8. The application of microstructural analysis to macroscale forms: the dynamics of the East Coast Late Devensian Glaciers

8.1 Introduction

In the Late Devensian ($\delta^{18}O$ stage 2) ice extended from Scotland down the North Sea coast of the UK. These glaciers left a suite of sediments, largely diamicts, that can be traced from the Cheviot Hills just south of the Scottish Border (NT 3865) to Hunstanton in East Anglia (TL 567341) (*Figure 8.1a*). Individual sediment units can be traced for distances on the order of a hundred kilometres (Madgett and Catt, 1978; Evans *et al.*, 1995), and have been studied for more than a hundred years (Wood and Rome, 1868), giving an excellent region-wide appreciation of their form and content. The sequence of sediments is best exposed along the Yorkshire coast.

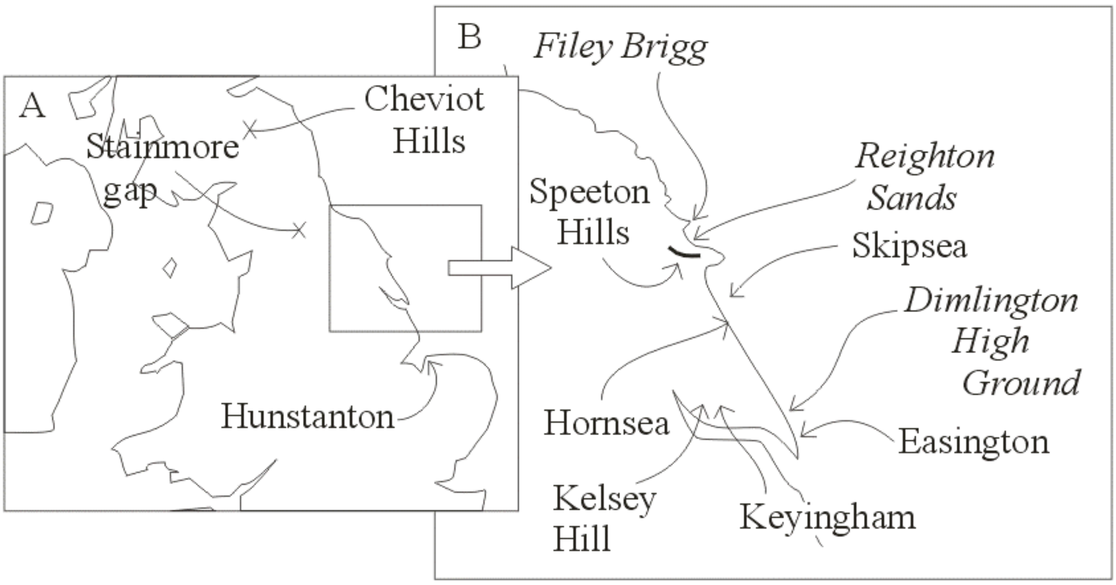

Figure 8.1 A) Map of locations discussed in the text. B) Location of sites on the East Yorkshire coast discussed in the text. Sample sites discussed in this chapter are in italics.

The diamicts of Yorkshire are probably subglacial tills (Evans *et al.*, 1995; Eyles *et al.*, 1994). They include rafts of older marine clays and sands (Catt and Penny, 1966), and soft clasts, some of which have been strung out into bands indicating shear deformation (*Figure 8.2*). Given this evidence the diamicts have been defined as deformation tills (Evans *et al.* 1995; Eyles *et al.*, 1994). This definition backs the seminal claims of the early soft bed modellers (Boulton and Jones, 1979; Boulton *et al.*, 1985) that till deformation was responsible for the extension of east coast glaciers so far from their small, and relatively low altitude, accumulation areas. The homogeneous diamict around the obviously deformed material is widely believed to be the same sediments mixed by high strain (Hart and Boulton, 1991; Eyles *et al.*, 1994).

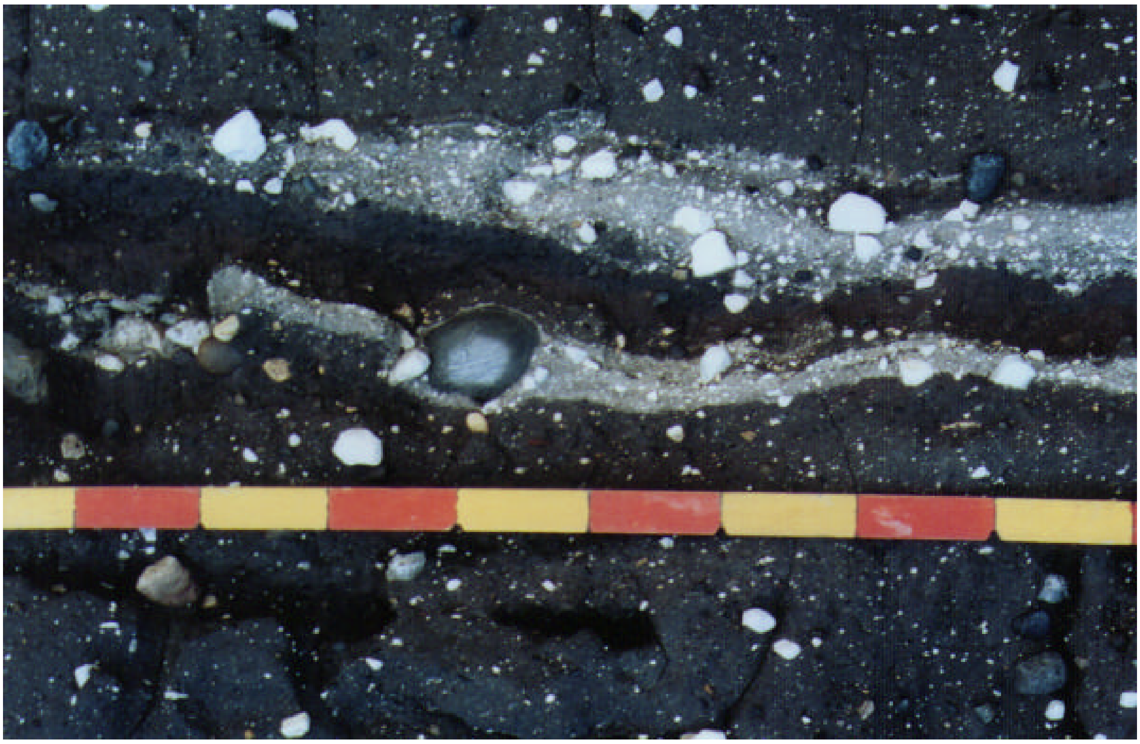

Figure 8.2 Shear extended chalk material at Hornsea, East Yorkshire Coast. Ruled divisions are 10 cm.

The Yorkshire sediments were deposited on flat marine plateaux (Kendall and Wroot, 1924; Valentine, 1952; Straw, 1961), and the flow of the glacier from its head to the terminus was relatively uninterrupted by topography. This means that any till deformation will have occurred under as near to 'textbook' conditions as one could hope for in an illiterate world. The sediments of the Yorkshire coast therefore provide an excellent suite of materials with which to examine;

1) the definition of the sediments on the basis of outcrop scale structural work;
2) the dynamics of the Late Devensian North Sea glaciers;
3) the potential processes and effects of deforming beds generally.

With this in mind, sediments were sampled from the 'Skipsea Till' in Yorkshire and its boundaries with the other local sediments. The Skipsea Till diamict, probably with a largely Scottish provenance, overlies a diamict known as the 'Basement Till' in Holderness, and bedrock further to the north. It, in turn, is overlain by the 'Withernsea Till' diamict, probably with a Lake District provenance (Kendall and Wroot, 1924; discussion in Madgett and Catt, 1978), between Easington (TA 403200) and Hornsea (TA 212472) (*Figure 8.1b*). The upper two diamicts were deposited by ice flowing down the east coast. Ice from Scotland was either superseded or superimposed (Carruthers, 1948; Madgett and Catt, 1978) by ice crossing the Pennines from the west at the Stainmore gap (*Figure 8.1a*).

Fluvial sand, silt, and gravel inclusions are found throughout the Skipsea and Withernsea Tills in the region. Two models have been proposed to account for the deposition and deformation of the sediments;

1) a single ice mass including ice streams of varying positions and velocities, depositing and deforming the diamicts, with the sands deposited from subglacial streams (Evans *et al.*, 1995);
2) a set of glaciers oscillating due to climatic variations or undergoing true surging across proglacial water-lain deposits (Eyles *et al*., 1994), some of which undergo partial disruption to form diamicts.

Sampling was therefore also carried out to investigate the nature of the fluvial events with the hope of distinguishing between the potential ice histories.

8.2 Methodology and sampling

Sediments were sampled from coastal cliffs after the removal of between 50 and 100 cm of surface material, following the techniques outlined in Chapter Three. Sample locations (Reighton Sands, Dimlington and Filey) are given on Figure 8.1b.

The boundary between the Withernsea Till and the Skipsea Till is largely inaccessible because of its height. This boundary may also represent a change in englacial sediment that has melted out, and therefore may not reflect subglacial conditions (Carruthers, 1948; Madgett and Catt, 1978). For these reasons, the boundary between the Basement Till and the Skipsea Till was chosen for sampling. Eyles *et al.* (1994) have shown that the Basement Till is Late Devensian, and thus that the Skipsea Till is a readvance unit. The boundary between the Basement and Skipsea Tills therefore gives information on the processes of readvance during the main glacial phase; a phase that may have been characterised by short-lived readvances or true surge type behaviour (Eyles *et al.*, 1994). The boundary between the diamicts varies in character, and this variety was accounted for in the sampling strategy. The different boundary morphologies sampled are summarised in Table 8.1.

Sample Site	Skipsea Till type and situation	Sub-Skipsea material	Lower Skipsea boundary nature
Filey Brigg (TA 125816)	Till homogenous. Suffered considerable overriding by glacier.	Jurassic Limestone	Homogeneous and sharp with bedrock.
Dimlington (TA 390218)	Till homogeneous. Suffered considerable overriding by glacier.	Basement Till and laminated silts.	Sharp 'shear' appearance.
Reighton sands (TA 145763)	Till homogeneous. 100m up ice from terminal moraine.	Sands.	Finite strain folding.

Table 8.1 Sample locations, diamict character, nature of lower boundary and the underlying material at the sample sites.

Material was also sampling from higher in the sequence at Filey Brigg to give information on the homogeneous areas of diamict, and the nature of the fluvial deposition events.

The microstructures from each of the three sites are detailed below, and conclusions drawn for each in turn in terms of processes and history. Information from the triaxial tests on the Skipsea Till (Chapters Six and Seven) is used in this interpretation. Finally, the chapter concludes with a review of the conclusions for each site, and the implications for the dynamics and history of the ice mass as a whole.

8.3 Filey Brigg

8.3.1 Introduction

Material was sampled from the coastal cliff at the inland southern end of a small peninsula known as Filey Brigg (TA 125816), just north of the main town of Filey (*Figure 8.1b*). The Brigg sediments (*Figure 8.3, Figure 8.4* and *Figure 8.5*) have been correlated with the Skipsea Till further south (Evans *et al.*, 1995). The area has been extensively studied on an outcrop and S.E.M. scale by Evans *et al.* (1995). However the authors failed to gain satisfactory thin sections for optical examination because of the very low permeability of the sediments (D.Roberts, pers.comm., 1994). Considerable information can be revealed at this intermediate level. Therefore success with similar sediments, and the otherwise complete prior work, dictated this sequence as the most suitable site for a detailed thin section investigation of the Skipsea Till.

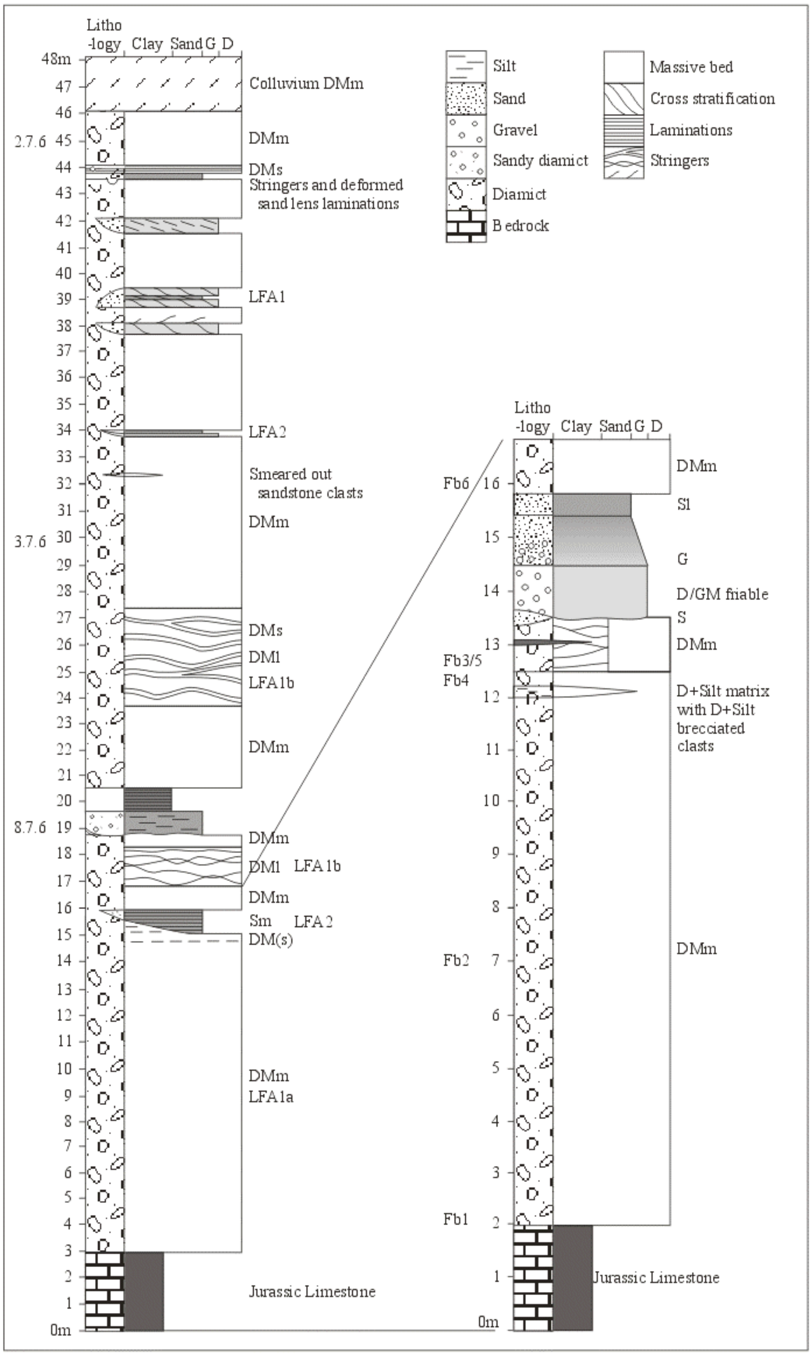

Figure 8.3 Sediment sequence at Filey Brigg, East Yorkshire coast. Compound sequence for the whole Brigg area from Evans et al., 1995, also showing the positions of their S.E.M.thin section samples 2.7.6, 3.7.6 and 8.7.6. Sequence on right is the stratigraphy at the sample site discussed in this chapter with heights of samples (Fb1 to 6) (after an original diagram by S.Church, 1996, unpub.).

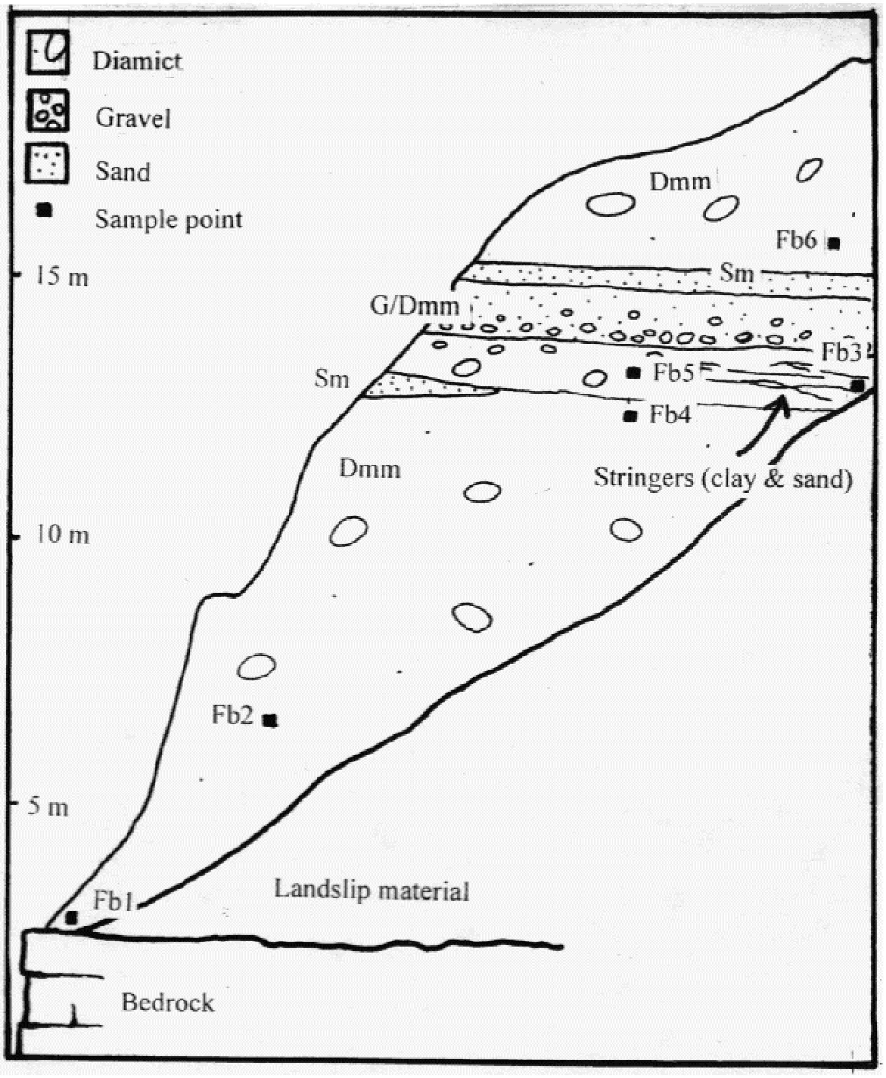

Figure 8.5 Sketch of the two dimensional form of the sampled sediments.

