2. Previous studies of microscopic glacial sediment structures

2.1 The problems involved in interpreting glacial sediments

The particles in granular materials can align during their deposition or deformation to form structures. Such structures reflect the processes forming them and, inevitably, effect the bulk properties of the materials. Considerable progress has been achieved in understanding in an holistic manner the way in which structures are caused and go on to affect the physical properties of soils, soft sediments and 'hard' rocks. It is only recently, however, that this holistic approach has been applied to glacial geology (Murray, 1990; Murray and Dowdeswell, 1992; and to a smaller extent Menzies, 1986; Talbot and von Brunn, 1987; Hooke and Iverson, 1995).

Much of glacial geology is occupied with the interpretation of the origins of sediments that may be glacial, and this is particularly true of glacial geology conducted at the visual, as opposed to regional or microscopic scales. Such studies have aimed to define sediment types on the basis of their origins, and to place sediments within this taxonomy. The taxonomy determined by the International Union for Quaternary Research (INQUA) Commission on Genesis and Lithology of Glacial Deposits is that of Dreimanis (1988) (See *Table 2.1* for the most common till types).

Till type	Short definition
Lodgement till	Deposited by plastering of glacial debris from the sliding base of a moving glacier by pressure melting and/or other mechanical processes.
Meltout till	Deposited by a slow release of glacial debris from ice that is not sliding or deforming internally.
Flow till	Derived from any glacial debris...in direct association with ice [redeposited by] gravitational slope processes, mainly by gravity flow, or by squeeze flow, [taking] place ice marginally, supraglacially, or subglacially, and subaerially or subaquatically.

Table 2.1 INQUA till definitions of common till types from Dreimanis (1988).

However, the failure of this scheme to separately define both deformation tills and glacitectonites lead to its partial abandonment in the late 1980's, when the importance of these till types became realised. In the absence of a reasonable standard taxonomy, this thesis follows a broadly processed based definition scheme. Lodgement is defined following

Dreimanis (1988), as is flow till, though the *subglacial* flows of Dreimanis are not included. In agreement with common practice these subglacially reworked materials are divided into glacitectonites, using the definition of Benn and Evans (1998) as being ‘rock or sediment that has been deformed by subglacial shearing but retains some of the structural characteristics of the parent material’, and deformation tills, which are the same, except that they have lost their primary structure. Meltout till, is here defined on purely processed based terms as a till derived from the meltout of debris from ice. This definition has in common with all others the fact that meltout till overlaps a number of other categories. The largest difference when compared with other definitions is that the meltout need not be from a stagnant glacier. This is to accommodate materials that are shown in Chapters Five and Eight of this thesis to have been deposited by meltout from *moving* ice, but have not been changed by the movement of ice over them. Such sediments do not fit comfortably in other taxonomies. Where reference is made to the interpretations of other authors it may be assumed that stagnant ice is responsible.

Tills interpreted on the visual scale are generally placed in the defined classes by a combination of their structure, fabric orientation, sediment type, and associations with other sediments, both in terms of their stratigraphy and associations into landforms (Benn and Evans, 1998). Much of the problems of the field relate to the ambiguous nature of this evidence. For example, shears may form both subglacially and in glaciomarine sediment flows. The evidence used in glacial micromorphology is largely identical to that used at the larger scale, and micromorphological evidence is chiefly used as a supplement to regional and visual scale studies. However, in other subject areas micromorphology is more process-orientated; each feature is taken in a much more explicit fashion to represent the mechanics of the material, and an environment is then derived from those that could account for the mechanics. Micromorphology is notably useful because it gives insights into the processes that are acting outside the assumptions of continuum mechanics. There is a vast body of work in material science and geology that can be exploited by glacial micromorphology to deal with the ambiguity of glacial sediments on a larger scale (see Chapter Three). For example, shear micromorphology gives a semi-quantitative estimate of the pressure on the material as it deformed, and such evidence is usually present even when the material appears to have deformed in a ductile ‘continuum’ manner on a larger scale.

The study of microscopic glaciogenic structures is still in its infancy, so it is perhaps unsurprising to find that most of the work dealing exclusively with micromorphology has so far been descriptive and taxonomic. The majority of studies that use micromorphology in conjunction with outcrop scale features do so to describe localised deposits; often to delineate sediment units (for example, Gravenor and Meneley, 1958; Madgett and Catt, 1978; van der Meer, 1987a), though sometimes with a view to describing the origin of the sediments as well (for example, Kluiving *et al*., 1991; Evans *et al*., 1995).

The aim of many studies has been the assignment of features to families that characterise different environments, and processes, of deposition and alteration (for example, van der Meer, 1993, subglacial deformation; Harrison, 1957, meltout from stagnant ice; Owen and Derbyshire, 1988, deposition from proglacial mudflows) using two methods. One method takes larger scale features for which we know the formational *processes*, and uses them as metaphors for similar small-scale features (see, van der Meer *et al*., 1985; van der Meer, 1987b; Talbot and von Brunn, 1987). For example, grain-size gradients suggest sediments settled through standing water (van der Meer, 1987b). Of course, there is the danger that the same processes are not acting in both cases; there may be small-scale subglacial processes we have never seen. In the case of graded material, strain gradients or illuviation may have sorted the grains (Lowe, 1975; Cowan, 1982; Menzies, 1986). A tectonic mechanism is also given in Chapter Five. Studies verifying the origin of features by creating them in the lab are rare (though see Menzies and Maltman 1992, and the related studies quoted therein; Murray, 1990; Murray and Dowdeswell, 1992). Even these studies can only suggest *one* process for the formation of each feature.

