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MICROSCOPIC EVIDENCE OF SUBGLACIAL DEFORMATION

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Subglacial deformation is by now a well established process. However, recognition of this process in Pleistocene tills is not always clear. Studies of thin sections of Pleistocene tills show that there are a variety of microscopic features caused by deformation. This paper gives a review of microscopic evidence for subglacial deformation and starts with a case where deformation could be established macroscopically, then traces the microscopic features through planar and rotational movements, which are described and separated accordingly. Attention is also given to features caused by crushing of grains and sediment dewatering. These studies indicate that almost all basal tills show evidence of subglacial deformation rather than sedimentary derivation. This implies that if we want to understand subglacial processes such tills should be described in tectonic rather than sedimentary terminology.

INTRODUCTION

It has been known for a number of years that part of the movement of an active glacier, resting on deformable sediments, takes place within this material. Boulton (1979, 1987) clearly demonstrated the existence of a deforming layer as a result of experiments carried out in a tunnel underneath Breidamerkurjökull in Iceland. The experiments were performed underneath a temperate glacier resting on a non-frozen bed. Echelmayer and Wang Zhongxiang (1987), working in a tunnel underneath Glacier No. 1 in the Tien Shan, which is a cold glacier resting on a frozen bed, also demonstrated movement within this frozen bed (see also Huang, 1992; Jing et al., 1992). From these two extremes it may be concluded that subglacial deformation is possible under a wide range of conditions and hence, that evidence of such deformation can be expected in many places. Apart from these direct observations, the deformation of subglacial material has also been approached theoretically. Based on geophysical data, Alley et al. (1986, 1987a, b) and Blankenship et al. (1986, 1987) assume that a deforming till bed exists underneath Icestream B in the Antarctic. Further considerations can be found in Boulton and Jones (1979), Boulton (1987), Boulton and Hindmarsh (1987), Clarke (1987), Hicock et al. (1989), Alley (1991), Hart and Boulton (1991), Hicock (1992) and Hicock and Dreimanis (1992).

Although there now exists a secure base for the existence of a deforming bed underneath glaciers and ice sheets, this does not mean that much is known about the actual movement of particles in this bed. The results of experiments (Boulton, 1979; Boulton and Hindmarsh, 1987) underneath Breidamerkurjökull demonstrate decreasing velocity with depth, but the final position of the annuli used does not allow an equivocal statement on the kind of movement that particles undergo in a deforming bed. Both rotational and simple horizontal displacement seem to have occurred. Rotational movement was also observed by Engelhardt et al. (1978) through borehole photography on the Blue Glacier in the U.S.A. The existence of rotational movement is easy to explain by the decreasing velocity with depth. The consequence of this decrease is that the top of any particle will move faster than its base, resulting in either shear or rotation. Only elongated or flat particles will remain in more or less the same position because the differential movement between top and base is not enough to overcome friction.

Many Pleistocene till sequences show macroscopic evidence of deformation in the form of shear planes (e.g. van der Meer et al., 1985), deformed soft sediment clasts (e.g. Rappol, 1983; Åmark, 1985), a deformed basal unit (e.g. Rappol, 1987; Rappol et al., 1989; Hart and Boulton, 1991), or otherwise (MacClintock and Dreimanis, 1964; Menzies, 1990a, b; Hicock, 1991; Hicock and Dreimanis, 1992; Hetu et al., 1992). From such sequences we may conclude that there is widespread evidence for subglacial deformation. However, many such sequences are discussed in terms of lodgement or melt-out, not in the tectonic terms of a deformable bed. Such discussion is not applied to massive and homogeneous tills, where macroscopic evidence of deformation is not apparent.

This paper presents the results of micromorphological investigations of tills which have led to the recognition of a variety of microscopic structures. The structures that will be described here all relate to subglacial deformation. After describing the micromorphological method, the structures will be presented starting with a case where deformation is observable macroscopically. The paper will conclude with an assessment of possible applications of the technique.
METHODS AND TERMINOLOGY

The observations presented in this paper are based on a study of several hundred thin sections of glaciogenic deposits, most of which are tills. With the aid of many colleagues (see acknowledgements) and students (van Gelder, 1988; Verbers, 1989; van Beek, 1990; van Ginkel, 1991), samples have been collected from as wide a variety of sedimentary settings as possible, from different countries (The Netherlands, Germany, Austria, Switzerland, Denmark, Sweden, Norway, Spitsbergen, U.K., Ireland, Spain, Argentina, Greenland, the Barents Sea and the Antarctic) and of different ages (mainly last and penultimate glaciations).

In general the characteristics listed by Alley (1991) for the Southern Laurentide till sheets also apply to the tills of the Northwestern European plain, the host of most samples. These characteristics are:

1. the tills are matrix-dominated,
2. often lack observable deformation indicators, i.e. they are massive,
3. exhibit sharp basal contacts with undeformed or weakly deformed sub-till sediments (Ehlers and Stephan, 1979; Rappol et al., 1989),
4. are overconsolidated,
5. sometimes contain limited sorted sediments, some with primary depositional features (Rappol, 1983; van der Meer and Wicander, 1992),
6. are characterized by uniform matrix properties,
7. occur as sheetlike deposits.

Most of the samples discussed here were taken in metal containers (van der Meer, 1994). When collecting the samples care has been taken to avoid present day soils or weathering zones. For the same reasons, samples were collected below any macroscopically visible disturbance like cryoturbations.

After transport to the laboratory in Amsterdam, the samples were air-dried, impregnated with an unsaturated polyester resin (full impregnation in a vacuum chamber), cut, mounted on glass supports and polished to ca. 20 μm thickness. (Murphy, 1986; van der Meer, 1987, 1994).