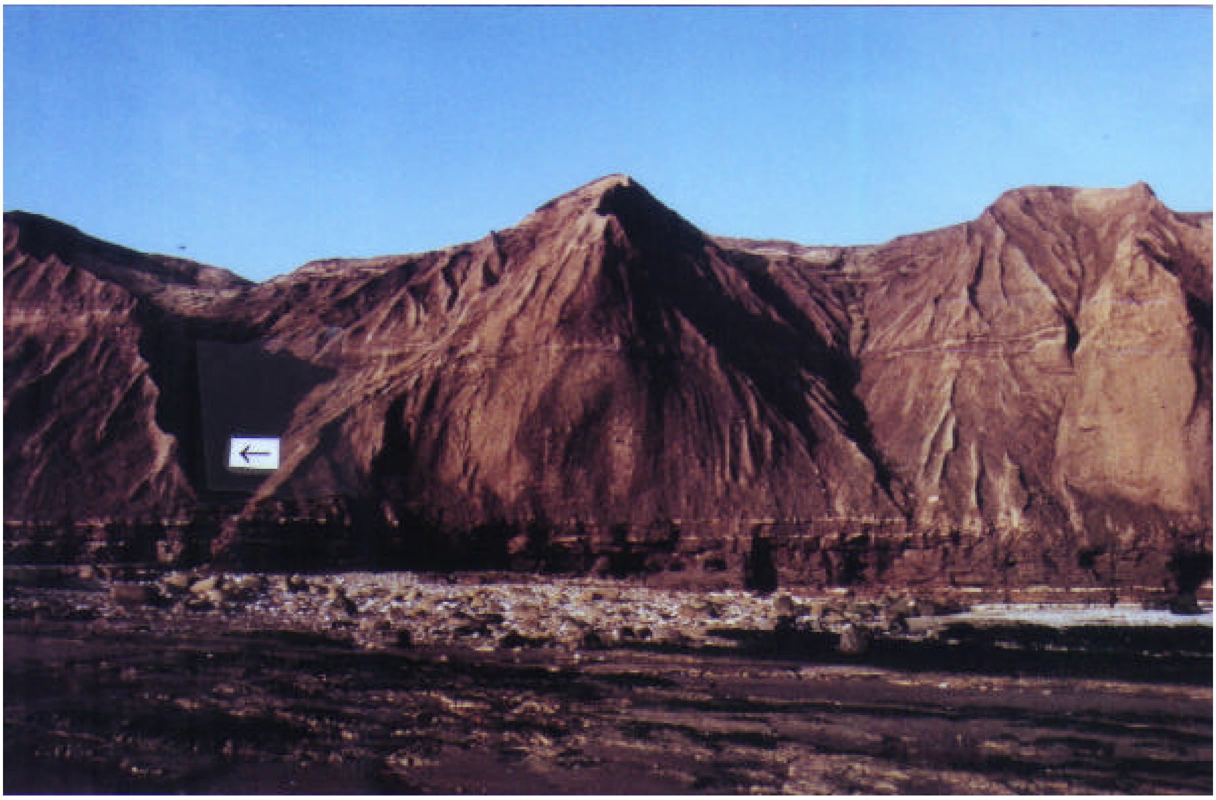

Figure 8.4 Photograph of Filey Brigg showing sampling site.

Evans *et al.* (1995) split the sequence into two alternating diamicts. The majority of the sequence is one massive diamict (lithofacies association 1a [LFA 1a]) (*Figure 8.3*) with an number of sub-angular clastic layers, smeared sandstone clasts, and a generally up-sequence coarsening of the particle size (Evans *et al.*, 1995). The S.E.M. revealed microstructure of the diamict as found by Evans *et al.* (1995) is of moderately aligned silts with occasional sand grains. In their sample 3.7.6 (*Figure 8.3*) the fabric is skelsepic around the sands and there is some silt bridging. There are also microshears (dipping west) and coarse grain silt areas. Their samples 8.7.6 and 2.7.6 are more strongly aligned, but again 8.7.6 has coarse silt patches with a lower alignment. Evans *et al.* (1995) suggest this is a deformation till showing a variable strain or rheological conditions.

The second till (LFA 1b) is split into two separate layers; one has laminae of clay which anastamose around diamict blocks. The S.E.M. revealed microstructure of the diamict again has areas of silts and sands, but with a highly varied grain size and alignment. They suggest this is a meltout till disrupted by high pressure fluids or differential strain. The other exposure of LFA 1b is of thin bands of diamict of various colours. They implicitly define this as having the same origin as the former exposure.

The upper level of diamict LFA 1a is bisected by sands. Evans *et al.* (1995) have suggested that these were deposited in subglacial 'canals' of the type outlined by Walder and Fowler (1994). 'Canals' are shallow, broad based, anastomosing streams with a bed of deforming sediment that is constantly inflowing and being removed. The alternative interpretation, that of Eyles *et al.* (1994), is that the sand bodies are proglacial and the diamicts subglacial, indicating oscillation of the ice front over the area.

8.3.2 Sampling

At the sampling location the fluvial events are represented by up to 4m of sediments. Several sand lenses, showing low strain, mark the base of a gravelly diamict. This diamict has a distinct boundary with gravels above which merge with laminated sands with height, above which diamict deposition is again resumed. It should be noted that sand lenses are not found lower in the sequence, and would, therefore, appear to be associated with the event ultimately responsible for the larger sand layer. Below the boundary with the gravelly diamict is a horizon of diamict which has, on one side of the exposure, layers of discontinuous and anastomosing clay (2 to 30 mm thick) and sands (~5 mm thick). Elsewhere on this horizon and below is homogeneous diamict.

The interdigitation of the sand stringers, sand lenses, clays, and diamicts points towards concurrent, very localised, formation within a single environment. This observation rules out the simple ice front oscillation over a sandur proposed by Eyles *et al.* (1994). Further evidence against Eyles *et al*.'s model as a general explanation for the sediments of the Yorkshire coast is given by Carruthers (1948) and Catt and Penny (1966), both of whom describe blocks of Withernsea Till within the sands and gravels of Kelsey Hill and Kirmington (*Figure 8.1b*). These sediments were regarded by Eyles *et al*. as those most likely to be 'proglacial' (ie. pre-Withernsea Till deposition). These blocks abut bedding in the water-lain deposits with little or no disruption, indicating syndepostion of the diamict and the sands/gravels. Thus, it is unlikely that the model of Eyles *et al.* is applicable as widely as they stated. However, there is an alternative proglacial explanation for the interdigitated sediments of Filey Brigg. As the sediments show only low to moderate strain, the diamict between must have suffered only moderate strain *after* their deposition (though the sediments may have been deposited into high strain material). The low strain indicates three possible depositional origins for the diamicts.

1) They are subglacial tills formed by deformation advection of material. The material may have been non-glacial, frozen or unfrozen, and was possibly partially decoupled from the ice in this area to give low strain. Any such lateral movement, however, would have to have been very low (metres on the basis of macroscale strain).
2) The diamicts are proglacial or subglacial diamicts reworked by mass movements, that is, they are 'flow tills'.
3) The diamicts are subglacial meltout tills, with the ice above moving or stagnant.

To resolve the problem diamict samples (*Figure 8.3* and *Figure 8.4*) were taken from;
1) in the diamict immediately above the laminated sands,
2) between the sand and clay bodies in the diamict below the sand lens horizon,
3) in the homogeneous diamict at the same height as '2',
4) immediately below sample '2' in the homogeneous diamict that extends to bedrock.

The main body of the diamict at Filey is homogeneous. When there is local evidence that deformation has occurred, such material is usually considered to have been mixed by infinite strain. The homogeneous material was sampled to examine this hypothesis.

The positions of the samples examined below are detailed on Figure 8.3. The samples were thin sectioned in north-south planes.

8.3.3 Results

The descriptions of the slides are given in Table 8.2, and this is directly followed by a summary. Descriptions are in terms of the general fabric of the diamict, and the fabrics in and around any inclusions such as clay bands or diamict pebbles. Skelsepic fabrics occur where matrix particles (F) and/or sand grains (G) are parallel to the edges of larger grains. Lattisepic fabrics are those where areas of fabric exist in two orthogonal directions, either pervasively or in a lattice of shear zones. An omnisepic fabric is where a large proportion of the sample has a single fabric direction. ‘SDF area’ refers to a Single Direction Fabric area. This is an area of material which has a consistent internal direction but is not large enough to qualify as omnisepic. Multiple SDF areas may be arranged in one or more directions or may be randomly aligned (RA). It is felt that the term ‘domain’ implies clays and a consistent sub-rectangular form. The term domain has also been applied to various sizes of fabric orientation, often under the impression it is unique to that scale. ‘Bands’ of material are taken to have a length to width ratio of greater than four; below this ratio, bodies are described as pebbles (distinct boundary with surrounding material) or patches (diffuse boundary). Other terms are defined in Chapter Two and the Glossary.

Shears and more pervasive fabrics are given in terms of their dip angle. Samples were cut in north-south and east-west planes so that shears and other fabric elements are given in terms of their dip angle downwards in a cardinal direction (N,S,E,W). The dip angles are means, often of very small populations. It is impossible to reliably assess the errors involved, however, the variation was $^{+}/_{-}$ 5° before the angles were taken to be different.

Position	Sample	General fabric	Inclusions
Diamict above the laminated sands.	Fb6a and b	Some Skelsepic (G+F) overprinting. Generally Omnisepic (a; 124° E, b; 115° N) , with occasional RA SDF areas. Both samples have intense SDF areas in the main fabric direction. Two shear sets in E-W sample (a) which developed synchronously. A major set at 124° E and another at 151° W. These cross the clay band.	7 clay rich bands through E - W sample (a) (low strained, 0.5 to 0.75mm thick in an area ~3mm thick). Strong fabrics in direction of sample fabric. 7+ Diamict pebbles (0.75 to 2mm) within these bands are skelsepic (F) near their clasts with RA SDF areas away from them. Some pebbles may be flow noses (often surrounded on only three sides by clays). 4 clay patches. 1 clay pebble.
Diamict at same level as clay/sand stringers.	Fb5a and b	(a) Some skelsepic (F+G) (2% of slide + overprinting). Non-organised (22%). Two sets of omnisepic fabric broadly split between the upper south half at 125°S (30%) and lower north (39%) which varies between 160°N and 160°S. (b) Skelsepic overprinting (G+F). Omnisepic at 130° E with intense SDF areas this direction.	(a) One clay band, originally omnisepic, now broken so that fabric in two halves at right angles. (0.5 x 0.5mm).
Diamict from within area of clay and sand stringers.	Fb3a and b	Some skelsepic overprinting (F+G). Patchy omnisepic fabrics. Sample (a) has intense SDF areas in the main fabric direction (113° E). In (b) the fabric is aligned with shears in the clay patches (150° S)	(b) 5 Clay patches + 3 pebbles and 5 clay bands (all 0.5 to 1mm long) with internal fabrics in the general fabric direction. One pebble with a skelsepic/RA SDF internal fabric. (a) 2 clay patches + 1 pebble. Internal fabric in general fabric direction.
Diamict from below the horizon containing clay and sand stringers.	Fb4a and b	Diamict patches of 3 types. 1) No clear fabric (a;13% of slide, b; 25%) 2) Skelsepic (G+F) (a;26%, b;17%) Both samples had intense SDF areas (0.1 to 0.6mm) in two direction. In (a) these were at 138° W (32%) and 128° E (29%). In (b) 100° S (28%) and 130°S (25%). Some evidence in (a) of slump noses covered in sand grains.	Numerous clay areas with single direction or RA SDF fabrics. 3 clay pebbles, 2 in (a) and 1 in (b) which contained a sand layer (all ~0.5 x 0.4mm). (a) 4 Clay bands (0.1mm thick, ~2.3mm long) finitely strained. These are associated with patches (layers?) of fine grained sand (0.5mm thick) with a horizontal fabric prior to straining. (a) Two shear sets in the clays at 138° W and 128° E. These developed synchronously and are in direction of local clay fabrics.
5m above rock bed	Fb2 a and b	Some skelsepic (F+G) round clasts. Largely structureless but with faint traces of SDF areas (too faint to gain directions).	
Just above limestone / sandstone	Fb1a and b	Small amount of skelsepic (F+G) behaviour. Structureless with no preferred orientation, though some faint RA SDF areas in (b) - (a) is too thick to tell. Matrix supported, but many clasts.	2 Clay inlyers (3 and 1.5mm) with sharp boundaries and fabrics of RA SDF areas. Long axis of few clasts in clays align parallel to walls.

Table 8.2 Summary of the micromorphology of samples taken from the sediments at Filey Brigg, East Yorkshire. The table is arranged such that the samples are in their stratigraphic position. The samples from the base of the sequence are lowest in the table.

Samples Fb4a/Fb6a (the diamict at 12.3 m and the diamict at 16 m, *Figure 8.3*) show small numbers of rhythmic alterations between of sandy layers and clay bands within the generally silt-clay matrix. Some of these alterations have the form of small clay slurry flows into the sandy material. Fb6a contains diamict pebbles with skelsepic fabrics within the clay bands, however there is no evidence of such features in the surrounding matrix. Along with these clay bands and others (width to length ratio of >4) the samples from higher than 12 m contain numerous clay pebbles (defined as having distinct borders) and patches (diffuse borders).

Samples from the homogeneous diamict at 5 m above the bedrock (Fb4a/b) have a skelsepic fabric, with no clay patches. Higher diamicts (12.3 m plus) have some skelsepic fabric, but this is not the dominant fabric. The external form of the clay areas in these higher diamicts indicate low strain deformation that varies across single samples, however, this low strain deformation has been overprinted by a more pervasive fabric which has aligned the internal fabric of the clay areas. This overprinting is strongest above the main sand body (ie., above 15.75 m, Fb6a/b) where it produces an omnisepic fabric. Below the main sands (ie., below 13.5 m) the fabrics are more varied within the slides, however, there are local fabrics in the same direction as the strong omnisepic fabric above 15.75 m. There is only one sample above 12 m that has no overprinted in its clay areas, and that is sample Fb5a.

Close to the bedrock (Fb1a/b) the skelsepic fabric of the material 5 m higher is replaced by a more random fabric with clay rich areas.

8.3.4 Interpretation

The fluvial deposits and surrounding diamicts

It has been shown above that, because of the interdigitation of the sands and diamicts, the only proglacial features that could explain the Filey deposits are flow tills. All the samples from around the laminated sands (Fb4a/b upwards) contain microscopic scale clay bodies that have suffered low strain deformation (*Figure 8.6*). These clay bands indicate either;

1) low strain reworking of local clay deposits (compatible with a subareal flow till);

2) the washing in of clay material by fluid moving through the sediment;

3) a meltout origin for the clay and maybe the diamict, possibly involving particle sorting.

