7. The Development of Micromorphology in Laboratory Tests

7.1 Introduction

Material from the cliff of Skipsea Till at Skipsea (*Figure 6.5*) was tested for its strength and hydrological response under deformation (Chapter Six). The material from two of the tests (tests 2 and 5) was thin sectioned to determine the microscopic structure. This gives information on the formation of various microstructures which will be used to interpret naturally occurring examples in Chapter Eight. The microscopic structure also illuminates the test results, and a number of the interpretations outlined in Chapter Six.

7.2 Methodology

Samples were removed from the cliff at Skipsea and tested such that the analogous applied stress on the samples in their 'natural' location would have been vertical. This was due to the difficulty in sampling such that the stress could be analogous to that applied horizontally (see Chapter Six). A confining stress was applied horizontally. Details of the test conditions and results are given in Chapter Six. Thin sections were prepared in vertical planes. The two test samples were selected to give a range of strains (test 2 went to 15% strain, test 5, 25%). Unaltered samples of Skipsea Till are examined in Chapter Eight. As the upper half of the sediments deformed to a greater extent than the lower half, sections were taken from both halves to give a larger strain range (these are denoted below as, for example, 15%- and 15%+). The thin sections from the upper halves of the samples were removed such that their planes were either across or with the strike of shears visible after the tests (for examples, see *Figure 6.10*). The samples were also selected to illuminate the rheological tests, particularly the unexpected high strength of the sediments and two contrasting hydraulic events:

1) Early hydrological events during deformation in which fluid was expelled locally from the samples and the overall permeability of the samples decreased;
2) Late hydrological events where fluid was expelled and these events were followed by a dramatic rise in the sample permeability.

Test 2 only passed through the former event, Test 5 suffered the only the latter.

Thin sections were blind-tested, that is, initially described without knowledge of their original sample or strain.

7.3 Results

The descriptions of the slides are given in Table 7.1. Descriptions are in terms of the general fabric of the diamict, and the fabrics in and around any inclusions such as clay bands. Skelsepic fabrics are where fine, '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 separate bands. 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 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. Other terms are defined in Chapter Two and the Glossary of fabrics.

Shears were seen on an unaided visual scale after the tests (*Figure 6.10*). The relationships of the sample plane to these shears are noted, as is the likely presence of such a shear within the thin section. Shears and more pervasive fabrics are given in terms of their dip angle. If the thin section plane is parallel to the shear dip '120° out' indicates a fabric falling at 120° outwards from the sample centre. If the thin section crosses the sample centre or runs parallel to the shear strike '120° right' indicates a fabric falling at 120° right if looking towards the sample centre. The sample centres are denoted by a 'c' on the small diagrams given to help the reader compare orientations with shear features etc. (these are only meant to convey an impression of orientations). Photographs of the more important features are provided in the section where the results are interpreted. The variation in strain between the upper and lower halves of samples means that the local strain falls either above or below the net sample strain. This difference is not calculable with the present equipment. The strain for each sample is therefore denoted as positive or negative in relation to the net strain.