The samples were studied under an ordinary petrographic microscope, preferably with a low magnification. The terminology used in the description of the thin sections is the terminology that has been developed by pedologists (Brewer, 1976; see also van der Meer 1987, 1994).

Micromorphological features can be grouped under several headings, like texture or plasmic fabric. Of these the plasmic fabric, which is the arrangement of the plasma, is only visible under cross-polarized or in circularly polarized light, because of the high birefringence of (re-)oriented domains. However, whether this is visible depends not only on the strength of the (re-)orientation, but also on the clay and carbonate content.

Firstly, a minimum amount of clay is necessary for the birefringence to show, while generally its strength increases with the clay content. As the strength of the (re-)orientation not only depends on clay content, but also on the stresses applied to the sediment, no general figure for the necessary, minimum amount of clay can be given.

Secondly, fine-grained carbonates disturb the view as they scatter the polarized light again. Thus, highly calcareous tills will not show birefringence clearly, no matter the strength of the (re-)oriented domains. In addition, the clay mineralogy should be taken into account, as swell-and-shrink processes may result in plasmic fabrics which are similar to those produced by certain glacially induced processes like rotation (Lafeber, 1964). For these reasons the clay and carbonate content as well as the clay mineralogy (especially presence of expandable clays) of the samples used in this study has been recorded whenever possible.

MICROMORPHOLOGY OF A MACROSCOPICALLY RECOGNIZABLE DEFORMATION STRUCTURE

Near Lunteren in the central part of The Netherlands, sections have been recorded over a number of years during the working of a large sandpit (van der Meer et al., 1986). The sequence in this pit consists of a glaciofluvial unit in-filling a depression floored by till. The depression is a primary feature at the surface of an ice-pushed ridge. While studying the till we observed that there was a number of directional indicators with a consistent trend:

- the primary basin is oriented NW–SE
- till macrofabrics consistently trend NW–SE
- small-scale drag folds underneath, flutes on top of, and shear planes within the till are compatible with this direction.

The evidence for subglacial deformation at this locality is thus hard to overlook (van der Meer et al., 1986). At one of the sites where detailed profiles were recorded, a small number of shear planes were observed and this structure was sampled for thin sectioning (No. R.745; Figs 14 and 28 in van der Meer et al., 1986). Isolated observations in this sample have been published before (van der Meer, 1987), but for the present study the thin section has been analyzed in greater detail.

When viewed macroscopically, thin section R.745, (Fig. 1) shows the presence of shear planes mainly in the form of incorporated and orientated clay and sand bodies. However, when viewed under the microscope it reveals much more evidence of shearing.

Figure 2 is a detailed sketch of the base of thin section R.745. There are two distinctly different sediment types present. The first is of a diamicitic type, which, because of systematic differences in matrix content, has visually been sub-divided into three subunits (D1–D3). The second sediment type is derived from rhythmites, as can still be discerned.
by the bedding traces (van der Meer et al., 1986; van der Meer, 1994). The overall pattern of the bedding traces indicate that this unit has been strongly deformed. Direct evidence of shear is visible under cross-polarized light: the fine-grained unit displays an anastomosing system of sigmoidal and intersecting discrete shears (Fig. 3). These shear planes can be traced over long distances especially in the continuous fine-grained bands (at the scale of a thin section). There is one set of smaller shears which cuts these continuous lines at a consistent angle. The shears can be described micromorphologically as long and continuous domains with a consistent direction; this is known as a unistrial plasmic fabric. Similar fabrics have been observed in natural clays (Skempton and Petley, 1967; Tchalenko, 1968a, b, 1970; Maltman, 1988) and have also been produced artificially in natural and remoulded clays (Foster and De, 1971; Maltman, 1977, 1987; Tovey and Wong, 1980). These observations are further proof that the highly birefringent lines in fine-grained material in tills (as in sample R.745) are discrete shears as suggested by Menzies (1990b) and Menzies and Maltman (1992).

Even stronger evidence of shear is presented by the zones indicated in a dark pattern in Fig. 2. These zones show a continuous high birefringence throughout. At a number of places a capital K is indicated in such dark zones. This K stands for kinking, because in these places the clay minerals are oriented in a herringbone or kinking pattern. This is demonstrated by the alternating light and dark bands when viewed under cross-polarized light (Fig. 4). This pattern indicates that the clay minerals are oriented in two consistent directions more or less at right angles to each other (van der Meer, 1982, 1987, 1994; Fitzpatrick, 1984; Menzies, 1990b; Menzies and Maltman, 1992; Bordonau and van der Meer, in press). Such a kinking fabric is indicative of strong shearing in a compressional regime. It has also been produced artificially (Morgenstern and Tchalenko, 1967; Tchalenko, 1968a; Foster and De, 1971; Maltman, 1977).

Hitherto deformation structures have only been described from the fine-grained unit. This does not mean that the diamicit subunits do not show such features. These subunits show a skelsepic plasmic fabric, whereby the clay particles are aligned parallel to the surface of the large grains so that they become visible as a zone of high birefringence around these grains (Fig. 5). It should be stressed that the strength of the plasmic fabric is not only caused by the original stress field, but also by the clay and carbonate content of the sample (see above). The skelsepic plasmic fabric is the result of pressures caused by rotational movement (Jim, 1990; van der Meer, 1987, 1994). In this particular sampling locality the clay content and the clay composition (see above) do not give any reason to assume that the skelsepic fabric has not been caused by direct glacial action (example 1, in van der Meer, 1994) as neither the total clay content nor the amount of expandable clays is high.

