9. Conclusions

The aim of this thesis was to investigate how glacial microstructures might reflect the processes and conditions forming them, and how these microstructures might then affect the situations they develop within. It is hoped that, on a more general level, this thesis has shown the immense amount of useful information glaciogenic microstructures might contain. This information is an essential adjunct to information collected at other scales. While each chapter of this thesis explores one particular area or process, it is hoped that in combination these studies provide information on the formation of some of the 'classic' glacial microstructures, and their effect on the materials in question.

9.1 The development of microstructures

9.1.1 Omnisepic fabrics and discrete shear

Thin sections from triaxial tests (Chapters Six and Seven) showed that omnisepic fabrics develop at low strain (15 to 25%), and that the grain orientation matches the direction of discrete shears seen at a larger scale. There was no evidence of discrete shear in the thin sections so it seems likely any higher strain areas are impossible to distinguish within the omnisepic fabric. This may not be important if we are examining the mechanics of the material in question, as the discrete shears appear to be very low strain features that have locked after their formation. It is not certain how such ambiguous strain features would appear in the field. Chapter Eight provided another example of an apparent high strain 'discrete shear', which, on the microscale appears to largely be the result of fluid removal of the diamict and the concentration of sands. Thus, discrete shear seen in the field need not represent high strains, however, as was discussed in Chapter Six, it seems likely that at some stage in subglacial deformation discrete shears must develop (below).

9.1.2 Lattisepic fabrics

The thin sections from the triaxial tests (Chapters Six and Seven) showed that lattisepic fabrics formed in areas of conflicting shear strain in two directions. This suggestion was confirmed by field evidence in Chapter Eight, where discrete and widely separated shears in two directions in the clay/silt beds of the Dimlington Silts were seen to be replaced by a pervasive lattisepic fabric in the more sand rich layers. Evidence was given from the thin sections from the triaxial tests (Chapter Seven) that the formation of lattisepic fabrics is aided by the alignment of grains between clasts trapped at different levels in a medium that is shearing in one direction. The dominance of omnisepic fabrics in thin sections from higher strain tests suggests lattisepic fabrics are eventually replaced by a single direction fabric.

9.1.3 Microscopic melanges

The formation of microscopic melanges appears to reflect coupling levels at the ice-bed interface. It was suggested (Chapter Five) that mixes of pre-consolidated material, silt beds, and unimodal sand beds, in high strain flow bodies formed as material melted out of the ice pushing against a lodging clast and pre-consolidated material flowed from the sides of the ploughing gouge. This interpretation is backed up by the overall geometry of the deposit in question (the thickness of the melange unit increases towards the clast), and a model of the processes which predicted reasonable ice-till properties and the correct thickness of material.

Melanges of diamict, clay bands with reworked diamict pebbles, and sands were examined in Chapter Eight. Here there is no evidence for consolidation prior to the material being placed in its present position (except in the pebbles which show a potentially high-strain fabric), and little evidence for coherent flow bodies. The combination of low strain in the clay bands, the presence of reworked material within them, and the bands morphology, suggests that these are water lain features. The interdigitation with the surrounding diamict suggests the materials were deposited synchronously. Thus, it is suggested that the sediments represent diamict meltout from the ice into a region of small, flowing, water bodies. Where the strain in the sediments can be quantified, such fabrics could give quantitative information about the level of coupling between the ice and the bed.

9.1.4 Skelsepic fabrics and till pebbles

Indicators were found in the thin sections examined in this research of the processes forming till skelsepic fabrics and diamict pebbles, however, the evidence is not conclusive and needs further investigation.

Skelsepic fabrics appear to form at low strains (<15%) within areas of shear strain in a single direction (Chapter Seven). There is evidence for the cohesion of clays to clasts (Chapter Seven), and this may initiate skelsepic fabrics by trapping silt and sand sized material which is then orientated by rotation of the clast against free material. Further investigation is needed of these processes, and could proceed in the laboratory by the deformation of materials with varying clay contents and clasts within a shear box.