In the second method, deposits of a known formational *environment* are sampled (for example, van der Meer, 1993; Owen and Derbyshire, 1988). While generally more reliable, this assumes that the microstructures have formed in their present environment or the environment indicated by their macroscale form. More importantly, materials forming today are hard to sample without deforming them. There is always doubt over the environment in which stiffer palaeodeposits formed. Even with this method the *causes* of individual features are still only estimated by the first technique; although the processes that could have acted are restricted by the environmental conditions.

2.2 The results of previous studies: an introduction to the structures

The following review will first introduce the microscopic scale fabrics found by glacial geologists. Some of these fabrics are shown in Figure 2.1. The orientation of particles, their spatial distribution, grain size and chemical alteration have suggested processes acting to form some features, and these are therefore also reviewed. Following this the attribution of these structures to facies characterising different depositional environments is outlined.

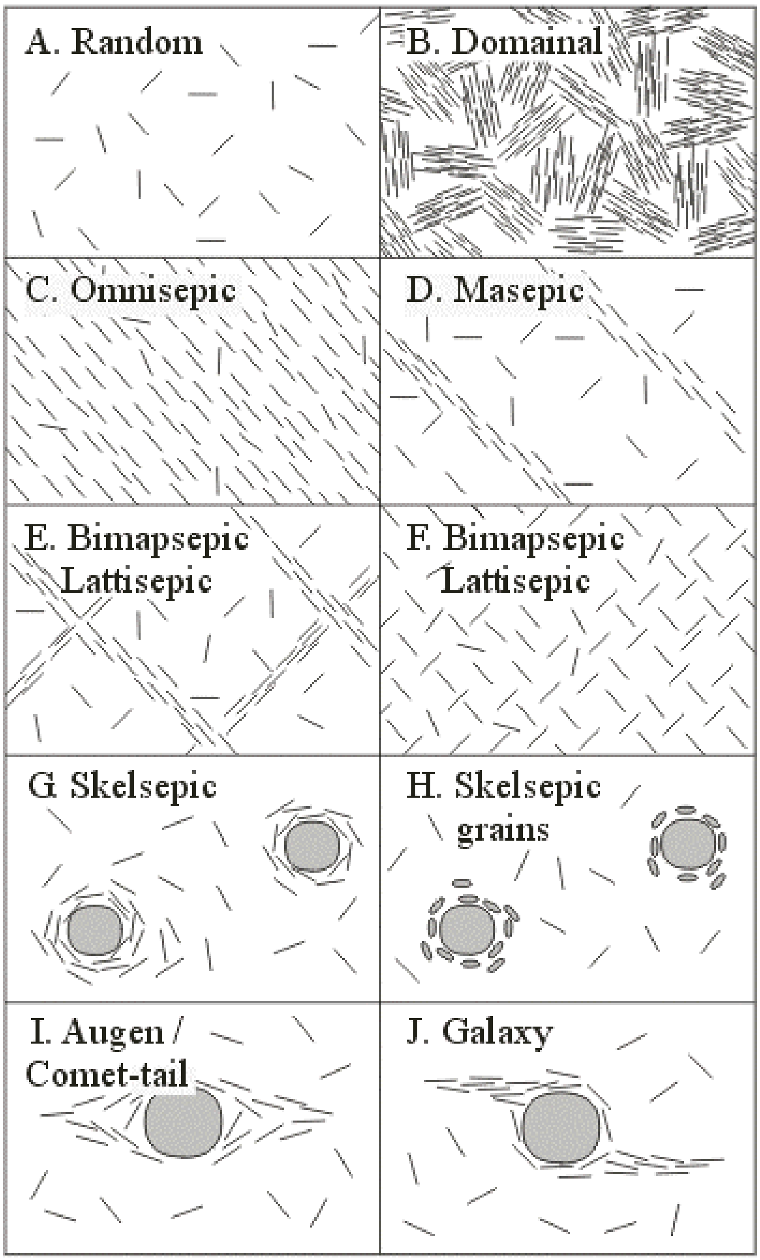

Figure 2.1 Common types of grain fabrics seen in microscope investigations of glaciogenic sediments. Such fabrics are also seen at scales up to the point at which the 'grains' are tens of centimetres long.

2.2.1 Grain size and shape

Grains' sizes may reflect the processes involved in forming them. Comminution has been suggested as a proxy for transport distance, though this approximation is limited by the production processes and grain mineralogy (Clark, 1987). Recent work on the fractal nature of fault gouges (Sammis *et al*., 1987) and tills (Hooke and Iverson, 1995) has suggested that the that size distribution in tills is due to grain-grain chipping. The scratching of grains is characteristic of glacial sediments (Whalley, 1996). The chemical environments the grains have passed through can also be estimated, for example by surface solution hollows (May, 1980).

2.2.2 Horizontal unidirectional, random and domainal fabrics

Just as the clast content of glaciogenic deposits may be strongly orientated on a metre scale, so may the sediment grains on a millimetre scale. Grain orientation occurs in silt and sand-sized material, however, the platy nature of clays means that orientation is particularly well seen in microscope studies of argillaceous material.