Higher-up in sample R.745 is a zone which mainly consists of the same diamicitic subunits. Apart from these, only one thin sand lense is present (Fig. 6, note orientation of detail within sample), which represents the actual shear plane as seen macroscopically in the field. In this part of the thin section there are no continuous discrete shears. Instead there is a consistent pattern of shears consisting of relatively short domains (Fig. 7), which is known as a masepic plasmic fabric and which has undoubtedly been caused by the inhomogeneous nature of the material. The consistent orientation of these shears makes a small angle with the orientation of the macroscopic shear plane. This is rather common for such structures (Maltman, 1987; Tchalenko, 1968b, 1970). In addition to these shear planes, this part of the thin section also displays a well developed skelsepic plasmic fabric (Fig. 8). The development of the skelsepic plasmic fabric in this part of the sample was stronger than at the base, described above. The weaker development at the base is due to the presence of fine-grained material in that part of the sample, which offered less resistance to deformation, and thus took up a larger part of the strain.
FIG. 2. Cartoon of part of the base of sample R 745 (see inset for position) demonstrating the distribution of diamicitic and rhythmite-derived material. Compare to Fig. 1. Discrete shears are mainly present in the finegrained zones.
FIG. 3. Anastomosing system of discrete shears in sample R.745. Cross-polarized light, field of view 18.0 mm.

FIG 5. Skelsepic plasmic fabric (oriented domains are parallel to surface of skeleton grains) as a result of rotation in same R 745. Cross-polarized light. Field of view 3.5 mm.

FIG 7. Shears in diametrical material in the upper part of sample R 745. Despite the presence of a lattice-skelsepic plasmic fabric (see text for explanation) the orientation of the shears stands out. Note the strong birefringence in the clay pebble in lower right. Cross-polarized light. Field of view 18.0 mm.
Together, the details of thin section R.745 demonstrate that particles in a deforming glacier bed may, side by side, experience two different types of deformation. The first is planar as indicated by the discrete shears. Within this process the fine-grained particles move relative to each other in such a way that they end up in a plane-parallel position.

The second is rotational, indicated — in this sample — by the skelleptic plasmic fabric.

**MICROSCOPIC DEFORMATION STRUCTURES**

In many till sequences macroscopic structures are not present or not exposed. Deformation can also be identified in homogeneous, massive tills in the form of rotational and/or planar movement of particles.

**PLANAR MOVEMENT**

Discrete shears, or a unistrial plasmic fabric (Brewer, 1976), have only been observed when the till is clayey. As mentioned before, tills that contain a limited amount of fines do not easily show a plasmic fabric.

In most cases the discrete shears that have been observed are less clear than those in the example from Lunteren, presented above. Often, this is caused by the size of the fine-grained inclusions in which they occur, as demonstrated by examples described in van der Meer (1987), Lagerlund and van der Meer (1990) and van der Meer et al. (1993). Figures 9 and 10 show discrete shears as they can be observed in a clayey till exposed along the Shochie Burn in Scotland (Paterson, 1974). The sample was a loose block separated by two fissures. In the field, slickensides could be observed on the structural elements of this till. In thin section the sample consisted of three more or less parallel zones, containing variable amounts of clay and silt, or being of a more diamictic nature (Fig. 9). Discrete shears can be observed in all three zones, under larger magnifications these appear as bundles (Figs 11a and b) of very fine, parallel discrete shears. Occasionally these adopt a step-like arrangement. Overall, the discrete shears show a strong orientation in two directions, with little cross-cutting. In the more clayey zones the discrete shears are associated with a well developed skel-lattisepic or even omnisepic (= all plasma re-oriented) plasmic fabric (Fig. 12). Similar observations were reported by Sitler and Chapman (1955) from tills in Ohio and Pennsylvania, by Johnson (1983) from the Lake Superior Red Clay and by Menzies and Maltman (1992) from tills in Ontario.

An example of unistrial plasmic fabric in fine-grained inclusions is shown in Fig. 13. Although the linear shape...
of the oriented domains is clear, it also shows that they are not as continuous as in clayey till (like the Scottish example). When the shearing continues such intraclasts are torn apart along the shears (Fig. 14). In the end this leads to elongated clasts or shear lenses. In some cases such lenses may be too coarse to show a well-developed plasmic fabric, but in those circumstances the shape of the clasts may be conclusive. This is especially the case if they occur close together and their original larger structure can still be recognized (Fig. 15). Presumably augenshaped lenses of till (Fig. 50C in van der Meer, 1982) pertain to the same category, as do boudinage structures (Fig. 16). The latter have been observed in banded sequences and must relate to an extensional regime.

**ROTATIONAL MOVEMENT**

Rotational movement within tills is shown by a number of phenomena, usually of a circular or an ellipsoidal nature. As such we can recognize a wide variety of pebbles or nodules.

In the first place there are 'pebbles' which consist of till and which do not have an internal plasmic fabric (type I). An example of a macroscopically homogeneous and massive till, build-up of such till 'pebbles' has been described extensively in van der Meer (1994; see also Figs 15 and 31 in van der Meer, 1987). In this example (Fig. 17a) it is obvious that, within the till there are no textural differences, that could have caused the formation of 'pebbles'. Nevertheless the whole till mass is arranged in 'pebbles' which are rounded to an ellipsoid shape in the higher parts of the profile. The 'pebbles' are delineated by the encircling voids. The shape of the 'pebbles' becomes more angular and flattened with depth (Fig. 17). This change from flat to round shapes is interpreted (van der Meer, 1994) as representing the diminishing velocity with depth in a deforming bed. It would appear that deformation within such profiles, of which several have been observed, starts with brecciation which produces angular structural elements (Menzies, 1990a). The ongoing deformation and the resulting interaction between the structural elements produces more rounded shapes. It looks as if in this type of deformation the bed has acted as a bed of ball-bearings or marbles. I propose to use the term 'marble-bed' structure for these tills. As there is no internal plasmic fabric in the 'pebbles' (Fig. 17c) it must be assumed that the pebbles moved as a whole and that no internal reorientation of fines occurred. This must have (as yet unknown) implications for the water content of the till during deformation, although, for the time being it is assumed that the water content has been low.

