Pore size, shape and connectivity in tills and their relationship to deformation processes

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Abstract

This paper describes how till bulk porosity and pore shape, size and connectivity relate to till deformation processes. Methods have been developed to examine till pores microscopically using thin section analysis, scanning electron microscopy (SEM) and X-ray computed micro tomography (µCT). Porosity is quantified using digital image analysis of thin section images from the petrographic microscope and SEM and from X-ray µCT. These methods were applied to a selection of Pleistocene tills with diverse properties. The micromorphological techniques have allowed porosity to be related to other till microstructures. Most of the microstructures examined, including the pores, have been interpreted to be indicative of either plastic or brittle subglacial deformation and the type and extent of till deformation has been interpreted to affect bulk porosity, pore type and pore connectivity.

1. Introduction

Despite increasing interest in till structure in the past 30 years, there is still limited knowledge about the geotechnical characteristics of tills, especially porosity. Till porosity has largely been ignored, principally because primary pore permeability has been found by some authors to be almost inactive in transporting groundwater. To the authors' knowledge, there is one publication about till porosity outside the field of hydrogeology: Murray and Dowdeswell (1992) describe shear deformation in laboratory tests that demonstrates that dilatation and till porosity increases along shear zones. There are few papers describing pore shape, size and connectivity. But porosity is an intrinsic property of any sediment, and must provide insight into that sediment's stress and formation history.

The aims of this study have been to identify methods of till porosity measurement, determine percentage porosity, describe pore shape, size and connectivity, and to interpret these results in the context of processes of deformation by which till pores have been formed and destroyed. This paper presents the results of till pore, and other microstructure, analyses on a selection of Pleistocene basal and flow tills, or debris flows, with diverse properties. We have interpreted modes of till deposition and deformation from pore types and bulk porosity, together with other till structures.

In this paper, the term 'porosity' relates to relatively small voids in till such as those associated with fissile structures and 'marble bed' structures (van der Meer, 1993, 1996), and smaller voids. (A glossary at the end of this article gives definitions of the terminology used.) The term 'porosity' does not here relate to very large voids such as extensive fissures, as examined elsewhere (e.g. Kazi and Knill, 1973; Grisak and Cherry, 1975; Haldorsen et al., 1983; Keller et al., 1988; Fredericia, 1990; Klint and Gravesen, 1999; Klint, 2001).

2. The study area

The study area was County Laois in the Irish midlands (1719 km²) (Fig. 1). County Laois can be divided into three main topographic and solid geology regions: the Slieve Bloom Mountains, in the northwest, are composed of Silurian shales and Devonian sandstones, the lowlands are
properties were collected from 13 sites in County Laois mapped as basal in origin. Basal tills were described as clay fractions separated using the hydrometer method. We clast lithology (Fig. 1), based on stone counts of the 5-10mm fraction. In all, 204 till bulk samples were analysed for this research. The tills were classified according to dominant bedrock lithology, with sample numbers (described in the text), bedrock boundaries, contours and inset of county location. From Kilfeather (2004).

composed of Lower Carboniferous limestones, and the Castlecomer Plateau, in the southeast, is composed of Upper Carboniferous shales and coal measures.

3. Methods

Detailed surface mapping of the Quaternary geomorphology of County Laois, and bulk sampling, sieving and stone count analysis of tills (Kilfeather, 1999), formed the basis of this research. The tills were classified according to dominant clast lithology (Fig. 1), based on stone counts of the 5–10mm fraction. In all, 204 till bulk samples were analysed for particle size distribution and petrography; 59 had the silt and clay fractions separated using the hydrometer method. We investigated the potential of using particle size distributions to derive estimates of till porosity.

In 2001, 24 undisturbed till samples with diverse properties were collected from 13 sites in County Laois (Fig. 1, Table 1). Most of the samples were taken from tills mapped as basal in origin. Basal tills were described as 'mature' where they contained sub-rounded and striated clasts, were matrix supported, normally to well consolidated and tended to be relatively thick. Basal tills were described as 'immature' where they contained only angular unstriated clasts, little or almost no matrix and were poorly consolidated. Immature tills were often seen directly overlying bedrock and could be just a few metres thick. At two sites the sediments were interpreted as flow till (Sites L and M, Fig. 1). These sediments were diamictons interbedded with sorted and bedded sands and gravels. The contacts between the diamictons and sorted sediments interdigitated and there were load, fold and flame structures at the contacts. Elongate clasts in the diamictons were vertically oriented, indicating sinking of clasts in a wet matrix. The diamictons contained boudins of sand and silt, were poorly consolidated but fissile.

