inferred that these were removed by a subsequent north-south flow along the east coast.

Elongation ratios of subglacial lineations are summarised in Table 1 and are used to infer relative ice velocity throughout the Late Devensian. Phase 1 has not been included within the analysis, as the flow sets are not situated within the Tyne Gap. The general trend is of low average elongation ratios (between 2 and 4) throughout the region. The highest mean elongation ratio (3.26) is in flow phase 4 with the lowest (less than 2.2) in phases 2 and 3. The maximum elongation ratio ranges between 4.11 for flow phase 2 up to 9.91 for flow phase 5. Throughout the flow series there is an initial lengthening of elongation ratios up to flow phase 4, followed by a decrease. This sudden decline to low mean elongations with little variation between lineations corresponds to a switch in flow, initially down the North Tyne valley and then SW into the Solway Lowlands. During flow phases 4 and 5 the elongation ratios are at their greatest mean, greatest maximum and greatest variance. There is also significant spatial variation in elongation ratios within individual flow sets.

Meltwater channels

Throughout the Tyne Gap there is a paucity of strongly aligned meltwater channels (Fig. 3b), especially for flow phases 6, 2 and 1. However, flow phases 3, 4 and 5 do show some evidence of associated meltwater drainage networks. Flow phase 3 has a NW-SE, flow trace-aligned series of channels. Flow phase 4 is associated with a series of parallel, ice-marginal channels situated on the northern flanks of the Pennines and a smaller series of aligned channels within the Solway Lowlands, encroaching into the western end of the Tyne Gap (Fig. 3b). Flow phase 5 has a series of west-east aligned meltwater channels situated at the eastern edge of the flow group where the topography starts to become more subdued (Fig. 3b).

The flow phases that are represented by abundant subglacial lineations but devoid of associated meltwater channels were likely formed as ‘synchronous’ fans (cf. Kleman and Borgström, 1996), indicative of sheet flow within the interior of the ice sheet. The relationship of flow phases 3, 4 and 5 with meltwater channels suggests formation occurred primarily during ice recession (Kleman & Borgström 1996). The absence of eskers during flow phase 3 (Fig. 5) suggests that subglacial drainage pathways did not develop, implying a ‘dry bed’ deglacial fan (Kleman & Borgström 1996). The alignment of channels parallel to ice flow but in transverse swarms in the Solway Lowlands (Fig. 3b) during flow phase 4 infers a deglacial fan, thereby demonstrating a series of stillstand positions with ice marginal/proglacial drainage. The ice occupying the Solway Lowlands dammed drainage against the reverse slope of the Tyne Gap, leading to breaching of the watershed (e.g. Gilsland; Trotter 1929). Sequential deglaciation of the Tyne Gap occurred through ice surface lowering as evidenced by channels on the flanks of the Pennines. Ice marginal drainage at the eastern edge of the Solway Lowlands corresponds to the final phase of west-east dominated flow through the Tyne Gap.

Moraines, glaciofluvial and glaciolacustrine deposits:
Three NNW-SSE orientated ridges were identified within 18 km of the east coast (Fig. 3b): the 2.4 km long Wansbeck (NZ 113 850) drift barrier (Smythe, 1908, 1912); a 6 km long ridge at Cramlington (NZ 280 785); and a 2.8 km long ridge east of Whalton (NZ 159 810). The ridges are transverse to the flow phase 5 lineations, and the Wansbeck and Whalton ridges are a chain, indicating that they were formed concurrently. A major kame belt in the Brampton region (Trotter, 1929; Huddart, 1970, 1981; Livingstone et al., 2008) wraps around the north-western edge of the Pennines and contains ridges, flat-topped hills and eskers of glaciofluvial sediment (depicted by overlaying superficial deposits on the NEXTMap data; Fig. 5.). Meltwater-dissected glaciofluvial sediments are identified along the Tyne Valley, and can be traced westwards to Gilsland, where they bifurcate, with one strand orientated NE-SW and another NW-SE (Fig. 3b). Two major glacial lakes are evident (Fig. 3b), specifically Lake Wear (Smith, 1981; Teasdale and Hughes, 1999), which covers large areas of County Durham and the River Tyne, and Lake Carlisle (Trotter, 1929; Huddart, 1970).

The geomorphic positions of the transverse ridges, at the margin of ice flow phase 5 and in close association with a series of meltwater channels and kame deposits (Smythe, 1912), suggest that they are moraines. They highlight the time-transgressive formation of ice flow phase 5 (Clark, 1999), marking a series of ice still-stands during recession. The Brampton kame belt is a major ice-marginal depo-centre (Trotter, 1929; Huddart, 1970, 1981) which was active during ice recession through the Tyne Gap. The glaciofluvial deposits of the Tyne Valley, also identified by Trotter (1929) and Yorke et al., (2007), record the former existence of a major drainage network.

2. Sedimentology and Stratigraphy

i) Willowford

Description

The section (NY 625 628) is located in a cutting of the River Irthing, just west of Gilsland (Fig. 1), and is in the basal 12.5 m of a 38 m high (160 m O.D.) lineation associated with flow phases 4 and 3. The surrounding area exhibits a series of cross-cutting landforms (flow phases 6, 4 and 3). Four major lithofacies associations were documented (Fig. 4).

Lithofacies association W1 (LFA W1) at the base of the section comprises up to 5.0 m of clast-supported pebble gravel. The basal 1.8 m contains horizontally bedded, clast-supported rounded and sub-rounded clasts, grading upwards into 1.3 m of massive, clast-supported boulder gravel with occasional sand scours beneath individual boulders (Fig. 4). Boulders are up to 1 m in diameter and are angular/sub-rounded. The top 2 m of W1 consists of horizontally stratified sand with a series of interbedded fills of massive pebble gravel (Fig. 4). The channelled gravels have erosional contacts with the stratified sand, are rounded/sub-rounded and clast supported.

Lithofacies association W2 (LFA W2) comprises 0.9 m of laminated and slightly deformed sand and silt overlying W1 (Fig. 5a,b). The basal 0.3 m consists of upwards fining coarse sand and laminated silt and clay rhythmites (Fig. 7b) with occasional dropstones up to 5 cm in diameter. Deformation is manifest as centimetre-scale contortions and wavy laminae (Fig. 5a,b) which show no sign of internal, penecontemporaneous soft-sediment deformation. The overlying 0.6 m of W2 are silt laminations dipping at 18°towards the SW (Fig. 4). These grade up into similarly orientated medium sand laminations, which contain attenuated clay pods forming flame structures, dipping, wavy laminae and contortions typical of soft sediment deformation (Fig. 5b).

Lithofacies association W3 (LFA W3) is characterized by dipping interbeds, <20 cm thick (Fig. 7c,d), of diamicton and sand, separated from the underlying W2 by an erosional, undulatory boundary (Fig. 4). The diamictons are massive, red and grey coloured and matrix-supported, with variable amounts of sub-rounded clasts (Fig. 5c,d). Loaded contacts and convolute bedding suggest that soft sediment deformation persisted during deposition. Sand from W2 has been sheared up and incorporated within the sequence (Fig. 5c,d).

Lithofacies association W4 (LFA W4) comprises 6.8 m of inter-bedded red and grey diamictons which have been heavily folded and attenuated (Figs. 4, 5e-g). The red diamicton is massive, matrix-supported, has a silty-sandy texture which becomes increasingly sandy up-sequence, and contains abundant sub-rounded to sub-angular clasts (Fig. 5g). In the upper 3 m of W4 the red colouration locally turns brown. The grey diamicton is predominantly massive, and contains some sand lenses higher up in the sequence (Fig. 5e). It is matrix-supported, friable, with a clayey-silty texture and has a moderate density of sub-rounded to sub-angular clasts. In places the grey diamicton contains pockets of angular clasts. Both diamictons have a high frequency of striae, with the angle of orientation parallel to the A-axis of the clasts. The red diamicton dominates throughout W4, with the grey diamicton interfingering as centimetre scale beds (Fig. 5f,g). Centimetre thick, wavy, roughly horizontal, sand laminations occur between and within the diamicton beds in the top 3 m and bottom 1m of W4 (Fig. 5e and see micromorphology below). W4 lacks major shear planes, but does contain folds and attenuated beds dipping west-southwest (Fig. 5g). Two thin sections collected from W4 display a number of rotational structures often associated with a series of lineations and grain-stacking arrangements. Two diamicton domains cutting obliquely down towards the ENE with folded, convoluted and diffuse boundaries are present, whilst one of the thin sections contains a horizontally aligned and laminated soft-sediment stringer which had been subjected to extensive deformation (series of faults, folds and marble-textured fine clay and silt).