None of the materials match the more heterogeneous sediment and porous character attributed to flow tills by Owen and Derbyshire (1988) and van der Meer (1993). In addition to this fact, there are no extensive unimodal clay bodies to rework in this part of the sequence, making a flow till origin for the clays unlikely. This dismissal is backed up by the similarity of the diamict fabric between the sand lenses and that in the *massive* diamict above the main sand body, which is probably too thick and homogeneous to be a subaerial flow till, and the wide variation

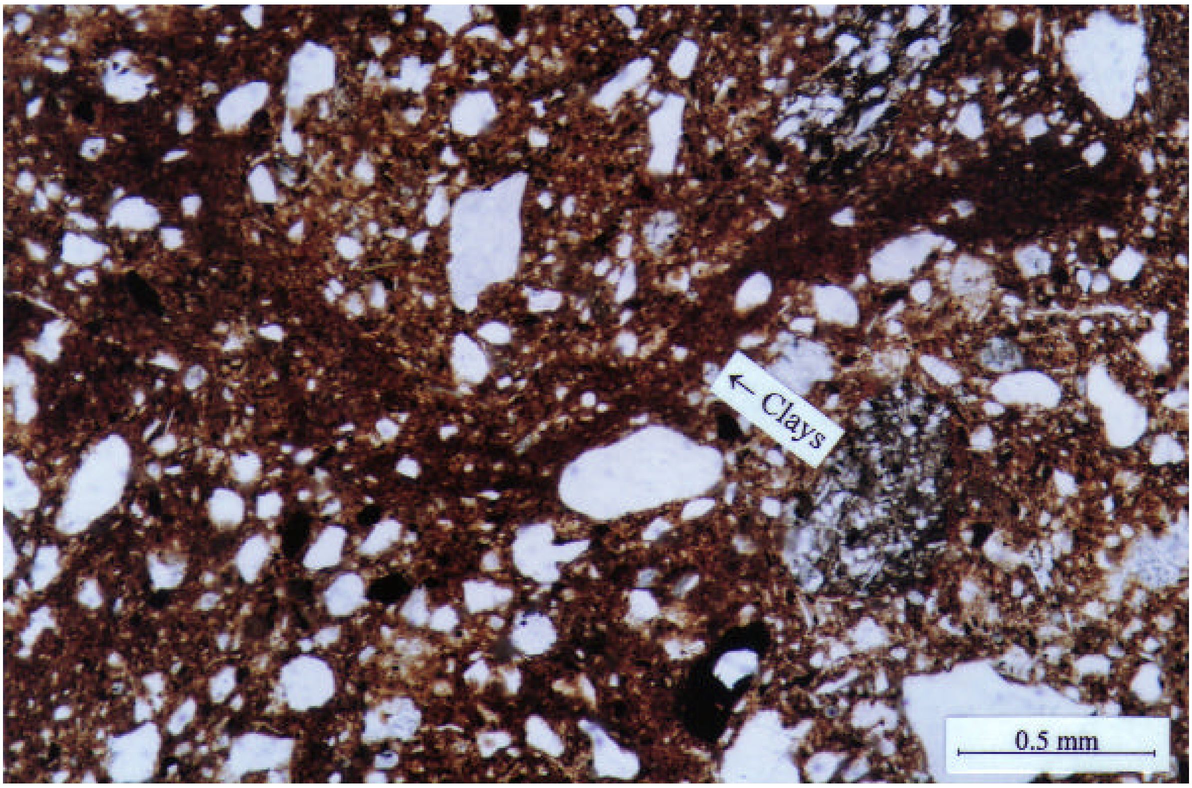

Figure 8.6 Photomicrograph of a clay body from sample Fb6a showing low strain deformation. Unpolarized light conditions.

in strain seen on a sub-millimetre scale in the slides, which may dictate against flow in a single body. When combined, these four lines of evidence place serious doubt on the proposed proglacial origin for the sands (Eyles *et al.*, 1994) by suggesting the intimately interbedded diamicts and clays are not proglacially reworked.

The rhythmite or microscale mass movement nature of the clays in sample Fb4a/Fb6a precludes the internal translocation cause for the clays. In addition to this suggestion, there are none of the more certain fluid through-flow features which might be expected, such as areas of more porous material (see Chapter Two). These facts suggest internal translocation reworking of the diamict is not responsible for the clays. However, the diamict pebbles in the clay band of Fb6a has the same fabric (skelsepic and randomly aligned patches) as the main diamict body deeper in the sequence (samples Fb2a and b). This may indicate the main diamict body *has* been reworked by water in some manner to produce the clays.

It seems highly unlikely that the clays could have been deposited by melt or water into a diamict forming by reworking of other local deposits, and suffer only low strain at this scale. This may suggest that *both* the diamict and clays melted out of the ice. The meltout origin hypothesis implies heterogeneous material is being supplied (diamict and unimodal clays) and cannot, alone, explain the diamict pebble in the clays of sample Fb6a. However, a meltout origin for the diamict, with small ice-sediment interface streams (microscale) producing the clays, explains the material without contradictions. It is worth noting that such a model does not assign any ultimate origin to the diamict, simply that this area was one of melt-off of the material from the base of the ice.

Meltout into a ephemeral subglacial stream environment explains all the features of the sediments. The presence of diamict pebbles in the clays of sample Fb6a but not the surrounding diamict shows that the conditions of clay deposition were different from those of the surrounding diamict and involved reworking. The possible sand-clay couplets seen in samples Fb4a/Fb6a may suggest a rhythmic depositional environment. This could be a subaerial lake, however, a subglacial possibility also exists in the form of subglacial cavity ponds (Van der Meer, 1987b; Owen and Derbyshire, 1988), activated repeatedly and flooded with new sediment. There is also some evidence of small scale material slumping in slide Fb4a and Fb6a (*Figure 8.7*), which would not be expected in material formed by the deformation of other beds or the deposition of large scale proglacial flow tills.

Such a model of mixed meltout and overflow matches the clay rich, laminated, sediments of LFA 1b (Evans *et al.*, 1995), which, in this model, can be seen to be of the same environment as LFA 1a, but possibly with a greater melt rate producing greater overflow activity and/or less subsequent deformation. Alternatively, the deposits of LFA 1b may represent the same melt rate as LFA 1a, with less diamict being produced because the ice had less sediment in it per unit of meltwater produced. As the area of diamict showing macroscale clay and sand stringers would appear to be at the transition between LFA1a and LFA1b, if not fully part of LFA1b, we can investigate the strain and melt/ice-sediment difference between the two LFAs in a quantitative manner.

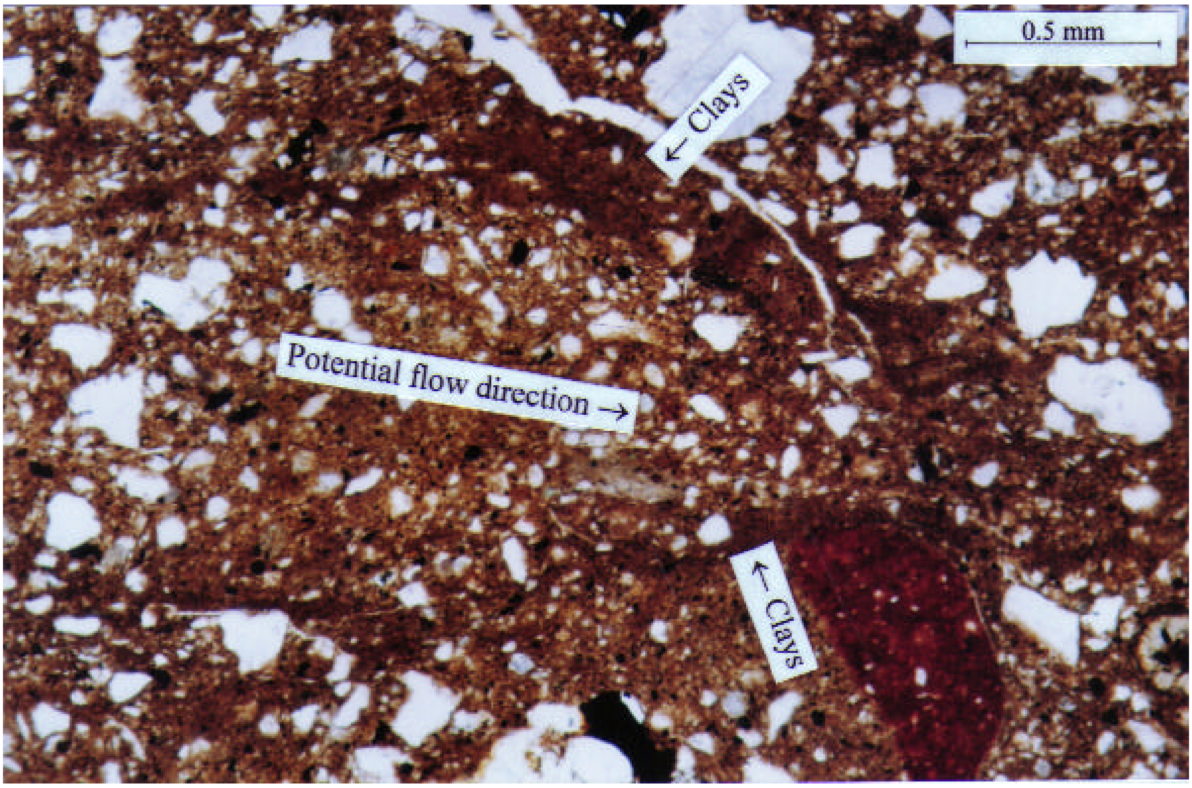

Figure 8.7 Potential small scale 'mass movement' deposit. Note how the clays are folded around an area that might have 'flowed' into them in a semi-coherent mass. Sample Fb6a, unpolarized light conditions.

A greater strain *or* a melt/ice-sediment variation may be causing the absolute difference in the number of clay areas between the two LFAs. However, the meltout variation can be normalised for, if we assume that the clay bands are formed by meltout and that, with strain, the bands break up into pebbles (with a distinct boundary with the diamict) and patches (with a diffuse boundary). Making these assumptions we can give an estimation of bulk strain without any dependence on the meltout. This is achieved by normalising the number of such pebbles and patches using the number of bands, to give a 'disruption value' representing the strain. These values are given in Table 8.3.

Sample area	Patches with graded boundaries with diamict	Pebbles - distinct boundaries with diamict	Bands - length to width ratio > 4:1	Disruption value
Diamict above sands	4	1	7	0.71
Diamict with stringers	7	4	5	2.20
Homogeneous diamict at the same height as diamict with stringers	0	0	1	1
Diamict below stringer level	3	0	4	0.75

Table 8.3 Clay body distribution in the uppermost samples taken at Filey Brigg. The table does not include patches of clay around large clasts, which may be concentrated during deformation (see Chapter Seven).

Thus, there is evidence (although the population sizes necessarily make this weak) that the diamict with the stringers has suffered the greatest strain during deposition, indicating that the greater presence of clay features within it may have been due to a melt and/or ice-sediment variation. Unfortunately the number of clay features in the diamict at the same level as that with the stringers is too small to justify any comparison between the two, which were presumably deposited synchronously.

There is no evidence as to the geometry of the 'microstreams' which deposited the clays, or why they formed. They may, for example, be part of an extensive ice-sediment interface water layer. However, it may be hypothesised that such water bodies will form when the melt rate is faster than the drainage into the sediment, in line with the development of larger (sand carrying) streams. This drainage will largely be controlled by the diffusivity of the diamict and the pressure-flux relationship in surrounding channels. While the largest sand bodies are at the top of one of the diamicts in question, the 'microstreams' were probably active as diamict was deposited near this upper boundary, and smaller sand bodies exist within the diamict.

The combination of the ice-interface water layer and larger streams indicates that the larger streams did not rapidly draw fluid from the surrounding ice-sediment interface. This suggests that the streams were at atmospheric pressure or had a *positive* hydraulic pressure to discharge relationship. In the case of a *negative* pressure-flux relationship large streams have a lower pressure than small ice-interface fluid layers, and rapidly draw water from them (Weertman, 1972). A positive pressure-flux relationship is one of the unusual features of Walder-Fowler canals (Walder and Fowler, 1994), and this evidence goes some way to confirming their calculations for soft bedded channels and Evans *et al.*'s (1995) interpretation of the sediments at Filey. However, the caveat must be given that the ice-bed boundary is not the ideal often envisaged in hydraulic models, and the above deposits may be possible under other water systems.

The appearance of these materials in the sequence may suggest a progressive rise in fluid availability. The final products of this increase may have been the gravelly diamict, which under this model would be left by winnowing of the diamict during or after deposition, and the laminated sands. An increase in fluid with height in this area matches Evans *et al's*. (1995) discovery that the sequence slightly coarsens upwards. There are two possible explanations for this increased fluid; an increase in melt rate or the increased amount of impermeable material between any given horizon and the potentially permeable limestone at the base of the sequence.

Deformation after deposition

As noted above, the clay bands in the sediments near the sand bodies have suffered low strain deformation. This strain varies within each slide, indicating the deformation is unlikely to have been synchronous across the whole slide. This should be contrasted with the strong omnisepic deformational fabric which cuts across the highest slides (Fb6a and b), including the internal clay bands (*Figure 8.8*), indicating post-depositional deformation has occurred overprinting the whole sample at once. The strength of this fabric suggests the overprinting occurred subglacially.

This omnisepic fabric contrasts with the skelsepic nature of the main diamict body further from the sand bodies (samples Fb2a/b). As expected with such overprinting, the samples between these two heights in the sequence (samples Fb5a/b and Fb4a/b) are semi-skelsepic and semisheared in the same directions. The samples from below the sand lens horizon (Fb4a/b) also show overprinting of clay bands. The fact that the overprinting spans the sand bodies suggests it occurred after their deposition (*Figure 8.8*). Thus, it seems likely that the low strain deformation occurred approximately synchronously with deposition of the material, whereas the omnisepic overprinting may have occurred after the sands were deposited.

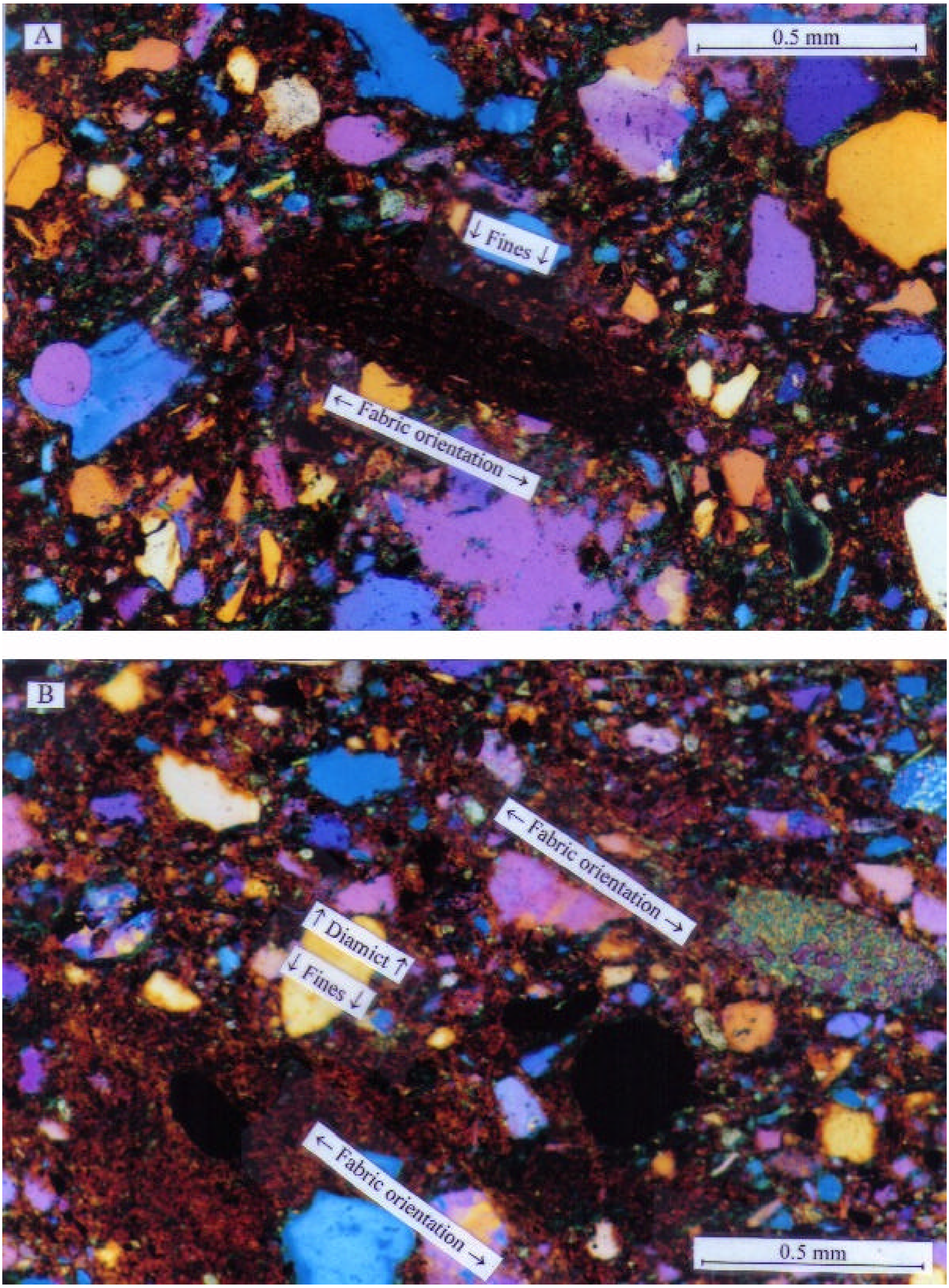

Figure 8.8 Photomicrographs of clay bands showing overprinting. a) Sample Fb6a. b) Sample Fb4a. Picture taken under cross polarized light with a tint plate.