Evidence from Dimlington High Ground (Chapter Eight) suggested that diamict pebbles do not form through the exploitation of shear weakened areas within tills, however, the features may still form through the removal of material leaving shear *hardened* areas. Shear hardening of material may occur where a random alignment is replaced by the orientation of grains in a single direction with an increase in face-face contact between clay grains. In the case of the pebbles at Dimlington, they appear to have formed at the base of a water body. A greater amount of statistical and environmental evidence is needed before a formation process can be attributed to diamict pebbles, and it is unfortunate that this evidence can only be collected when such features are fortuitously discovered within sediments. Even when diamict pebbles are found, it is rare that appropriate collaborative evidence is present.

9.1.5 Multiple fabrics within sediment bodies

The presence of multiple sets of superimposed fabrics, and information on how the form of fabrics change with stress and hydraulic conditions (Chapter Three) allows the reconstruction of the stress and hydrological history of the deposits. Examples are presented in Chapter Four for a single sediment bed at Criccieth in North Wales, and in Chapter Eight for Filey Brigg, Dimlington High Ground and Reighton Sands in Yorkshire. Such a methodology gives us important information on the response of the sediments to the surrounding conditions, and how these responses affect those conditions. This information has been supplemented in this research with laboratory tests to give details of how the ice is coupled to soft beds, the conditions at the interface between the two, and the response of the sediment to stress and hydraulic conditions. This information is reviewed in the next sections.

9.2 Ice-bed coupling

In Chapter Five it was shown that the microstructure of the sediments allows the production of a model of the ploughing and lodgement of clasts initially trapped in the base of the ice. This model predicted reasonable ice velocities (~20 to 60 m a^{-1}) and till residual strengths (~20 to 50 kPa) for the ice at Criccieth in North Wales when meltout material was assumed to have little effect on the decoupling of the ice from the clast. The model gave similar order of magnitude results when the meltout material was assumed to have an effect. The model thus appears reliable, and can be used to predict the time until lodgement of clasts, the force on the clasts during the period they are decoupling from the ice and coupling to the bed, and the associated meltout material levels which will go to produce the matrix of the lodgement till. Example results for clasts with diameters of 0.01 m, 0.11 m, and 1 m were given in Chapter Five.

Future model developments will look at reducing the number of potential ice velocities and till residual strengths at Criccieth by constraining the model to produce the same proportions of meltout material and pre-consolidated material that can be seen in the thin sections. It is also hoped to develop the model into a full, multisize, multiclast, bed model in which the ice responds to the process of clast lodgement. This may be achievable by relating the clast decoupling length of the model given in Chapter Five to the decoupling length used in the basal shear stress model of Kamb and Echelmeyer (1986).

At Filey Brigg (Chapter Eight), the micromorphology was seen to imply decoupling between the ice and its sedimentary bed. The presence of a fluid layer, or set of micro-streams between the ice and the bed may explain the low strain in the material. To this explanation may be added the fact that the meltout nature of the material at Filey, and possibly Reighton Sands, may have led to low strains being recorded in any one horizon, if the meltout accumulation rate was high enough. The presence of thin sand bodies, and possibly rhythmites, within the sequences of the Yorkshire coast may suggest both water flow and ponding occurred at the ice-sediment interface. The juxtapositioning of larger sand bodies and this ‘decoupled ice’ micromorphology at Filey Brigg *may* reflect a positive flux / fluid pressure relationship in the water bodies responsible for the large sands beds, though given the imperfect nature of the ice-sediment interface this is far from definite.

9.3 Till response to stress and fluid build-up

Laboratory tests on the Skipsea Till presented in Chapter Six indicated that when the material was deformed under a pure shear geometry it responded by undergoing work-hardening with stick-slip behaviour. While shear events *did* occur, the strain along them appeared to be low. Thin sections taken from the samples indicated that the discrete shears usually seen in unimodal sediments did not form in this material, which has a broad grain size range. Thus, it appears that the larger grains in the material disrupted the propagation of the discrete shears which are suspected as being responsible for work-softening in unimodal sediments. Such disruption may be related to the work-hardening response of the Skipsea Till. It has been suggested that stick-slip behaviour seen in other environments may be due to the interaction of harder areas of the materials with shears (Chapter Three). The work-hardening seen in the Skipsea Till may be contrasted with the more unimodal till that the clast ploughed through at Criccieth (above). Here the ploughing model suggests a low residual strength for the till, and this matches the more discrete shear seen in thin sections from below the ploughing trace.