The undisturbed till samples were acetone dried and then impregnated with crystic resin in a vacuum chamber. After impregnation, the samples were hardened and then cut in half to be made into thin sections. One half was polished and then mounted on glass, ground to a thickness of about 25 μm and cover-slipped. (See Lee and Kemp, 1992 for full details of the laboratory procedures.)

The thin sections were analysed on a Petroscope and a petrographic microscope, using magnifications of ×25–×85 and ×63–×520, respectively. The microstructure was described according to the terminology of Brewer (1976), van der Meer (1993, 1997), Menzies (2000) and Stoops (2003), under the headings: texture, structure, voids, neoformations and plasmic fabric. The size, shape and arrangement of all of these features was described and classified. This was followed by interpretation of the thin sections. The pore descriptions from thin sections are limited to those >25 μm in diameter because this is the approximate thickness of the thin sections, so smaller pores cannot be properly discerned.

Scanning electron microscopy, of polished sub-samples from seven of the remaining resin-impregnated till blocks, was used to examine and describe pores that were too small to be observed in thin section. Images were taken in the backscattered electron imaging (BEI) mode at magnifications of ×25, ×75, ×230 and ×1300. This provided a good overlap with the light microscope analysis and allowed pores to a minimum of about 1 μm to be studied; pores of a smaller size were not considered in this study.

Digital image analysis, of photomicrographs (petrographic microscope photographs) from 10 thin sections and from SEM images of 14 sub-samples, was used to measure percentage porosity in two-dimensions. The image analysis was performed using Idrisi software, following the methodology of Zaniewski (2001) and Zaniewski and van der Meer (2005). Photomicrographs were taken at ×63, ×125 and ×320 with the sample kept in the same position on the microscope stage.

Experimental X-ray computed micro tomography (μCT) was carried out on fourteen sub-samples from seven resin-impregnated till blocks, in order to investigate the
Table 1
Bulk sample attributes, thin section sampling details and micromorphological features including pore types and their relative abundance in thin sections

<table>
<thead>
<tr>
<th>Field sites and descriptions</th>
<th>Bulk sample attributes</th>
<th>Thin section sample attributes</th>
<th>Plasic fabrics</th>
<th>Voids</th>
<th>Neoformations</th>
</tr>
</thead>
<tbody>
<tr>
<td>TULI Type</td>
<td>Field description all matrix supported unless otherwise stated</td>
<td>Petrography, %</td>
<td>Texture, %</td>
<td>Main glacial structures</td>
<td>Fabrica</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quartzite</td>
<td>Feldspar</td>
<td>Kaolinite</td>
<td>Lepidoblastia</td>
</tr>
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<td></td>
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<td>matrix</td>
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<tr>
<td>A. Kilfecither, J.J. M. van der Meer</td>
<td>147 25 10 10 18 35</td>
<td>47</td>
<td>7</td>
<td>3208* 2</td>
<td>ps</td>
</tr>
<tr>
<td>B. well consolidated fossil diamicts</td>
<td>18</td>
<td>12</td>
<td>9</td>
<td>10 49</td>
<td>41</td>
</tr>
<tr>
<td>C. normally consolidated, slightly clay poor, fossil diamicts</td>
<td>42</td>
<td>12</td>
<td>23</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>D. well consolidated, fossil diamicts</td>
<td>82</td>
<td>22</td>
<td>13</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>E. over-consolidated fossil diamicts</td>
<td>73</td>
<td>12</td>
<td>8</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>F. normally consolidated diamict</td>
<td>15</td>
<td>6</td>
<td>2</td>
<td>18</td>
<td>47</td>
</tr>
<tr>
<td>G. poorly consolidated, clast dominated to clast supported diamicts</td>
<td>97</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>37</td>
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<tr>
<td>H. bored well consolidated fossil diamicts (skeletal sediment beds)</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>1</td>
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<td>I. over-consolidated fossil diamicts with sand lenses and stretched clay beds</td>
<td>0</td>
<td>0</td>
<td>23</td>
<td>31</td>
<td>45</td>
</tr>
<tr>
<td>J. normally consolidated, clast rich diamicts</td>
<td>28</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>K. over-consolidated diamicts</td>
<td>11</td>
<td>7</td>
<td>8</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>L. normally consolidated diamicts everywhere bored soil and sand with rare structures</td>
<td>no bulk sample</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M. over-consolidated diamicts interbedded with sorted sediments</td>
<td>61</td>
<td>29</td>
<td>6</td>
<td>4</td>
<td>13</td>
</tr>
</tbody>
</table>

Lithology: ps = plasma supported, gs = grain supported, gd = grain dominated.