While the strong fabrics of the samples suggest subglacial deformation, the overall strain as suggested by the clay bodies, is low. The ice depositing these sediments extended at least as far as a morainic system on the Speeton Hills (*Figure 8.1*), suggesting the materials underneath should exhibit high strain if well-coupled to the ice base. The low strain of the sand lenses and clays therefore indicates a rapidly rising deformation layer of low strain, or only low coupling between the ice and sediment. Three factors may have contributed to these situations;

1) drainage stiffening of the sediment, and the resultant enhansed regelation which will have lead to meltout deposition (though there was not enough drainage to initiate discrete shear);
2) a high melt rate (note the unusually large (> 50 m) amount of material deposited in this area over 4 ka (see Chapter Six for dating details);
3) the separation of the ice from the sediment, as implied by the clay bearing micro-streams suggested above (probably incompatible with the regelation deposition in ‘1’, above).

In the case of the latter hypothesis, clay bands and patches may give a semi-quantitative estimate of the separation of the ice and sediment where low strain conditions can be quantified through the whole sequence.

The triaxial tests outlined in Chapter Six showed that, under the test conditions, diamicts supported higher stresses than those usually associated with unimodal clays. If the unimodal clays seen here had a different strength from the diamict they may have protected diamict pebbles within them, for example, in the diamict above the sands (Fb6a) where skelsepic diamict pebbles within some of the clays have not been overprinted (*Table 8.2*).

The overprinting of the samples after the deposition of the sands appears to have affected all but one omnisepic clay area. The single clay area in the homogeneous diamict at the same level as the diamict with the macroscale sand and clay stringers (sample Fb5a) does not show omnisepic overprinting in the same direction as the diamict in the slide (*Figure 8.9*). This difference could be due to variations in the resistance of the material to realignment (see intense patches described in the triaxial sediments, Chapter Seven). However, there is another, less probabilistic, explanation.

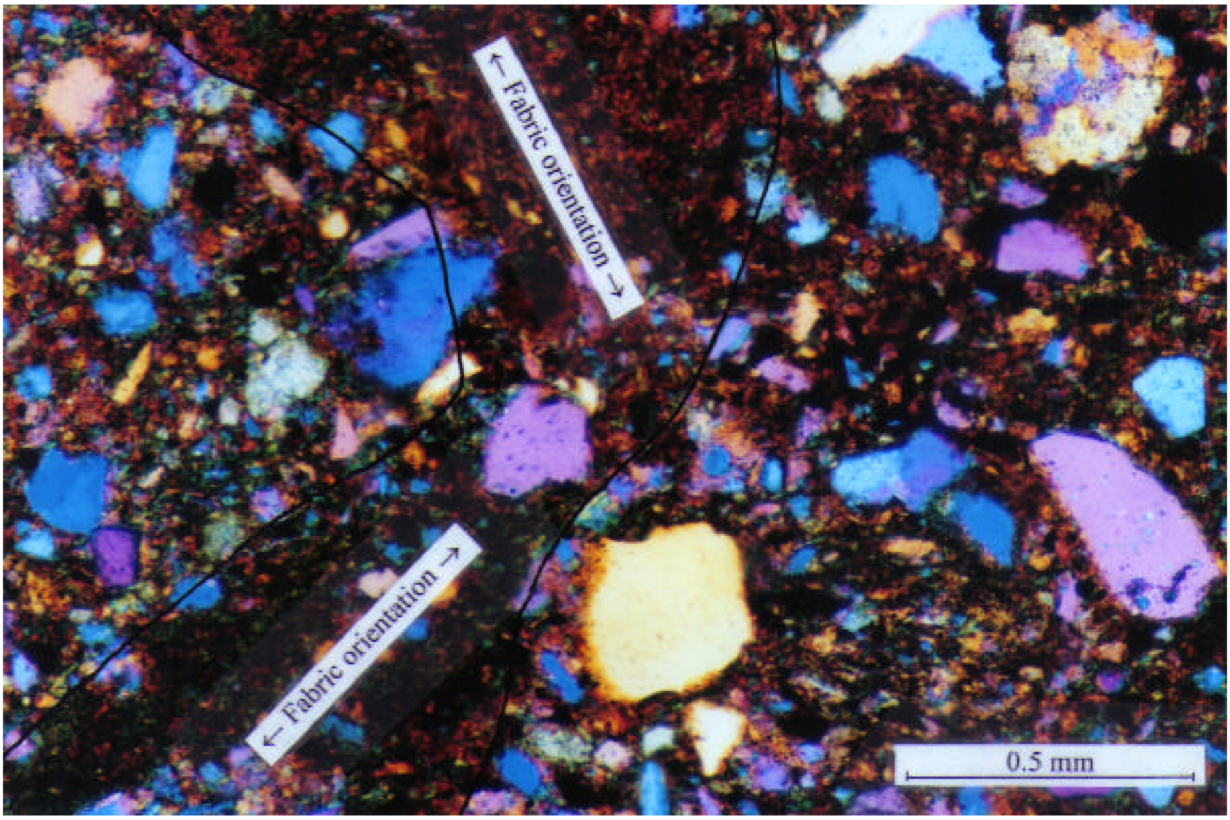

Figure 8.9 Photomicrograph of clay band from sample Fb5a. Note that the internal fabric of the clay has not been overprinted after the band's deformation.

A model explaining the microstructural variation can be developed based on the relative strengths of the sediments at different effective pressures. The strength of sediments is reasonably well modelled using the Mohr-Coulomb equation (*Equation 3.1*), which gives strength as a function of a constant cohesion and a pressure dependent internal friction term. Generally clays have a high cohesivity but do not gain strength rapidly with increased effective pressures because of their small angle of internal friction. At Filey, however, the diamict contains silts, sands, and larger clasts, and will probably have a lower cohesivity and a higher angle of internal friction. As can be seen from Figure 8.10, because of these differences, there may be a point at low effective pressures where clays will be stronger than diamicts.

The micromorphology of the samples suggests the combination of shear stress and effective pressures moved from conditions where all the material was deforming to give an omnisepic fabric, to a situation where, in the material with the inconsistent clay fabric, only the diamict was deforming internally. The two stress paths that could have produced this situation are given in Figure 8.10. It should be noted that a shear stress variation between the two sample points is unlikely on this scale (Kamb and Echelmeyer, 1986), and we would expect all the material to suffer the same stress changes. Therefore, the difference in behaviour is attributed in these models to the material with the inconsistent fabric having a higher effective pressure than elsewhere. This suggests a drainage potential variation in the sediment on a scale of metres.

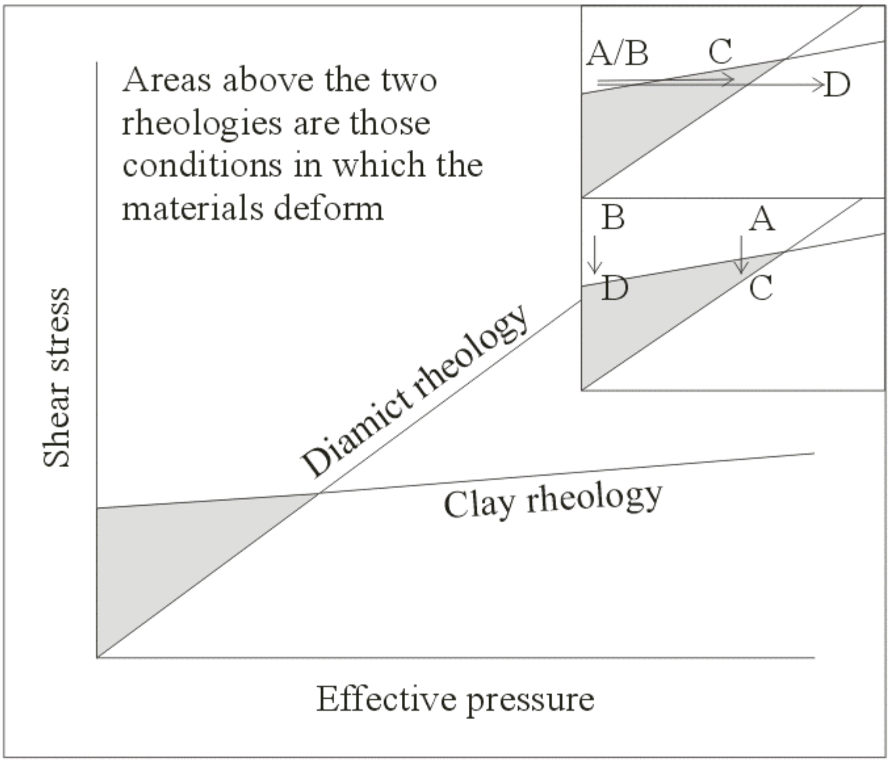

Figure 8.10 Hypothetical shear stress - effective pressure paths accounting for the microstructures observed in the upper part of the sequence at Filey Brigg, East Yorkshire coast. Main diagram shows the suggested rheologies of the material. The inset diagrams are paths which may have produced the strain evidence presented in the text. A and B are the starting conditions for the material with the inconsistent fabric and elsewhere respectively. C and D are their respective final conditions.

The homogeneous diamict

The main body of the Skipsea Till is skelsepic (Fb2a/b, at 7m in Figure 8.3). In three dimensions this probably accounts for the randomly orientated patches of fabric seen in two dimensions. Comparison with the low grade deformation fabrics in rhythmites at Dimlington (below) suggest that the skelsepic fabric is produced by strains of greater than 2%. We cannot say that the strain here was too low for an omnisepic fabric to develop as the development of an omnisepic fabric might be controlled by clast density and/or ice thermal regime. The absence of clay patches in these sections may be due to a lower melt rate than that discussed above or greater ice coupling. A lower meltout rate reduces the rate at which the deforming layer rises, and any given horizon will suffer greater strain. On the basis of the triaxial test samples (Chapter Seven) the strain would probably have had to be greater than 25% to remove the clays if present.

The more random fabric of the till close to the bedrock (Fb1a/b) cannot be attributed to any specific cause (contrast with the fabrics at Dimlington, below). However, given the presence of clay patches here, their absence in the homogeneous area of the till body (Fb2a/b), and the discussion above on the nature of the sediments at the top of the sequence, it might be suggested that this material is undeformed meltout material that has been protected by the irregularity of the bedrock surface and/or drainage into the potentially permeable bed.

Summary: The clay bands in the sediment indicate its origins. Flow tills are dismissed as the micromorphology is dissimilar to other flow tills, there are no clay bodies in the area to rework, and the fabrics are continuous across macroscale units that show no flow till bedding. The interdigitation of sands, clays, and diamicts on two different scales suggests the diamicts have not been deposited over proglacial water lain deposits in the simple manner suggested by Eyles *et al.* (1994), though this cannot be refuted absolutely for the large laminated sand body at this site. The rhythmic nature of some of the clay bands dictates against the deposition of the clays within the diamicts by translocation. A model of diamict meltout into an environment of intermittently active micro-streams that rework older diamict into clay rich units seems to explain the sediments without contradiction. This situation matches the discharge-pressure relationships suggested for canals by Walder and Fowler (1994). These clays suffered syndepositional deformation, shown by variable strains within each slide. This material was then overprinted with an omnisepic fabric after the deposition of the sands. Earlier sediments were probably initially protected from deformation by bedrock irregularities or drainage into the bedrock, however, in the middle of the sequence the absence of clay bands seen at the top and base of the sequence suggests higher strain.

8.4 Dimlington

8.4.1 Introduction

Samples were taken from the coastal cliff at Dimlington High Land (TA 390218, *Figure 8.1b*). The sedimentology, petrology and structure of the area has been studied by Catt and Penny (1966), Madgett and Catt (1978), and Eyles *et al.* (1994). Sampling was carried out to reveal the processes at work in the advance (Madgett and Catt, 1978) or readvance (Eyles *et al.*, 1994) of ice over the area.

The lowest material exposed in the sequence at Dimlington (*Figure 8.11*) is the 'Basement Till' which rests on a marine platform at approximately -34m O.D. (Catt and Digby, 1988). This diamict is overlain by the 'Dimlington Silts'; organic, rhythmic, freshwater deposits (*Figure 8.11*). This boundary was sampled with the hope of deriving information on the nature of high strain till fabrics through comparison with the low strain silts. The upper part of the Basement Till and the remnants of the silts have been gently folded into basins by the ice depositing the overlying Skipsea Till. The Skipsea Till truncates the silts. The geometry of the basins suggest that the ice moved from the north east (Madgett and Catt, 1978).

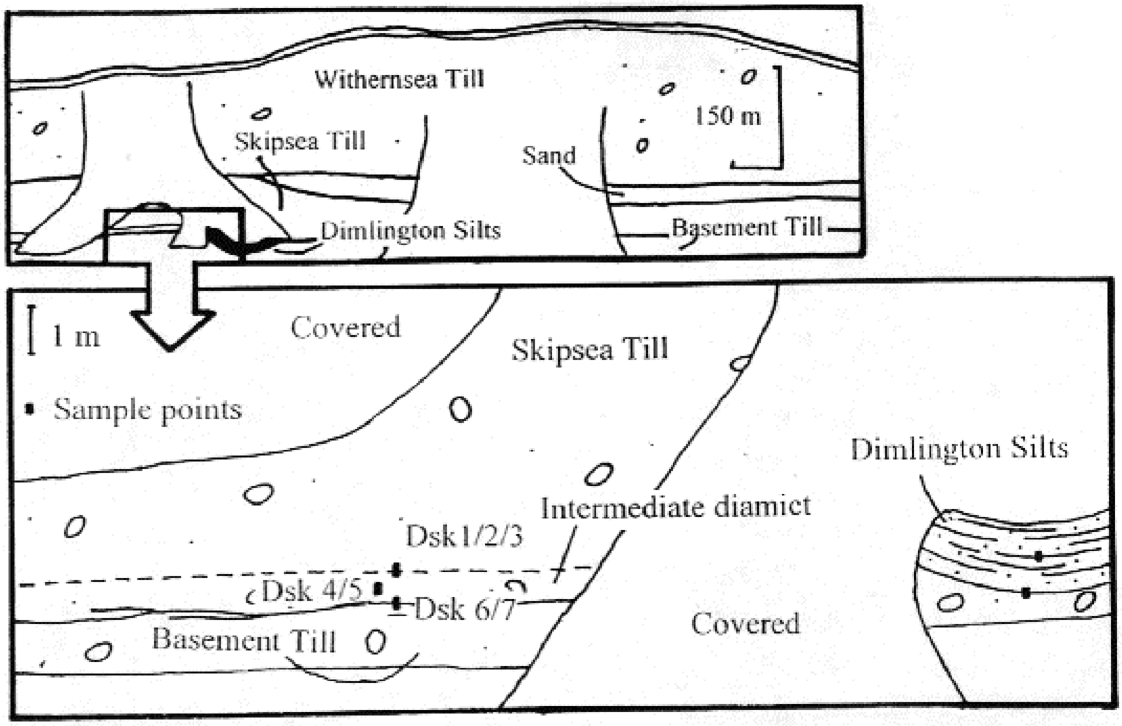

Figure 8.11 Sediment sequence at Dimlington High Ground, East Yorkshire coast. Inset shows the position of the sample site at the scale of Catt and Penny's (1966) survey of the area (though note that the area's structure has changed because of coastal retreat).

The silts have been seen picked up into the lower Skipsea Till (Eyles *et al.*, 1994), however the top of the silts presently exposed at Dimlington is obscured by landslide material, therefore it was not possible to sample this boundary. However, samples *were* taken from where the Basement Till and higher diamict are in direct contact (*Figure 8.11* and *Figure 8.12*). At these places the Basement Till has a sharp contact with the higher diamict. In areas the boundary is formed of thin (mm) resistant layers, continuous on the order of metres, with slightly undulating lengths (m wavelengths, mm amplitudes), and *en échelon* areas of greater resistance within them. Such forms are often described as 'shear zones' by researchers. There has been no micromorphological work to confirm that such features are formed by shear.

Above these so-called 'shear zones' at Dimlington, there is a 1m thick layer of diamict intermediate in colour to the two main tills, but also similar in colour to the Dimlington Silts; the stratigraphic position of which it occupies (*Figure 8.12*). This material has a sharp boundary with the overlying 'true' Skipsea Till, and the boundary does not appear to have a 'shear' morphology. This material is regarded as a sub-unit of the Skipsea Till and will be referred to as the 'intermediate diamict' in the discussion below, thereby distinguishing it from the main body of the Skipsea Till. The Skipsea Till is broken up by Eyles *et al.* (1994) into numerous such sub-units, which they suggest are deformed blocks of older material. They either imply that grouped together, such sub-units represent a recession-transgression cycle of ice movement, or that each unit is itself representative of such a cycle. Which they are suggesting is not clear from their discussion as it implies all sands with undeformed bedding may be proglacial, and that such sands form sub-units within the Skipsea Till, while suggesting the Skipsea Till as a whole is the product of a single cycle. Samples were taken from the boundaries between the Basement Till, the intermediate sub-unit and the main body of the Skipsea Till, as well as from the body of the sub-unit and the main body of the Skipsea Till.

Figure 8.12 Photograph of the sediments sampled at the boundary between the Skipsea Till and the Basement Till at Dimlington High Ground, East Yorkshire coast. Open ended sample boxes are in the approximate sample positions.