However, the profile of the ice along the Yorkshire coast suggests that the shear stress at the base of the ice was less that 10 kPa over the area the triaxial and thin section samples were taken from (Chapter Six). As this is an order of magnitude lower than the stresses supported in the triaxial tests, other processes than work-hardening deformation must have been responsible for the shallow profile of the ice. Evidence for two such processes was outlined in Chapter Eight; the decoupling of the ice from its bed by fluid bodies (above), and the presence of discrete shears in areas where they can form with less disruption. The latter matches with the presence of horizontal weaknesses in the material used in the triaxial tests (Chapter Six). Thus, it is suggested that tills respond to stress with a mix of work-hardening in areas under a pure shear geometry, for example, between two clasts, but that discrete shear may occur in some areas to work-soften the material. Further research is needed to build this information into a semi-quantitative estimate of how such materials respond to varying their size distribution.

The laboratory tests suggest that tills may buffer fluid pressure increases, strain in the material leading to increasing fluid pressures until a threshold is reached and hydraulic fracture occurs or the fluid is released down immobile shear features, such as areas of omnisepic fabric (Chapters Six and Seven). In the tests this led to a stabilisation of the pore fluid pressure at ~470 kPa, approximately 100 kPa lower than the upper threshold. The instantaneous hydraulic conductivity of the material changed from ~$4x10^{-12}$ to $1x10^{-11}$ m s^{-1} during these drainage events.

The results in Chapters Six and Seven represent the first combined stress and hydraulic testing of real, undisturbed, glacial sediments in a triaxial rig. It is seen that the mixed size of the material in these tests leads to a response which follows a distinct model of development, but in a manner which makes it impossible to quantify when, or if, certain elements of the model will occur. This makes examining these events difficult. Future triaxial tests will aim to recreate real sediments, but in a more controlled way. It is hoped to carry out experiments looking at the response of mixed clay-silt-clast materials, using neutrally buoyant clast replacements. This will allow a quantitative estimate of the effect of varying clast density on the rheology of the material and the development of microstructures.

Field evidence is also presented for other buffering mechanisms which would prevent fluid pressure building up in the Skipsea Till. At both Reighton Sands and Dimlington High Ground there is evidence for the removal of fine material by throughflowing water. At Dimlington, the whole of the sequence that has been eroded can be measured within one thin section, allowing the calculation of the amount of material eroded. This was shown to be 0.0046 m^3 for fines for each m^2 of ice base, or, for the extremely unlikely event of this occurring under the whole glacier, a sediment volume on the order of $1x10^8$ m^3.

The build up of fluid and the stress response of the till under the Yorkshire ice may have been determined by variations in the geometry of the ice-bed interface and at Dimlington, the response of the diamict was shown to have changed over time, possibly reflecting the variation of this boundary. It is worth noting that in the situation where the fluid flow occurred through the sediment at Dimlington, the diamict was seen to show discrete shear and a horizontal omnisepic fabric suggesting the sediment deformed to lower the supported stress. This may be compared with the results from Filey, where fluid flow could occur at the ice-bed interface and decouple the ice, and there was seen to be non-horizontal and low strain fabrics, perhaps suggesting that work-hardening in the diamict was allowed to continue because the supported stresses were lowered by the decoupling.

Thus, this thesis hopes to account for the origin of omnisepic and lattisepic fabrics, microscopic melanges and some clay banding features (*Figure 9.1*). It also investigates the formation of till pebbles and skelsepic fabrics (*Figure 9.1*), though can make no definitive statements on their origin. The development of micromorphology in sediments in the field and laboratory allows the rheology of subglacial diamicts to be outlined. In addition this thesis has examined how micromorphology reflects the coupling/decoupling processes between the ice and the sediment under it (*Figure 9.2*). It is hoped that this thesis contributes to the continuing process of understanding the ice-bed interface and how microstructures reflect and affect the conditions at this interface.