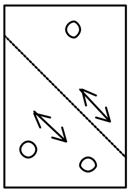
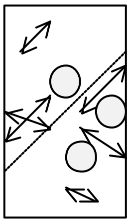
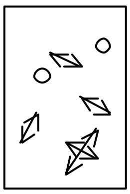
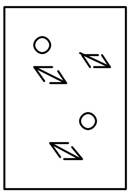
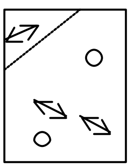
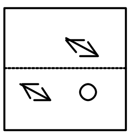
Strain / position	**Sample No. / diagram**	**General fabric**	**Inclusions**
In plane of strike. Shear within section. 15%+	T27  Key: c Omnisepic fabric Skelsepic Shear	Skelsepic fabric within other fabrics. Weak Omnisepic (135° out) fabric (100% of slide). Patches of intensity in Omnisepic fabric where skelsepicism (F+some G) increases. Most intense fabrics are on sample outer side at top. No large cracks not associated with clasts. Clasts well distributed but many clast rich patches. Clasts only locally aligned.	Clay patches (<1% total slide) with internal fabric at 135° 'out'. Clays contain heavy mineral fragments and other fine sand grains.
In plane of strike. Shear within section. 15%+	T22  c Key: Large clast Lattisepic fabric	Almost no skelsepic fabric, though (G+F) around some clasts. Three large clasts (<7x7mm in 90° triangle) control fabric directions parallel to their sides, but these fabrics are not skelsepic (ie. carry on in same direction after clasts end). Fabric greatly variable but large SDF areas in two directions (120° 'in', 72% of slide, 130° 'out', 20%). Lattisepic fabric in one area (3%) and unorganized in another (5%). Clasts poorly distributed in clast rich patches. Considerable cracking in area between large clasts at 130° 'out' even where surrounding fabric at 120° 'in'.	Clay patches (~2% total slide), at least two of which may be a brecciated clay band. Fabric the same as that surrounding them. Clays contain heavy mineral fragments.
In plane of strike. Away from shear. 25%-	T52 c 	Skelsepic (G+F) within other fabrics & areas with just this fabric (12% of slide). Large SDF areas in two directions (115° right, 69%, 160° left, 8%). Fabric weak in patches especially at 160° left. Lattisepic (6%) and unorganized (5%) areas. Clasts generally well distributed but with clast rich patches. No cracks not associated with edge of clays.	Considerable clay bands (8%) showing finite strain on the order of 50% shortening. Fabric generally at 115° right, but cut by shears at 170°, 130° and 90° left. These shears were synchronous with the main fabric development (can be seen moving out of bands into surrounding material). Clays contain heavy mineral fragments.
Across strike. Away from shear. 25%-	T54 c 	Skelsepic (G+F) within other fabrics & areas that are only this fabric (20% of slide). Omnisepic fabric (125° right, 72%). Fabric weak in patches. Unorganized areas (8%). Clasts well distributed but with occasional clast patches. Cracks exist not associated with large clasts.	Sample has large clast (13x11+mm) in section and had two large clasts closer than 7mm to the sample plain found during preparation. No silt or clay concentrations.
In plane of strike. Shear within slide. 25%+	T51 c 	Skelsepic (G+F) within other fabrics. Large SDF areas in two directions (120° right (95% of slide), 120° left where shear crosses (5%)). Small amount of local clast alignment, but not in any one direction. Clasts well distributed. Considerable cracking.	No silt or clay concentrations.
Across strike. Shear within slide. 25%+	T53 c 	Skelsepic (G+F) within other fabrics. Omnisepic fabric (113° right, 100% of slide). Small amount of local clast alignment, but not in any one direction. Clasts well distributed. Some cracking.	One large clast (10x6mm) in section. Silts are concentrated around large clasts. Otherwise no silt or clay concentrations.

Table 7.1 The micromorphology of the triaxial test samples. Strain increases towards base of table.

7.4 Interpretation

There is a progression in three fabrics as the strain increases:

1) the material becomes more evenly distributed with strain and unimodal clay patches disappear, particularly after 25% strain;
2) the skelsepism of the samples increases, especially in the 25%- samples;
3) the sample undergoes greater crack development (away from material heterogeneities which are likely to cause cracking during sample preparation).

There is also a less plain progressive development of omnisepic fabrics from the relatively weak fabric of T27 to the stronger fabrics of later tests. In discussing this it is essential to distinguish between thin sections across the plane of strike and those parallel to the dip of the shears recorded on a visual scale, as shear has been implicated in the formation of these fabrics (Chapter Two). In the former, the omnisepic fabric in the shear direction increases from 72% of the slide area for 25%- strain to 100% of the slide area for 25%+ strain. In the case of sections parallel to the shear dips, the omnisepic fabric varies from a weak 100% or stronger 20% fabric at 15%+ strain, to 69% of the slide area at 25%- strain, and only 5% at 25%+ strain. However, the figure for 25%+ hides the fact that the omnisepic fabric in the direction of shear seen at a visual scale is heavily concentrated in the area where the shear was seen at the larger scale. Thus, there is some evidence that omnisepic fabrics are a shear strain feature. There is also evidence for the intensification of omnisepic fabrics with the overall shear strain, and intensification close to areas that have been seen to have sheared on a larger scale.

It will be shown that the fabric development suggests the processes by which high stresses are supported by the sediment during deformation, and the way the sediment hydrology responds to deformation.

7.4.1 Sample history

The low strain samples (<25%) have numerous unorientated areas and clay/sand patches (*Figure 7.1*). These decrease with strain suggesting that they are the natural fabric of the sediment. During the tests omnisepic strain fabrics become stronger, both in the direction of visible scale shears where they cross the samples, and in the conjugate direction away from such shears. This development to a well mixed and orientated sediment with mild strain indicates that only low strain occurred in the samples prior to the tests. It cannot, however, be said that prior to the tests the strain in the material was less than 25% as the strain alignment direction may have differed during the sediment's deposition and/or deformation, and the brecciated clay bands in the samples confirms the samples *did* suffer strains greater than 25% before the tests were initiated.