n/a = samples that did not have fines separated by hydrometer
* = very few/poorly developed, o = rare/poorly developed, oo = more common/better developed, ooo = frequently occurring/well developed.
* = present
* = present and only seen in SEM
*7 = uncertainty about whether the planar voids relate to a fissile or marble bed structure or whether their orientation is random
horizontal voids
value of this technique for examining pores in three-dimensions (3D). X-ray CT reveals 3D structure as determined by variations in density, and to a lesser extent atomic composition. The samples can be viewed as multiple cross sections or as reconstructed 3D blocks (Fig. 2). Microfocus X-ray CT instruments have a high resolution (presently up to 4μm in 3D), but this high-resolution imaging can only be obtained for small samples. The samples prepared for μCT were cut as cylinders with diameters of approximately 18 and 10 mm, to allow magnifications of ×15 and ×26 and resolutions of approximately 19.2 and 16.3 μm, respectively, in 3D. Up to 1000 slices were reconstructed at right angles to the long axis of the cylinders; the volumes of sediment analysed were from 720 mm³ for some of the 10 mm diameter cores to 4668 mm³ for some of the 18 mm cores. The application of CT for the examination of soil macroporosity has already been demonstrated (e.g. Perret et al., 2000), but μCT is still relatively new to the earth sciences. We present here the first description of till microstructures in 3D.

Finally, till porosity observations and measurements were related to other till microstructures. Increasingly, examination of till microstructures has revealed that tills possess deformational characteristics which demonstrate, in parallel with field investigations, that tills are or were deforming glacier beds (see Menzies et al., 2006 and references therein). In this study, development of till structures including pores was investigated within this context, and glacier bed dynamics were interpreted from till structures.

4. Results

4.1. Field observations of till and bulk properties

Tills, dating from the last glaciation, make up a substantial proportion of the glacial sediments in County Laois and are found throughout the county in the uplands and lowlands. They are predominantly derived from the local bedrock lithologies (Fig. 1).

4.1.1. Particle size distributions and clast petrography

The particle size distributions of the tills vary greatly, but samples form quite distinct populations based on their dominant petrography (Fig. 3). Sandstone till samples generally contained more sand than other samples, as would be expected, and shale samples contained more silt and clay. The 59 samples for which the fines were separated contained between 0.4% and 25% clay. The degree of sorting of the till samples varied from 2.9 to 4.9 (Fig. 4), signifying very poorly sorted to extremely poorly sorted sediment (Folk and Ward, 1957). The broad pattern that emerged was that most of the shale dominated till samples were extremely poorly sorted and mostly negatively skewed or almost symmetrical. The sandstone till samples were

Fig. 2. X-ray computed micro tomography. (A) Original radiograph of cylinder-shaped till sample, the denser areas are darker shades of grey and the less dense areas are pale; 400 of these are taken of each sample at 0.9° steps through 360°. (B) Two reconstructed slices through the cylinder; approximately 1000 of these are reconstructed. (C) A reconstructed 3D cylinder of part of the original scanned sample with the pores and dense grains isolated.
poorly sorted, and tended to be more positively skewed than the shale till samples. The limestone till samples spanned most of the range of the other samples. There is a poorly defined association between decreasing sorting and more positive skewness, especially with the sandstone and shale till samples.

4.1.2. Field observations of till porosity

The most visible difference in till porosity characteristics in the field was between 'mature' tills, which were found almost throughout the county, and 'immature' tills, which were in one area in the southwest of the county (for example site G). The immature tills of the southwest had little fine-grained material to infill pores between clasts and appeared much more porous than mature tills. More subtle changes in grain size and consolidation did not cause differences in porosity that were perceptible in the field.

Many matrix supported mature tills appeared, from field observation or viewing with a hand lens, to be non-porous. The main exception to this was the porosity resulting from distinctive sub-horizontal fissility in many mature limestone and sandstone tills. The fissile partings were plate-like structures < 3 cm long, and more commonly < 1 cm long. Fissile partings are clearly visible not only because of the fissile appearance of the till but iron or manganese is frequently precipitated along the partings.

4.2. Till microstructures

The texture of the majority of the samples was plasma supported (Table 1) with sub-angular to sub-rounded grains. Samples from the immature coarse-grained tills are grain supported with angular grains, and those taken from flow tills in the southeast are also relatively coarse grained.