Clast macrofabrics from W4 (Fig. 6) (S_1 = 0.44 - 0.74) display orientations that parallel the surface bedforms (SW-NE), at least in the upper half of the diamicton. Orientations are oblique to streamlining in the lower half of the diamicton. Clast lithological analysis (n = 300) was carried out on the gravels in W1 and both the red and grey diamictons in W3 and 4 (Fig. 7). The gravels are dominated by Carboniferous limestone (the local bedrock), quartzitic sandstone, greywacke and coal. The red and grey diamictons contain similar lithologies including andesites, rhyolites and slate from the Lake District, local Carboniferous limestone, Scottish greywacke, Criffel and Dalbeattie granite and metamorphics, and Solway Lowland (St Bees and Penrith sandstone) rocks (Fig. 7).

Interpretation

The massive cobble-gravel and interbedded sand towards the top of W1 were deposited in an increasingly higher energy system which was capable of transporting clasts up to 1 m in diameter and characterized by a series of gravel bars typical of a proglacial braided river network (Miall, 1977). The overlying laminated silts and sands with dropstones (W2) are interpreted as glacilacustrine. Small scale deformation structures were probably imparted by a later stage of glacial over-riding. The overall fining-upward sequence represented by W1 and 2 is a depositional record of fluvial drainage dammed by encroaching glacier ice. The arrival of ice in the drainage basin is recorded by the thinly bedded and deformed sands and diamicton with loaded boundaries of W3, which was deposited by intermittent debris flows (cf. Lawson, 1979; Lawson, 1981). Load structures and deformation in W3 suggest high water contents and concomitant soft sediment deformation (Lawson, 1981). The presence of far-travelled erratics indicates that these sediments were related to glacial advance.

The red and grey diamictons of W4 are interpreted as subglacial traction tills (sensu Evans et al., 2006). Evidence for this includes: (a) stones that are commonly striated and have a far-travelled provenance; (b) intercalated diamictons exhibiting a series of dipping fold structures, attenuations and boudins typical of glacially deformed materials; (c) very compact, mono-lithological, clast dominated, pockets of grey diamicton interpreted as rafts of bedrock that have been crushed and rafted up into the diamicton (e.g. Hiemstra et al. 2007); (d) microstructures of both ductile (skelsepic fabric, turbates) and brittle (lineations, grain stacking, fissility) deformation typical of a high stress environment (Van der Meer, 1993; Menzies, 2000; Menzies et al., 2006); and (e) macro-fabric orientations and S_1 eigenvalues in the upper sections which are consistent with the inferred direction of ice flow (Benn, 1995; Evans, 2000).

The range of S_1 eigenvalues in W4 (Fig. 8) indicates that the mode of formation involved a range of stress regimes (Evans et al. 2006, 2007). Horizontal sand stringers are interpreted to have formed in a low energy subglacial environment, possibly during decoupling of the basal ice and the development of a thin water film (cf. Piotrowski and Tulaczyk, 1999; Piotrowski et al., 2001, 2006). Stringers suggest that deformation was not pervasive. Indeed, incomplete homogenisation of the two tills indicates low strains, thus suggesting that the till is immature. The mixed provenances displayed by both the red and grey diamicton could have resulted from subglacial cannibalisation of pre-existing sediment, possibly deposited from previous glacial episodes or by way of the shifting dominance of Ice Dispersal Centres in the Lake District and Scotland (Lunn, 2004). However, the grey diamicton does contain a higher percentage of local Carboniferous lithologies which, when interpreted in conjunction with the two distinctive colours, suggests different flow paths or timing of flow.

ii) Hayden Bridge

Description

Hayden Bridge (NY 844 638) is located on the south flank of the South Tyne Valley (Fig. 1) at an elevation of 160 m O.D., 95 m above the South Tyne River (65 m O.D.) and in an area containing flow phase 4 lineations. Three major sedimentary associations were identified from 2 sites and borehole data (LFA HB1-3; Fig. 8 & 9A-D).

Lithofacies association HB1 (LFA HB1) comprises >6 m of matrix-supported, dark grey diamicton containing sand lenses and rounded/sub-rounded clasts of predominantly local lithologies (sandstone, limestone and dolerite), although there are some far-travelled erratics such as St Bees sandstone, greywacke and green andesite. Rare striations were observed on the clasts. The sand lenses predominate in the upper 3 m and the upper boundary with HB2 is erosional. This diamicton occurs either directly on top of bedrock or on an intervening unit of sand and gravel.

Lithofacies association HB2 (LFA HB2) comprises a discontinuous series of boulders, gravel and sand (Fig. 9A). At site 1 this is ca. 2 m thick near the base of the section and is composed of cobbles and boulders (up to 0.5 m in diameter), overlain by stratified and massive gravels and sands. This implies a general sequence of fining that grades up into HB3. At site 2 the gravel and sand of HB2 is massive throughout.

Lithofacies association HB3 (LFA HB3) consists of ca. 3 m of laterally discontinuous, stratified silts and sands fining upwards into laminated clay (Fig. 9C/D). The laminated clay sequence contains a series of centimetre-scale sand lenses. The top of the sequence coarsens into sandier beds which grade into LFA HB4, comprising up to 5 m of massive, matrix supported sand and coarse gravel (Fig. 9C).

Interpretation

HB1 is interpreted as a subglacial till based on its massive appearance, occurrence of striations and far-travelled erratics. HB2 is interpreted as glaciofluvial due to the abrupt lateral and vertical changes in particle size and geometry, which are characteristic of the fluctuating discharges of proglacial streams (e.g. Miall 1977, 1978; Marren, 2001). The discontinuous diamicton unit situated between sand and gravel lithofacies could relate to either debris flow deposits or a subglacial till associated with an oscillating ice front. HB2 therefore represents a proglacial, braided drainage network that drained eastwards along the South Tyne River. The general fining upwards trend suggests an increasingly ice distal environment (e.g. Marren, 2001) associated with ice recession westwards over the Tyne Gap watershed. As ice retreated westwards a series of meltwater channels drained into the main Tyne Valley (e.g. the Gilsland meltwater channel). To the west of Gilsland the deposits are split into a SW-NE 'train' dominated by Lake District erratics and a NW-SE 'train' by a Scottish provenance (Trotter, 1929), thus indicating a decoupling of two previously convergent ice flows.

The stratified silts and sands grading upwards into laminated clays (HB3) are interpreted as glaciolacustrine sediments deposited in a lake formed in the Tyne Valley.

iii) Borehole logs

Haltwhistle Bypass

Borehole logs from the Haltwhistle Bypass (NY 705 632) at ca. 130 m O.D. (Fig. 1) in an area of flow phase 6 and 4 lineations, reveal four lithofacies (Fig. 10), from bottom to top: 1) a 10 m thick diamicton which changes upwards from dark brown to red-brown, the boundary being marked in places by thin clay/sand intercalations; 2) a laterally variable unit of boulders, gravel and sand, ranging from dense grey sand with cobbles and boulders to brown silty sand; 3) a 2m thick mottled diamicton; and 4) upwards fining sands and gravels. The borehole logs drilled at lower elevations (Fig. 10) are composed almost entirely of sand and gravel resting directly on bedrock, with the exception of borehole 238, which contains a thin orange-brown, mottled diamicton.

The sandwiching of sand and gravel between diamictons along Haltwhistle Bypass, is typical of many sites in northern England (cf. Huddart and Glasser, 2002). The upper diamicton is interpreted as glacial in origin and its mottled appearance is likely related to weathering, as is typical of diamictons along the east coast (Eyles and Sladen, 1981). The sands and gravels which stratigraphically overlie diamictons are interpreted as glaciofluvial outwash, in which upwards fining indicates increasingly ice distal deposition (Miall, 1977).