The grains of undeformed sediments are usually found with either a random (*Figure 2.1a*) or single direction orientation (*Figure 2.1c*). Random fabrics are rarely attributed a cause. In glaciology a single orientation has been termed 'omnisepic' by van der Meer (1987b; 1993) following Brewer (1976; similarly for all '-sepic' nomenclature following). When fabrics are horizontal they are often attributed to consolidation by a force perpendicular to the alignment, or settling through fluids. Van der Meer *et al*. (1985) note fluvial fabrics are weak compared with glacial processes (below) and the same has been found in other fields in the case of consolidation (Chapter Three).

Because clays are electrostaticly charged they can form patches with an internal alignment while settling and under consolidation. These 'domains' may be randomly aligned with respect to each other (*Figure 2.1b*), or lie all in one direction (See Rieke and Chilingarian, 1974, and Chapter Three for discussions on domains in undeformed sediments). In glacial sediments, however, these domains are rare. They are most likely in material deposited in saline situations, but are strongly dependent on the clay type involved. Their absence in glacial sediments suggests that if they ever exist in the glacial environment then they are easily removed. Menzies and Maltman (1992) have described a fabric consisting of isolated patches of orientated material in a generally random matrix. This is too discontinuous, however, to be defined as domainal. They associated the fabric with differential pore water movement and, as such, indicative of a meltout till.

2.2.3 Non-horizontal unidirectional fabrics

Commonly the orientation of omnisepic fabrics is not horizontal (*Figure 2.1c*). Gravenor and Meneley (1958) found grains with dips of up to 30°, which were taken as a proxy for larger clast orientation. Given our present ignorance of subglacial deformation this correlation appears optimistic. However, the correlation is backed up by Harrison (1957), Ostry and Deane (1963), Korina and Faustova (1964) and Evenson (1971), all of who found a good match between grain and clast orientation in till deposits. Various explanations have been put forward for these findings. Harrison suggested direct deposition by meltout was responsible for both grain and clast orientation, with alignment being developed in up-glacier dipping shears and between ice crystals. Evenson (1971) and Sitler and Chapman (1955) suggested reorientation in shears as well, but during sediment deformation under the ice. Seifert, in 1954 (translated in part in Harrison, 1957), found that microfabric orientations varied from ice flow transverse to ice flow parallel near outcrop scale “shear layers”. Pervasive subglacial deformation may also occur as the diminishing velocity of the sediment with depth (Boulton and Hindmarsh, 1987) revolves particles into new orientations (van der Meer, 1993).

On the basis of outcrop scale structures and the similarity to folding, Kluiving *et al*. (1991) have attributed crenulated fabric in a till to regional compression of the sediment. This would appear a reasonable interpretation, however, investigation is needed into the spread of kinking fabrics (localised crenulation) associated with shear (Chapter Three) so it seems wise to use large scale indicators to confirm compression where crenulation is seen.

2.2.4 Lattisepic, bimasepic and masepic fabrics

Diamicts sampled by Korina and Faustova (1964) showed a complex clay fabric, in which the clay minerals were arranged in a ‘lattisepic’ fabric (*Figure 2.1e*). This consists of two sets of thin, linear areas, each with a single, length-parallel, internal orientation, arranged at around 90° to each other, though the term is also used to describe a more pervasive mix of grains in two directions (*Figure 2.1f*). The lattisepic fabric is a particular case of the more general 'bimasepic' fabric in which the angle varies between the two sets of bands (or more, tri-, quad- etc.) (for example, Sitler and Chapman, 1955; van der Meer, 1987b).

Korina and Faustova suggested that lattisepic orientation is due to the meltout of clays that were aligned between ice crystals in debris-rich ice. It seems unlikely that the ice between aligned bands would have been replaced by more sediment without disrupting the bands. Paul and Eyles (1990) have shown that the fabric of sediments in ice can only survive meltout in very limited circumstances. An alternative is that lattisepic fabrics form after the sediments are deposited. Shrink-and-swell clays can produce lattisepic orientations, however, these will be weak (van der Meer, 1987b; 1993). The subglacial rotation of sediment blocks under shear has been suggested as one cause of the fabric (van der Meer, 1987b; 1993). Girdle fabrics, where particles are orientated in planes, are the three dimensional equivalent of lattisepic fabrics. Lafeber (1964) has implicitly suggested that girdle fabrics form between two close, rotating, clasts. An alternative explanation; that the fabric develops through the constraint of shears, is examined in Chapter Three, Seven and Eight.

In a 'masepic' sample there is only *one* set of bands, all pointing in the same direction, and each with a single, length-parallel, internal fabric (*Figure 2.1d*). Various mechanisms have been suggested to account for masepic fabrics (Korina and Faustova, 1964; Sitler and Chapman, 1955). It is now accepted that most of these structures are caused by syn- or post-depositional shearing (Menzies and Maltman, 1992; van der Meer 1993). As grain reorientation strengthens the material, masepic areas *may* appear as fractures or erosion resistant bands in the field, especially in palaeodeposits (but see cautionary notes in Chapter Eight). It has been suggested that masepic areas develop into wholesale omnisepic fabrics with greater shear (van der Meer, 1993). While shear zones often develop in several directions in one shear event, and bimasepic fabrics can often be seen to be shear zones, the conditions for the development of masepic and bimasepic fabrics are probably different, particularly in terms of stress.