Turbate structures were found in samples from almost all sites, though they are poorly formed in flow tills, and...
absent in grain supported till. Lineations are found in all samples containing turbates, apart from those in which the turbates are very poorly developed. They have not been found in the flow tills or grain supported tills. Samples from eight of the 13 sites contain beds and bands of diverse size, composition, structure, frequency and shape. Most of the samples containing beds or bands also contain sorted sediment pockets, usually of the same composition and structure as the bands. Five samples contain diamicitic intraclasts; four samples have, and two possibly have, a marble bed structure associated with an absence of, or very poorly developed, turbates and lineations. Crushed grains occur in the grain supported tills, or tills containing coal grains.

Plasmic fabrics are moderate to well developed in six sandstone or shale-dominated samples. The limestone tills do not show plasmic fabrics due to the cloaking affects of carbonates. Strong microfabrics are found in one flow till sample, banded till samples from Slieve Bloom, and samples from a shale till in the Castlecomer Plateau.

4.2.1. Pore types

Pores described in this study are: vesicles, vughs, simple and complex packing voids, planar voids delineating fissile partings, planar voids delineating marble bed structures and other planar voids (Fig. 5). The voids have been described in samples in their dried state; they may, therefore, differ from the voids in the field by being slightly enlarged, though this would be minimal as the samples were dried in acetone. The pores are classified using soil science terminology. Some pore classifications have genetic implications in pedology, but these do not apply to till pores where the names are used only descriptively. Table 1 shows the types and relative abundance of pores. Figs. 6-10 contain a selection of petrographic microscope, SEM and µCT images of different pore types.

Vesicles are small (large silt/fine sand sized), rounded, smooth-walled and isolated pores. When viewing vesicles at high magnifications, using SEM, many of them were found to be irregularly shaped, and could be classified as small vughs. Most really rounded small pores, within till matrix, were found in flow tills (Fig. 6A and B). Some SEM samples were found to contain small vesicles not visible in thin section (Table 1). In a sample from site A, vesicles in the skeleton grains were the result of weathering and gave those grains a 'honey-comb' appearance (Fig. 6C). Vesicles, in a sample from site B were 4–24 μm in diameter, which is less than the thickness of the thin sections and could only be seen in SEM images. The SEM and µCT sub-samples from site E (Fig. 6D and E respectively) contain clusters of vesicles, mostly about 40 μm in diameter, which were found also to be isolated in 3D when examined using µCT. The thin sections from site E did not dissect these vesicle clusters.

Most samples contain vughs. Vughs are more irregularly shaped than vesicles and vary greatly in size. They were commonly 1–2 mm in diameter or smaller and the largest vughs were 4–5 mm in diameter, but these were rare. Their configurations varied from site to site as either isolated, connected to one another, or connected by planar voids, in more-or-less equal proportions. The largest vughs were in a banded sandstone till from the Slieve Bloom Mountains, and many of these were connected by planar voids associated with fissility (Figs. 7A and 6B), as were those in samples from site B. Tomography results showed that these vughs and the connected planar voids form a continuous 3D network through the sample. The vughs in the weathered till from site A were also mostly connected by planar voids (Fig. 6C). Many vughs in samples from sites C, K and J are elongate and connected in a line so that they resemble strings of beads, or a discontinuous widening and narrowing planar void (Fig. 7C). While vughs are usually visible in thin sections because they tend to be
Fig. 6. Thin section, SEM and X-ray computed micro tomography images of vesicles. (A) Vesicles and vughs in flow till as seen in thin section with crossed polarisers (site M). (B) Vesicle in flow till as seen in SEM (site M). (C) Vesicles in skeleton grains produced by weathering as seen in SEM (Site A). Some planar voids are connected to the vesicles. (D) Pockets of isolated vesicles and vughs, in a till described as over-consolidated in the field, as seen in SEM (Site E). (E) Densely packed diamicton that is relatively uniform in texture. In this X-ray computed micro tomography image there are only occasional small isolated vesicles and vughs and a thin planar void associated with fissility runs sub-vertically, towards the right of the image (Site E).

relatively large, small isolated vughs in over-consolidated till at site E, are visible only in SEM (Fig. 6D). Flow till samples tend to have relatively large and many vughs; in samples from site M (Fig. 6A), they have 2-axes of up to 0.24 mm.