Hexham map sheet

Mineral Assessment Report 65 (resource sheets NY 86, 96) for the Hexham region of Northumberland describes a series of boreholes throughout the area (Lovell, 1981). The Hexham district lies between 30-60 m O.D. in the Tyne Valley and up to 300 m O.D. on the fells to the north and south. Located in the Carboniferous Namurian grits, the region contains predominantly west-east orientated flow phase 4 lineations. A series of borehole logs reveal 2 major lithofacies associations connected with Late Devensian glaciation (Lovell, 1981).

Lithofacies association HX1 is a grey-brown diamicton resting on the Carboniferous bedrock. It ranges from a veneer to 60 m thick and contains a series of sand lenses. The diamicton is dominated by locally sourced rocks (sandstone, limestone and dolerite), with a minor component of Lake District (Borrowdale Volcanics and granite) and Scottish (granite) erratics (Lovell, 1981). This lithofacies also appears as thin layers locally overlying the gravel and sand of lithofacies association HX2.

Lithofacies association HX2 comprises coarse gravel and sand, with gravels dominating in the Tyne Valley and sandier deposits towards the south-west (Lovell, 1981). These deposits form prominent hummocky features throughout the district. Lithologically HX2 is dominated by Carboniferous sandstone and Namurian limestone and also contains greywacke, Borrowdale Volcanics, quartzite and Scottish and Lake District granites (Lovell, 1981).

The diamicton is interpreted as a till by Lovell (1981). The foreign erratics offer some support for this interpretation, but taken in isolation there is insufficient evidence to be more specific and the diamicton can only be defined as glacigenic. Erratics from both the Lake District and Southern Uplands indicate that the ice flows in the region were complex due to temporally overlapping trajectories and sediment reworking. The thin upper diamicton has been interpreted as a solifluction or fluvial/lacustrine reworked deposit (Lovell, 1981). HX2 is attributed to glaciofluvial activity due to its stratigraphic relationship with HX1, the presence of foreign erratics, the kamiform nature of deposition and its textural variability. The relatively fine-grained nature of the deposits suggests ice distal deposition.

Inter-site correlations:
The Hexham map-sheet boreholes display a lowermost grey/brown diamicton interpreted to be glacial. The colour, erratics and stratigraphic position of this diamicton resting on bedrock allows a tentative correlation with other sites, implying that deposition occurred over a distance of at least 19 km. Indeed, previous research suggests that the lower grey diamicton is ubiquitous over Northern England (Huddart and Glasser, 2002; Clarke, BG. et al., 2008). The two-tiered colour structure of the lower diamicton at Haltwhistle and the sand intercalations are also akin to the red-grey diamicton sequence at Willowford (W4). This lateral continuity throughout the Tyne Gap region, together with the presence of Lake District and Scottish erratics indicates that the diamicton is likely to be a subglacial till. Sands and gravels stratigraphically positioned above the lowermost diamicton and exhibiting high energy glaciofluvial conditions (cf. Miall, 1977) and upwards fining are pervasive throughout the Tyne Gap. Fining upward sequences are interpreted as an increasingly ice distal signature. The upper red diamicton is more disparate and generally thinner than the lower till and could be a re-advance till (Huddart and Glasser, 2002) or alternatively a series of mass flow deposits.

Discussion:

1. Ice sheet dynamics through the Tyne Gap corridor

Glacial geomorphological mapping (Livingstone et al., 2008) has been used to reconstruct three main stages of ice flow through the Tyne Gap. These stages are based on relative age of the ice flow phase, ice trajectory and subglacial conditions identified from the geomorphology and stratigraphy.

Stage I: The Tyne Gap as a major flow artery for convergent Scottish and Lake District ice
Stage I was characterized by convergent ice flow from the Scottish Southern Uplands and the Lake District, with local flow from the northern Pennines (Fig. 11a). Based on the lineations and macro-fabric data from Willowford, flow converged into the Solway Lowlands, overtopped the Tyne Gap col (152m O.D.) and extended to the east coast. Initial overtopping of the Tyne Gap followed a phase of glaciolacustrine sedimentation on the reverse slope at Willowford (see Fig. 4), with ice damming the

pre-glacial fluvial system of the River Irthing. The diamicton on the reverse slope near Willowford was initially deposited in a series of debris flows, which reworked and incorporated the lacustrine sediments (cf. Eyles 1987; Bennett et al. 2002).

Geomorphological evidence suggests that flow through the Tyne Gap was initially dominated by Lake District ice, forcing flow in a north-easterly and then easterly direction (phases 6 and 5, Fig. 11a). Thus, during the earliest phases of flow, Scottish ice was subsidiary to Lake District ice. This is supported by till fabrics from Willowford which display a SW-NE orientation. This suggests that a Southern Upland ice divide must have been situated south of the mountains in the Solway Firth, driving ice eastwards and causing coalescence with Lake District ice in the Solway Lowlands (Fig. 11a).

The corollary is that the earliest geomorphological evidence relates to flow that occurred after southwards migration of the ice divide. This southwards migration (cf. Salt and Evans, 2004; Roberts et al., 2007) was driven by ice expansion out of upland areas, particularly in Scotland (Boulton and Hagdorn, 2006). The indistinct provenance of the diamictons (Fig. 7) gives further credence to this argument, with a very complex build up of both Lake District and Scottish ice occurring within the Solway Lowlands (Hollingworth, 1931) and Tyne Gap, producing a mixed clast lithology (e.g. Willowford) due to cannibalisation and homogenisation of pre-existing diamictons.

During stage I the ice flow direction shifted from a SW-NE to a W-E orientation (Fig. 11a). This reflects a change in dominance between the contribution of Lake District and Scottish ice to flow through the Tyne Gap and also the migration of the Solway Firth ice divide, leading to re-establishment of Scottish flows across the region (flow phase 4). Shifts in ice flow trajectory which typify stage I can therefore be reconciled by the migration of ice divides and ice dispersal centres.

Stage II: Scottish influenced ice flow down the North Tyne

During stage II the growing influence of Scottish ice resulted in a major change of ice flow in the Tyne Gap (Fig. 11b). The dominant movement at this stage was southeast, down the North Tyne Valley. This reflected continual northwards migration of the ice dispersal centre and dissipation of the Solway Firth ice divide. As the ice divide migrated northwards, so the impact of the Tyne Gap as an easterly flowing artery weakened. This resulted in the gradual recession and stagnation of the eastward margin of ice flow 5 leading to the time-transgressive deposition of kame deposits (Fig. 11c; Smythe, 1912), meltwater channels and transverse moraines at still-stand positions (Fig. 3). The geomorphological, sedimentological and stratigraphic evidence within the South Tyne Valley suggests that ice flow down the North Tyne Valley and out of Bewcastle Fells failed to reach the southern-most edge of the Tyne Gap. Geomorphological mapping also reveals similarly orientated south-easterly flow lineations sourced in the Bewcastle Fells that continue into the Solway Lowlands and Tyne Gap (Fig. 3b). Thus, the ice divide must have straddled west-east across a large section of the Southern Uplands, allowing movement of ice into the Solway Lowlands and Tyne Gap along a broad front, with localised faster flow down palaeo-valleys (Fig. 11b). However, the elongation ratios suggest that these localised zones of faster flow were not comparable to the convergent flow during stage I (Table 1). Despite the weakened Lake District signal of phase II, SW-NE eskers associated with the

Brampton kame belt (which formed during stage III, Fig. 11c) indicate that ice continued to flow across the Tyne Gap at a late stage of glaciation (Fig. 11b). Phase 4 meltwater channels (Fig. 3c) are interpreted as ice-marginal, cut during ice surface lowering towards the end of stage II and beginning of stage III when ice started to downwaste and retreat from the Tyne Gap.

Stage III: Drawdown of ice into the Irish Sea

Following dissipation of the Solway Firth ice divide, ice was drawn down from the Solway lowlands into the Irish Sea Basin and contributed to the Irish Sea Ice Stream (Fig. 11d) (Evans and Ó Cofaigh, 2003; Ó Cofaigh and Evans, 2007; Roberts et al. 2007). This had a major effect on flow trajectories within the Tyne Gap (Fig. 11d), with flow switching direction to the SW, back across the Tyne Gap and into the Solway Lowlands (phase 2). East of the Tyne Gap, the ice stagnated and retreated westwards (Fig. 11c) depositing a series of kamiform deposits within the Tyne valley (Yorke et al., 2007). Borehole logs at Hexham and Haltwhistle and exposures at Hayden Bridge reveal a series of glaciofluvial deposits within the South Tyne Valley suggesting initiation of a major proglacial drainage system. The fining upwards sequence is typical of an increasingly ice-distal environment, with the discontinuous, thin upper diamicton thought to relate to either debris flow deposition or a minor ice-marginal oscillation. As ice retreated onto the reverse slope at Brampton, ice stagnated in the lee of the Pennines (Fig. 11c).