The second type of 'pebble' structure consists of fine-grained material and is still part of the original sediment host (type II). In this sense it resembles the 'marble-bed' structure described above. The difference with the till 'pebbles' (apart from composition) is that in this case the 'pebbles' do have a distinct internal plasmic fabric. In some cases they can best be recognized by this plasmic fabric and not by a pattern of voids (Fig. 18). Up to now the 'pebble' structure has been recognized in a series of samples from Broomfield in Essex, U.K. (Whiteman, 1987). Figure 18 demonstrates some of these clay 'pebbles'. Figure 18a (plane light) together with Fig. 18b (cross-polarized light) clearly visualizes the difference in orientation of the plasmic fabric of pebbles and host sediment. It is probable that the deformation of this type of material, leading to the formation of 'pebbles', was a much more plastic process than the formation of the first type of till 'pebbles' described above. However, one must bear in mind, that clays behave different from tills regardless of water content.

Type III of 'pebble' structure consists of isolated elements of either till or fine-grained sediments.
FIG. 8. Skelsepic plasmic fabric is also present in the diamictic material in the upper part of sample R.745. Note the small angle that shears make to the sand lense (compare to Fig. 1). Cross-polarized light, field of view 18.0 mm.

FIG. 10. Discrete shears in sample R.756. Because of the clear presence of two directions of oriented domains, this is also known as a bimasepic plasmic fabric (long, straight oriented domains in two directions). Cross-polarized light, field of view is 9.0 mm.
FIG. 11a. When the discrete shears in sample R.756 are viewed at larger magnification it becomes obvious that the shears are actually made up of bundles of smaller domains. At this scale it becomes again appropriate to talk about shear zones. Cross-polarized light, field of view 4.5 mm.

FIG. 11b. Discrete shears in sample O.639 (Irish Sea Till) from Clonca, Ireland, can be seen also to consist of bundles and not of one single plane, despite a lower clay content. Cross-polarized light, field of view 5.6 mm.
FIG. 12. In this part of sample R.756 all the fine material is (re)oriented. In the lower lefthand and the upper righthand corner the resulting pattern should be classified as latti-skelsepic, in the remaining part of the sample as omnisepic. Note the discrete shears that run as parallel, dark bands from top left to bottom center. Cross-polarized light, field of view 18.0 mm.

FIG. 13. Fine grained intraclast in sample Mi.28 (Elsterian till) from Süderheide, Germany, shows discrete shears, also known as a unistrial plasmic fabric. Note the clear plasmic fabric in smaller intraclasts. Shape, orientation and plasmic fabric all point at planar movement. Cross-polarized light, field of view 18.0 mm.
FIG. 14. Elongate intraclast in sample R.748 (Saalian till) from Lunteren, The Netherlands, shows the effect of continuous shearing. Development of cracks leads to the formation of smaller, stable intraclasts like the one shown top left. Plane light, field of view 10.6 mm.

FIG. 15a. Sheared intraclast in sample O.838 (Saalian till) from Emmerschaam, The Netherlands. The shape of small fragments in combination with their position demonstrates that a larger intraclast has been sheared as a first step in the production of rounded intraclasts like the ones on top. Plane light, field of view 18.0 mm.

FIG. 15b. A large magnification is necessary to demonstrate the presence of a (skel-lattic)plasmic fabric in the sheared intraclast depicted in Fig. 15a. This demonstrates that deformation does not automatically lead to a plasmic fabric. Cross-polarized light, field of view 3.5 mm.
FIG. 15c. For comparison a detail of sample Mi.54 (Elsterian till) from Wellen, Germany, shows a coarse-grained tense, highlighted by postdepositional Fe-precipitation, the shape of which indicates deformation. Plane light, field of view 11.2 mm.

FIG. 16. Sample O.806 (Irish Sea Till) from Ballycotton, Ireland, demonstrates deformation by boudinage of a diamicitic layer. Note shearing at righthand side. Plane light, field of view 18.0 mm.
FIG 17b. Detail of sample R.971 from the decalcified part of the Wijnjewoude profile showing well-rounded structural elements. Plane light, field of view 18.0 mm.

FIG 17c. When viewed in cross-polarized light and at the same magnification it is obvious that in sample R.971 deformation has only lead to a very weak development of the plasmic fabric. This was found in the whole Wijnjewoude profile (not depicted in subsequent figures).
FIG. 17d–f. Details of resp. samples R.972, R.973 and R.974 in the Wijnjewoude profile, demonstrating the increasing angularity with depth of structural elements. Field of view 18.0 mm in all figures.
FIG. 18a. 'Pebble' type II in sample Mi.211 (till) from Broomfield, U.K., consisting of the same material as the host sediment. The large pebble in top centre is clearly visible, other rounded structures in this part of the sample are not. Plane light, field of view 7.0 mm.

FIG. 18b. The same detail of sample Mi.211 seen in cross-polarized light, demonstrates the existence of rounded structures depicted by plasmic fabrics in the host sediment, and not by voids. Note the unistrial plasmic fabric (discrete shears) in the host sediment. Although the pebbles internally do not seem to have a well-developed plasmic fabric, this is only apparent and caused by turning the stage. Showing the pebbles with their internal plasmic fabric lessens the contrast between pebbles and host. Field of view 7.0 mm.
FIG. 19a. A thin clay band in sample O.644 (Weichselian till of British provenance) from the Dutch sector of the North Sea, is dissected by short and parallel discrete shears. The resulting plasmic fabric shows angular pebbles. Cross-polarized light, field of view 5.2 mm.