2.2.5 Skelsepic fabric and astronomical curiosities

The alignment of particles parallel to the sides of large grains (skelsepic fabric) is a common micromorphological feature of glaciogenic sediments (*Figure 2.1g*). Seeing skelsepic fabrics is more difficult where they have developed around areas of matrix, whether local or exotic. Van der Meer (1993) hypothesised that such matrix areas were stiffer and possibly dryer than the rest of the material and the fabric was formed by rotation. Lafeber (in figure 5 of Lafeber,

1964) suggests that skelsepic fabrics form through the interaction of large grains. It may be that skelsepic and bimasepic fabrics are interrelated (van der Meer, 1993, and references therein). However, such associations are based on the juxtaposition of the two fabrics in thin sections, and these may display features from multiple events. Consolidation has also been suggested as an origin for skelsepic fabrics (Harrison, 1957). Clay swelling has also been put forward as a possible cause (van der Meer, 1987b).

Orientation of big silt and sand grains around larger grains can occur with or without an associated skelsepic clay fabric (van der Meer, 1993) (*Figure 2.1h*). Van der Meer has suggested that the absence of a clay orientation in these situations indicates a 'flow' (pure shear?) rather than a 'shearing' (simple shear?) origin. That a pure shear geometry produces some of these features has also been put forward by Menzies and Maltman (1992). They found 'comet [tail] like structures' associated with grains (see figure 4e of Menzies and Maltman, 1992) (*Figure 2.1i*). These, they suggested, may result from pure shear in a confined horizon. Alternatively they suggest they may be due to pore water winnowing of the finer sediments (see Clarke, 1987 for a theoretical basis). The equivalent features under simple shear are the 'galaxies' of material strung out in opposing directions at the base and apex of soft clasts (van der Meer, 1993) (*Figure 2.1j*). Van der Meer (1993) suggests these may develop into augen-shaped areas akin to those seen in metamorphic geology (though note that these form by recrystalization; for a review see Simpson and Schmid, 1983). Further rotation, he notes, might be responsible for the development of the classic grain and skelsepic fabric orientation around large grains. It is not obvious why Van der Meer considers the *lack* of a skelsepic clay fabric allows for the introduction of pure shear as a condition in the formation of grain skelsepic fabrics, as discussed above.

Distinct pebbles of material may often be found in the matrix. The pebbles may be of local material (van der Meer, 1987b), implying deposition and then brecciation, or reworked from older sediment (Menzies and Maltman, 1992; van der Meer, 1993). Pebbles have been classified by van der Meer (1993) into types based on a mix of form and possible origin.

Type I) Composed of local till with no internal fabric. Recognisable by surrounding voids, [possibly] formed by slight deformation.

Type II) Composed of local till with an internal fabric, [possibly] formed by 'plastic deformation'.

Type III) Composed of till or fines with an internal fabric, formed by brecciation.

A more consistently genetic classification could be based on Cowan (1985). The environments so far examined in the literature give little indication as to the processes forming the pebbles. They are found in areas both with (van der Meer, 1993) and without (van der Meer, 1987b) shear fabrics. Neither need reflect the origin of pebbles, as the pebbles could have been inherited in these situations (see Chapter Eight for evidence of one formational environment). Type I pebbles have been attributed to the freeze-thaw creation of voids by Sole-Benet *et al*. (1964) in a Mediterranean environment. Van der Meer (1993) found Type I pebbles displaying an upwards dissipation and rounding at one site, and this was taken to indicate a strain origin through rotational movement with a downwards reduction in strain. However, it is possible such a velocity gradient could be responsible for the morphology of the pebbles without being active in their initial formation. Equally, such strain may be periglacial rather than subglacial.

2.2.6 Pores, fissures and structures associated with hydrology

Very little work has been completed in the important area of fabrics associated with fluid throughflow. Menzies and Maltman (1992) have suggested that patches with a single fabric orientation in a otherwise random matrix are representative of fluid throughflow in meltout (*Figure 2.2a*). They also suggest diffusely sheared sediment with ripped up pieces of more coherent sediment may be from an area of pervasive movement in a slurry piping event (*Figure 2.2b*).

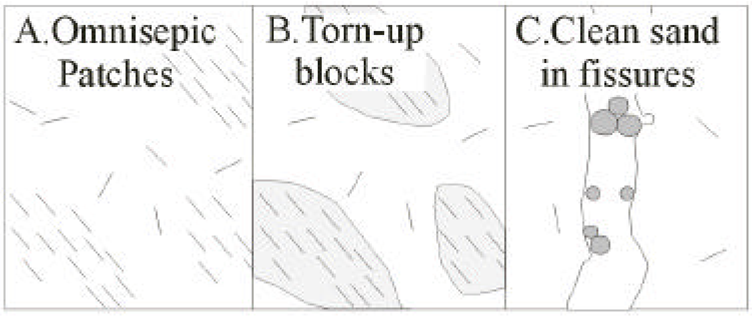

Figure 2.2 Microscopic fabrics caused by the interaction of water and grains in glaciogenic sediments. A)Broad patches of grains with one orientation (Menzies and Maltman, 1992). B) Blocks of local or exotic sediment torn-up by pipe flow (Menzies and Maltman, 1992). C)Clean sand washed into fissures. The fissures may be caused by water flow (van der Meer, 1987b).