The progressive retreat of ice into the Solway Lowlands followed by ice flow into the Irish Sea basin ended the eastwards transfer of ice and resulted in the Tyne Gap being abandoned as an ice flow artery. Subsequent flows (phase 1) were topographically constrained with no evidence for encroachment into the Tyne Gap.

2. A palaeo-ice stream?

Stage I flow displays several features consistent with a palaeo-ice stream in the Tyne Gap. Flow from the Lake District and Southern Uplands converged on the Tyne Gap, east of the Solway Lowlands, before entering a narrow (25 km wide) topographically-constrained trunk between Cold Fell to the south and the Bewcastle Fells to the north. Flow was then easterly through the Tyne Gap, as indicated by a 50 km long, W-E orientated set of lineations (Figs. 3 & 11). The true length of the ice flow trunk is not known as the lineations are overprinted by N-S orientated bedforms. It is not known whether the Tyne Gap ice was confluent with ice moving south from the Cheviots and Tweed valley during stage I or if it formed a lobate margin in the North Sea Basin. Throughout stage I, a series of ice flow shifts occurred, suggesting that the Tyne Gap ice stream was not static (cf. Anandakrishnan and Alley, 1997; Bindschadler and Vornberger, 1998).

Although stage I lineations are highly attenuated and well developed, their elongation ratios are only between 2:1 and 4:1. These are significantly lower than those documented from other palaeo-ice streams (e.g. Stokes and Clark, 1999; 2001). Furthermore no mega-scale glacial lineations were observed in the Tyne Gap. It is possible that this reflects the influence of substrate control in that the lineations that do occur are predominantly bedrock moulded. The flow switches observed during stage I also suggest that ice flow may have been transient. Therefore, of the three main factors observed to be accountable for attenuated bedforms in drumlin fields (cf. Stokes and Clark, 2002), ice flow duration and sediment supply in the Tyne Gap are not conducive to the formation of highly elongate features, thereby making it difficult to infer relative flow velocities.

The stratigraphic and sedimentological data from Willowford suggests that subglacial deformation was not pervasive. However, clast macrofabrics from W4, intercalated tills, micromorphological evidence of rotational and planar structures, and rafted and crushed bedrock all suggest that subglacial stresses were sufficient to deform the substrate. Although evidence of till deposition in the Tyne Gap has generally been recorded as the tripartite division of grey till → sands and clays → red till (Hughes et al., 1998), glacial diamicton (till) is patchy throughout the region and large areas are characterized by streamlined bedrock. This sparsity of till does not predispose against streaming, as ice streams over hard beds have been proposed (e.g. Evans, IS. 1996, Stokes & Clark 2003, Roberts and Long, 2005, Bradwell et al. 2008). It does, however, suggest that soft bedded flow is unlikely to be a significant mechanism for streaming in the Tyne Gap.

Hence we argue that there is evidence for a topographic ice stream in the Tyne Gap during Stage I. The pass acted as a major artery for flow transferring a disproportionate flux of ice out of the Solway Lowlands from both Scottish and Lake District sources. Interestingly, relative flow velocities are not significantly different to other flow phases. However, the general mosaic of bedrock and drift deposits coupled with the dynamic shifts in ice flow offers an explanation for this.

3. Wider implications for the British-Irish Ice Sheet

It has been proposed that a tripartite glacial sequence was deposited along the east coast of England during the Late Devensian. First, the ‘lower boulder clay’ (Smith, 1981), a greyish-blue till containing abundant Carboniferous rocks, was deposited by ice moving eastwards through the Pennines (Raistrick, 1931; Catt, 1991; Douglas, 1991) including the Tyne Gap. Consequently, the lower till can be stratigraphically correlated with flow stages I and II in the Tyne Gap. Second, the ‘middle sands’, were interpreted by Smith (1981) as the glaciolacustrine deposits of Lake Wear, thought to have been deposited between westerly retreating ice and a southwards flowing Tweed-Cheviot ice stream off the east coast (Teasdale and Hughes, 1999). This equates to flow stage II/III involving Tyne Gap stagnation and westerly retreat (Fig. 11c). The Tweed-Cheviot ice stream flowing southwards down the east coast may have been in existence during flow stages I and II, although the Tyne Gap was dominant (Raistrick, 1931). Third, the upper red diamicton (Smythe, 1912) records flow stage III when Tweed-Cheviot ice became dominant and pushed inland (cf. Catt, 1991).

South-westerly flow into the Irish Sea basin (Livingstone et al., 2008) only occurred during flow stage III. This late stage switch in ice flow direction is thought to be associated with the dissipation of the Solway Firth ice divide and northwards migration of the ice dispersal centre back into the Southern Uplands. With flow no longer being forced eastwards through the Tyne Gap, ice was free to drain into the topographic low of the Irish Sea basin.

Roberts et al. (2007) identify two flow phases of the Irish Sea ice stream during the last glaciation on the Isle of Man, with phase II interpreted as a late stage advance initiated in the Solway Lowlands. The relative chronology of glacial events in the Tyne Gap thus ties in with drawdown of ice into the Irish Sea ice stream. Ice flow during stages I and II, relates to phase I on the Isle of Man (Roberts et al., 2007), with western Southern Uplands and Highlands ice providing most of the ice flux. This is consistent with flow phases B-C of Salt (2001) and Salt and Evans (2004) in south-west Scotland. Highland ice from the Firth of Clyde coalesced with Southern Upland ice, forming a powerful SSW flow into the Irish Sea. This was postulated to have occurred during the LGM, when the Irish Sea ice stream was at its maximum (phase C; Salt, 2001, Salt & Evans 2004). These powerful southwards-directed flows buttressed and compressed Lake District and Solway Lowland ice, forcing it to overtop and flow eastwards through the Tyne Gap. During deglaciation Tyne Gap and Solway Lowland ice acted as a major ice source for the Irish Sea ice stream (phase II; Roberts et al., 2007). In the south-west Southern Uplands the ice divide migrated eastwards during stage D-F (Salt, 2001), causing the central Southern Uplands to become increasingly important, and thereby supplying the majority of ice down the North Tyne (stage II), eventually allowing ice to drain south-west into the Irish Sea (stage III). At this stage the Tyne Gap was part of a major Solway Lowlands ice stream tributary to the Irish Sea ice stream. Eventually topographically constrained flow became pervasive throughout the area (phase F, Salt, 2001; phase 1, this paper).

Conclusions:

- Streamlined subglacial bedforms provide evidence for former dynamic flow within the Tyne Gap during the last glaciation, and indicate three main flow stages:
    - Stage I is associated with major arterial ice flow moving generally eastwards and driven by ice sourced from both Scotland and the Lake District. Evidence for dynamic flow shifts are indicative of migratory ice divides, reflecting competition between Scottish and Lake District dispersal centres.
    - Stage II was dominated by Scottish ice moving south-eastwards down the North Tyne Valley, deflecting the eastward flowing ice, as a result of continual northwards migration of the ice dispersal centre and dissipation of the Solway Firth ice divide.
    - Stage III when the influence of ice in the Tyne Gap waned due to drawdown into the Irish Sea basin followed, by ice retreat westwards into the Solway Lowlands.

- For at least part of this history (stage I) flow through the Tyne Gap occurred as a topographic ice stream, as indicated by a strongly convergent geometry, streamlined subglacial bedforms and some evidence for deformable bed conditions.

- During deglaciation a major proglacial drainage network developed in the Tyne Valley. As ice retreated across the Tyne Gap watershed, ice stagnated against the reverse slope, leading to the formation of Lake Carlisle and the Brampton kame belt.