FIG. 19b. By turning the stage a second set of similar discrete shears becomes visible, which explains the angular nature of the resulting isolated pebbles. Note that this set of shears continues for a short distance into the surrounding host diamicton. Cross-polarized light, field of view 5.2 mm.
FIG. 19c. Pebble type III in sample R.669 (Saalian till) from Lunteren, The Netherlands, is characterized by numerous intraclasts. In this case both diamicitic and clay/silt intraclasts are present in a different and inhomogeneous diamicitic host. Development of cracks and consequent shearing off of protuberances increases the roundness of the intraclasts. Plane light, field of view 18.0 mm.

FIG. 19d. Same detail of sample R.669 in cross-polarized light demonstrates the strongly developed internal plasmic fabric of all intraclasts. Note the difference in plasmic fabric development in the host sediment. At this magnification it is difficult to see that cracks in intraclasts are often related to discrete shears. Field of view 18.0 mm.
FIG. 19c. Detail of sample R.748 (Saalian till) from Lunteren, The Netherlands, shows the resulting rounded intraclast of stable shape ('pebble' type III) which is the result of processes outlined in Figs 19a–d. Plane light, field of view 4.5 mm.

FIG. 19f. The same detail seen in cross-polarized light and at the same magnification demonstrates the well-developed omnisepic plasmic fabric in this intraclast. Note that the plasmic fabric is partly developed as a 'shell'.
FIG 19g. 'Pebble' type III of the same stable shape is present in sample Mi.595 (Irish Sea Till) from Enniskerry, Ireland, as demonstration of the widespread occurrence of such shapes. Plane light, field of view 3.5 mm.

FIG 20a. Detail of sample Mi.212 (till) from Broomfield, U.K., shows tails of skeleton grains encircling a small gravel particle, acting as core stone ('milky way' or 'galaxy structure'). Note the torn off fragment of the gravel particle in SW quadrant. All this testifies to the rotational origin of this structure. In the SE quadrant alternating zones of fine-grained material and skeleton grains (the tails) extend for at least the diameter of the gravel particle. Plane light, field of view 13.8 mm.
FIG. 20b. The same detail of sample Mi.212 seen in cross-polarized light (same magnification). The tails of fine skeleton grains are less well visible, but note the clear skelsepic plasmic fabric around part of the core stone. This demonstrates the genetic relation between this type of fabric and the 'milky way' structure.

FIG. 20c. A similar, though less spectacular 'milky way' structure is visible in sample O.809 (Irish Sea Till) from Ballycroneen, Ireland. Note that more than one round pattern can be discerned. The resulting structure can be described as turbate. Plane light, field of view 5.6 mm.
FIG. 20d. Detail of sample Mi.595 (Irish Sea Till) from Enniskerry, Ireland, demonstrates that core stones are not necessary to produce a turbate structure, as long as something acts as a node during rotation. Alternatively the core stone may be present outside the plane of the thin section. Plane light, field of view 5.6 mm.

FIG. 20c. Detail of sample O.664 (Saalian till) from de Woude, The Netherlands, shows a partly inconspicuous turbate structure. It is most prominent in the lunate lining-up of skeleton grains near the top. Plane light, field of view 9.0 mm.
FIG. 20f. The same sample seen under cross-polarized light and at the same magnification shows that, despite the turbate structure, there is no plasmic fabric development. Only at larger magnifications a very weak skelsepic plasmic fabric becomes discernable.

FIG. 20g. Detail of sample Mi.211 (till) from Broomfield, U.K., shows, besides pebbles type II, a complex turbate structure. Plane light, field of view 11.2 mm.
FIG. 20b. The same sample seen under cross-polarized light and at the same magnification. Comparison with Fig. 20f will show that sample Mi.211 does have a better developed (skeltepie) plasmic fabric. It shows by the overall brighter colour of the matrix.

FIG. 21a. Sample Mi.599 (Irish Sea Till) from Shanganagh/Corbawn Lane, Ireland, shows triangular extensions to a small gravel particle. This structure is known as a pressure shadow and is clearly related to shear. Plane light, field of view 9.0 mm.
FIG. 21b. The same sample seen under cross-polarized light and at the same magnification shows that the clay lines possess a clear plasmic fabric. The lack of a plasmic fabric in the diamicitic triangle to the left of the gravel particle demonstrates the nature of the pressure shadow.

FIG. 21c. A double example of a pressure shadow comes from sample R.167 (Würm till) from Léchelles, Switzerland. Both the large gravel particle and the small one underneath show the structure. Plane light, field of view 5.6 mm.
FIG. 21d The detectability of a pressure shadow in sample Mi.161 (Saalian till) from Steenwijk, The Netherlands, is increased by the presence of Fe-stained clay. Plane light, field of view 7.0 mm.

FIG. 22a Sample R.418B (Würm till) from La Tuffierc, Switzerland, possesses separations of fine material. The presence of grading to both sides (dark material is clay, greyish material is silt) and because of cross-cutting relations these features are interpreted as water-escape structures. Sample comes from the base of the till which overlies gravels. Cross-polarized light, field of view 18.0 mm. The high carbonate content prevents detection of a plasmic fabric.
FIG. 22b. Similar separations can be seen in sample O.940 (Wisconsinan till) from Bariloche, Argentina. A shear plane possibly cuts obliquely through this unit. Sample comes from the base of the till which overlies gravels. Plane light, field of view 18.0 mm.