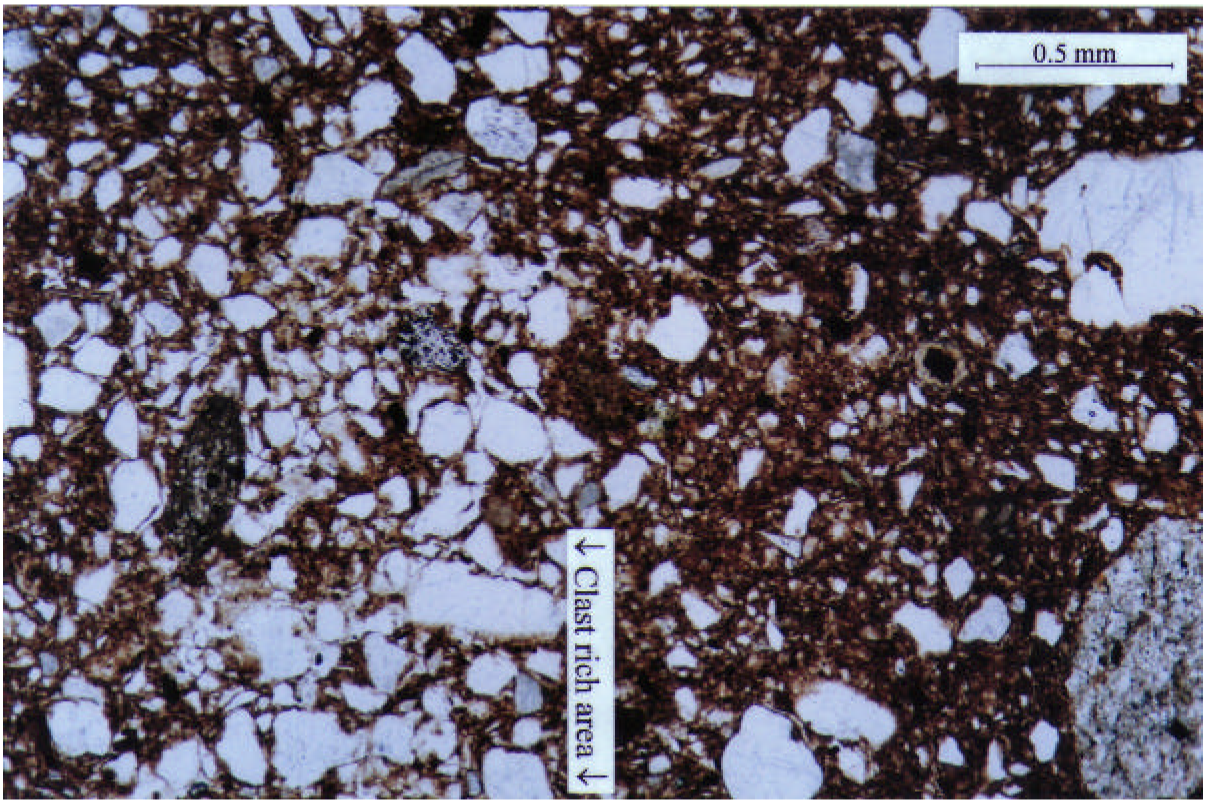


Figure 7.1 Photomicrograph of a clast rich patch from slide T22. Unpolarized light conditions.

7.4.2 Strength and fabric relationships

It will be remembered that Chapter Six posed two hypotheses relating to sediment strength;

1) yield events involve the (limited) development of shear zones, which were identified from their hydrological response and visual scale presence;
2) shear movement is limited by the multi-modal nature of the till, leading to work-hardening not seen in fine grained unimodal sediments, and a spreading of the shear strain in broad zones and/or various directions.

The omnisepic fabrics in the thin sections match the direction of the shear zones visible by eye at the end of the tests in slides T27 and T51. In T22 the orientations are reminiscent of conjugate shears, one orientation matching the direction of the visual scale shearing, the other close to orthogonal to it. These relationships suggest that the omnisepic fabric is formed by shear, and that omnisepic fabrics can be used as an indicator of local shear strain direction. Work by numerous authors (Chapter Three) shows that in *unimodal* sediments, deformation usually results in discrete shears. The development of a wider, omnisepic, shear fabric during the tests on the diamict therefore confirms that discrete shear development is prevented by clasts (Chapter Six). The shear of thick areas of sediment was shown by Logan *et al*. (1992) to require a longer strain period than thinner depths of material. This fact, plus the fact that discrete shear fabrics are an important component of the yield and weakening of unimodal sediments (Chapter Three), lends indirect evidence to support the hypothesis that clast disruption of shears causes the test samples to work-harden. It is still possible, however, that the presence of clasts affects work-hardening, but their shear disruptive action is completely separate.

Lattisepic fabrics are only found in the slides with large patches of internally uni-directional fabric in two different orientations (*Figure 7.2*). This suggests lattisepic fabrics form where conjugate shear areas abut each other. In T22 shears in these abutment zones can be seen forming by extending from clast sides. These sides are in the two approximate directions expected for conjugate shears (quasi-orthogonal shears mirrored around the applied stress, see Chapter Three). The clasts must provide stress concentrations that aid the initiation or rotation of the shear fabrics. Clasts close to each other also transform simple shear geometry conditions between them to pure shear geometries, and force the intermediate fabric at 90° to the overall simple shear direction (*Figure 7.3*). This alignment is so close to the usual conjugate shear direction that these areas may be exploited by shear in the conjugate direction.