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Tables:

Table 1:

Statistical summary of elongation ratios for ice flow phases 2-5 in the Tyne Gap (phase 1 not in Tyne Gap)

	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Count	267	745	859	324	421
Minimum	1.16	1.07	1.13	1	1
Maximum	4.11	4.94	8.85	9.91	9.6
Mean	2.19	2.15	3.26	2.72	2.23
SD	0.62	0.67	1.47	1.33	0.99

Figures:

Figure 1:

(a) Location map of the study area, (b) Topography of the Tyne Gap and the surrounding area, (c) The Tyne Gap: topography, place names, major rivers and field locations (in red).

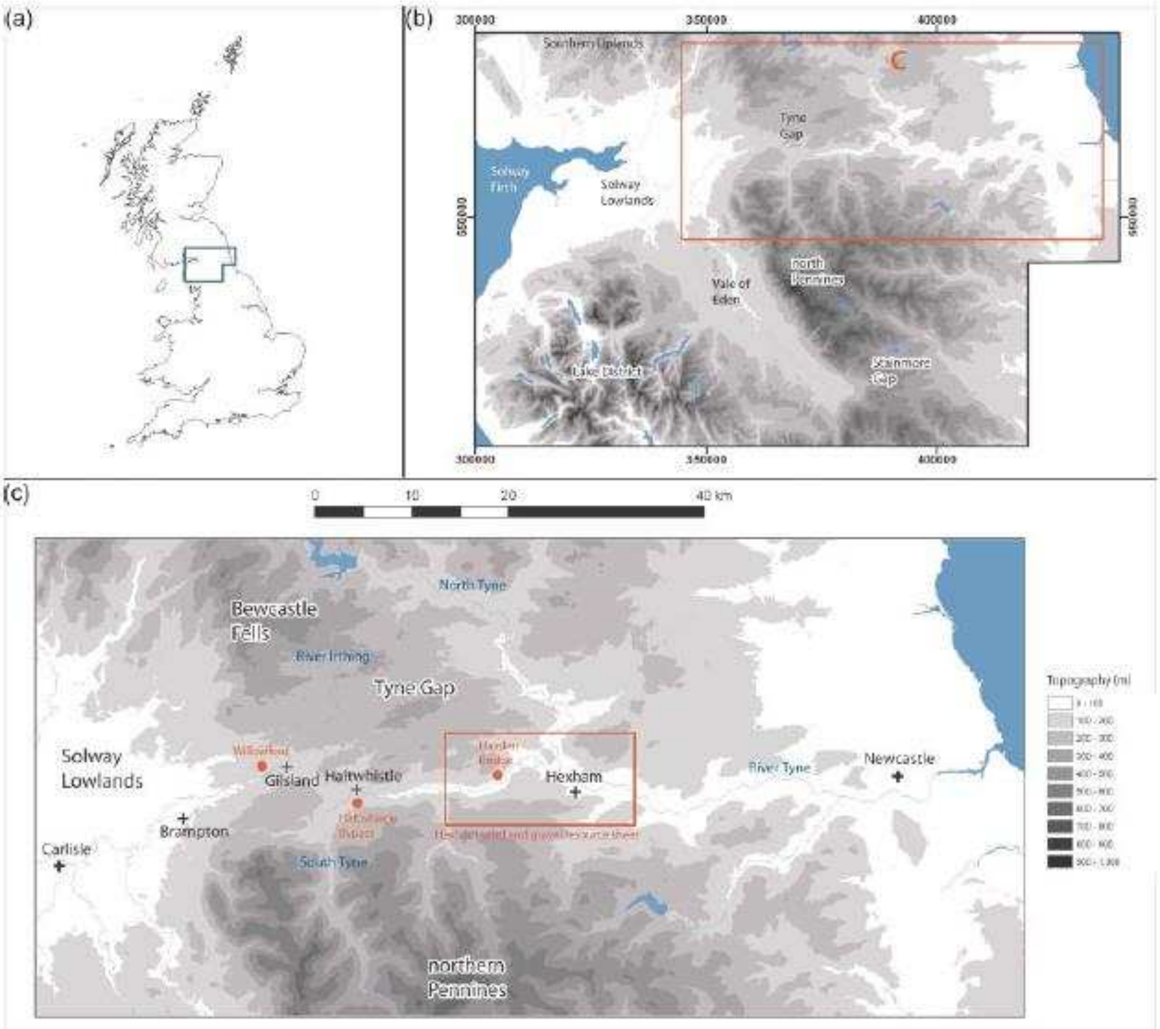

Figure 2:
1:625k bedrock geology map of northern England and the Scottish Borders. Granites: Sh = Shap, Esk = Eskdale, Enn = Ennerdale, Th = Threlkeld, Sk = Skiddaw, Ca = Carrock Fell, C-D = Criffel-Dalbeattie pluton. Extrusive igneous: BVG = Borrowdale Volcanic Group, BVF = Birrenwark Volcanic Formation. SLA = Skiddaw Slate Series. Note the Whin Sill orientated SW-NE in the Tyne Gap

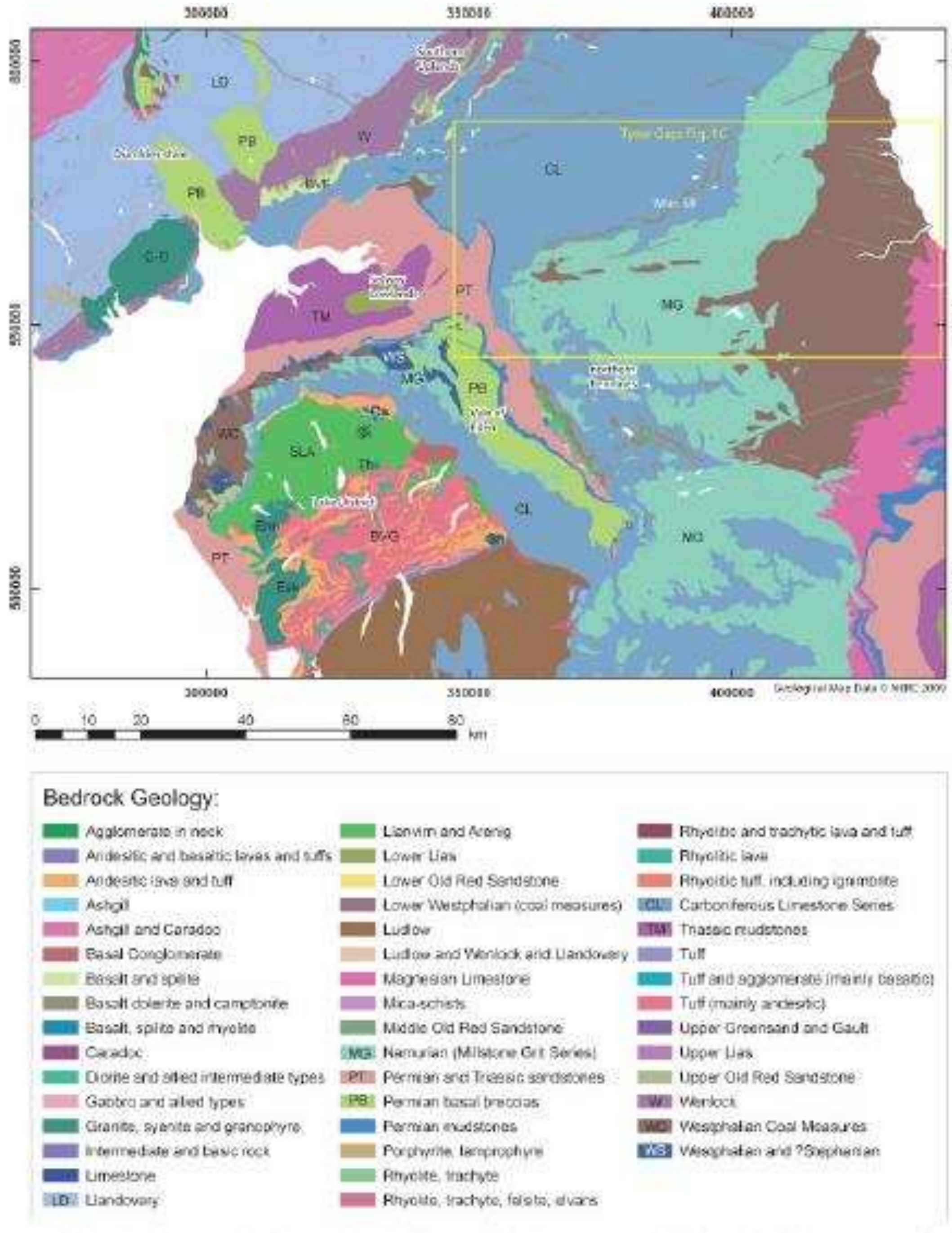

Figure 3:
(a) NEXTMap DEM of the heavily lineated Tyne Gap; (b) mapped subglacial bedforms (with lineations colour coded according to flow set); and (c) flow phases identified by cross-cutting relationships. (NEXTMap Britain data from Intermap technologies Inc were provided courtesy of NERC via the NERC Earth Observation Data Centre)