Silt injection pillars may have been formed by high fluid-pressure sediment translocation (van der Meer, 1987b). Van der Meer (1987b) has noted the occurrence in several samples of linear but discontinuous pores forming a 'fissile' fabric, often highlighted by the presence of iron and/or manganese precipitates. This fissility is unrelated to the grain orientation. Clean skeletal grains and translocated silts in the fissures suggesting they were formed by, or at least were a path for, water (van der Meer, 1987b) (*Figure 2.2c*). Work by Murray (Murray, 1990; Murray and Dowdeswell, 1992) suggests that deformational features such as shears and dilatant areas, common in till thin sections, are extremely efficient drainage paths (Chapter Three). Probably the most significant indicator of pore fluid conditions is the form of deformational features (Menzies and Maltman, 1992). However, the relationship is complex, for high fluid contents may simultaneously act to weaken fabrics while encouraging greater strains.

Air-filled pores may also be a significant component of any thin section. Harrison (1957) and van der Meer (1993) suggest that high porosity indicates subaerial mass movements, during which air has been trapped.

2.3 The results of previous studies: attribution of microstructures to glacial environments

The above structures have, piecemeal, been attributed to various broad glacial environments. This attribution suggests that such environments have characteristic suites of microstructures. In order to critically assess this notion, the next section draws these associations together, giving the predicted microscopic components of glaciogenic facies. Some of the environments that will be discussed below are outlined in Figure 2.3.

2.3.1 Stagnant ice meltout environment

Two sets of features *could* be present in unaltered meltout till, if such a sediment exists. These are structures inherited from when the sediment was trapped in the ice, and structures formed during the meltout period. Bell (1981), Harrison (1957), Korina and Faustova (1964) and (implicitly) Gravenor and Meneley (1958) have suggested inheritance is responsible for all the micromorphology of till bodies not reworked by proglacial mass movements (*Figure 2.3a*). This suggestion seems unlikely, however, for even the situations where large-scale features may be inherited are limited (Paul and Eyles, 1990). Such conditions will be more stringent for microstructures, for which even small strains result in total disruption. If the ice is in contact with the subglacial sediment, and meltout material does not have to fall across a gap at the interface, vertical grain-grain support inevitably develops (Iverson and Semmens, 1995). This support implies considerable consolidation and reorientation in materials with a wide grain-size distribution. Given these factors, inheritance of structures from the ice seems implausible. Much *more* likely is the presence of features formed during the meltout process, such as winnowed beds or consolidation structures.