Planar voids are elongate and narrow. They were found in most thin sections. Planar voids, demarcating fissile partings that were also visible in the field, were identified in samples from seven sites (Table I). In some samples fissile partings are small and randomly oriented or even predominantly vertical. Sub-horizontal fissile partings tend to form more continuous networks, for example the fissile structures in samples from sites B, F, H and M. The largest fissile partings in the centre of a sample from site H, mostly dip to the right (Fig. 8Ai and Aii). Small, very well defined partings lie between the larger parting (Fig. 8Aiii and Aiv) and dip to the left, and many elongate silt grains can be seen oriented with their long axes parallel to the planar voids or skeleton grains. These very small and well-defined fissile partings are not found in other samples. The significant difference between the sample from site H and other samples is the dominant grain shape. This is a predominantly shale till with blade shaped grains; other tills examined using SEM are predominantly limestone or sandstone, and these form more rounded grains. The fissile partings from site H form an extensive and continuous pore pattern through the sample (Fig. 7B). Petrographic microscope and μCT images of till from site B (Fig. 8B and
Fig. 7. Thin section, SEM and X-ray computed micro tomography images of vughs. (A) Large vugh in sandstone till as seen in thin section with plain light (site H). There is an iron stained clay cutan surrounding part of the pore and the sediment around the pore has been leached to a paler colour. The vugh is connected to other vughs (outside the field of view) by planar voids representing fissility. (B) Vughs connected to a parallel planar void system representing fissile partings as seen in pCT (site H). (C) Vughs connected to one another in a formation that looks like a string of beads, in a till described as over-consolidated in the field, as seen in SEM (Site K).

C, respectively) show a less complicated fissile structure, with relatively large sub-horizontal partings connected by partings almost at right angles, but the fissile partings in this sample also form a network through the 3D space of the μCT sample.

Planar pores in till form other, non-fissile, configurations also (Table 1). As described in the paragraph above relating to vughs, some planar voids (sites C, K, and J) could also be described as a string of vughs, widening and narrowing along their length. Some thin sections contain infrequent planar voids that are randomly oriented or occasionally run around the outside of skeleton grains. Planar voids that surround, or almost surround, aggregates of till have been termed 'marble bed’ structures by van der Meer (1987, 1996). The marble bed is best developed in samples from site K (Table 1, Fig. 9) and also forms a continuous network through the 3D space of the μCT sample.

Planar voids varied greatly in width from less than 30 μm to 1 mm. In tills described in the field as well consolidated, they tended to be narrower than those in tills described as poorly consolidated. Very wide planar voids demarcating fissile structures were found in poorly consolidated tills interpreted as flow tills (sites L and M).

Packing voids were found in poorly consolidated tills (complex packing voids) and in tills lacking fine-grained sediment (simple packing voids). Most tills containing packing voids were very porous (Table 1), and these pores were interconnected. In the very coarse, immature, lime-stone tills simple packing voids could be up to 1 mm wide (Fig. 10A and B). Sorted sediment pockets or bands (Table 1) contained simple packing voids. In coarse (sand sized) bands or pockets the voids were between 60 μm and 0.5 mm in diameter, while in sorted silt bands there could be less than 30 μm between grains. Fig. 10C shows packing voids in a sorted sediment band in a flow till, and Fig. 8C shows simple packing voids, in a sorted sediment band connected to fissile partings in the diamicitic part of the sample.

Finally, the shape of pores, and other structures may vary, when thin section samples have been taken at varying angles to ice flow direction. To date there has been no systematic investigation of the effect of thin section orientation on structure. In this study two sites samples were taken both parallel and perpendicular to flow (G and H) and the shape and size of pores and other structures are found to be comparable.

4.3. Percentage porosity

The results in Table 2 demonstrate that till has relatively low porosity. Measured porosities from SEM images are generally higher than from petrographic microscope images. This is due to the higher resolution of the SEM images: the lowest magnification petrographic microscope images have 13.6 μm pixels while the lowest magnification SEM images have 3 μm pixels. Also, the SEM images measure porosity along a single plane, as opposed to a
Fig. 8. Thin section, SEM and X-ray computed micro tomography images of planar voids associated with a fissile structure. (A) Dense network of fissile partings in shale dominated till as seen in SEM at increasing magnifications (site H). (Aii) Shows the largest fissile partings, picked out with the dotted lines and connected to large vughs. They dip to the left and to the right. (Aiii) Shows fissile partings that predominantly dip gently to the right. (Aiv) At this very high magnification of \( \times 1300 \) fissile partings of <1 \( \mu m \) in diameter can be seen. They are almost at right angles to the larger fissile partings and clay and silt particles are aligned parallel to them. (B) Wide interconnected fissile partings as seen in thin section with plain light (site B). (C) Fissile partings connected to packing voids associated with a sorted sediment band as seen in \( \mu CT \) (site B).

minimum porosity through the 25 \( \mu m \) thickness of a thin section. Pore volume as derived using \( \mu CT \) is also in a similar range as, or slightly lower than, the values for porosity from thin sections and SEM, with the exception of the \( \times 15 \) image from site B (Table 2), because this sample happens to dissect a sorted sediment band containing packing voids (Fig. 8C). This pattern of slightly lower volumetric porosity measurements is consistent with the findings of Bullock and Thomasson (1979), who found that sample porosity, in most cases, was slightly higher when measured using image analysis of thin sections than when measured using water retention measurements.