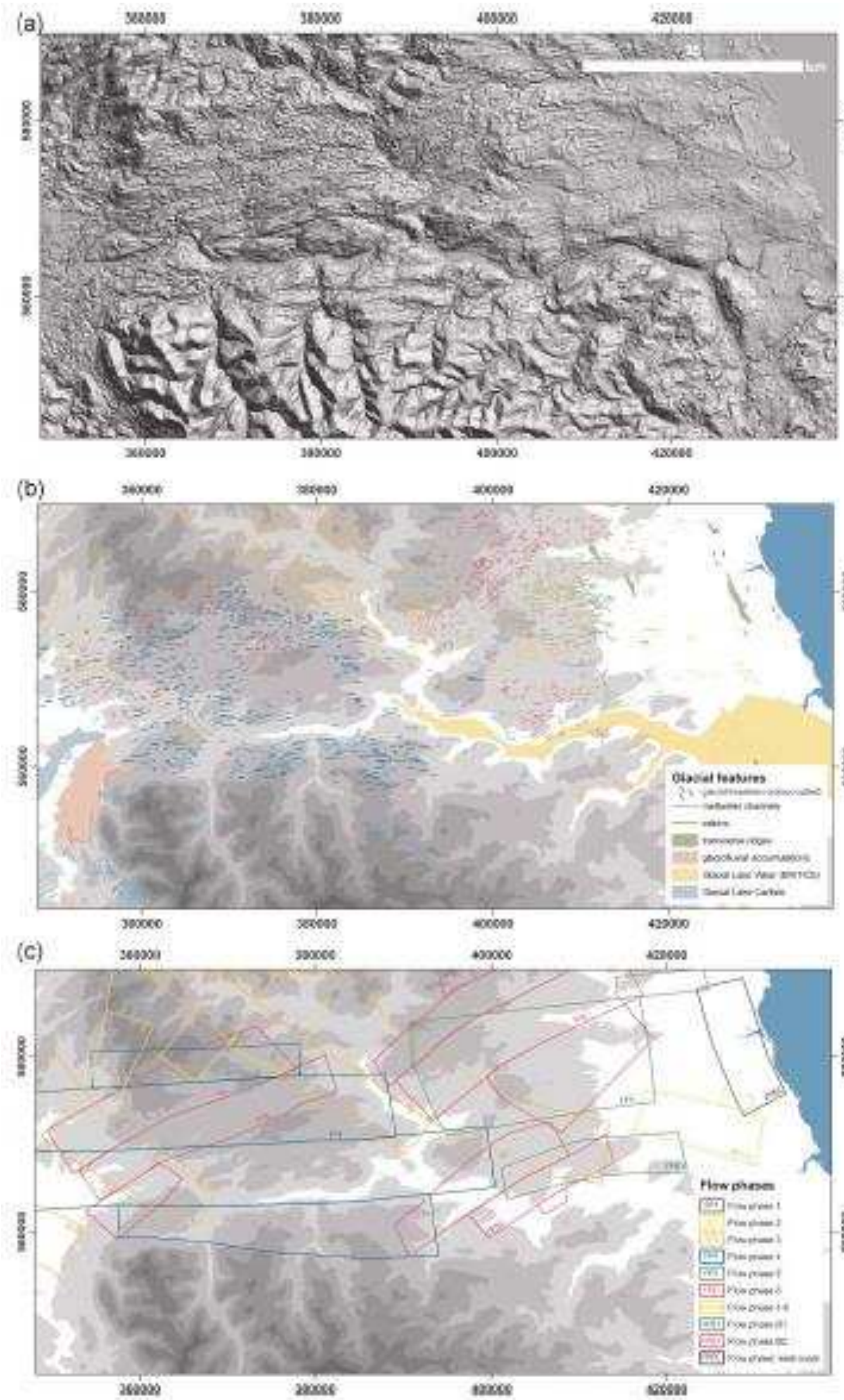

Figure 4:
Composite stratigraphic log from Willowford field site (lithofacies codes from Benn and Evans, 1998). Boxes indicate thin sections and crosses refer to clast fabrics taken from the sections. Multiple fabrics have been taken laterally across some field sections.

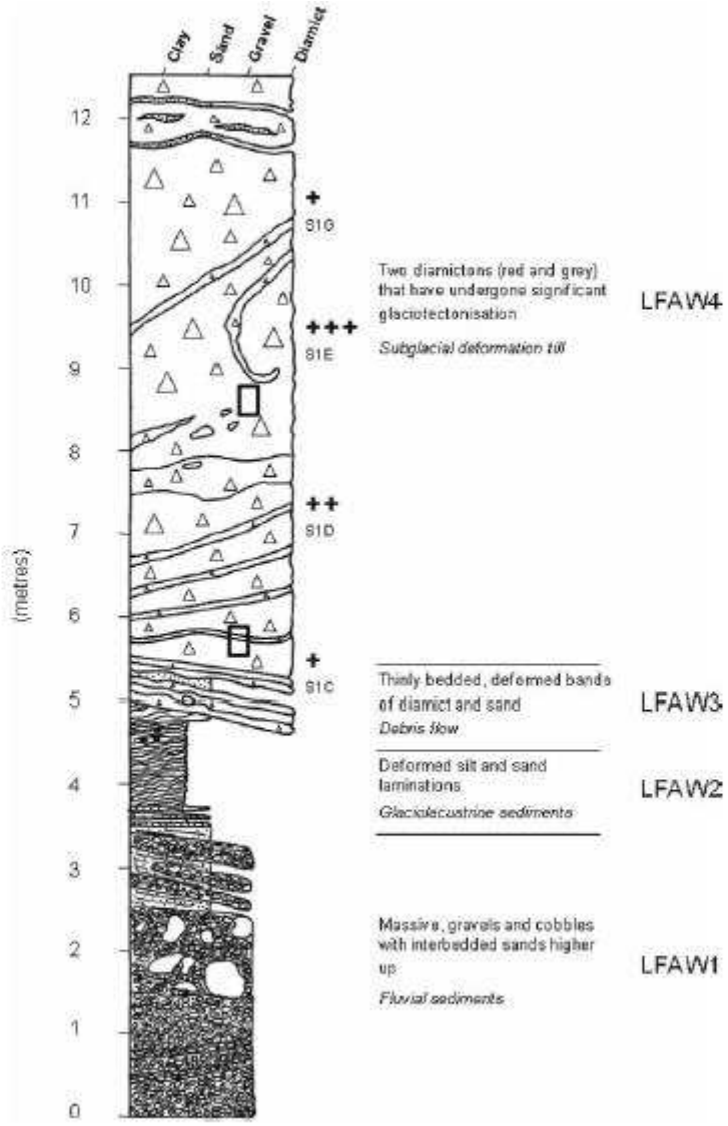

Figure 5:
(A) and (B): LFA W2: examples of slight deformation structures within sands and silts interpreted as glaciolacustrine deposits.
(C) and (D): LFA W3: examples of thinly bedded, deformed diamictons and sands interpreted as debris flow tills.
(E) – (G): LFA W4: Glaciotectonised diamictons (red and grey), with interbedded sand layers near the top of the sequence interpreted as a subglacial deformation till.