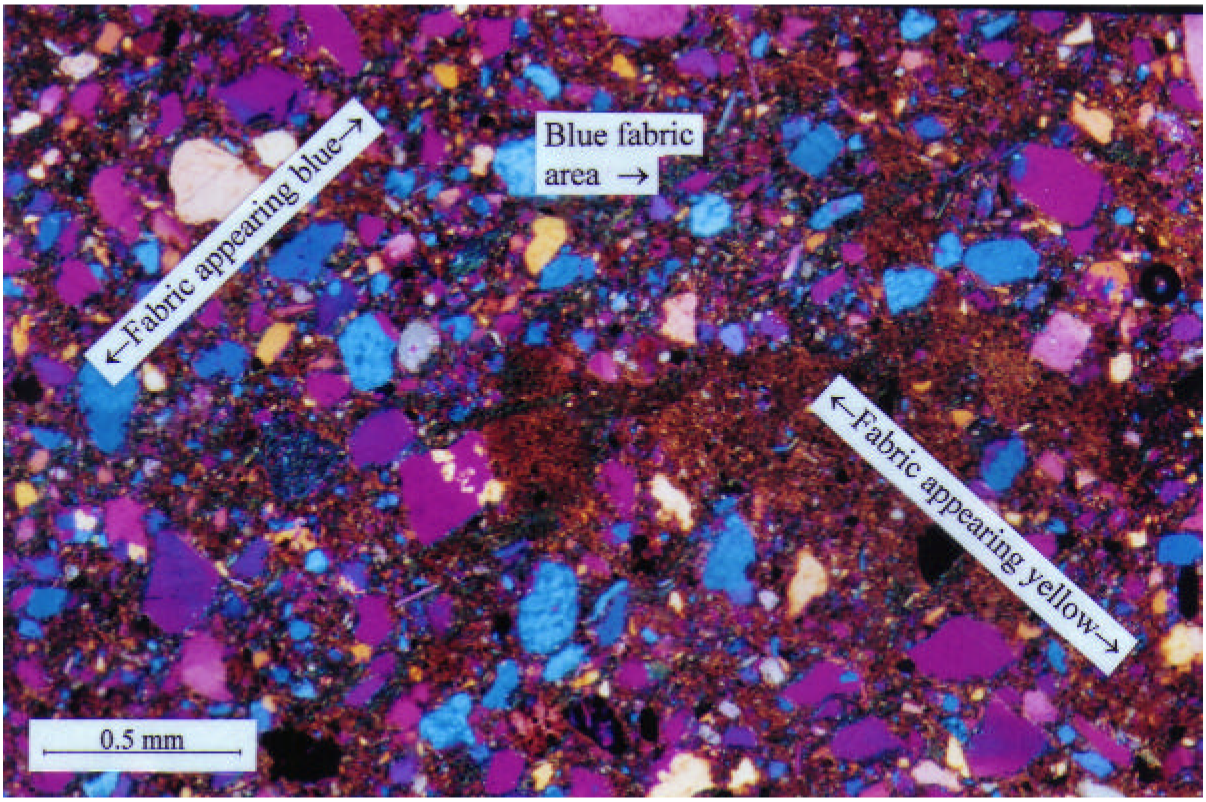


Figure 7.2 A pervasive lattisepic fabric photomicrograph from T22. Cross polarised light with a tint plate. Yellow areas of matrix are orientated in one direction, blue areas are aligned in another direction, along with some other thin grains.

Thus, lattisepic fabric represents a nascent shear fabric which develops in areas of conflicting shear alignment. Such a fabric is expected to development under pure shear geometries, where there is more likely to be several dominant shear directions; a situation that may also be encouraged by the clast obstruction of shears. Very local development of lattisepic fabric is expected under simple shear geometries when propagating shears interact during the development of complex décollements (Chapter Three). The increase in omnisepic fabric between strains < 25% and > 25% suggests one fabric or the other will come to dominate the material with greater strain in most cases.

It should further be noted that lattisepic fabric formed from conjugate shears in one vertical plane will probably appear as omnisepic in a vertical plane cut at 90°. Such a development can be seen in the samples described above (*Table 7.1*). Those thin sections cut parallel to the dip of the visual scale shears have two or more fabric directions (though one is often dominant), whereas those sections cut across the strike of shears are completely omnisepic.