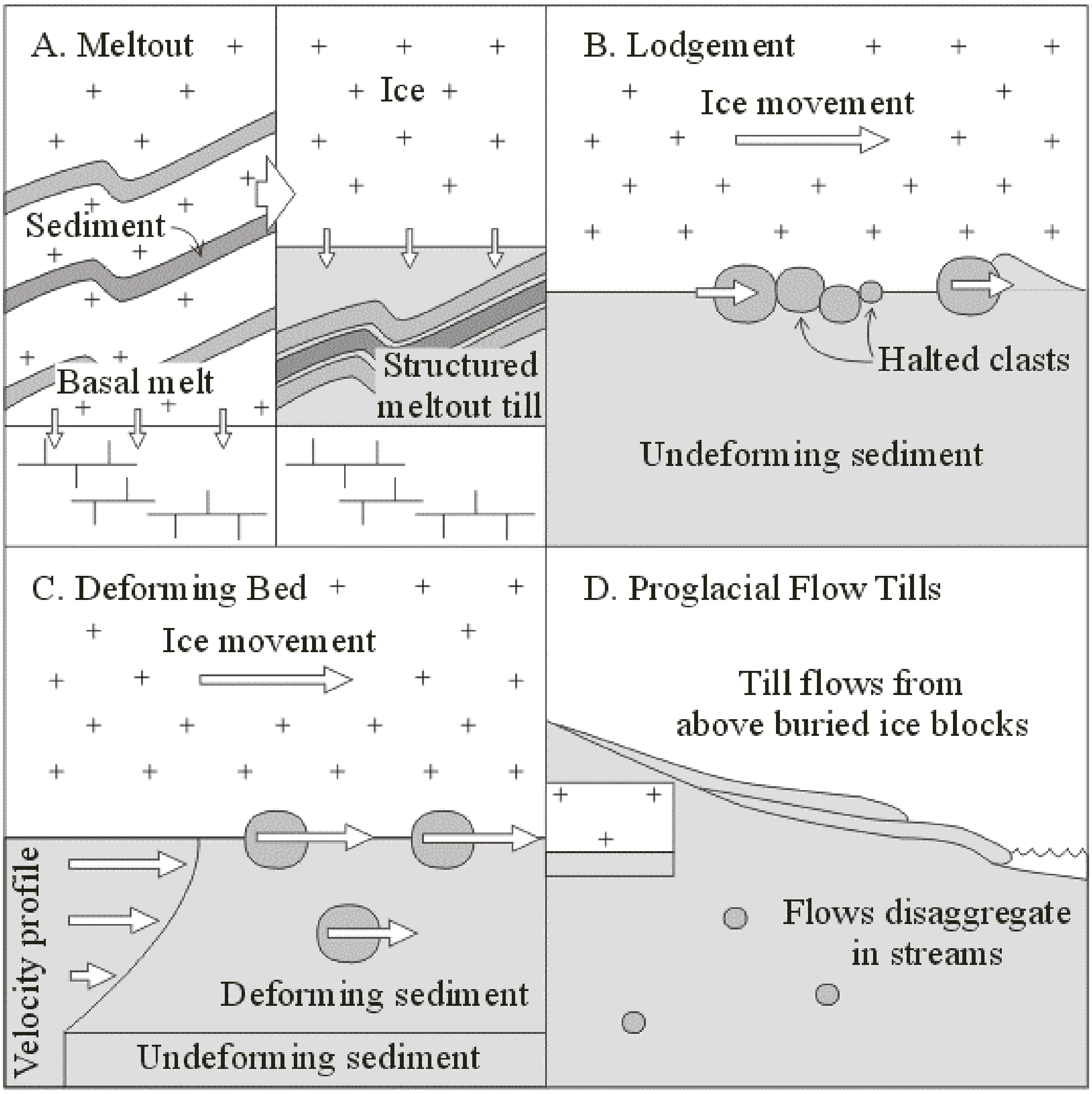

Figure 2.3 Frequently quoted situations in which glaciogenic sediments form. A) Structures coherently melt out of the basal ice. B) Material in the base of the ice lodges in a stiff bed. C) The glacier deforms a soft bed incorporating material from below and within the ice. D) Material melts out of the ice and flows off the top of ice blocks into streams.

Paul and Eyles (1990) have shown that, in almost all situations, meltout materials shear and dewater as the build-up of fluid at the melt-front reduces the sediment strength. This work was at the metre scale, but necessarily holds for smaller scales. Such structures will only be absent where there is supraglacial meltout on to an absolutely horizontal surface or subglacial meltout into protected hollows far from the ice margin. The former will lack shear features, the latter will lack shear *and* dewatering features. These conclusions match those of recent micromorphological studies. Fluid throughflow features (*Table 2.2*) have been identified as potential indicators of meltout materials, based on the hypothesis that the fluid pressures will be higher than normal. However, in most ice models homogeneous subglacial sediments rapidly become saturated, so low effective pressures may also occur under normal subglacial conditions.

Feature	**Notes**	**Author**
High number of voids	c.f. flow tills (below)	Van der Meer (1993)
'Patchy' orientation	From piping and throughflow	Menzies and Maltman (1992)
Load structures	Will depend on increasingly high pore fluid pressures as grain size decreases	After Paul and Eyles (1990)

Table 2.2 Microscale indicators of high water pressures (low effective pressures) in glaciogenic sediments.

Harrison (1957) and Korina and Faustova (1964) suggest that *sand* grains and large clasts show the same orientation when deposited by meltout. This fabric may be specific to passive meltout environments. The fabric seems unlikely in other glacial environments, where clasts would rotate or plough and alter the local stress field responsible for the alignment of the sand grains. However, Korina and Faustova give no indication of how widespread such a fabric is at their site, or the relationship between their sample positions and the measured clasts. These relationships are of paramount importance in deciding if the fabric is reliable, as the orientation could be produced by shear at a distance from the clasts. Van der Meer (1987b) suggests graded beds combined with an absence of dropstone fabrics are indicative of melt deposition into thin subglacial cavities. However, such fabrics can also be found in *proglacial* rhythmites (Chapter Eight). It is suggested that the beds in question would have to be very thin to show grain size dropstone deformation.

The above discussion shows that there are no reliable criteria for recognising meltout from stagnant ice. Details of structures indicative of meltout are given in Chapters Five and Eight. However, these structures are associated with the specific cases of meltout associated with lodgement and a specific local water system respectively. One hypothesised criteria that has not been discussed before is the presence of ice-collapse areas in material deposited through shallow water layers. Fluvial deposition into standing water *may* be identifiable by a light omnisepic fabric and the absence of infinite strain deformational structures. A collapse fabric in such material has not, as of yet, been observed, and mineral solution may produce a similar fabric. However, Harrison (1957) and Ronnert and Mickelson (1992) have suggested that porosity in some tills may be 'fossil' and represent areas of sediment previously filled by ice.

2.3.2 Glacier moving by sliding over a soft bed (lodgement)

There have been no attempts to define till lodgement structures (*Figure 2.3b*) separately from those structures associated with general till deformation (*Figure 2.3c*). It might be that lodgement only produces finite strain features in sediments (that is, ones in which we can calculate the strain). However, *finite* shear need not be *exclusive* to lodgement. For example, such strain is to be expected in meltout material that flows a short distance. Subglacial sediments might also be reset after infinite deformation by fluid throughflow. *If* small-scale grain alignment matches clast alignment on an outcrop scale (Gravenor and Meneley, 1958; Korina and Faustova, 1964) lodgement may be reflected in grain orientations, as has been suggested for larger clasts (Glen, Donner and West, 1957; Dowdeswell and Sharp, 1986; Hart, 1994). However, despite the start made by Hart (1994), there has been insufficient work to confirm this suggestion on the larger scale. At present there is insufficient understanding of the processes involved in clast orientation to warrant an investigation of smaller-scale grain alignment. A set of structures associated with lodgement under specific circumstances is given in Chapter Five, and these can be used as criteria for lodgement except in cases where there is subsequent infinite strain.

2.3.3 Glacier moving by soft bed deformation

Van der Meer (1993) has hypothesised that the following sequence of glacial microstructures exists (*Table 2.3*), based on the deformational model of Boulton and Hindmarsh (1987) (*Figure 2.3c*).