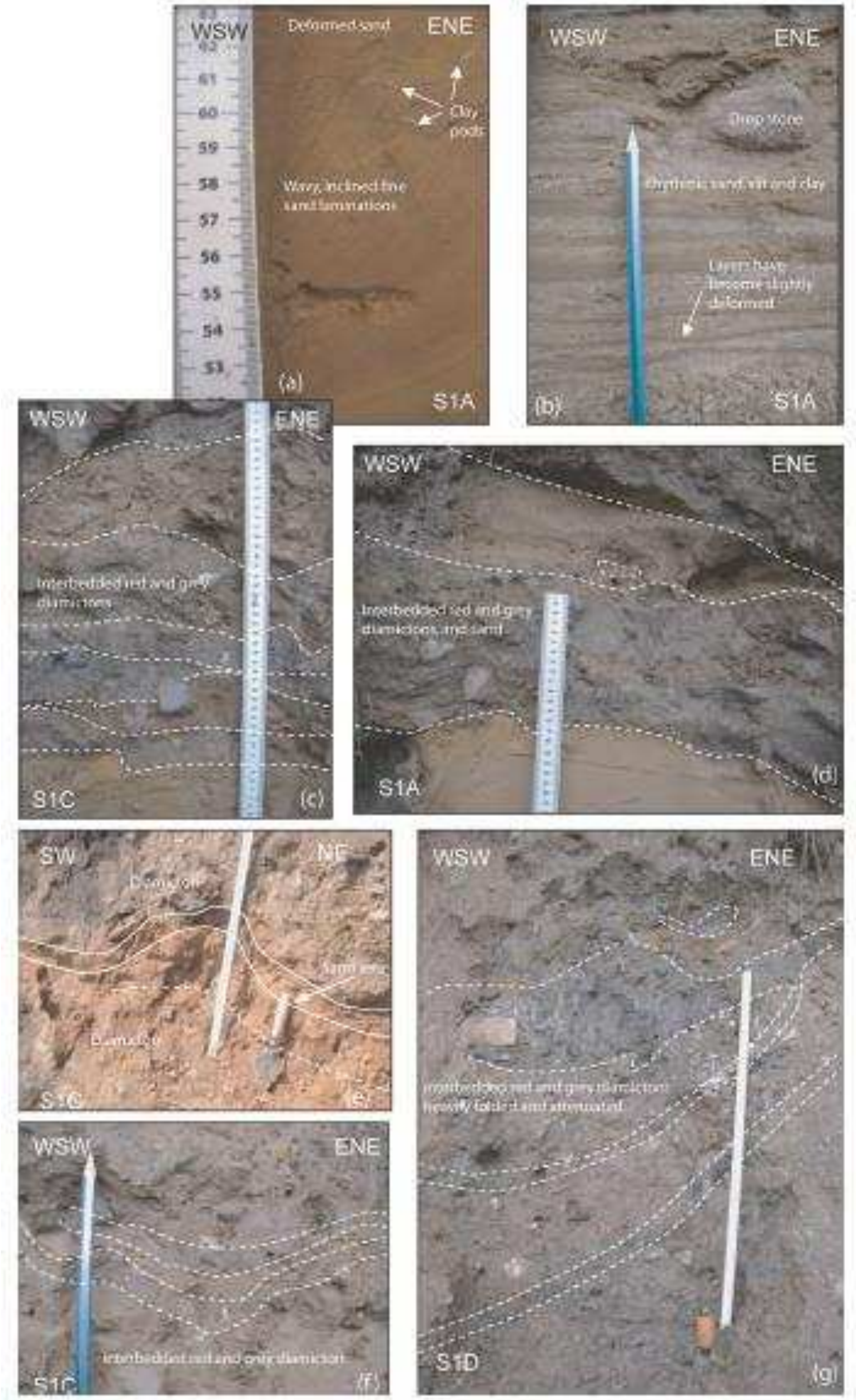

Figure 6:
(A) Clast macrofabric data for the two tills within LFA W4, at Willowford (samples taken from 50 clasts from locations shown on Figure 7). (B) Ternary Diagram showing clast fabric shape (cf. Benn, 1994). (C) Modality-Isotropy plot (cf. Hicock et al, 1996).

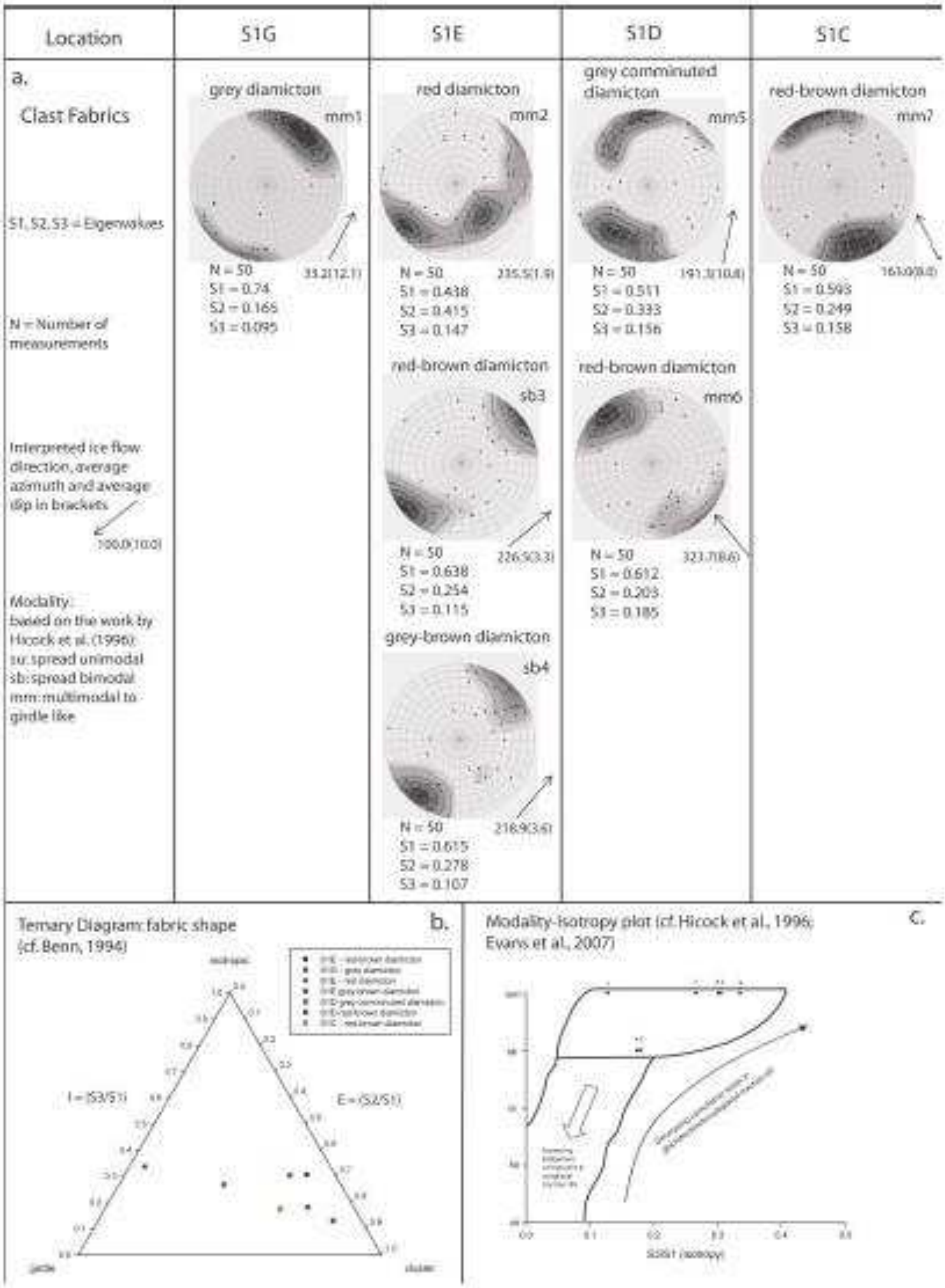

Figure 7:
Provenance data at Willowford: clast lithologies (n = 300) collected from the red and grey diamicton and fluvial gravels; and clast morphologies (samples taken from 50 clasts).