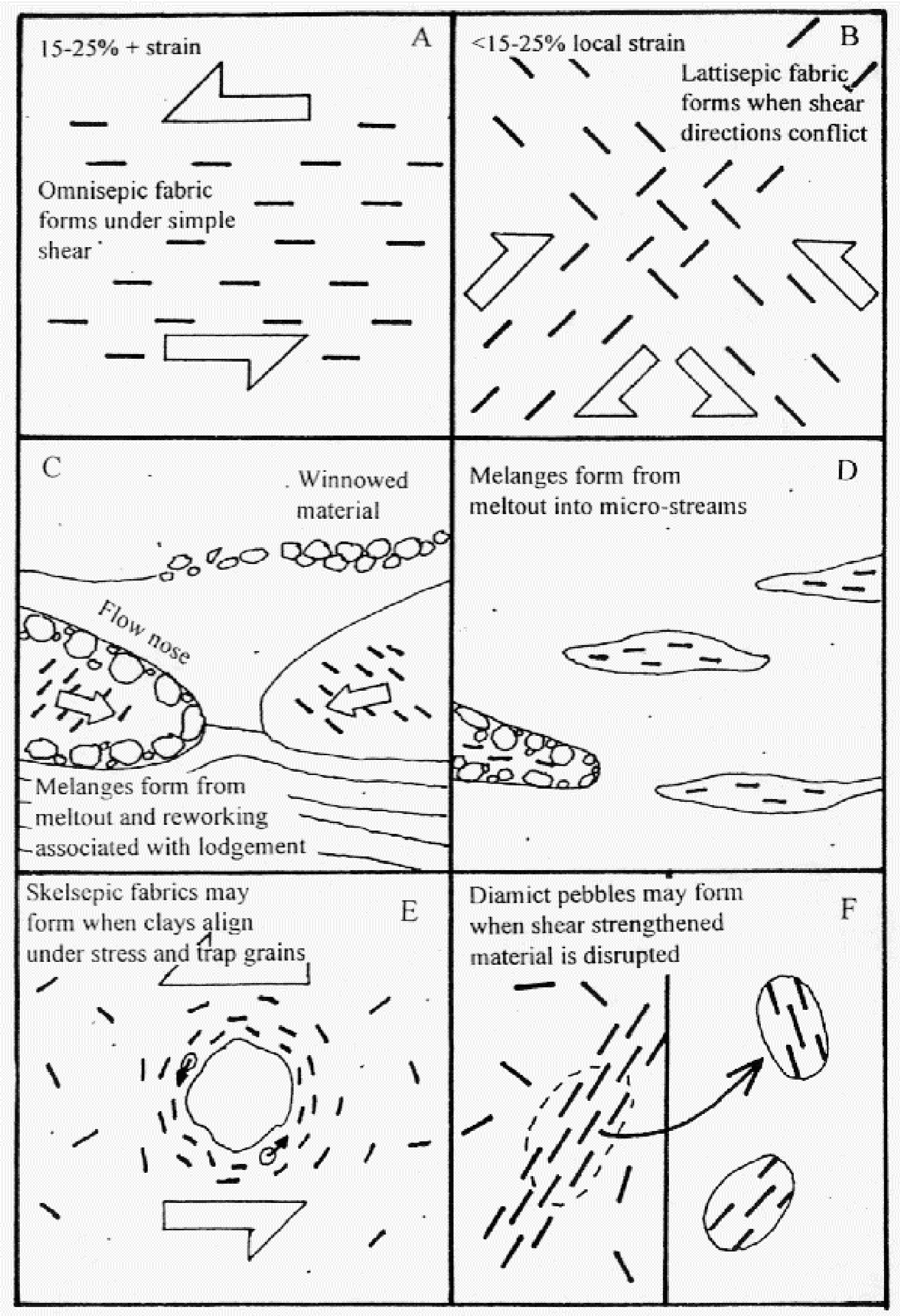

Figure 9.1 Summary of the main conclusions on the origin of microstructures in this thesis. For further information, see the following chapters; A) Chapter seven, B) Chapters seven and eight, C) Chapter four, D) Chapter eight, E) Chapters seven and eight, F) Chapter eight.