The orientation of sand sized grains might have been expected given the development of other fabrics, but did not occur (though note the one example in sample T27). This suggests greater strains are necessary for sand alignment if it occurs. Some authors have suggested skelsepic fabrics indicate clast rotation (Chapter Two). The experiments throw some light on the formation of skelsepic fabrics, though the information is not conclusive. Two facts point towards shear rotation of clasts and the cohesion of clay grains to them as the origin of skelsepic fabrics. Firstly, in sample T27 the most intense skelsepic fabric is associated with the edge of the most intense omnisepic shear fabric. Secondly, clays and silts are often found concentrated around clasts in 'halos' with less sand grains (*Figure 7.4*). Cohesion may be initiated onto clays trapped in irregularities in the clast surface. Their size means that clays are

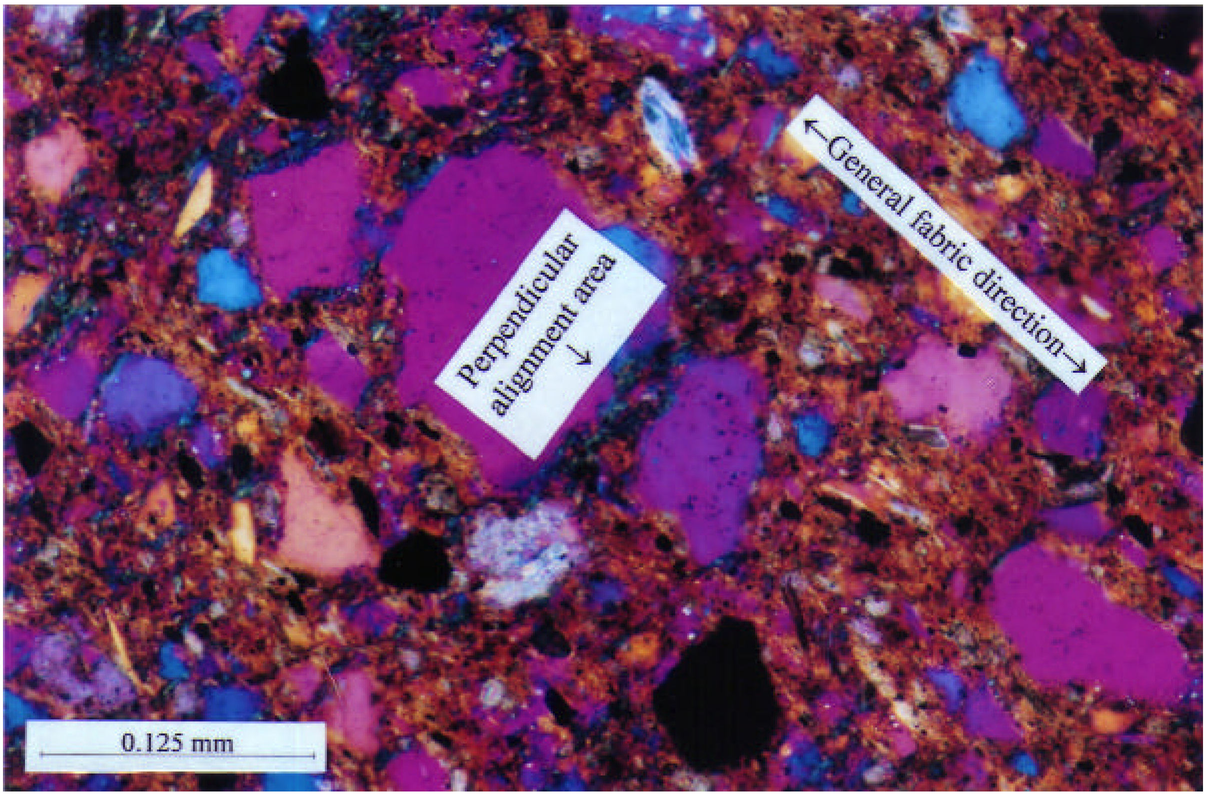


Figure 7.3 Photomicrograph of clasts within a sheared fabric that have developed an fabric parallel to their sides between them. Unpolarized light, Slide T22.

less likely to be removed from the surface of large clasts by abrasion against other grains that they rotate past. While silts have little cohesion of their own, silt grains trapped in cohesive clays would be less likely to be pushed away from a rotating clast than large sand grains. If this hypothesis is correct, skelsepic fabrics would vary with clay content and strain. There is insufficient clay variation to test this here.