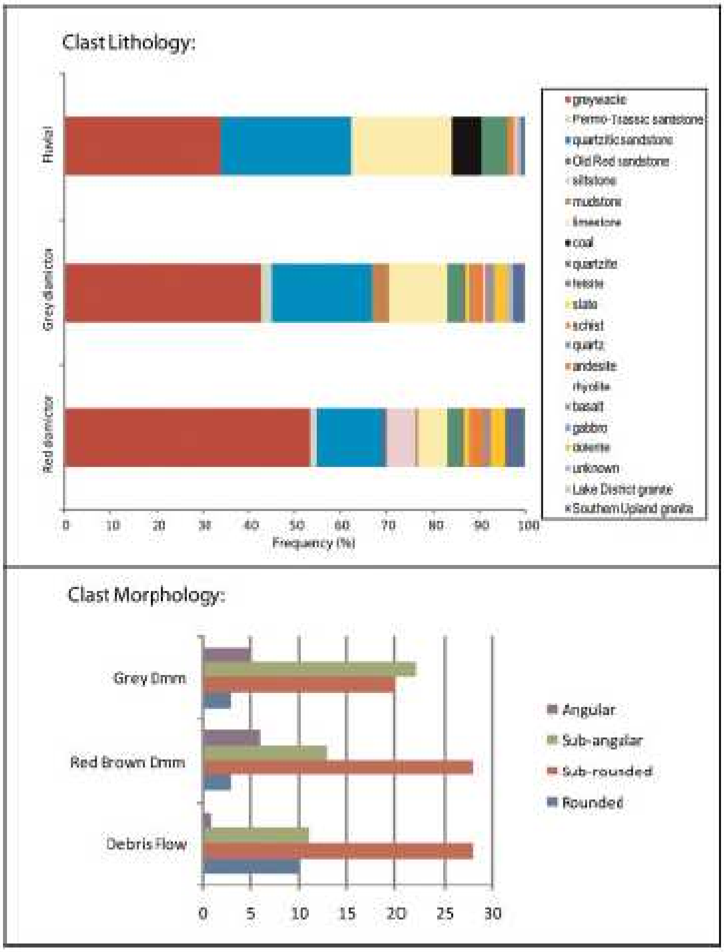

Figure 8:
Borehole logs (BGS) showing stratigraphic sections and borehole locations at Hayden Bridge field site.

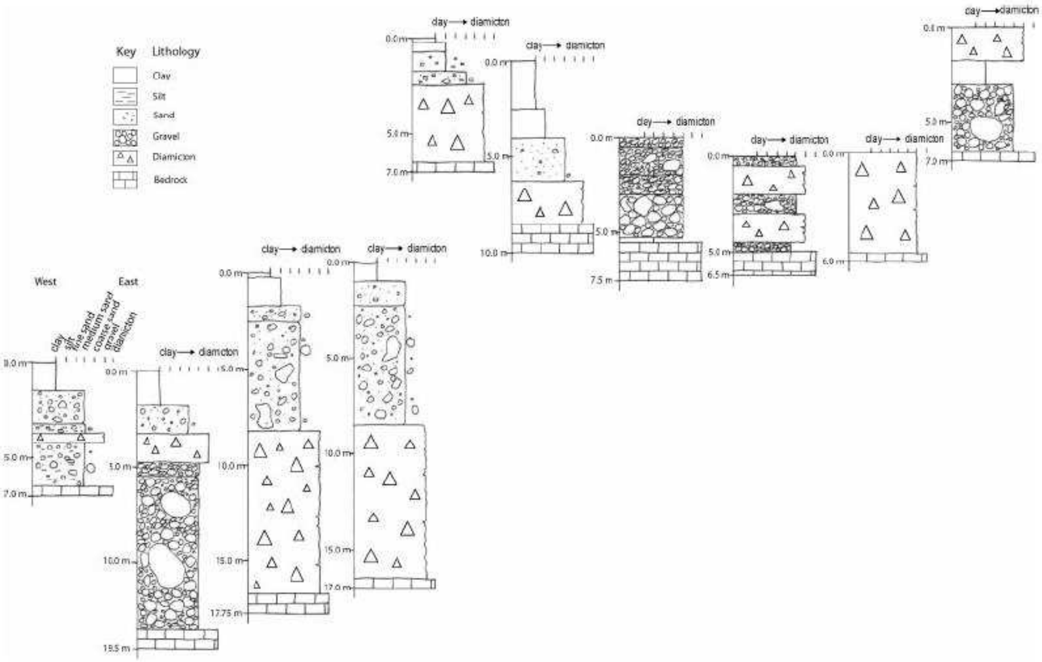

Figure 9:
Photographs of lithofacies exposed at Hayden Bridge: (a) gravels and sands of unit 2; (b) diamicton of unit 1; (c) silts and sands which fine up into clay laminations. These are overlaid by sand and gravel deposits; (d) silts and sands which fine up into clay laminations.

Figure 10:
Borehole logs showing stratigraphic sections and borehole locations at Haltwhistle Bypass (BGS).

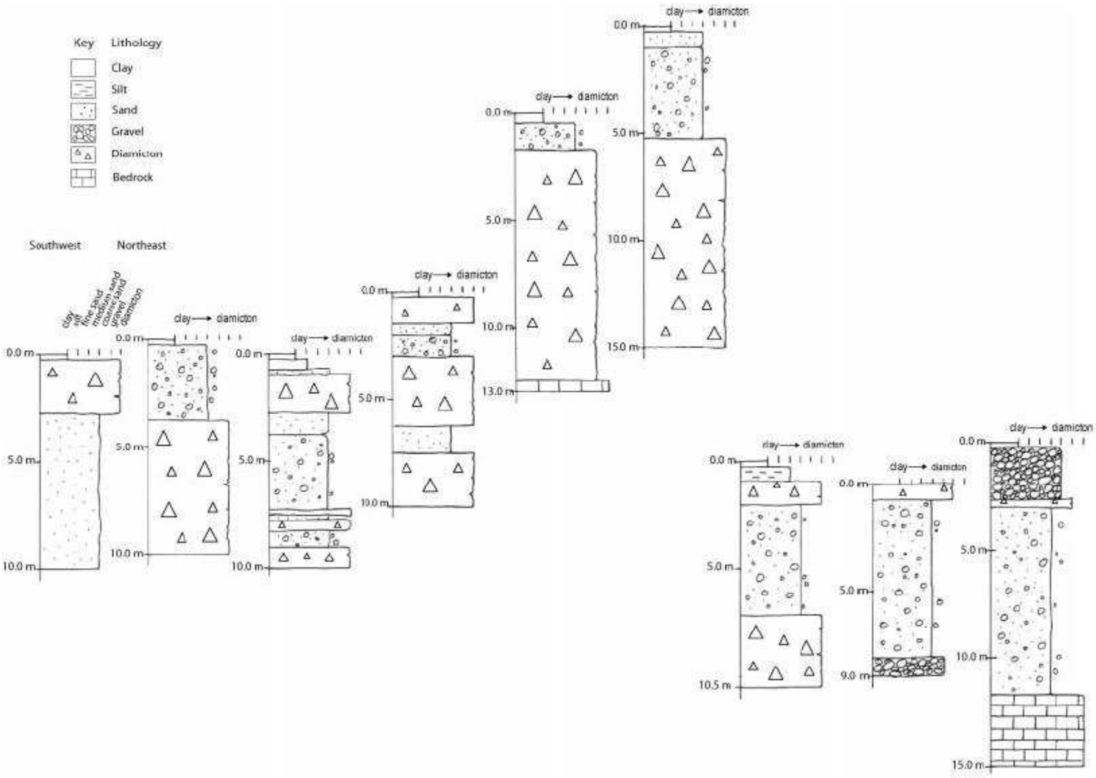

Figure 11:
Map showing inferred ice flow phases within the Tyne Gap. Dotted lines indicate ice divides; dashed lines are streams of local ice movement. (NEXTMap Britain data from Intermap technologies Inc were provided courtesy of NERC via the NERC Earth Observation Data Centre)

(a) Stage I: Flow through the Tyne Gap as a topographic ice stream (phases 6-4)

(b) Stage II: Scottish ice breaching the eastward flowing ice artery, with south-easterly flow down the North Tyne. Initial retreat resulted in glacial Lake Wear forming between the North Sea ice lobe and ice stagnating within the Tyne Gap (phase 3)

(c) Stage II/III: Westerly retreat of ice back into the Solway Lowlands resulting in a proglacial drainage network in the Tyne Gap, the formation of Brampton kame Belt and finally, the sequential development of glacial Lake Carlisle.

(d) Stage III: Drawdown of ice into the Irish Sea Ice Basin (phase 2)