Place in sequence	**Feature**
Upper pervasive deformation zone	Omnisepic fabric generally
	Discrete shears
	Type I pebbles (*in situ* with no internal fabric)
	Type II pebbles (*in situ* with internal fabric)
	Skelsepic fabric
Middle pervasive deformation zone	Lattisepic fabric generally
	Discrete shears
	Type I pebbles (*in situ* with no internal fabric)
	Pressure shadows
	Masepic fabric
Lower pervasive deformation zone	Skelsepic fabric generally
	Discrete shears
	Type I pebbles (*in situ* with no internal fabric)
	Type III pebbles (reworked)
	Kinking fabric
Upper brittle deformation zone	Discrete shears
	Type I pebbles (*in situ* with no internal fabric)
	Discretely sheared soft clasts
	Crushed grains
	Dewatering and escape structures (presumably involving downwards escape)
	Kinking fabric

Table 2.3 Hypothesised position of microscale features in a deforming bed with a vertical decrease in velocity down from the ice-sediment interface (extracted from van der Meer, 1993).

None of these structures would appear restricted to formation by subglacial deformation. However, if such a sequence is located it would be strong confirmation of van der Meer's hypothesis that the amount and type of pervasive deformation can be delimited using these structures.

Shear zones are formed by deformation and, as such, are an indication of strain. However, there has been little discussion, even in van der Meer (1993), of the extent to which deformation till can be distinguished from small movements during meltout, lodgement, or consolidation. The presence of till pebbles has been implicitly suggested to indicate significant till movement ('reworking', van der Meer, 1987b; 1993), though to what extent this transport is in the ice or till is not clear. Skelsepic fabric development seems a likely candidate for recording large strains, if rotation is part of that development. The formation of bimasepic, skelsepic and till pebble fabrics needs investigation before their morphology can be used as an indicator of infinite strain. A start on such an investigation is made in Chapters Seven and Eight.

2.3.4 Proglacial / stagnant ice terrain

In an environment of proglacial ice blocks, we expect supraglacial till combined with flow and meltout tills (*Figure 2.3d*). The difference between till reworked by proglacial mass movements ('flow till') and tills deformed subglacially will be slight as they both deform internally. The two are probably more easily distinguished on the outcrop scale (for example, Boulton, 1977; Kemmis, 1981). Even then there is considerable controversy (B.G.R.G. Subglacial Working Group Workshop, Isle of Man, 1996; Saunders 1968; Boulton, 1977; Kemmis, 1981). Both subglacially deformed tills and flow tills could include areas of shear, reworked till pebbles, and skelsepic fabric. Pure shear geometries may also occur in both tills. Two possible criteria for recognising flow tills are their consolidation state, and the related porosity.

Fabrics indicative of high pressure consolidation are not expected in flow tills as they have not been overridden by ice. However, clay and silt fabrics *have* been found in suspected flow tills by van der Meer (1993), and patches of material consolidated subglacially may survive reworking. More doubt is cast on consolidation as a criteria as it varies considerably in subglacial tills (Boulton and Dobbie, 1993), and could be disrupted by throughflow. Dewatering disruption can occur in both proglacial and subglacial environments (Paul and Eyles, 1990). Either way, pre-consolidation is easier to assess in the laboratory by examining the loss of porosity under restressing (Boulton and Dobbie, 1993) than by looking for consolidation fabrics in the micromorphology of samples.

Air-filled pores may be indicative of the subaerial entrapment of air, and are common in flow tills (van der Meer, 1993; Owen and Derbyshire, 1988; Harrison, 1957). Such pores should be discontinuous to indicate that they are not formed by fluid. Pores caused by water may be associated with weak sediment fabrics, and could lead to confusion. However, dead end pores *have* been found to form during sediment consolidation (Lowe, 1975). Thus, the examination of consolidation and porosity in sediment thin sections does not appear to give reliable enough information to assess the difference between proglacial flow and subglacial deformation.

2.3.5 Glaciomarine/glaciolacustrine environments

Glaciomarine/glaciolacustrine materials are deposited into large water bodies at, or near, the ice front, and usually include a large amount of sediment from the ice mass. The chief indicators of such environments are fossils. These are usually calcareous exoskeletons, though fish remains have been interpreted as having been trapped in near-glacial marine pools by sea ice (Bell, 1981). Fossils may, of course, be reworked from prior marine deposits. Microfossils are less likely to survive the rigors of the subglacial environment, suggesting whole specimens might be a reliable sign of glaciomarine deposition. However, whole shells are found in terrestrial deposits in limestone areas. Derived fossils can be determined by the presence of limestone erratics and secondary calcite in shell chambers.

Loading and dewatering structures caused by density variations in the sediments may also indicate lacustrine or marine conditions. However, none of these features are exclusive to the glaciomarine environment. Dropstone fabrics, where pebbles indent lower beds and are draped over by later deposits, may be more characteristic. However, in deforming till, grain-grain contacts could conceivably push particles into laminae, causing the traditional drop-stone flexure of the underlying sediment.