8.4.2 Results

The descriptions of the slides are given in Table 8.4 in terms of the general fabric of the diamict and the external and internal fabrics associated with any inclusions such as clay bands or diamict pebbles. The nomenclature used is that of Table 8.2. Shears and more pervasive fabrics are given in terms of their dip angle downwards in a cardinal direction (N,S,E,W). Samples were cut in north-south and east-west planes. Other terms are defined in Chapter Two and the Glossary. A summary of the chief results is given after the table.

Position	**Samples**	**Fabric**	**Inclusions**
Skipsea Till just above boundary with intermediate diamict	Dsk1	Some grain skelsepic behaviour. Largely a faint ($CaCO_3$ stained?) omnisepic fabric (140° W but variable).	
Intermediate diamict - Skipsea Till boundary	Dsk2 / 3	Broadly omnisepic fabric (2; 117° E, 3; 96° N but variable outside intense patches in latter) over... An area (5mm thick) of clay bands (0.5mm max. thickness) over... A coarser material with a fabric of RA SDF areas, these areas possibly have a modal direction in Dsk2 (*Figure 8.13*).	Band of clays with a faint horizontal fabric (also in patches of diamict between bands) disturbed in areas by a finite strain of < 5%. Sharpness of boundary is independent of strain local to it.
Intermediate diamict between Basement Till and Skipsea Till	Dsk4 and 5	(5) Some skelsepic (F) on the order of 2-3 grains around some clasts. One wide clay rind found around a large clast. Strong omnisepic fabric (85° S). (4) Fabric in two directions (130° W / 160° E - latter more widespread) Both slides have intense SDF areas in the prominent fabric direction.	
Boundary between basement Till and intermediate diamict.	Dsk6 and 7	Diamict with an omnisepic fabric (6;106° S) over... Diamict with fabric of SDF areas (~5mm) over... A 16mm layer of sand / matrix with a skelsepic fabric. The upper boundary of this is sharp in one sample and diffuse in the other. The sandy material is almost clast supported. The lower boundary of this sandy horizon is sharp. This is over... Basement Till with SDF areas in two directions and cracking (6; 180° NS / 92° S, 7; 106° W / 140° E).	The sand/matrix layer contains lenses of clean sand in the E-W plain (horizontal 6.4 x 1mm and 3 x 0.31mm). The Basement Till has shears in both the directions of the fabric patches. These end at the sharp but irregular boundary with the sands where they hit grains. A mature, discrete, shear (‘A’) is found just below the boundary where development of such a feature could first have formed without interference from the irregular boundary.
Dimlington silts	Ds1 and 2	Couplets of sands/matrix and silts/clays. Strong horizontal fabric. Two shear sets (1; 133°S and 164°N, 2; 150°W and 120°E). Lattisepic fabric around sand grains.	Some sand layers contain diamict pebbles.
Boundary between silts and Basement Till	Ds8, 9 and 10	Sand/matrix (~0.5mm) and clay/silt (~0.15mm) couplets over a thick clay layer. All have strong horizontal fabric and one shear set (9; 130°W, 10; 167°W, 8; none). These are over... A 10mm layer of mixed diamict pebbles, diamict and sand with sand layers over... Diamict.	The upper Basement Till is exclusively diamict pebbles, but these merge with depth to form a matrix with pebbles in it. These finally disappear at the base.

Table 8.4 Summary of the micromorphology of samples taken from the sediments at Dimlington High Ground, East Yorkshire coast. The table is arranged such that the samples are in their stratigraphic position. The samples from the base of the sequence are lowest in the table

The Skipsea Till (sample Dsk1) shows an off-horizontal omnisepic and skelsepic fabric. Its boundary with the underlying Intermediate diamict (Dsk2/3) is marked by a series of slightly buckled clay and diamict bands with a faint horizontal fabric. Under these bands the diamict becomes coarser, with a fabric in numerous directions, possibly with two modal off-horizontal angles (*Figure 8.13*). Further away from this boundary (Dsk4/5) the fabric of the Intermediate diamict gains a strong horizontal alignment in the north-south plane, and this fabric is seen to be comprised of two high angle fabric directions when sectioned east-west.

The boundary between the Intermediate diamict and the underlying Basement Till (Dsk6/7) is marked by a sand rich layer which is almost sand grain supported. The sand layer has diffuse and sharp boundaries with the Intermediate diamict (which has a more random fabric at the boundary) and a sharp boundary with the lower Basement Till. The layer contains lenses of clean sand with no matrix. Below this layer the Basement Till includes a mature, discrete shear (denoted as shear 'A' below) which is continuous across the sample, and which has developed in the highest area that such a shear could form without interference from sand grains. The Basement Till also shows less well developed shears in at least two directions in both thin section planes. There are also broader fabric patches in both shear directions in each thin section plane.

Thin sections from the Dimlington Silts (Ds1 and 2), show them to be composed of rhythmic couplets of clay with silts and sand with silts, each with a strong horizontal fabric. The clay-silt layers have shears in two high angle directions, which become more pervasively lattisepic in the sandy layers. The boundary between the Dimlington Silts and the underlying Basement Till (Ds8, 9 and 10) is marked by a 10 mm layer of mixed diamict pebbles and sand rich layers, which coalesce into diamict with depth.

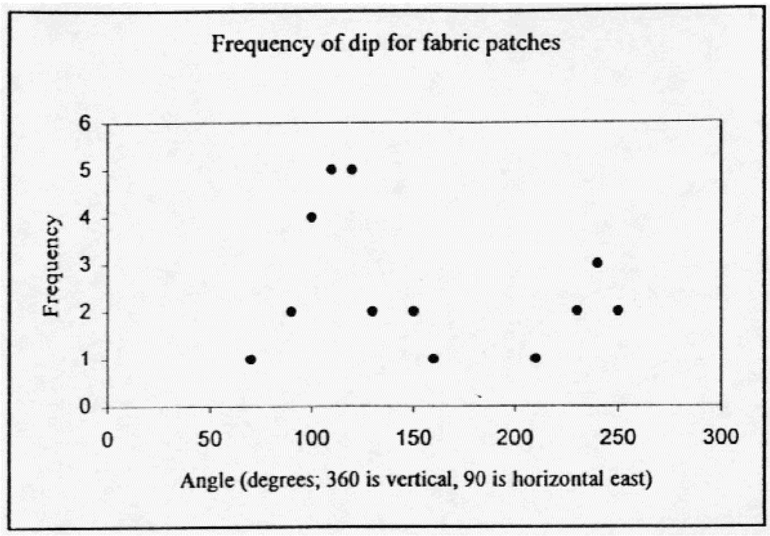

Figure 8.13 Frequency of dip angles found in Dsk2. This slide contained the only SDF orientation for which there was uncertainty as to whether the fabric was aligned or random on the basis of a visual interpretation of frequency data. The fabrics appear to be in two directions, however, the fabrics are random in the north-south plain as seen in Dsk3. This figure is referred to within Table 8.4.

8.4.3 Interpretation

The boundary between the Basement Till and intermediate diamict

The material at the boundary between the Basement Till and the intermediate diamict (Dsk6/7) progresses up from the Basement Till, through a very sand rich diamict layer containing clean sand lenses (*Figure 8.14*), to a zone of intermediate diamict with disturbed fabric, and finally, to omnisepic intermediate diamict. The Basement Till has a complex fabric, which may be a result of overprinting in front of, and under, the ice depositing the Skipsea Till (see Filey Brigg, above). Table 8.5 outlines the shear fabric change through the whole sequence.

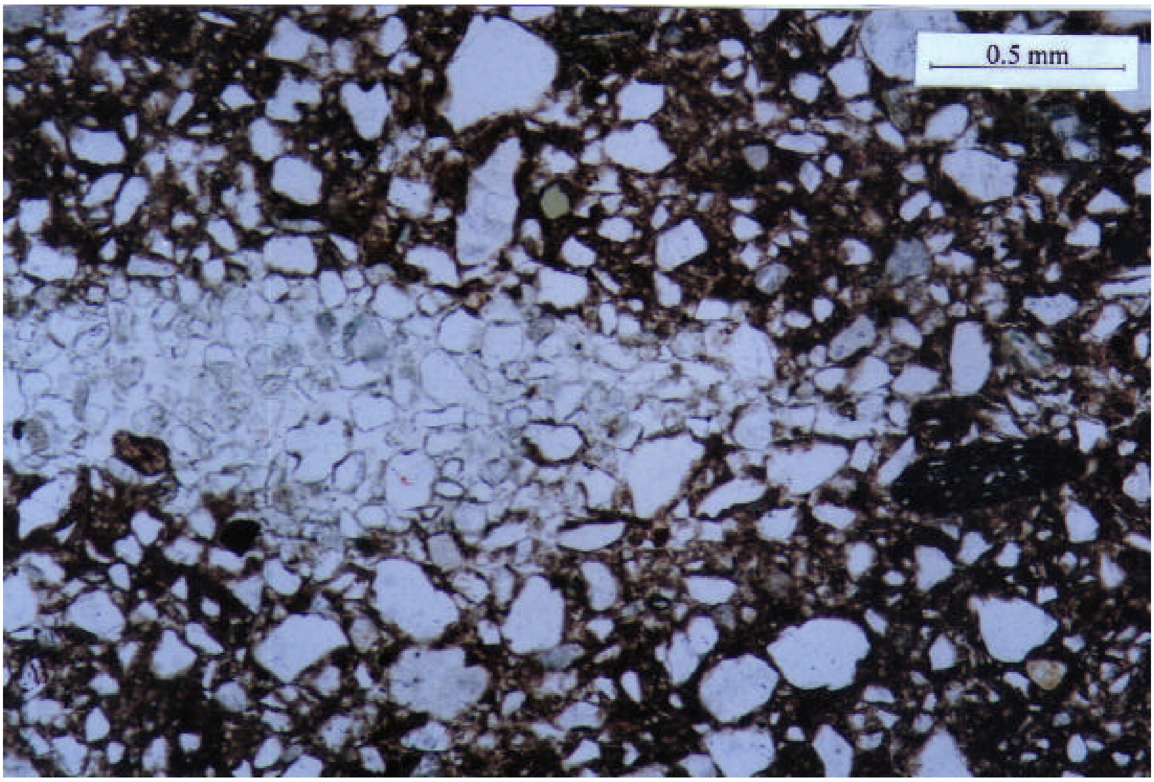

Figure 8.14 Photomicrograph of clean sand lenses in sample Dsk7. Unpolarized light conditions.

Sample	East-west plane	North-south plane
Skipsea Till above intermediate diamict	117°E	
Intermediate diamict	130°W 160°E	~ 90°
Dimlington Silts	150°W 120°E	133°S 164°N
Dimlington Silts near Basement Till	167°W 130°W	
Basement Till under intermediate diamict	106°W 140°E	~90° 180°
Basement Till under Dimlington Silts	157°W 147°E	Sample too shallow to see unpebbled fabric

Table 8.5 Shear fabrics measured in the thin sections from Dimlington High Ground (in order of height in the sequence, top down).

This gives contradictory evidence for and against overprinting, and without a greater understanding of the different rheologies it will be impossible to decide the matter. That some overprinting has occurred is indicated by the presence of a well developed single shear 'A' at the top of the Basement (*Figure 8.15*). This formed by avoiding the sand rich material where such material encroaches on the Basement Till, indicating shear *after* the sands were deposited.

The fact that the top of the Dimlington Silts rise above the height at which, elsewhere, the Skipsea and Basement Tills are in direct contact (*Figure 8.11*) indicates that the silts were removed from these direct contact areas. The order of development must have been; the removal of the silts, then the formation of the sand rich material, and then décollement along the single shear 'A'. The sand/matrix mix is unlikely to be loess or proglacial sands. Loess has been found below, and lacustrine sands above, the Dimlington Silts (Eyles *et al.*, 1994), but neither were seen on the outcrop scale at the time of sampling. It is unlikely that proglacial sands would survive the truncation of the sequence in such a thin layer, and therefore the sand rich material must be associated with the intermediate diamict.

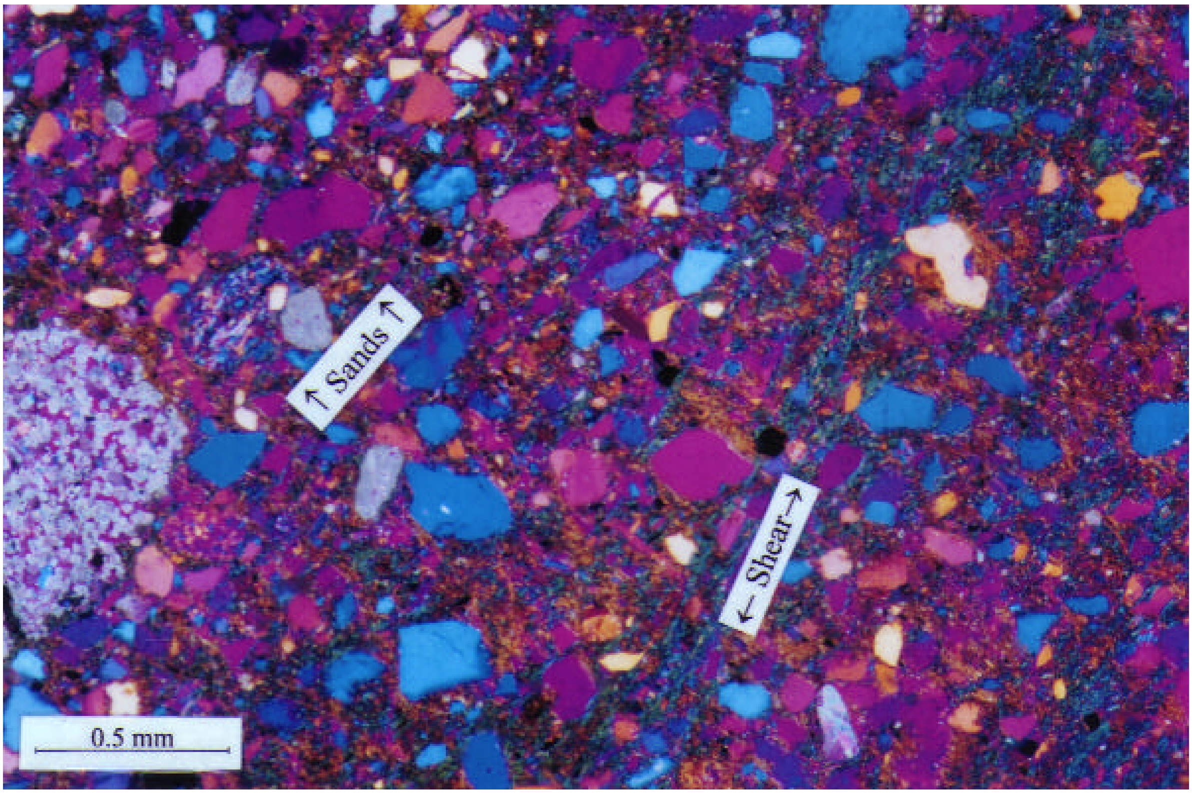

Figure 8.15 Photomicrograph of shear 'A' at the top of Basement Till. The orientation of the sheared fabric gives it a green colour. Sample Dsk6, under cross polarized light with a tint plate.

It is simplest to explain the sands as subglacially concentrated and deposited. The clean sand lenses within the sand rich diamict probably attest to fluid throughflow (for a theoretical basis see Clarke et al., 1984 and Clarke, 1987). This throughflow will have winnowed out the matrix and weakened the rest of the material allowing it to mix. It is unlikely that there was a subaerial escape route for the fluid which forced its way through this material. It is also unlikely that the sand lenses are buried subaerial channels, as this would imply they had been left clean while the deposition of sand mixed with matrix continued around and above them.

The throughflow winnowing hypothesis is tested by comparing the long axis size of the sand grains in the intermediate diamict, the sand/matrix material, and the clean sand lenses. The sand sizes are also compared with the same sediments in the alternative sampling plane to eliminate grain rotation as a factor as far as possible. The sizes were compared using the 'Student's t' test (Hoel, 1984, sample size of twenty five). It is to be expected that the sand grains in the proposed throughflow areas will be the same size or larger than those in the diamict under the throughflow hypothesis. Variations in sand source or deposition might be expected to show up as a grain size variation. The 't-scores' are presented in Table 8.6. Values for the 't-scores' of over 1.316 or under -1.316 would have shown the samples to be significantly different at 90%.

Grains sampled	**Clean sand lenses E-W plain**	**Sand rich material E-W plain**	**Intermediate diamict E-W plain**	**Sand rich material N-S plain**
Intermediate diamict N-S plain	0.048507	-0.28134	-0.79552	-0.56268
Sand rich material N-S plain	-0.36865	-0.63059	-1.13507	
Intermediate diamict E-W plain	-0.15522	-0.50447		
Sand rich material E-W plain	-0.310446			

Table 8.6 't-scores' showing that the sands in the intermediate diamict, the sand rich material, and the clean sand lenses, are from the same grain population. Only grains larger than 0.01 mm were measured. There were no clean sand lenses in the north-south plain. Note that none of the comparisons rise above the 90% significant.