FIG. 23. Crushed grains in sample O.606B (Saalian till) from de Woude, The Netherlands. Some grains are completely crushed, while others still have an intact core. Note displacement of part of the large grain in top centre. Cross-polarized light, field of view 3.5 mm.
encased in the till body. Production of such 'pebbles' starts with brecciation of the till mass or a till bed, or of fine-grained bands within the till. Usually such 'pebbles' are simply explained as being 'reworked'. It should be realized that reworking starts with deformation. It has been possible to recognize, by combining observations in different samples, the whole sequence from brecciation of fine-grained bands to well rounded, isolated 'pebbles'.

The first step can be observed in a till from the North Sea (van der Meer and Laban, 1990) which shows the brecciation of a thin clay band (Figs 19a and b). This clay band is cut by numerous short and intersecting discrete shears. As the shape of the resulting 'pebbles' demonstrates continuation of movement along the shears, this leads to angular structural elements. Such angular structural elements have been described in earlier papers on the subject (van der Meer et al., 1983, Plates 1C and 1G, 1985). After these elements become detached, protuberances and edges are quickly worn off by rotational movement as evidenced by the development of cracks across them (Figs 19c and d). Once they are well rounded the 'pebbles' seem to be little influenced by further movement. Such stable 'pebbles' have been observed in a number of samples, not only from The Netherlands (Figs 19e and f), but e.g. also from Ireland (Fig. 19g; van der Meer et al., 1994) and Sweden (Lagerlund and van der Meer, in preparation). In most samples both till and fine-grained 'pebbles' can be observed side by side (van der Meer et al., 1983, 1986; van der Meer, 1987, 1994). The till 'pebbles' differ from the 'marble-bed' type of till 'fabric' by their obvious internal plasmic fabric (Fig. 19). a feature they share with the fine-grained 'pebbles'. As such it is assumed that this means that the till had acquired this plasmic fabric before brecciation occurred. In most cases the internal plasmic fabric of the 'pebbles' can be described as skel-sepic or skel-lattisepic (van der Meer et al., 1983). Production of the last type of till 'pebbles' was thus presumably different from the formation of till 'pebbles' as described for the 'marble-bed' structure.

Different circular elements that can be discerned at the macroscale consist of a clear arrangement of skeleton particles. It has been known for some time that fine skeleton particles may be oriented parallel to the surface of a large skeleton grain (Figs 20a, b and c), the 'core stone' (Sitler and Chapman, 1955). This arrangement, that can be described as a 'milky way' or galaxy structure, is assigned to rotation, which causes the small grains to adopt a position of least resistance parallel to the larger grain. Examples of this have been described in van der Meer (1994) and van der Meer et al. (1993). Because this alignment was known, it was not really surprising to find circular alignments of skeleton grains without a 'core stone' (Figs 20d–h) in the same samples as those which show the parallel orientation (van Ginkel, 1991). The circular arrangements of skeleton grains not only have no obvious, coarse node around which they formed, but there is also no textural difference between the centre and the arrangement itself. Still, this centre acted as the node during rotation and we can hypothesize that it may have been a drier and thus harder spot within the deforming till bed.

A feature which is clearly related to this circular arrangement is the pressure shadow (Fig. 21). This feature, which is well known macroscopically (e.g. Hart and Boulton, 1991) is a good indicator of rotation due to shearing (Simpson and Schmid, 1983; Hamner and Passchier, 1991). However, it only does so if the tails are oriented eccentrically. In most of the observed cases the actual tails are not so clearly defined that the interpretation of relative movement is straightforward. Pressure shadows in tills have been observed a number of times (van Beek, 1990; van Ginkel, 1991), but no systematic study has yet been carried out.

In a number of cases the structures described above are found in close association with a distinct plasmic fabric. Whenever this plasmic fabric can be clearly discerned it should be described as a skel-sepic plasmic fabric (oriented domains parallel to surface of large grains), though lattisepic plasmic fabrics (short oriented domains in two perpendicular directions) or omnisepic plasmic fabrics (all plasma re-oriented) have also been observed. The association of different rotational structures and a skel-sepic plasmic fabric gives further support to the interpretation of the skel-sepic plasmic fabric as being the result of rotational movement (Sitler and Chapman, 1955). In many cases it can be observed that a lattisepic plasmic fabric is associated with a skel-sepic plasmic fabric (see also Tsui et al., 1988), and the proper terminology should be skel-lattisepic or latti-skelsepic plasmic fabric (depending on which of the two is dominant; Brewer, 1976). Hence we may assume that they are also genetically related. This is supported by Jim (1990) who indicates an ellipsoidal movement for lattisepic plasmic fabrics (see also Menzies and Maltman, 1992).

An omnisepic plasmic fabric indicates that all the fine material is (re-)oriented in one or more distinct directions. Although this implies a strong stress-field, and although it is found associated with rotational structures, the actual motions of the particles in this type of plasmic fabric are difficult to deduce.

**ADDITIONAL OBSERVATIONS**

Additional indicators of subglacial deformation exist in the form of dewatering or water-escape structures and crushed (quartz) grains (van Ginkel, 1991; van Ginkel and van der Meer, in preparation).

Dewatering structures related to shear can be expected to show up in different ways. Muller (1983) indicates that fissility is a property that is related to escape of pore water during lodgement. It should be stressed that his conception of lodgement involves deformation. Rappol (1983) described matrix-free sand grains of unknown origin in the open planes of a fissile...
till. It is here proposed that such grains may well be the result of washing due to dewatering. Observations on the microscopic nature of fissility (van der Meer, 1987), i.e. lack of continuity of fissures, lack of textural differentiation of the sediment host, can be regarded as supporting M ullers views.