Random fabrics are likely in glaciomarine deposits, but occur elsewhere as well (see above). In a detailed four-dimensional analysis of a hand specimen Talbot and von Brunn (1987) suggest that in proglacial glaciomarine environments, sediment and fluid can be tidally pumped through tills by the glacier resulting in microscopic diapirs. All that is necessary is that pore fluid pressures are high enough to dilate channels, and then small-scale faults are used as pathways. Again, though, diapirism is not confined to the glaciomarine environment, and very localised subglacial pressure changes (Blake, 1992; Jansson, 1995) could be envisioned to have the same effect. For practical purposes a number of features in combination must be present to reliably define these sediments. Hart and Roberts (1994) suggest the following suite of structures, that might be found on a microscopic scale, as indicative of glaciomarine sediments:

1) Laterally continuous, ungraded rhythmic alterations of fine and coarse laminae with low shearing.

2) Whole shells.

3) Onlapping beds.

4) Loading/water escape structures.

5) Internally intact blocks that have slumped under gravity.

6) Highly variable fabric directions dependent on water content.

7) Sedimentary, rather than tectonic, boundaries.

8) Localised deformation.

2.3.6 Non-glacial overlays

Finally, to add to all this exasperating uncertainty, glacial sediments may record previous depositional environments (Menzies and Maltman, 1992) and subsequent environmental superimpositions - notably from periglacial and pedogenic processes.

Pedogenesis is, largely, easier to spot than periglacial alteration. This partly reflects the maturity of pedology as a science compared with glacial micromorphology, and partly reflects the fact that major pedological changes are more or less limited to the soil horizons obvious on an outcrop scale (see, Mücher, 1985; Kemp, 1995; Kemp *et al*., 1995, on microstructures associated with palaeosols, as well as Fitzpatrick, 1984 for a detailed discussion of soil microstructures). A number of processes *do* act at levels not identifiable on the outcrop scale. All are associated with the transport of materials by soil pore waters (for example, see Madgett and Catt, 1978; Bouma *et al*., 1989).

Clays deposited by postdepositional translocation are often visible as cutans (clay drapes) on grains in tills and around pores (Fitzpatrick, 1984). Clay translocation may also occur subglacially producing sandy areas in till (van der Meer, 1993; Clarke, 1989). Translocated chemicals can highlight boundaries and give information on the relative ages of events (Chapter Four), but staining can interfere with the identification of fine structures and grain size changes using fabric birefringence under cross polarised light. Voids with a drab of impurities may indicate the dissolution of limestone postglacially. These voids may later collapse leaving just the deformed drab (van der Meer, 1987b). Carbonate may be deposited in pores and crystal growth move grains. Silicate dissolution has been associated with the embayment of quartz grains the subsequent local disturbance of fabrics (May, 1980).

Small scale periglacial structures are less well understood. Slope processes such as slumping will produce structural suites which also will form in other environments. Freeze-thaw can produce voids around material which are less ambiguous (Sole-Benet *et al*., 1964), however solifluxion could produce a pebble structure from these. Other features formed in this environment are shown in Table 2.4.

Feature	Cause	Author
Millimetre scale flame like intrusions of lower material	Gravity	Sole-Benet *et al*. (1964)
Horizontal planar pores	Freeze thaw	Sole-Benet *et al*. (1964)
Domains	Freeze-thaw	Sole-Benet *et al*. (1964)
Cracks and shears	Freeze thaw and solifluxion	Coutard and Mücher, (1985)
Sand grain orientations in flows	Injection of soft material between frozen blocks (take 15 to 23 cycles of freeze-thaw to develop)	Sole-Benet *et al*. (1964)
Silt intrusions	Translocation of silt into silt lenses resulting from the formation of segregation ice lenses	Coutard and Mücher, (1985)
Clay coatings	Illuviation	Bouma *et al*. (1989)

Table 2.4 Microscopic fabrics associated with periglacial activity.

2.4 Conclusions

The assignment of sediments to different glacial environments or processes is fraught with difficulties, compounded in glacial micromorphology by working at a scale that is at odds with daily experience. In the real world, sediments undoubtedly result from a mix of depositional processes that cross environmental boundaries in a most inconvenient way. A process based perspective, concentrating on how features form and how they change under different stress and hydraulic conditions will aid in the reconstruction of environmental information, and put us in the best position for looking at how the sediments affect the surrounding conditions. While this thesis makes no claims for adhering to this policy completely, it is hoped a process-based approach is discernible within some of the following chapters.

The next chapter examines what can be learnt about the causes and effects of microscopic structures from other subject areas that include the deformation of soft sediments in their remit. The separation of 'macro' and 'micro' scale processes is essentially one of viewing equipment.

Morgenstern and Tchalenko (1967) define 'microstructures' as 'those structural features which require the resolving power of at least an optical microscope for their study'. Given that this is anthropogenic anyway, a more appropriate division is probably between the models of structures that include the effect of individual grains and those taking grain-grain effects in bulk and the sediment as a continuum. The scale independence of structures like shear zones (Tchalenko, 1970) down to the grain-grain level suggests this is reasonable. The fact that the smallest shear zone size may be fixed at 8-16 times the mean grain diameter (Mühlhaus and Vardoulakis, 1987; Bardet and Proubet, 1992) prevents the arbitrary scaling of such features below this level and suggests this division may be objective in some situations. Plainly grain-grain interactions should ideally be taken into account in all situations, continuum mechanics being a non-ideal representation of bulk grain-grain effects. The division is a monument to our own inabilities rather than any real situation. Because the structures seen in thin section *can* be scaled in this way to outcrop size, and models exist for such large features, the discussion in the next chapter does not exclude larger structures.