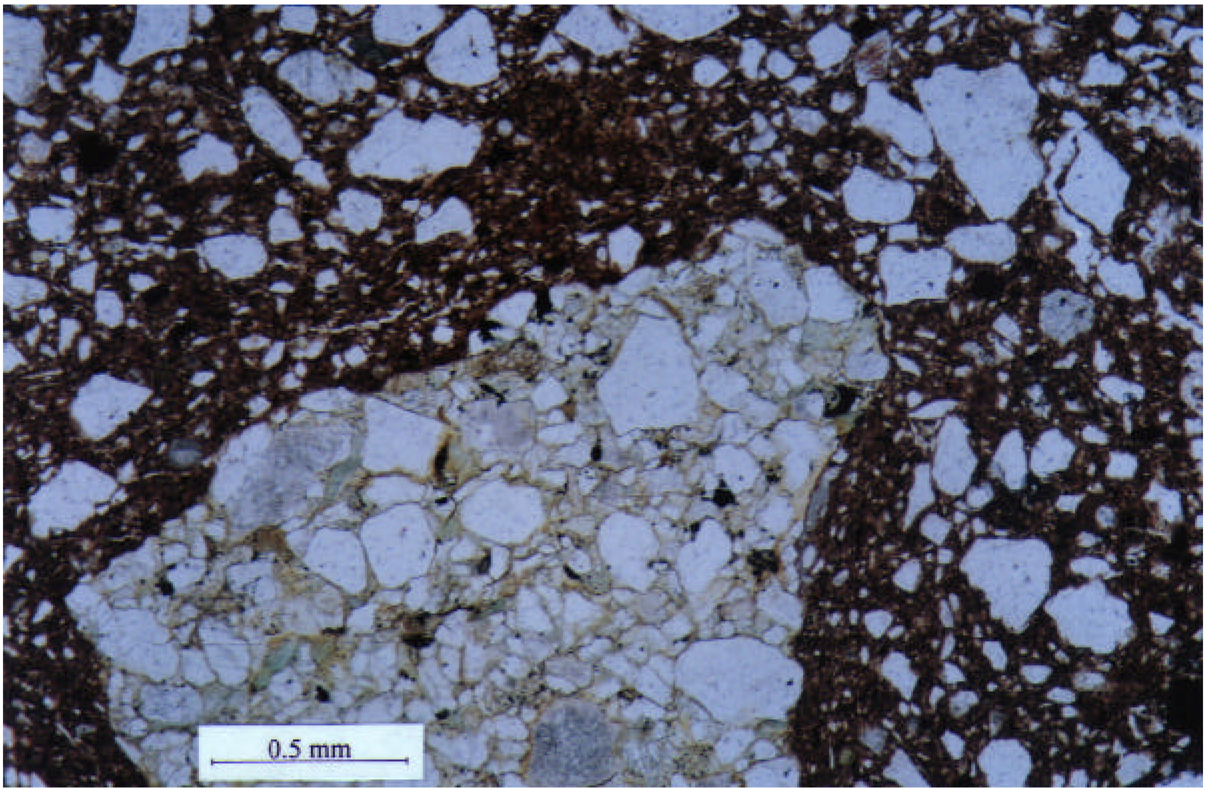


Figure 7.4 Photomicrograph of clay/silt concentration around a clast. Unpolarized light, slide T22.

7.4.3 Changes in hydrology during deformation

During the tests the samples underwent fluid expulsion events while developing higher fluid pressures, and other expulsion events during which permeability in the samples dropped (Chapter Six). The following interpretation was given;

‘through-flow channels are present in the sample, possibly in the form of hydraulic fractures or inactive shears’.

The fabric development illuminates the nature of these throughflow channels. The pervasive fabric indicates that the collapse of discrete shear networks was *not* responsible for the events in which fluid was expelled and permeability rose. The absence of discrete shears despite the characteristic 'shear-like' stress, fluid expulsion, and permeability signals suggests the omnisepic fabrics acted locally as broad shear or dilatant zones, and this may explain the high volume of fluid expelled. Alternative suggestions, such as a dilation-collapse wave travelling across the whole sample would have to coordinate fabrics with differing orientations and, therefore, frictional properties, which is physically unlikely.

The pervasive fabric also suggests throughflow and an organised fabric can coexist. The mixing of randomly orientated fabric patches with a single internal orientation and completely disorientated fabric has been attributed to throughflow disruption (Menzies and Maltman, 1992). Strains of less than 25% removed the disorientated areas in the tests reported here. This suggests that fluid disorientation cannot withstand synchronous or subsequent strain, or alternatively, that lower effective pressures than the minimum seen in these tests (~100 kPa) and/or greater throughflow rates are necessary to disrupt fabrics during deformation.

Hydrofractured throughflow channels were predicted to exist in Chapter Six on the basis of large, permanent falls in pore fluid pressure as the tests proceeded. Microscopic cracks *are* found in the samples (*Figure 7.5*). However, before suggesting the cracks developed during the tests, it should be noted that cracks are often seen in thin sections and are usually dismissed as being due to sample preparation; particularly sample drying. On top of this, there is some cracking in the sample that was only taken to 15% strain and never underwent a permanent increase in permeability (test 2). However, two points should be noted:

1) The cracking increases in the sample that experienced a permanent pore fluid pressure fall (test 5), and at the top of that sample, where additional strain dilation is considered to be highest and could have contributed to opening channels (Chapter Six).
2) The cracks are modally vertical (*Figure 7.6*), which is the direction one would expect if they developed by hydraulic fracture parallel to the minimum effective pressure (Price and Cosgrove, 1990). None of the other sample fabrics are vertical. This modal crack direction points to tensile hydrofracture as the confining pressure was released at the end of the tests. However, the average direction of cracking belies the fact that the crack morphologies vary from straight to kinked (*Figure 7.5*). This morphology suggests the exploitation of areas of the shear fabric and possibly implicates shear weakening and/or dilation in the crack

formation. If hydraulic fracturing occurred along such lines of weakness, it is possible they were also exploited by fluid during the tests in local tensile stress regions.