None of the compared samples are significantly different at the 90% or higher confidence levels. There is no statistical difference between the material in the clean sand lenses and the other areas. This suggests that only particles smaller than the smallest measured grains (0.01mm) were removed by throughflow. The intermediate diamict is 64.5% matrix, whereas the matrix content of the sand rich material is 44.5% (100 sample point-counts; averages of both sampling planes - there was only 1% difference between each). Thus 31% of the matrix was removed by throughflow erosion. Given the thickness of the sand-rich layer this is 0.0046 m^3 for each metre squared of ice-bed interface. The size of this figure is revealed when recalculated for a glacier 400 km long and 50 km wide (as may have been the case on the east coast). The sediment lost to the proglacial environment through this mechanism is then $9.3x10^7$ m^3, though it is likely the event was much more localized than this in reality.

The clay layers above the intermediate diamict at its boundary with the main body of the Skipsea Till (Dsk2/3) would, at some time, have been an aquitard between the ice, which was presumable supplying fluid if it was warm bedded, and the intermediate diamict. The absence of sand lenses at the boundary with the main body of the Skipsea Till therefore suggests the throughflow of fluid had stopped winnowing the sediment before this aquitard was deposited.

Given that throughflow is responsible for the sand concentration at the boundary between the Basement and intermediate diamicts, the disturbed nature of the fabric immediately above the sand rich material can also be attributed to this mechanism. The simple overriding of the rough surface of the sands is not necessarily enough to disturb the fabric of this material (see the Reighton Sands samples, below). The triaxial tests (Chapter Seven) suggest that throughflow rearrangement is overprinted at even low strains, therefore the fabric may have been disturbed *after* the overlying omnisepic fabric stopped forming. However, given that the unorientated material has transferred stress across itself without aligning at some point, it is possible the omnisepic fabric formed after the sands were concentrated, the unorientated material not orientating because it was strengthened by drainage into the clean sand lenses.

A drainage event between the sand's concentration and formation of shear 'A' is also indicated by two other lines of evidence:

1) The proposed translocation concentrating the sands implies that the material forming the sands was saturated, and therefore probably had little strength. It is more likely to have been able to transfer stress to the underlying material after a drainage event.

2) The discrete nature of the shear 'A', which suggests a high effective pressure (see Chapter Three).

Three possible scenarios account for any drainage event:

1) The throughflow channels proposed above, maintained open by the clean sand grains within them, drained the sediment.

2) The till layer built up, allowing a greater drainage area through the main diamict body (though it is impossible to know how much material there was above the sand rich layer when it formed).

3) The high melt rate or fluvial event supplying the pore fluid necessary for the proposed translocation ended.

The combination of discrete shear in the top of the Basement Till and an unorientated layer in the intermediate diamict also suggests that the intermediate diamict could not strain as effectively as the underlying finer grain sediments. Thus, these fabrics may provide more weight of evidence for the sediment responding to stress by a mix of work-hardening and localised discrete shear (work-softening) as outlined in Chapters Six and Seven.

The sequence reflects the manner in which microstructures buffer the pore fluid pressure of tills, providing a stabilising effect. The above diamict may have responded to higher fluid pressures with an increased number of channels containing cleaned sands. The sequence also indicates that the resistant and shear-like nature of the sediment on an outcrop scale is not due to the décollement shear zone (which is only a few grains thick), but the winnowed sand rich layer. Other 'shear zones' interpreted from an outcrop scale may, in fact, represent depositional permeability discontinuities exploited by fluid.

The intermediate diamict and Skipsea Till

The intermediate diamict is only present where the Basement Till and Skipsea Till are not separated by the Dimlington Silts. Given that there are no rhythmites in the intermediate diamict, and we have no idea how much the Basement Till was truncated, it is impossible to determine the origin of the material in the intermediate diamict using micromorphology, though the material is *likely* to be a mix of the three other sediments at the boundary.

The intermediate diamict has an omnisepic fabric with intense patches suggesting that shear stress could not be released through the production of narrow shear zones, probably because of the presence of clasts (Chapters Six and Seven). The development of fabrics under triaxial deformation (Chapter Seven) suggests that the sub-horizontal omnisepic fabric was formed strain under a sub-horizontal simple shear geometry. This is the only case in the samples examined in this research of the simple shear ('shear-box') geometry suggested by Boulton and Hindmarsh (1987) to be representative of subglacial deformation. This may point to greater coupling with the ice, or sediment, above with no irregularities projecting into the sampled horizon. The absence of the clay patches seen at the two other locations in this chapter may point to shear destruction or, alternatively, less water flow between the ice and sediment (that is, greater coupling between the two, which would probably result in greater strain as well).

The boundary between the intermediate diamict and the main body of the Skipsea Till is marked by a clay band. Below this is disturbed or possibly bi-directional intermediate diamict (*Figure 8.13*). Above the clay band is aligned Skipsea Till from the main Skipsea Till body. Comparison with the fabrics at the base of the intermediate diamict suggests that the disturbed nature of the diamict immediately below the clay band indicates fluidization of the diamict, possibly during deposition of the clays, though the justification for this comparison is limited, especially given the possible bi-directional fabric. The boundary between the clays and the overlying material is diffusely mixed in areas, and this is unrelated to later low strain buckling of the clays, backing up the fluidization hypothesis.

Because the clay layers here may be horizontally continuous we cannot refute the possibility that these clays are proglacial (in contrast to Filey where the sediments were seen to be interdigitated on a metre to sub-millimetre scale). It seems unlikely that such a thin layer would escape destruction from the marginal compression seen at the front of the same ice mass at Reighton Sands (below) and in the folding of the Dimlington Silts, however, the possibility exists that equally thin sand layers *have* survived at Reighton Sands (below). Nor can Eyles *et al.*'s (1994) implication that the sub-units in the Skipsea Till are blocks of older material be refuted, as the clays may have been deposited in a hydraulic fracture line between the two materials. It must, therefore, only remain a *possibility* that the clays reflect water flow at the ice-sediment interface. Because of this uncertainty over the origins of the clays, no definite statement can be made regarding the origin of the Skipsea Till material here (contrast with

Filey Brigg diamicts, and also note that there are no macroscale structures in the Skipsea Till at this site to aid in an interpretation).

Dimlington silts

The Dimlington silts are formed from layers of sand in matrix in couplets with clay/silt layers. The clay/silt layers have a strong fabric, probably due to the combination of a prior horizontal fabric and consolidation (the bedding of the material has not been lost through extensive shearing which might otherwise have caused the fabric). That such a horizontal fabric can develop may suggest some of the horizontal fabric of the intermediate diamict is due to consolidation. The sand and matrix layers in the rhythmites have responded differently to the low strain than the clay/silt layers. While the clay/silts show two discrete conjugate shear sets, the sand and matrix layers have developed a pervasively interlaced lattisepic fabric. Such a fabric was predicted to develop under these conditions in Chapter Seven. The lack of skelsepic fabric in the sand and matrix layers suggests this fabric type does not form at less than 2% strain, although grain density and effective pressure may have an effect.

The fabric at the boundary between the Dimlington Silts and the Basement Till (Ds8/9/10) is dominated by the presence of diamict pebbles of various sizes, and sand-rich layers (*Figure 8.16*). Both fall off in frequency with distance below the boundary. The fabric away from these features is similar to that at the top of the Basement Till directly under the intermediate diamict (Dsk6/7). The absence of the pebbles below the intermediate diamict suggests that the Basement Till below the intermediate diamict must have been at some depth below its original upper surface. In both the sets of slides the Basement Till displays a broadly lattisepic fabric, both also having intense patches of fabric in the two lattisepic shear directions (*Figure 8.17*). This suggests a similar history. Such a history may have influenced the formation of the pebbles.

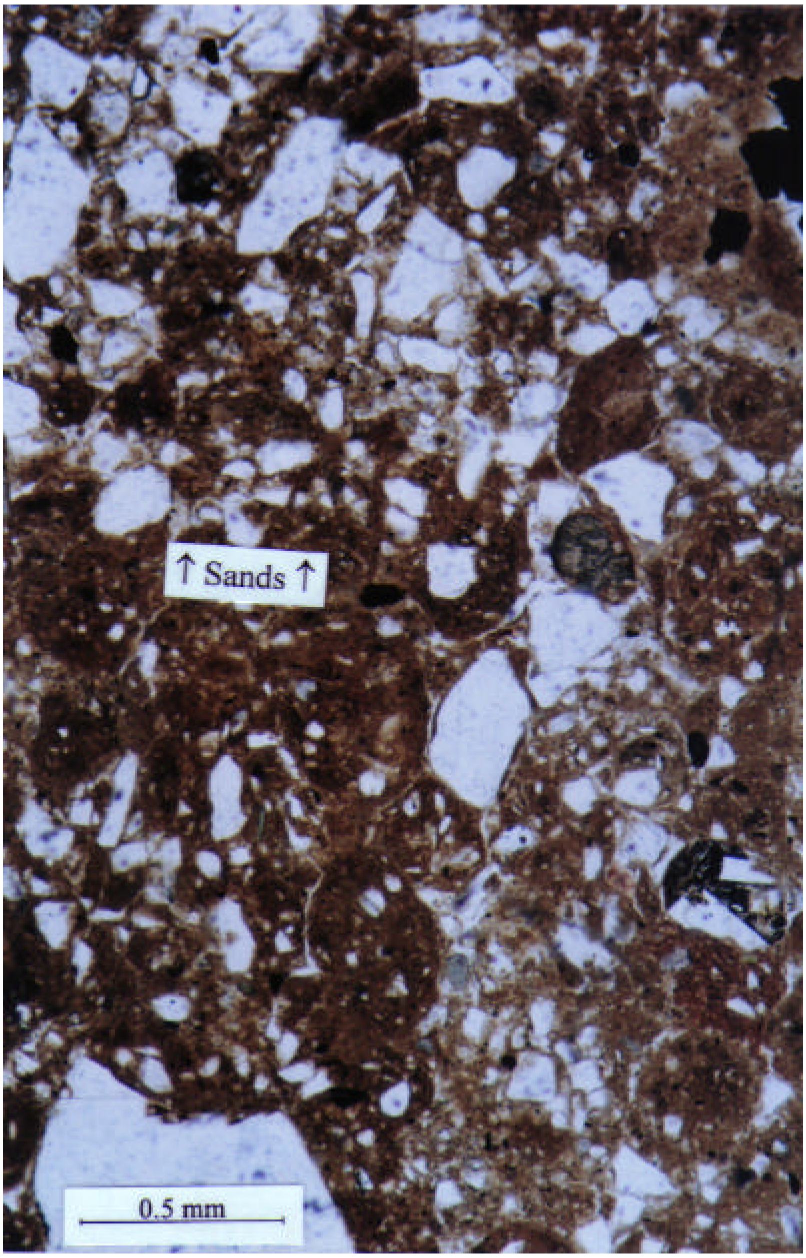

Figure 8.16 Photomicrograph of diamict pebbles in the sands and diamict at the top of the Basement Till under the Dimlington Silts. Sample Ds9, under unpolarized light conditions.

The interior material of the pebbles strongly resembles the material around and below them, suggesting that the pebbles are of Basement Till, rather than Skipsea Till washed into a proglacial environment. As was noted above, there is little evidence either way that the shears were not present before the Dimlington Silts were deposited. It is shown in Chapter Six and Seven that shear zones *may* be sites of weakness under tensile effective stresses, or low compressive stresses when associated with shear dilation. On top of this, shears are, by definition, weak areas under shear stress at some point in their history. Given these facts, the hypothesis is put forward that the shears influenced the formation of the pebbles. Two potential processes can be envisaged;

1) the shears weakened the material along their length and their lattisepic layout demarcated areas which became pebbles;

2) the shears strengthened the material in the intensely sheared patches by increasing face-face clay contacts, and these patches became the pebbles.

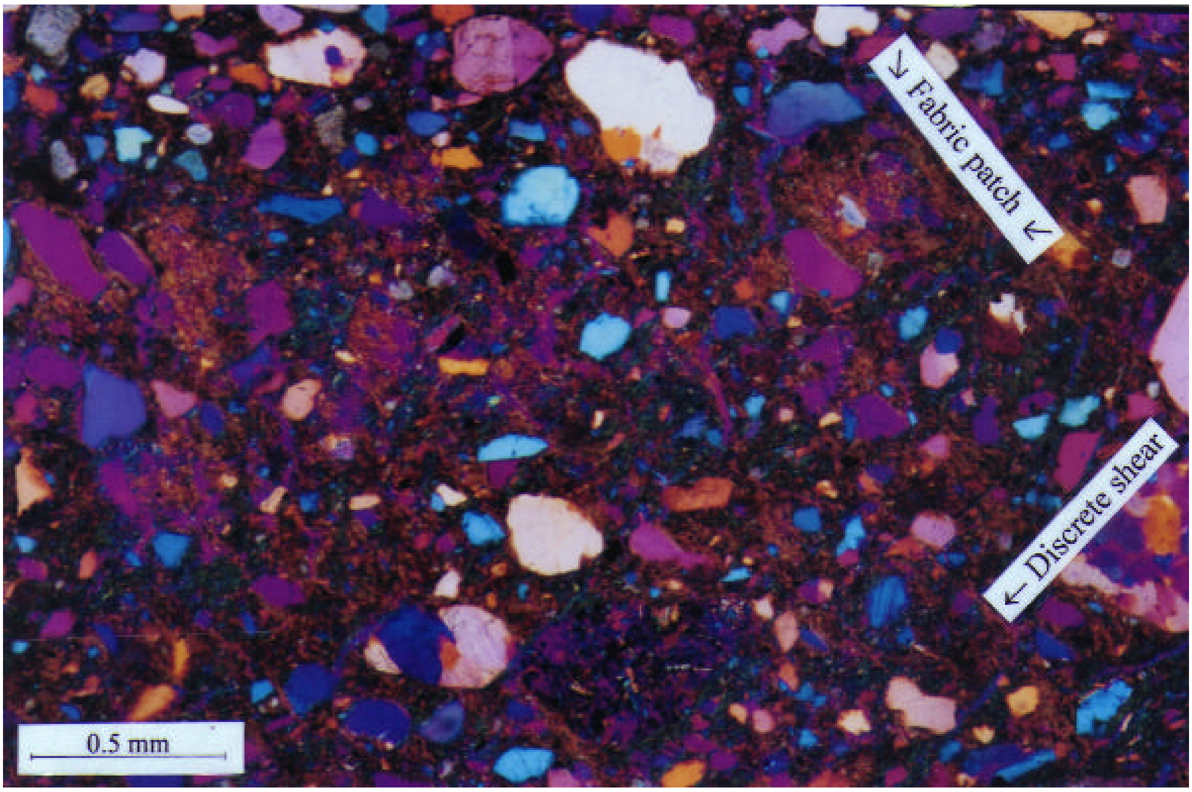

Figure 8.17 Photomicrograph of slide Dsk6, showing the Basement Till. Note the discrete shears and patches of shear aligned material. Cross polarized light conditions with a tint plate.

The former hypothesis is based on that suggested by van der Meer (1993), the latter is an alternative suggested by the micromorphology. The hypotheses were tested by statistical comparison of the micromorphology.

It was plain that the pebbles found just below the surface of the Basement diamict (in the upper low-sand layer) are probably larger than could be produced by the shear fabrics that were found lower in the sequence in either hypothesis. To test this probability, the long axes of this pebble population alone was compared with the shear data from the top of the Basement Till under the intermediate diamict using the Rank Sum test (Hoel, 1984, p.342 - sample size 30). The shear zone data is twofold; the distance between shears transverse to the shear direction, and the length of intense patches in the shear direction (always the longest axis of such patches). Linear shears with widths of less than 10 grains, were ignored in the measurement of the intense patches as being unlikely to form the ovoid pebbles through hardening (these shears are discrete from the intense patches in practice). The data from each sampling plane is compared with the other plane to eliminate as far as is possible the potential the pebbles have rotated. The results are presented in Table 8.7 as the probability that the tested pair of sizes are the same. Those not significantly different at 10% significance are in bold.

The strong difference between all the tested features in the north-south plane and the pebbles in the same plane indicate that the shear features cannot be determining the pebble size without some rotation. The distance between the shears is also not responsible for the pebble size, whatever the rotation. The only variable tested that could be responsible is their development from the shear patches probably followed by the rotation of the fabric/pebbles. It should be noted that the lack of similarity between the pebbles and patches in the north-south plain, but their similarity in the east-west plain is not contradictory as pebbles may have their form

	North - South Plane pebbles	**East - West Plane pebbles**
North-South Plane shears...		
Patch along shears at 92	0.0035	**0.119**
Patch along shears at 180	0.0052	0.0681
Between shears at 92	0.001	0.0401
Between shears at 180	0.001	0.001
East-West Plane shears...		
Patch along shears at 106	**0.3669**	**0.2709**
Patch along shears at 140	**0.102**	**0.3669**
Between shears at 106	0.0021	0.0721
Between shears at 140	0.001	0.0274

Table 8.7 Probabilities that shear fabrics could be controlling the size of the diamict pebbles at the top of the Basement Till. Those probabilities that are in bold are those for which the hypothesis is possible given a 10% significance as a cut of point for the hypothesis being unmaintainable.

determined by the fabrics in one direction and rotate into two preferred orientations. Given the results presented in Table 8.7 we can dismiss the suggestion that shears weaken the sediment and are exploited to produce pebbles. The opposite, however, may still be hypothesised; that shear alignment strengthens the sediment along the shears and the removal of the surrounding areas leaves the sheared patches as pebbles.