Those samples that show marked differences in porosity at different magnifications in petrographic microscope and SEM analysis, do so because different sized voids are visible at these magnifications. For example, the petrographic microscope \( \times 63 \) image and two of the SEM \( \times 25 \) and \( \times 75 \) images from sample 3251, site K, contain planar voids that delineate the marble bed structure in this till, but the higher magnification images describe the porosity of the till mass between the large pores. This apparent decrease in porosity has also been observed in other samples (Table 2). Conversely, in most of the SEM images, the percentage porosity increases from the \( \times 25 \) images to the \( \times 75 \) images, indicating that there is a greater area of pores with \( b \)-axes of \( >1 \mu m \) (the \( \times 75 \) image pixel size) in an area of 1.8 mm\(^2\) than there are pores \( >3 \mu m \) (the \( \times 25 \) image pixel size) in an area of 17.5 mm\(^2\). Likewise, in some cases there is an increase in porosity in the \( \times 230 \) images, indicating a greater area of pores of \( >0.33 \mu m \) in an area of
Fig. 9. Thin section, SEM and X-ray computed micro tomography images of planar voids associated with a marble bed structure in shale-dominated till (site K). (A) Dense till aggregate surrounded by a network of planar voids as seen in thin section with plain light. (B) Dense till aggregates partially surrounded by a network of planar voids as seen in SEM. (C) Dense till aggregates partially surrounded by a network of planar voids as seen in μCT.

0.21 mm² than there are pores > 1 μm in an area of 1.8 mm² (for example sample 3267, site E, where very small voids, typical of this till, are described in the high magnification images only). There is yet no method to compare measurements of porosity from a variety of different magnifications (Ringrose-Voase, 1987). The different magnifications of μCT analysis are not comparable in the same way because different cylindrical samples were used for each magnification.

The highest porosities were measured in sorted sediment bands and pockets and in immature tills. A × 75 SEM image from an area characterised by simple packing voids, in the immature till from site G, is 43.72% pore space; an area with relatively densely packed plasma and grains is 12.71% pore (× 63 thin section image). It is clear that porosity does vary greatly in this immature till, but it is always high. The sorted sediments in samples 3258 and 3260 also have relatively high porosities (Table 2), but sorted sediment in sample 3255 does not have high porosities because it is silt, which contains no packing voids large enough to be visible in thin section.

The remainder of the samples has porosities from 1.04% to 7.16% (× 63 petrographic microscope images). The two samples with the highest porosities in this group were from site H and contain large or frequent fissile partings (sample 3258 and area 'I' of sample 3257) and the next highest percentage results from abundant pores resulting from weathering (sample 3269, site A). The rest of the diamicton samples have measured porosities of between 1.04% and 4.4% (× 63 images). Within this group of samples, the higher percentages resulted from the inclusion of fissile or marble bed voids, the highest two being from the diamicton part of flow till samples (site M). Those samples, or parts of samples, containing turbate structures tend to have low porosities: the diamicton parts of samples from site H, and samples 3016 and 3017, site B. However, the sample taken from site E, for which there are the lowest measured porosities (~1%), is a very dense massive and structureless till, described as over-consolidated in the field.

5. Discussion

5.1. Deriving estimated bulk porosity of till from grain size distributions

As part of this study we investigated the possibility of estimating till porosity from particle size distributions. As first described by Burminster (1938), there should be a relationship between grain size distributions and porosity: sediments with a poor degree of sorting are less porous than those that are well sorted, and sediments that are skewed towards the coarse end of the curve are the least porous. This effect is most pronounced when the sediment has a great range of sizes, though porosity does not
Fig. 10. Thin section, SEM and X-ray computed micro tomography images of packing voids. (A) Grain supported, poorly consolidated till containing little plasma and wide simple packing voids; as seen in thin section with plain light (site G). Circles mark positions of shattered grains. (B) Grain supported to grain dominated, poorly consolidated till containing little plasma in the left side of the image and coarse plasma on the right. Contains simple and complex packing voids, as seen in SEM (site G). (C) On the left side of the image there is a network of packing voids in a sorted sediment band in this flow till (site M), as seen in μCT.

decrease indefinitely with increased range (Peronius and Sweeting, 1985). Accordingly, the till samples in this study that should theoretically be the least porous are from sites G and H (Fig. 4). However, as has been described in Section 4.3, this is not the case.