Thus there is contradictory evidence as to whether the cracks were responsible for the pore fluid pressure drops, and it is safest to leave the matter open. The most parsimonious scenario is that weaknesses set up during the tests were exploited during the sample removal from the equipment.

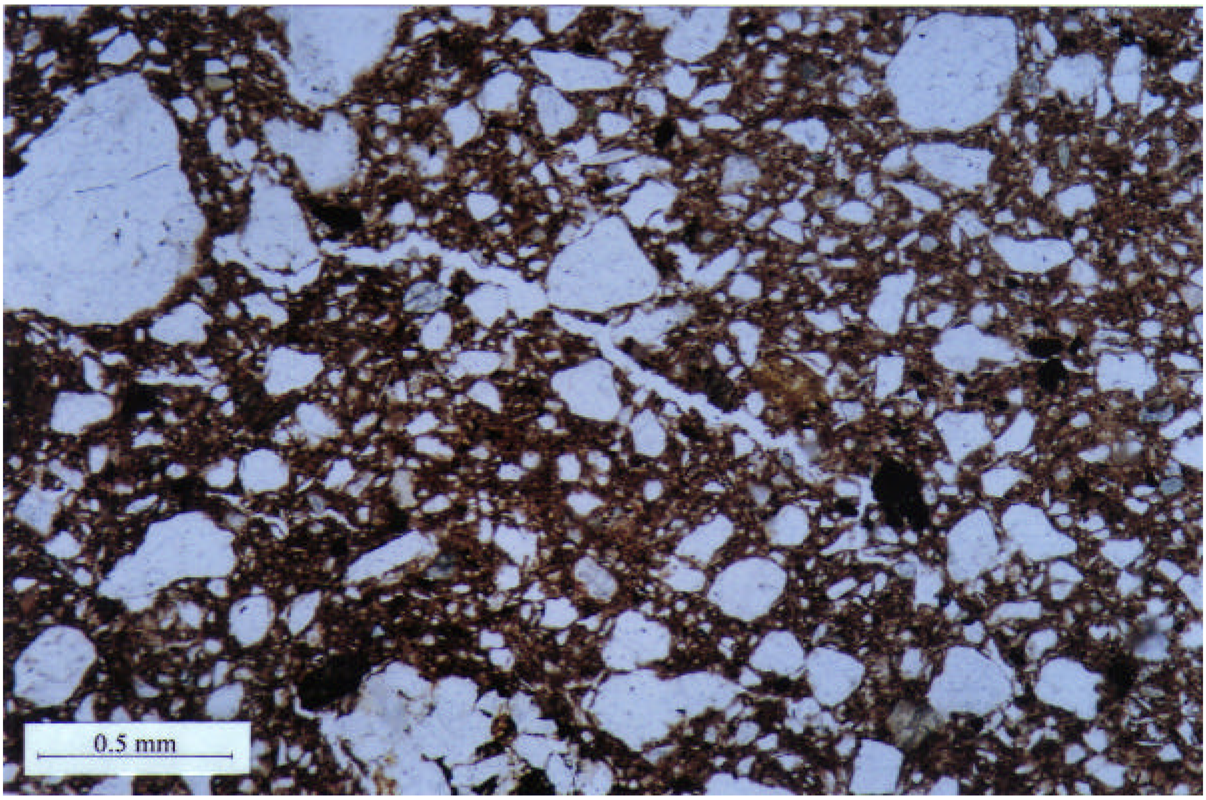


Figure 7.5 Cracking in thin section T51. Note the straightness of the cracking despite the heterogeneity of the material. Unpolarized light.