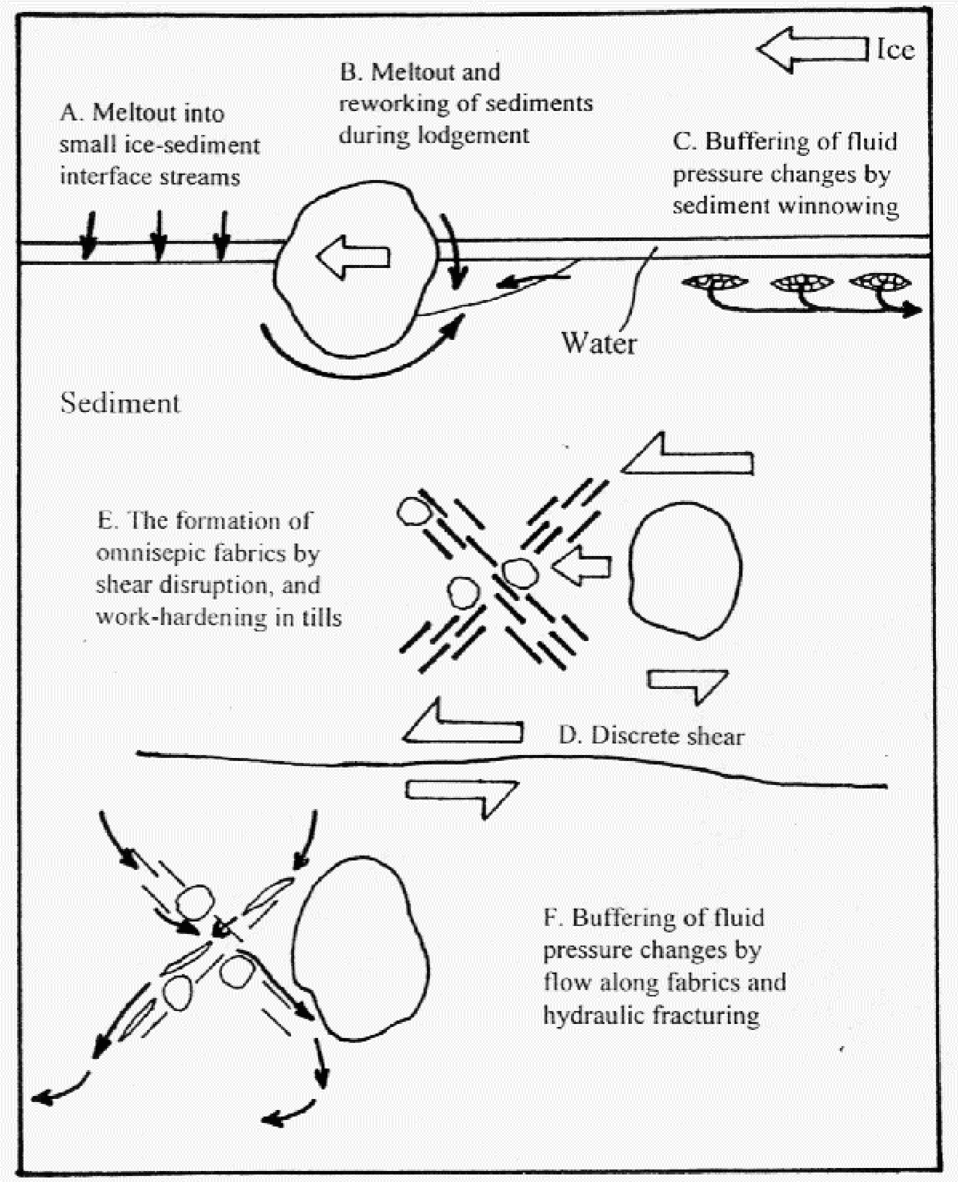

Figure 9.2 Summary of the main conclusions on the processes acting at the ice-sediment interface and below. For further information, see the following chapters; A) Chapter eight, B) Chapter five, C) Chapter eight, D) Chapters six, seven and eight, E) Chapters six, seven and eight, F) Chapters six and seven.