Murray and Dowdeswell (1992) described the effect of deformation of sedimentary glacier beds on through-flow and concluded that it increased because of dilation. The same effect had been described before by Boulton et al. (1974). Effectively there seems to be no difference between fissility and dilation.

Menzies and Maltman (1992) described a polygonal distribution of fine grained plasma within coarser grained matrix plasma and suggested a relation to mobile porewater.

Water escape structures related to more forceful dewatering, have been observed several times ( van der Meer, 1987; Van Beek, 1990) and are shown in Fig. 22. These were all found at the base of till sequences overlying coarse-grained outwash, where they show as very thin and short, clayey to silty, sometimes graded bands. Although it can be assumed that grain separations are caused by water escaping under pressure, features of this type have not been studied enough to definitely relate them to the known deformation structures in the same samples. Related observations have been described by Menzies (1986) who observed clay illuviation in till; he interpreted this clay translocation as having occurred subglacially. It is not suggested that dewatering or water-escape structures alone are evidence of subglacial deformation. Only in combination with other evidence can it be regarded as such.

Sufficient studies of crushed quartz grains have been carried out to be treated as a separate deformation structure. There are indications from studies based on SEM work ( e.g. Mahaney et al., 1988) as well as on studies of grain size distribution ( e.g. Boulton et al., 1974) that crushed quartz grains have a wider occurrence ( L. Owen, pers. commun.; Owen and Derbyshire, 1988). The assumption that fines are produced by the continuous production of single flakes, rather than the complete shattering of grains, is based on studies of grains that have been removed from their surroundings. In thin sections grains can be observed in their original position, and the results of such an observation from several thin sections from one borehole in The Netherlands is recorded here (van Ginkel, 1991; van Ginkel and van der Meer, in preparation). In these samples several zones of crushed quartz grains were observed at different depths. Generally speaking these zones do not seem to have an obvious position or shape, although they all possess sharp boundaries.

The characteristics of the crushed grains vary from those which have been crushed completely, to those where the core is still intact ( Fig. 23). The grains that have been crushed completely have lost their original shape and the fragments have been separated from each other. In rare cases it is possible to observe that only half a grain had been crushed and that the fragments are all in close proximity, clearly indicating limited (subglacial) movement.

Currently, the implications of crushing quartz grains in a subglacial environment are little understood, although it is likely that point-loading leads to pressures that are sufficiently high to shatter the grains. This must have consequences for our understanding of the role of porewater pressures in the subglacial environment. More information will be needed before such relations can be understood. The co-existence between dilation and crushing noted by Boulton et al. (1974) has not been observed in thin sections.

The crushed grains described above were observed in samples that also demonstrated the circular arrangement of skeleton grains. Although other evidence of deformation is distinctly lacking in the thin section samples from this borehole, the association of crushed grains and a circular arrangement is considered adequate evidence for a deformational origin for the crushed grains. A future implication of this research is that the occurrence of crushed grains will provide a basis from which it may be possible to deduce figures for moisture content of the sediment at time of deformation.

DISCUSSION AND CONCLUSIONS

All the samples described above come from sites without any evidence of postdepositional disturbance of the tills by slope movement, weathering or soil formation. Since the amount of expandable clays in all samples is low (Haldorsen et al., 1989; Rappol et al., 1989) where known, indication of movement can be related to movement in the deformable bed either during or after deposition. The observations cited above clearly demonstrate that this movement can be planar as well as rotational.

It is possible that microscopic deformation structures may also be the result of surficial processes like creep or flow such as would be developed in flow tills. However, it should be stressed that flow tills from Spitsbergen (van der Meer, 1987) and the Alps (unpublished) do not show any of the deformation structures described above. These flow tills can be characterized by the fluid shape of soft sediment inclusions combined with a lack of plasmic fabric. Periglacial slope processes may form similar features by the process of creep, such as 'pebbles' and skewespic plasmic fabric (van Vliet-Lanoë, 1985). However, as indicated in van der Meer et al. (1993) these periglacial forms can be differentiated from the glacial by the high porosity of periglacial slope deposits, which is far greater than that of basal tills.

Although the approach adopted in this paper has emphasized individual micromorphological characteristics, it is important to consider the various attributes as part of micromorphological assemblages which, in some cases can be related to macroscopic features such as shear structures. For instance sample R.745
demonstrates that several deformational forms such as discrete shears, kinking, till and clay 'pebbles', and a well developed skelsepic plasmic fabric occur side by side, although in certain cases only one type of deformation may be recognized. In the example where only till 'pebbles' have been produced (marble-bed type), no re-orientation of the clays (e.g. leading to a skelsepic plasmic fabric) has occurred. The observations also demonstrate that massive tills do contain genetical information of deformation when studied at the microscopic scale.

Microscopic evidence of subglacial deformation is listed in Table 1 and depicted diagramically in Fig. 24.