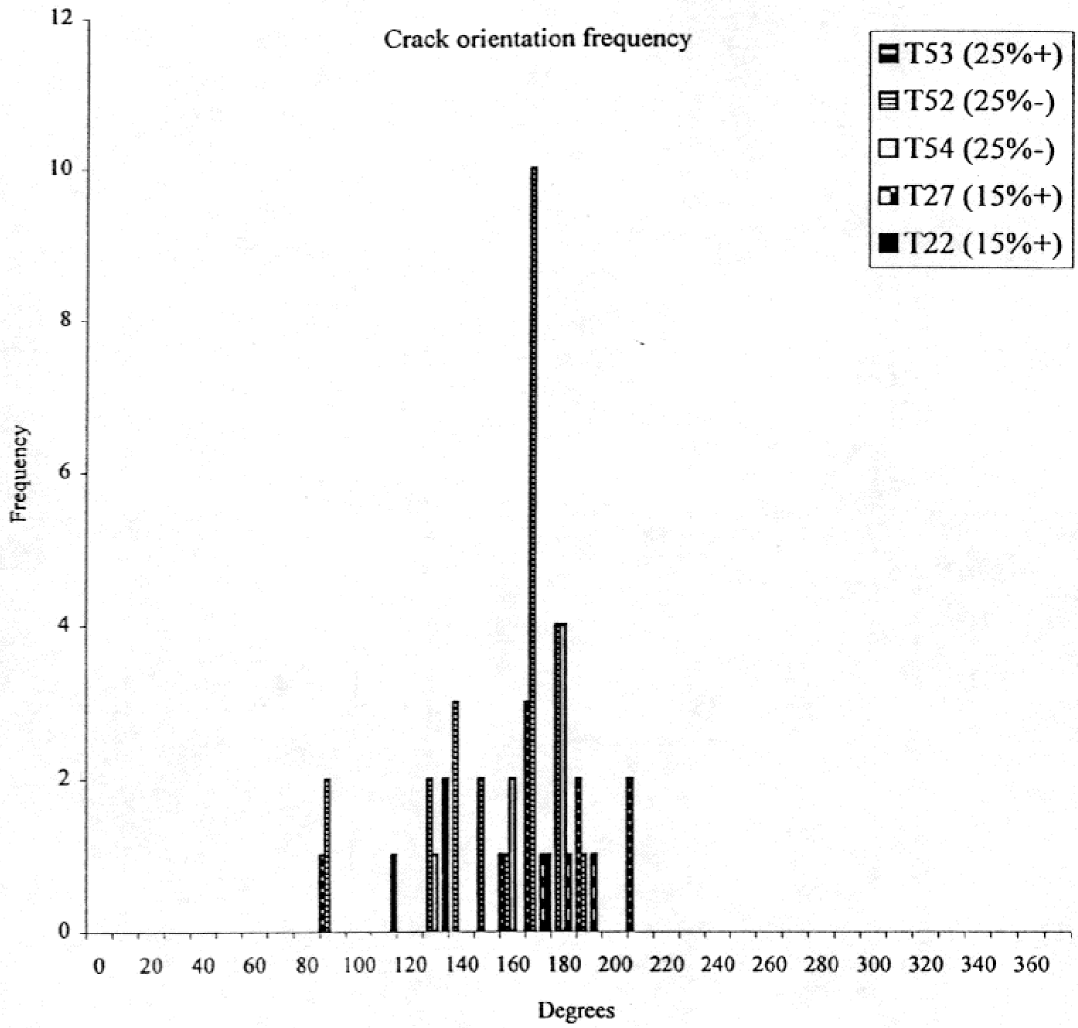


Figure 7.6 Crack orientations for the cracking in the thin sections prepared from the test samples. Measurements were taken in the range 90° to 270°, and the results are categorised in 10° bins.

7.5 Conclusions

Skipsea Till samples were subjected to triaxial testing (Chapter Six) and then thin sectioned for micromorphological study. The low strain prior to the sediments being used in the triaxial tests invalidates the experiments as an analogue of subglacial deformation at this particular site. However, the sediment tested here broadly matches that expected in the region as a whole, and subglacial sediments generally. In this sense the experiments provide a reasonable analogue for other localities that may have experienced higher strain. The triaxial sections show that omnisepic fabrics are formed by local simple shear, and that omnisepic fabrics can be used as an indicator of local simple shear deformation direction. Unimodal sediments develop weak discrete shears at low stresses after which their deformation is enhanced. The high strength of the test samples may result from the absence of such shears, which seem to have been disrupted by the presence of clasts. The triaxial tests also suggest lattisepic fabrics represent nascent shear fabrics developing in areas of conflicting shear stress directions. Clasts limit fabric directions between themselves to those which are suitable for the exploitation by, and development into, conjugate shears. It is likely that propagation of one of the conjugate shear sets will occur with greater strain and lead to an omnisepic fabric.

There is some evidence from the thin sections that skelsepic fabrics are formed by shear rotation and the cohesion of clay grains to clasts. If this is the case we would expect skelsepic fabrics to vary with clay content and strain and this could be tested triaxially.

The triaxial tests underwent fluid expulsion events associated with decreased permeability, and a reduction in supported stress. Such a response is usually attributed to discrete shearing (see Chapter Three). However, the samples failed to show such discrete shears, suggesting that the broad omnisepic fabrics found can also act in a similar manner.

The triaxial samples also underwent catastrophic and permanent *increases* in permeability during the tests, associated with fluid expulsion events. There is contradictory evidence from the thin sections as to whether hydraulic fracturing aided by shear dilation is responsible for such increases, and it is safest to leave the matter open. It is probable that weaknesses set up and exploited during the tests were further opened during sample preparation.

It is apparent from the tests that throughflow removal of fabrics is not possible if there is syn- or post-throughflow deformation without higher throughflow rates or lower effective pressures than the minimum seen in the test samples (~100 kPa). It is, however, worth noting that the randomization of fabrics can occur for several reasons and the individual sequence of events at any given site must be examined to draw out the processes acting to produce the fabric.

The following chapter uses the above discussion, and the results developed in prior chapters, to analyse the sediments deposited by the Devensian glaciers of the Yorkshire coast.