Fine-grained particles have an important property other than their small size: clays have surface electrical charges, so clay sized grains encourage the formation of agglomerates thereby potentially increasing porosity. The percentage clay in a selection of publications (Boadu, 2000; Grisak, 1975; Haldorsen et al., 1983; Hendry, 1988; Keller et al., 1986; Lind, 1989) varies from about 1% to 30%, but it would appear from these data that percentage clay in till does not have a great influence on porosity (Kilfeather, 2004).

We have identified one published data set of till particle size curves with associated porosity measurements (Lind and Nyborg, 1988). Eleven of the Laois particle size distributions were found to be comparable to that data set and thus may have similar porosities, though Lind and Nyborg (1988) and Lind (1989) found that porosity of till is generally independent of mean grain size, but weakly correlated with sorting. The degree of sorting of the Laois till samples varied from 2.9 to 4.9 (Fig. 4) and the sorting of the 30 samples of Lind and Nyborg varied between 2 and 4.2 (Fig. 29, Lind and Nyborg, 1988). Given this similarity it could again be suggested, tentatively, that the porosity of the Laois till samples might be similar to the porosity of the samples of Lind and Nyborg. Theirs is a very large range of porosity, from 2.5% to 32% (effective porosity, or pores >15 μm) but with three-quarters of the samples tested with between 3% and 10% effective porosity (as derived using suction moisture content). The images of the Laois thin sections taken at × 63 have a pixel size of 13.6 μm resulting in image classifications that describe pores greater than about 15 μm in diameter, therefore roughly indicating the effective porosity of the samples. Effective porosity of the Laois samples ranged from 1.04% to 18.88% (Table 2) and the mean effective porosity is 7%. The very coarse, immature tills from the southwest of the county are different to those described by Lind and Nyborg (1988) and Lind (1989) and if these samples are excluded then the mean is reduced to 5%. The mean porosity of the lowest magnification SEM images, excluding the results from the immature tills, is also 5%. These results are similar to those found by Lind (1989). Since porosity values obtained from thin section image analysis should be higher than those obtained by moisture suction content (Section 4.3), it can be said that the County Laois tills are probably less porous than the tills analysed by Lind and Nyborg (1988) and Lind (1989).

It would seem that particle size distribution has a very limited effect on the overall porosity of tills, at least in the
Table 2
Measurements of percentage porosity on a selection of thin sections, scanning electron microscope and X-ray computed micro tomography images from twelve samples

<table>
<thead>
<tr>
<th>Site</th>
<th>Sub-sample</th>
<th>Petrographic microscope</th>
<th>Scanning electron microscope</th>
<th>X-ray micro CT</th>
<th>Brief description of field and micromorphological observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Area Porosity (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>× 63 × 125 × 320</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>3269</td>
<td>5.15 4.81 2.89</td>
<td></td>
<td></td>
<td>Weathered massive limestone till</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a 9.56 b 9.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>3016</td>
<td>2.21 1.6 2.34</td>
<td></td>
<td></td>
<td>Limestone dominated, sandstone rich, well-consolidated fissile till</td>
</tr>
<tr>
<td></td>
<td>3017</td>
<td>a 1.77 b 1.76</td>
<td></td>
<td></td>
<td>* sample dissected sediment band</td>
</tr>
<tr>
<td>E</td>
<td>3267</td>
<td>1.04 1.28 0.4</td>
<td></td>
<td></td>
<td>Very well-consolidated limestone till with fissile partings observed in field section</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a 0.64 b 0.66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>3270</td>
<td>12.71 16.75 20.24</td>
<td></td>
<td></td>
<td>Clast dominated to clast supported limestone till. * relatively densely packed area</td>
</tr>
<tr>
<td></td>
<td>3301</td>
<td>19.34 19.26 9.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>3257</td>
<td>d 1.98 2.75 1.44</td>
<td></td>
<td></td>
<td>Sandstone till containing fissile partings. * a highly weathered sandstone grain occupies almost half of this image</td>
</tr>
<tr>
<td></td>
<td>3258</td>
<td>l 5.41 5.9 9.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>3251</td>
<td>3.15 3.33 1.45</td>
<td></td>
<td></td>
<td>Shale dominated over-consolidated till with marble bed structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a 2.22 b 12.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>3255</td>
<td>d 4.4 1.68 0.93</td>
<td></td>
<td></td>
<td>Limestone dominated, poorly consolidated fissile flow till. * the top left corner of this image includes an area of the overlying diamicton that contains fissile partings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>s 2.02 1.38 1.63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3260</td>
<td>d 4.1 1.63 1.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>s 18.88 17.66 13.91</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Superscript figures refer to figure numbers in this article and roughly correspond to the areas on which image analysis was done. d = diamictic area of the thin section, s = sorted sediment area, l = area of multiple lenticels/fissile partings.