The statistical evidence *in favour* of sediment strengthening is weak (note significances), and this should be held as a possibility rather than a probability on the strength of the above data. Alternative controls may be found. The potential for pre-determining a sampling strategy to continue such a validation is limited by our lack of understanding of the depositional constraints on pebbles.

It will be noted that no environmental origin has been given for the pebbles yet. As the pebbles have formed at the top of lake-covered diamict, the pebblization process may have occurred within the diamict or under fluvial shear. Whichever origin is true, these pebbles point to low effective pressure conditions, for this would seem necessary for the survival of the pebbles under rotation/shear. This location provides the *only* environmental evidence associated with diamict pebbles. There may, of course, be more than one process forming them. If pebbles reflect high fluid pressures, they may be important in maintaining the buoyancy of clasts in the low strength diamict (contrast with Clark, 1991 on the origin of clast pavements by fluidization of tills). The diamict pebbles will act as clasts do in a clast-supported diamict at a larger scale, building up a supportive skeleton within the diamict.

Summary: The deposits at Dimlington High Ground were sampled to investigate the readvance mechanisms of the Skipsea Till depositing ice, and the nature of low strain deformation. It has been suggested that the truncation of the pre-glacial Dimlington Silts was followed by the deposition of the intermediate diamict. This was then disrupted by fluid throughflow, which created a set of clean sand microchannels. It is unlikely that there was a subaerial escape route for the fluid which forced through the resulting high-friction, sediment clogged sandy diamict. It is also unlikely that the pure sand lenses are buried subaerial channels, as this would imply they had been left clean while the deposition of sand mixed with matrix continued around and above them. Thus, the micromorphology of the material changed to buffer high pore fluid throughflow. At some point after this, the material drained and stress was transferred to the top of the Basement Till, which underwent discrete shear. Also at some point after this, a clay band was deposited at the top of the intermediate diamict. The intermediate diamict deposited between the depositional times of the two boundaries suffered horizontal simple shear of the type suggested by Boulton and Hindmarsh (1987). Examination of the Dimlington Silts backs up the proposal in Chapter Seven that lattisepic fabrics form in areas of conflicting conjugate shear fabrics. The lack of skelsepic fabric in the sand and matrix layers suggests this fabric does not form at less than 2% strain, though clast density and effective pressure may effect this. Comparison between diamict pebbles at the top of the Basement Till and shear fabrics from deeper in the sequence refutes the hypothesis that the pebbles formed when shear-caused weaknesses were exploited. However, the same analysis cannot refute an alternative hypothesis; that shear alignment strengthened the material in patches and these stronger patches were released to become diamict pebbles.

8.5 Reighton Sands

8.5.1 Introduction

Material was sampled from the top of the coastal cliff (TA 147757) just North of the morainic Speeton Hills (*Figure 8.1b*). The sequence has been studied by Lamplugh (1881), Melmore (1935), and Catt and Penny (1966). Coastal retreat will have significantly changed the structural appearance of the location since these studies. The structure and sedimentology of the sample site is given in Figure 8.18 (see also *Figure 8.19*). The local structure is ever changing and complex, but broadly one of low strain folding and the possible rafting of pre-glacial sediment units. The visible sequence at the sample site starts at ~25 m O.D. and is of a shell and sand lithofacies (the 'Speeton Shell Bed') (lithofacies E) overlain by faintly laminated sands (lithofacies D), above which is a grey diamict unit (lithofacies A) (variously ascribed on the basis of colour and geology to the Withernsea, Skipsea and Basement Tills; Melmore, 1935). The boundary between the diamict and sands is diffuse to sharp with patches of recumbently folded chalk gravel (lithofacies C). The diamict also overlies a brown diamict which takes the place of the chalk gravel (lithofacies B) and has a sharp boundary with the surrounding lithofacies.

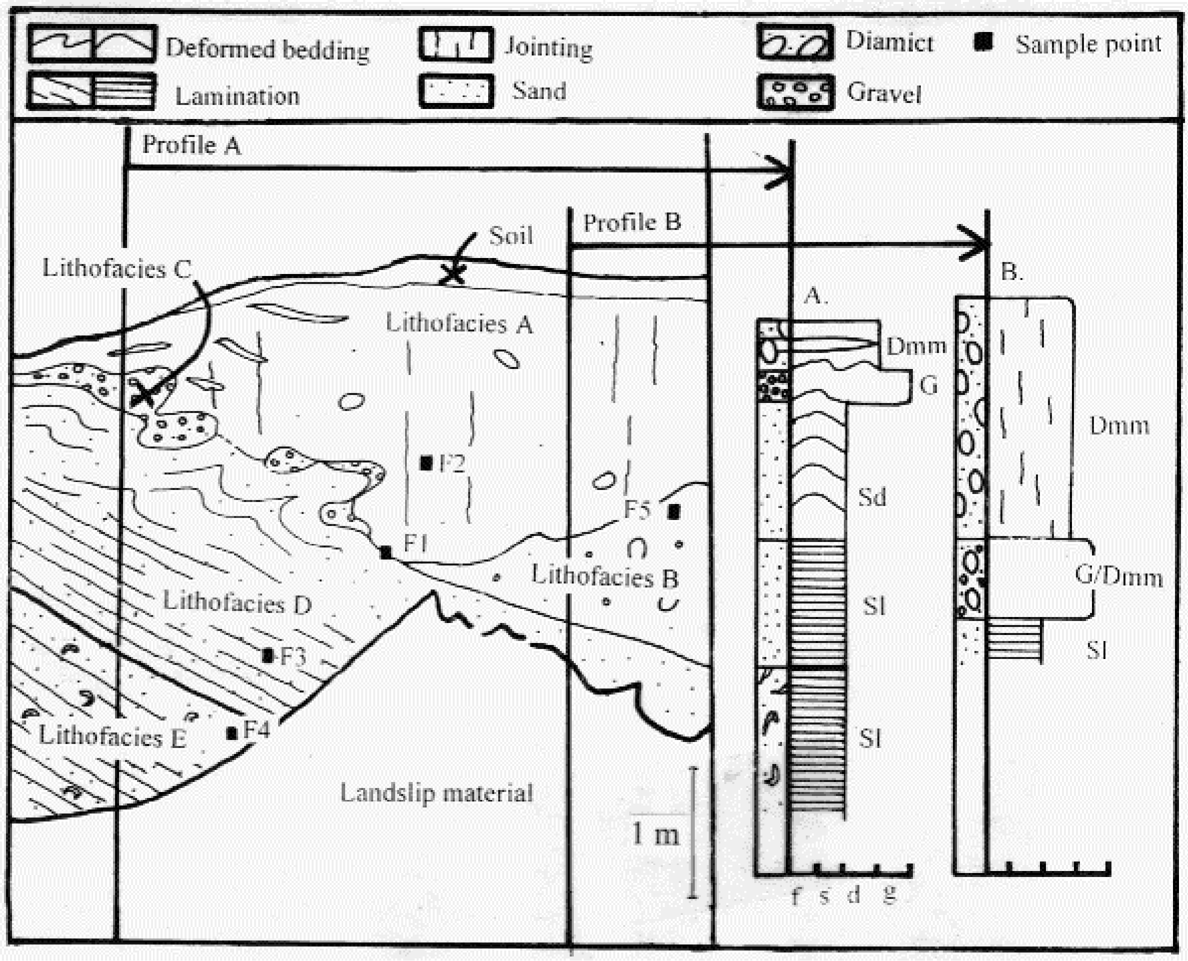

Figure 8.18 Sediment sequence at Reighton Sands, East Yorkshire coast. The visible sequence starts at ~25 m O.D. Lithofacies A) Grey diamict. B) Brown diamict. C) Chalk gravel. D) Faintly laminated sands. E) Massive shells and sands.

Figure 8.19 Photograph of the sample site at Reighton Sands.

Samples were taken to elucidate the nature of the diamict formation and low strain deformation fabrics. Samples were taken from lithofacies E and D, the boundary with the blue-grey diamict (lithofacies A) where sharp and uninterrupted, the body of lithofacies A, and lithofacies B (*Figure 8.18*).

8.5.2 Results

The descriptions of the slides are given in Table 8.8 in terms of the general fabric of the diamict and the external and internal fabrics associated with any inclusions such as clay bands or diamict pebbles. The nomenclature used is that of Table 8.2. Shears and more pervasive fabrics are given in terms of their dip angle downwards in a cardinal direction (N,S,E,W). Samples were cut in north-south and east-west planes. Other terms are defined in Chapter Two and the Glossary. A summary of the chief results follows the table.

Position	Sample	Fabric	Inclusions
3.5m above sands; lithofacies B	F5a	Diamict (~33% of sample) with patchy Omnisepic fabric at 90°. Many shears but three dominant sets (90°, 140°N, 135°S) which cross into the surrounding material.	Clay bands (~22%) in couplets with distinct and diffuse bodies of silt and long iron minerals (~45%). Fabric of these bodies parallels their outer form as they have contorted in low strain shear (<10%). Concentrated glauconitic sand bodies.
3.5m above sands (A)	F2	Identical to F1, though less shears.	
Diamict above sands; lithofacies A	F1b and a (part of slide furthest from sands)	Very strong grain and fabric alignment. In sample (b) this is in three areas. Two areas (20% and 30% of slide) orientated in approximately the same direction (41° N and 33° N - but very confused in the latter), separated by a third at 48° S (but variable). Shears in the first two areas are at 48° S and include 'mature' (infinite strain) shears. (a) Broad fabrics at 305° NNW and 240° NWW. (a/b) High porosity of two types; 1) small patches (on the order of ~0.5mm) of porous fabric; 2) linear areas (>3mm x <0.5mm).	Many clay rich blocks (~4 mm^{-2}), often, but not exclusively, iron stained on the outside. These are of two sorts… 1) omnisepic bands of various orientations (~0.5 to 0.1 thick, up to 3mm long); 2) smaller rounded pebbles with interior fabric paralleling exterior surface. The borders with the matrix are sharp for both sorts, though inclusions of the matrix occur. Shears in the blocks splay at the borders, but only enter the matrix for a few grains length.
Boundary between sands and till; lithofacies A and D	F1a (part of slide nearest sands)	Diamict over sands. Fabric matches the sand boundary close by, but becomes omnisepic further away (~0.5mm) to 240° NWW. The sands are heavily iron stained and not orientated.	
Boundary between sands and till - below boundary; lithofacies A and D	F1c	A matrix and sand mix with a poor horizontal orientation over... A layer of large quartz and chalk grains (~1mm thick), then fine grains over... Large grains again and then low matrix small sands (~4.5mm thick) with an irregular boundary over... Matrix rich sand with a mild (but stronger than above) horizontal fabric and grain orientation.	The material contains glauconite, heavy minerals, and iron-rich laminated clays. Also, the upper most material includes iron stained blocks of mixed sand and matrix.
Sands; lithofacies D	F3a/b	Very angular to rounded sands, very well sorted (~ 0.1mm diameter), homogeneous, in a clay matrix. Sub-horizontal sand fabric.	One lense (0.75 x 3+mm) of disrupted chalk.
Shells and sands; lithofacies E	F4a/b	Glauconitic sand. Wide size range but < 0.5mm diameter, except for long (~1mm+, length:width ratio ~7) grains rich in heavy minerals. Some unfabriced clay matrix with sands in (~1cm thick) lenses showing low strain.	

Table 8.8 Summary of the micromorphology of samples taken from the sediments at Reighton Sands, East Yorkshire coast. The table is arranged such that the samples are in their stratigraphic position. The samples from the base of the sequence are lowest in the table

The boundary between the sands of lithofacies D and the diamicton lithofacies A (sample F1c) is marked by alternating layers of sand rich silt matrix and large sand grains, including chalk layers (in the same stratigraphic position as the chalk rubble lithofacies C). The large grained layers are partially iron cemented. The diamict directly above these layers has a fabric that parallels the perimeter of the nearest sand grains (F1a). This fabric becomes largely omnisepic within 0.5 mm of the boundary, however, this omnisepic fabric is disrupted by broad areas orthogonal to it. These broad areas match the direction of more discrete shears within the omnisepic fabric. This material is also highly porous in patches and linear areas (both on the order of 0.5 mm wide). The material also contains clay bands with omnisepic internal fabrics in a variety of directions, and clay pebbles with an internal fabric paralleling their exterior form. The clays areas have been iron stained (unlike the surrounding diamict), and sheared synchronously with the surrounding material. Sample F2 suggests lithofacies A is less sheared away from the boundary with lithofacies D, but is otherwise unchanged with height.

Lithofacies B (F5a) is a melange of interlayered clay-silt units, glauconitic sands, and diamict. The internal fabrics of the silt-clay units parallel their exterior form, and they have undergone low (<10%) strain. The glauconitic sands match those of lithofacies E (F4a/b). The diamict has a weak omnisepic fabric which has been disrupted by shear that was synchronously with the deformation of the other materials in the melange.

8.5.3 Interpretation

The boundary between the sands and lithofacies A is sharp (Sample F1a). The uneven upper surface of the matrix rich sands is directly overlain with diamict. The fabric of the diamict initially mirrors the surface of the sands, but gains a distinct single alignment away from the boundary (*Figure 8.20*). Just below this boundary (F1c) the matrix rich sand alternates in layers that are cleaner and have larger grains. The stress conditions at the boundary of the diamict must at some point have been suitable enough to force the diamict fabric parallel to the sands, but not to set up a shear zone at the boundary or move the sands. This may indicate that the sediment was saturated and weak, or the boundary fabric is due to consolidation rather than the shear seen higher in slide F1a. A highly fluid situation is also implied by the higher lithofacies A material (samples F1a/b and F2). Sample F1b has a wide shear zone with indicators of fluid throughflow in the form of porous zones (see Chapter Three for details of how shear geometries reflect the effective pressure).

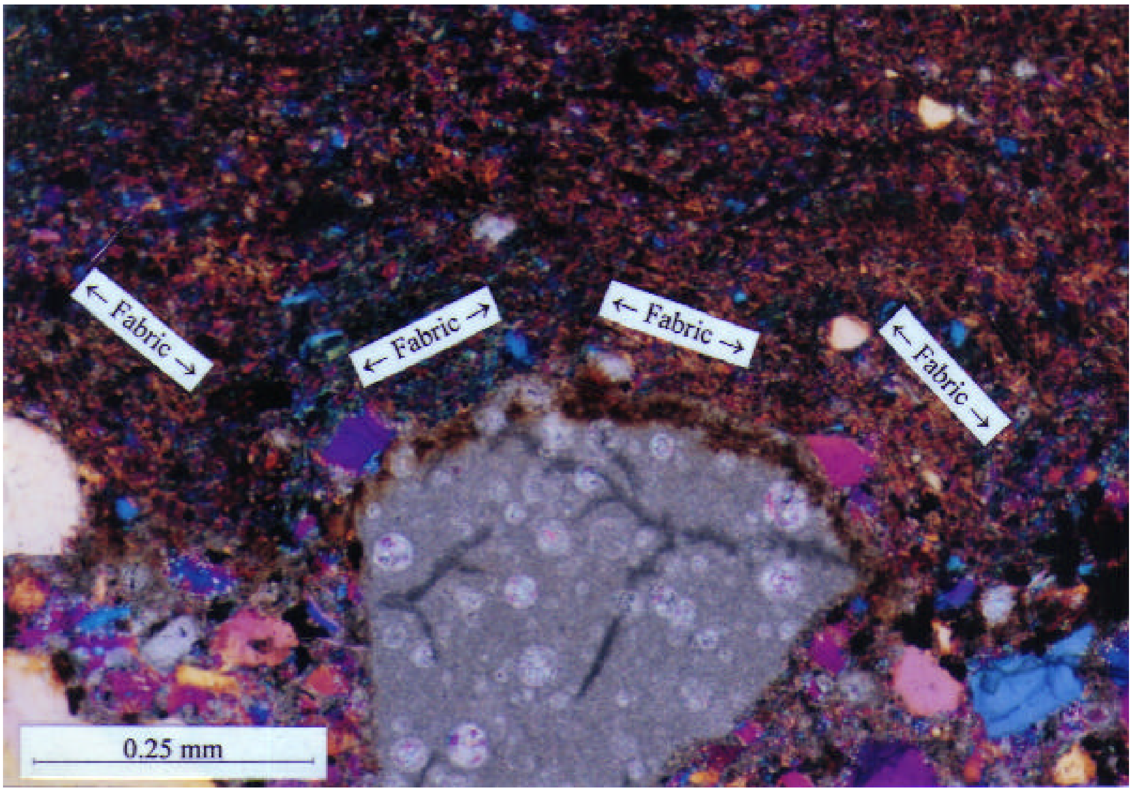

Figure 8.20 Photomicrograph of fabric following the sands at base of lithofacies A, the long axes of the long dark grains follow the general fabric direction. Sample F1a, under cross polarized light with a tint plate.