In the descriptions of the microscopic deformation structures mention has been made of the relationship with water content of, and porewater pressure in

FIG. 24. Illustration of the most common microscopic deformation features observed in subglacial sediments. See Fig. 26 for the (tentative) relative position of each feature in a deforming bed.
TABLE 1. Microscopic structures indicative of a deformation till. Note that the codes have been used in Fig. 26 to indicate their relative position in a deforming bed

(1) Evidence of Planar movement
(a) the shape of structural units in the till
(b) discrete shears or a unistrail plasmic fabric
(c) a kinking plasmic fabric
(d) a masepic plasmic fabric and its varieties

(2) Evidence of Rotational movement
(a) 'pebble' type I: marble bed structure (till 'pebbles' without internal plasmic fabric)
(b) 'pebble' type II: in situ 'pebbles' with internal plasmic fabric
(c) 'pebble' type III: rounded intraclasts with or without internal plasmic fabric
(d) circular alignment of fine skeleton grains with or without 'core'
(e) pressure shadows
(f) skelesepic, lattisepic and omnisepic plasmic fabrics or combinations of these

(3) Other
(a) crushed grains
(b) dewatering and water-escape structures.

the deforming till mass. It is most probable that these two properties are of great importance in the resulting type of structure. However, as indicated in the section on methods and terminology, clay content and clay mineralogy are other factors that determine the microstructures of tills. From evidence used to produce this paper it appears that in NW Europe clay mineralogy is less variable than clay content. Attempts to use microscopic deformation structures to reconstruct Pleistocene (or even older) subglacial conditions will require an evaluation of these structures in relation to water content and porewater pressure along with knowledge of clay content and clay mineralogy. This can be tested with controlled experiments in the laboratory, although the quality of the results is constrained by the dimensional properties of shearboxes (e.g. Murray and Dowdeswell, 1992) which greatly restrict the size of materials that can be investigated. The variety of the results presented here can also be tested by samples collected from present day environments. However, even this is constrained by the difficulty of measuring the desired parameters in situ and the difficulty of finding sites that are analogous with the Pleistocene evidence. For instance, alpine glaciers on a steep rocky slope are not comparable because of relief and bedrock proximity, and the Greenland and Antarctic ice sheets are in different latitudes.

It is the opinion of the author that at present, the best approach to the problem is theoretical. For instance, the diagram presented by Alley (1991) shows that faulting occurs at the base of the deforming till, and ploughing occurs at the top (Fig. 25). Between these extremes a zone of pervasive till shearing accommodates most of the velocity. It is reasonable to expect that the depth of the deforming till will decrease for a lower water content and that under those conditions the zone of faulting may increase at the expense of the zone of pervasive shearing.

Clay and fine silt content will also influence the depth of the deforming till. At a given water content, a low clay content should result in a higher permeability, which will lead to a thinner deforming bed. It is possible that a low clay content may also lead to an increase in the zone of faulting, relative to the zone of pervasive shearing. Taking these considerations into account, Fig. 26 attempts to relate the microscopic features listed in Table 1 and Fig. 24 to the different zones of the deforming till bed.

Dewatering structures are therefore likely to be expected at the transition between the zone of faulting and the zone of pervasive shearing. Within the zone of faulting dilation accounts for higher hydraulic conductivity which may lead to washing of grains. In this case zone of faulting will be the domain of structures 1a (faulting of structural units). 3a (crushed grains) and part of 2a (marble bed structure). The remaining structures will be typical of the zone of pervasive shearing. This does not imply a rigid locational distribution although it is probable.

FIG. 25. Diagram, after Alley (1991), indicating the different deformational processes and their position in the glacial/subglacial system. In Fig. A a glacier bed with a relatively high water and/or clay content is implied. Figure B demonstrates one of the possible changes in configuration in case of a low water and/or clay content. It should be realized that such changes occur both in space (horizontally and vertically) and in time (in an accreting till mass the zones move upward).
that structure 1c (kinking) and 2b (in situ 'pebbles' with internal plasmic fabric) will be found preferentially at the base of the zone of pervasive shearing, where strain is highest. Structures 1b (discrete shears), 1d (masepic plasmic fabric) and 2e (pressure shadow) are expected higher in the deforming bed, with structures 2c (rounded intraclasts) and 2d (circular alignments) possibly occupying the highest level. In accordance with the same principles, plasmic fabrics are expected to be associated with circular rotational movement at the base, and elliptical movement near the top because of the higher velocity. The implication of this model is that a skelsepic plasmic fabric is expected lower down in the profile, a lattisepic plasmic fabric is expected higher up, and the omnisepic plasmic is likely to occupy the highest position.

This pattern will be complicated further by the fact that over time water content is unlikely to be constant causing variations over time in the thickness of the deforming till and the thickness of the constituent zones. Further complication arises from the fact that all these processes may operate in an accreting till mass with the different zones (themselves of variable thickness) moving upwards as the sequence thickens. At the base of the deforming bed till structures are fossilized irrespective of the processes operating at the time of fossilization. Given the fact that Boulton and Dobbie (1993) indicate that the thickness of a deforming bed may vary between 4 and 47 m depending upon the range of conditions, it can be expected that a highly variable microscopic pattern will develop in Pleistocene tills.

Although quantification is not available, the overall impression obtained from thin section studies, is that deformation structures occur in the majority of samples from Pleistocene tills. This has several important implications:

1. the studied tills have experienced subglacial deformation,
2. observed microstructures are not related to deposition and thus tills do not show sedimentary facies,
3. microstructures are related to deformation and are an expression of tectonic facies,
4. subglacial tills should be described in tectonic terms,
5. as long as sedimentary terms are used to describe subglacial tills, progress will be restricted in the understanding of subglacial processes.

In conclusion, it is apparent that recognition of the microscopic structures described above enables reconstruction of subglacial conditions. This type of information is vital for modelling the behaviour of Pleistocene glaciers and ice sheets; which is itself a pre-requisite for the prediction of the future behaviour of existing ice bodies.

Where surface exposures show macroscopic structures micromorphology evidences the quality of the reconstruction. Where the surface exposures show massive, structureless tills micromorphology may be the only available technique for genetic studies. Of especial importance is the fact that this technique can be applied to borehole material, where, in the case of samples taken from the sea-bed, no additional information is available. Hitherto, this type of material has given little more information often than a description as a diamict, which in turn would be termed a 'till' assuming it occurred in an acceptable lithostratigraphic position (van der Meer and Laban, 1990).

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