The clay patches in lithofacies A (samples F1a/b and F2) may be meltout products or throughflow translocation deposits (both matching the high fluid content of the diamict). The origin of the diamicts, therefore, cannot be determined (contrast with Filey Bay, where there were no other throughflow microstructures). However, the clays' strong orientation and the fact that some of the pebbles show fabrics paralleling their outer surfaces points to material that has been sheared and possibly consolidated, subglacially or proglacially.

Proglacial deformation of the sequence could have been responsible for the consolidation and throughflow. However, the various orientations in the clays in F1 a/b and F2 suggests that they had a fabric prior to their breaking up and being mixed into the diamict, thus the following sequence is necessary (*Figure 8.21*);

1) the clays are suspended in throughflow fluid within the diamict (fluid moving faster than the skeleton and eroding fines from it; see Clarke, 1987, for background theory),
2) the clays are deposited again in the diamict (fluid moving slower than the skeleton),
3) the clays are consolidated/sheared to give them a fabric (fluid moving faster than the skeleton but not fast enough to winnow),
4) the clays are broken up in a matrix that is being winnowed (fluid moving faster than the skeleton and eroding).

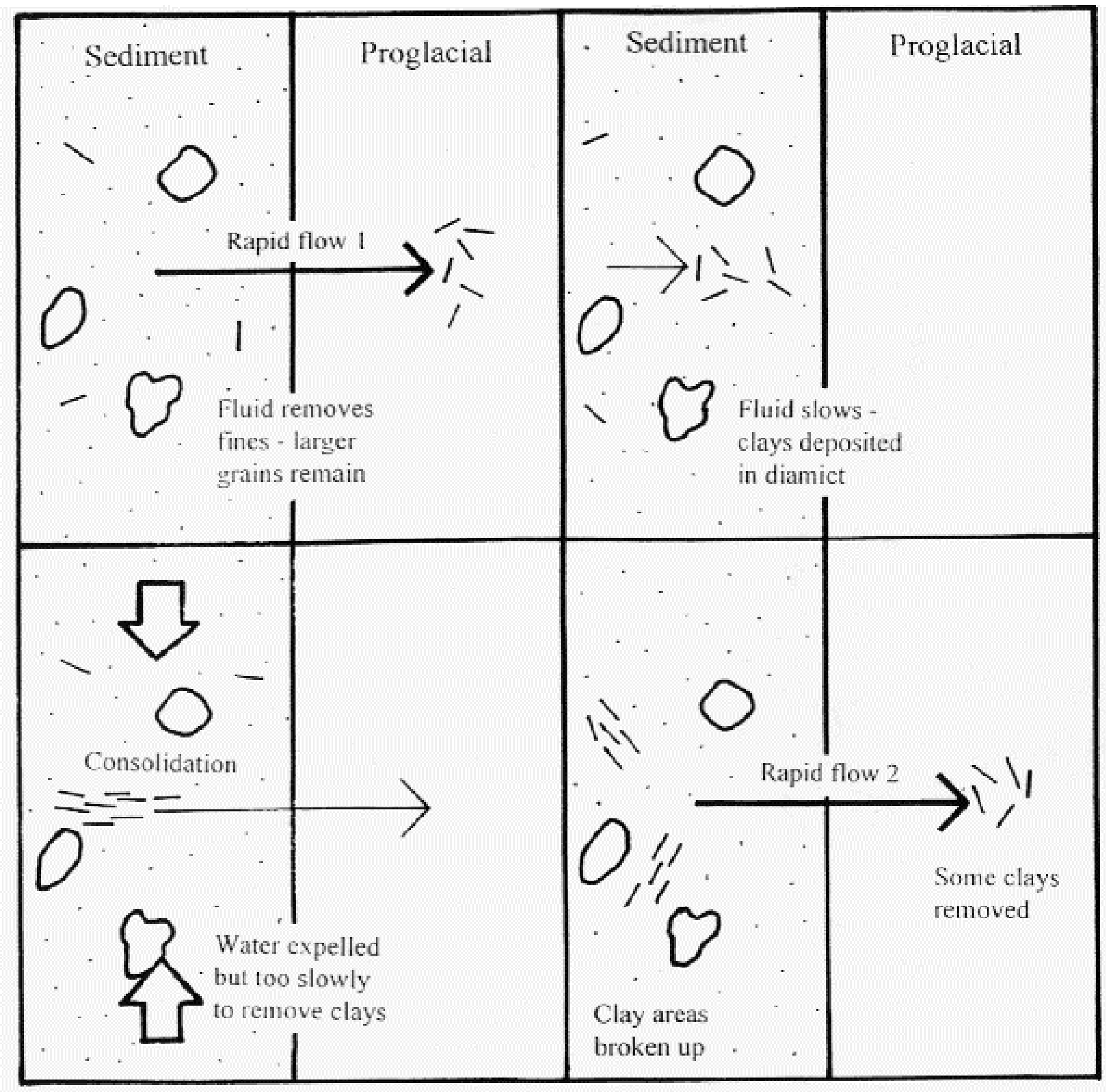

Figure 8.21 Potential fluid-flow / deformation history for lithofacies A.

This sequence implies a two part throughflow sequence. A two advance formation for the material, with the fabric development and throughflow being forced proglacially is more complex than a single advance with intermittent throughflow and deformation subglacially. However, the former interpretation matches Eyles *et al.*'s (1994) multiple-surge hypothesis for the formation of the material.

The low strain in sample F5a allows us to see that on the microscale lithofacies B is a melange being produced by the incorporation of heterogeneous materials (*Figure 8.22*). The silts and clays may be in couplets, though strain makes this difficult to confirm. If they are in couplets, these rhythmites may be from a proglacial lake or deposition in intermittently active subglacial ponds, both of which may have contributed to the sediments saturation.

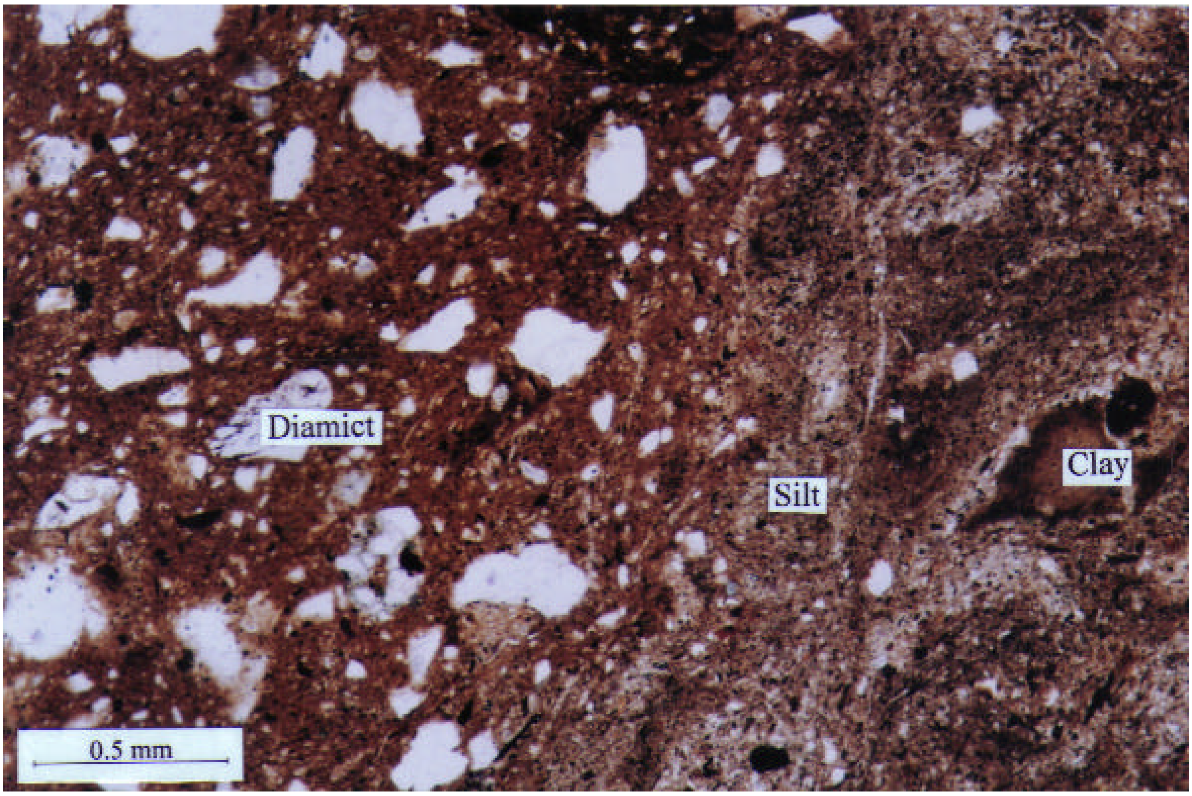

Figure 8.22 Photomicrograph of the melange of diamict, silts and clays that makes up lithofacies B which appears to be a diamict on an outcrop scale. Sample F5a, under unpolarized light conditions.

The highly fluid nature of lithofacies A indicated by its microstructures can be compared with the diamicts overriding the lake-deposited rhythmites at Dimlington, which appear to have been, relatively, drier. On the basis of such a comparison it might be tempting to dismiss lacustrine conditions as the cause of the sediments saturation at Reighton and invoke a high marginal melt rate. This would match the potential meltout origin of the diamicts and the possible throughflow described above. However, the sands overridden at Reighton may have stored a far greater amount of fluid than the Dimlington Silts, and this could have been expelled into surrounding sediments during deformation.

Summary: The micromorphology of the Reighton Sands sediments suggests two alternative sets of conditions, which, unfortunately, match exactly with the two models proposed for the whole region. The rhythmitic sediments, sheared diamicts and clay rich patches seen in the sequence may either suggest a series of multiple advances of ice up to, or over, the area through a proglacial water body, or a single advance with a high basal melt rate and water ponding at the ice-sediment interface. Unfortunately the present macroscale morphology is consistent with either explanation. Equally, past research in the area has concentrated (with only controversial results) on whether the Speeton Shell Bed has been thrust into its present position, and on regional diamict correlations (Lamplugh, 1881; Melmore, 1935; Catt and Penny, 1966). These studies offer no evidence that can be used to elucidate the specifics of the glacial history of the diamicts. Both models may therefore be regarded as likely in this marginal ice position.

8.6 Conclusions

8.6.1 Sediment strength and fabric development

The above interpretations provide additional information to that provided in Chapters Six and Seven on the manner in which subglacial materials strain and develop small scale structures.

At Dimlington High Ground an omnisepic fabric developed in the intermediate diamict, but this development was followed by the transferral of stress to the boundary with the underlying basement sequence where a discrete shear developed. This suggests the omnisepic fabric was ineffective in releasing stress and discrete shears formed where they could. This backs up the rheology suggested in Chapter Six after the discovery of work-hardening behaviour in laboratory-deformed Skipsea Till.

However, there is evidence that discrete shear décollement did *not* occur during the deposition of the main body of the Skipsea Till at Dimlington. Here the layers of the sequence expected to be weakest (unimodal clays) did not show discrete shear deformation (though note that conditions may have existed at Filey in which clays were stronger than diamicts, and the clays may have formed *after* the diamict aligned). It should also be noted that examination of the 'shear' fabric at the boundary between the intermediate diamict and Basement Till at Dimlington suggests many 'shears' identified at an outcrop scale may be areas of fluid exploitation due to permeability changes, and do not necessarily represent strain.

There is also evidence from the micromorphology of the area that lattisepic fabrics do not aid the formation of diamict pebbles by weakening the material relative to areas between the shears. However, there is still a possibility that shear strain strengthens the sediment by locally aligning cohesive clay grains, and these stronger areas form pebbles. Further evidence is given that pervasive lattisepic fabrics form where conjugate shears interact in clast rich material.

8.6.2 Glacial hydrology

The micromorphology of the samples reflect the hydrological system at the ice base. The deposits on Filey Brigg are probably formed by melting of ice with a variable sediment content into an environment of sand depositing streams. The ice was probably separated from the sediment by thin, clay depositing, fluid layers, which reworked the previously deposited diamict. The combination of an ice interface water layer and larger streams indicates that the streams did not rapidly draw fluid from the surrounding ice-sediment interface. This suggests that the streams were at atmospheric pressure or had a *positive* hydraulic pressure to discharge relationship, one of the features of Walder-Fowler canals (Walder and Fowler, 1994).

The massive sand bodies high in the sequence at Filey Brigg suggest that the streams depositing the sands finally became dominant over the deposition of the diamict. The rise in available water suggested by the sands, if not the ice interface clays, is probably due to an increase in the melt rate and/or the increased amount of impermeable material between any given horizon and the potentially permeable limestone at the base of the sequence. Following deposition of the massive sands *all* the sediments were subjected to further low strain deformation. The sediment was possibly deforming under a low effective pressure and the strain may have been dependent on the heterogeneous drainage potential of the material. This low strain overprinting may indicate that low effective pressures are associated with deep deforming layers.

At Dimlington, higher levels of fluid than could drain through the sediment did not immediately result in a water layer between the ice and bed. Here the boundary between the active diamict and the basement sequence was exploited by the translocation of fines and the formation of sand filled channels. Some 31% of the local matrix was removed in this event (0.0046 m^3 for each metre squared of ice - bed interface). That a fluid layer did not form may suggest that the interface between ice and sediment was more coupled than at Filey because of its geometry.

8.6.3 Low sediment strain: ice - sediment coupling

Ice interface fluid was inferred to exist at Filey through the deposition of clays. This water may explain why the subsequent strain, which brecciated the clays, was so low. Such a water layer would have decoupled the ice and sediment. Clays deposited at the ice and sediment interface could give a semi-quantitative estimate of the separation of the ice and bed, but only where the strain is quantifiable through the whole of the sequence. In higher strain areas the mixing in of clays could occur without greater ice-sediment coupling if the deforming layer rises slowly, for example, and if the meltout rate is lower. Under such conditions there will be increased strain in any one horizon and less preserved clay bodies despite potentially weak coupling.

The hypothesis of greater coupling across the ice-sediment interface at Dimlington than elsewhere in the area matches the development of a strong, sub-horizontal, simple shear fabric in the 'intermediate' diamict. There is equivocal evidence, but it seems likely that at some stage deposition like that at Filey (across a decoupled ice-sediment interface) took over at Dimlington. Clays are deposited higher in the sequence than the sub-horizontal fabric, and the strain may be lower (the sediment has not developed a horizontal omnisepic fabric, probably the only potential infinite strain fabric). This change could have been due to the increasing mass of impermeable sediment between the ice and the exploited boundary with the basement sequence (where the clean sand lenses drained fluid). This aquitard build up could have lead to fluid at the ice boundary, and the submergence of roughness important in transferring stress to the bed (similar to the thickening of the sequence at Filey, above).

8.6.4 Low sediment strain: meltout of the diamicts

Low strain is seen in the upper units at Filey, and possibly the Skipsea Till at Dimlington and the Skipsea Till from Skipsea examined in Chapter Seven. The extension of diamicts far inland from these points suggests a potential for high strains, whether the glacier remained over the sediments (Evans *et al.*, 1995) or repeatedly surged inland (Eyles *et al.*, 1994). The lack of such high strain therefore suggests a rapid rise in the deformation layer and/or decoupling of the ice or higher sediment. Decoupling may have been due to ice-sediment interface fluid and/or discrete shear in the sediments (as discussed above).

A rise in the deforming layer may be attributable to a high meltout rate. This hypothesis matches the proposed meltout nature of the diamicts at Filey, as well as the water logging of the sediments at Reighton Sands. The sediments used in the triaxial tests in Chapter Six have a similar microstructure to the deposits at Filey, but include sand rich patches and have been deformed in the laboratory, and therefore no definitive origin can be ascribed to them.

A high meltout rate may have been characteristic of this glacier, the majority of which lay below present day sea level, probably in the local ablation zone. The supply of ice would have to have been maintained by having several accumulation areas, a high accumulation rate, or true store-and-purge surge behaviour (as opposed to climatically induced movements). In the case of the Skipsea Till at Dimlington, and the material around the sands at Filey, melting could have been enhanced by increased drainage stiffening the sediment and enhancing regelation, although this may be incompatible with models of greater coupling between the ice and bed.

8.6.5 The nature of glaciogenic sediments in the area and the ice mass depositing them

The glacial history and deposition in the area is reflected in the microstructures and their interrelationships. In many ways, the results of this study resolve the dialectic battle between the previous interpretations for the area, and explain the contradictions in the outcrop scale evidence. Evans *et al.*'s (1995) model of a single ice mass with subglacial channels is verified by this study for the Filey field site, at least for the smaller sand lenses. The regional low strain conditions used as evidence by Eyles *et al.* (1994) are explained in this context as being due to decoupling between the ice and bed, and possibly within the bed itself. On top of this, the high melt rates may have increased this decoupling, and raised the deformation layer by adding more material, reducing the strain in any one horizon. Doubt is cast on the idea that the diamicts of the area are advected older deposits which have not been incorporated into the ice at some point. However, the overriding of proglacial lacustrine areas and shallow water bodies proposed by Eyles *et al.* is still possible at Reighton and Dimlington and surge-type behaviour may have been necessary to maintain the ice presence under a high melt rate.