Underlined figures denote that these images contain large voids that are not visible in the higher magnification image(s).
larger pore size range (>15 μm or so). Also it would seem likely that any very coarse till, such as immature tills of the southwest (sampled at site G) will, contrary to the theories of Burminster (1938), be very porous. The prediction of pore size distributions from particle size distributions is mathematically very complex. Despite the efforts of many researchers, there is yet no universally accepted relationship between particle size distribution and pore size distribution for unsorted or poorly sorted sediments or materials. Besides, our results show that it is certainly the case that till structure is a more important control on porosity than texture.

5.2. Indicators of porosity from field observations of till

Porosity of tills is difficult to discern in the field, with the exception of fissile partings (Fig. 11). Since fissile partings may have a dramatic effect on porosity, increasing it by two to three times (for example at site H, Table 2), these may be very useful field observations. However, fissile partings might also have a very limited effect on porosity (for example at site E); field descriptions of consolidation will give a good indication as to whether or not fissile partings do greatly increase porosity (see below). Iron or manganese can frequently be seen precipitated along fissile partings illustrating that these pores are interconnected at the field scale and form anisotropies along which ground-water is transported (all be it at a slow rate presumably). Most sorted sediment bands and pockets are also visible in field section and, since these can have a dramatic effect on till porosity, these are useful observations.

Descriptions of consolidation may give a good indication of porosity, although the descriptions are subjective. When comparing field descriptions of the degree of till consolidation with bulk porosities there appears to be a good correlation between the two. The least porous samples are from a fissile till that was extremely difficult to sample in the field due to its degree of over-consolidation (site E, Table 2). Thin section, SEM and tomography revealed that the fissile partings in this till are both widely spaced and very narrow. The combination of structural and consolidation observations of the till from site E, in the field, make it clear that this is not a very porous till. There is an increasing degree of porosity in the normally consolidated tills and finally in two tills described as poorly consolidated.

5.3. Affect of till petrography on porosity

The number of samples on which image analysis has been performed precludes any conclusions about whether till petrography has a significant influence on porosity. Different rock types affect the grain size distribution of till, but as discussed in Section 5.1 this attribute probably has little direct effect on porosity in the majority of tills. However, different bedrock types also produce different grain shapes, and this may have an affect on structure, which may in turn have an affect on porosity. For instance fissile structures described in SEM images in the predominantly shale till from site H are particularly well developed (Section 4.2, Fig. 8A), even down to minute fissile partings only seen at magnifications of × 1300. Other limestone- and sandstone-dominated tills that contain fissile partings, but which have more rounded grains; such as those from site B, contain only the relatively large fissile partings. The predominantly blade-shaped grains in the shale till allow a strong grain fabric to develop under shear stress which in turn encourages the development of a parallel fissile structure and anisotropy of the till. A strong till fabric may, therefore, be indicative of a parallel void structure (Nyborg, 1989).

5.4. Microscopic methods for describing till pores

Thin section analysis allows pore size, shape and connectivity to be described and percentage porosity to
be measured using image analysis. Low magnification images were found to be the most useful because they include large pores and pore configurations. Illuviated clay (cutans), or precipitates of iron and manganese (Table 1 and Fig. 7A) in pores can also be observed and indicate that the pores are hydraulically active. Thin section analysis allows porosity to be related to other till structures.

Image analysis of SEM images allows very quick and easy measurements of till porosity and gives a more definite porosity measurement than image analysis of photomicrographs, because occasionally there is ambiguity between pore spaces in photomicrographs and areas where the thin section may have had material removed during processing. However, scanning electron microscopy is not useful for examining most other till structures.

The experiments with X-ray μCT illustrate the suitability of this method for the measurement and analysis of till porosity. Using μCT to examine the planar fissile partings and marble bed structures confirms that these features, and some vughs, are connected in 3D. This is an important addition to the two-dimensional observations.

5.5. The development and removal of pores in the deforming glacier bed

Any sediment overridden by a glacier may start out with high bulk porosity. As a glacier overrides this sediment, the normal stress caused by the weight of the ice combined with the shear stress due to its forward motion will cause shear stresses within the sediment. These stresses will be greatest at the top of the sediment, now a till bed, and will diminish towards the base. Particles will rotate due to the differences in velocity between the top and the bottom of the particles (van der Meer, 1997). The finest particles will be mobilised most easily. Larger particles will become mobilised if the shear force is great enough, combined with the effect of the movement of the surrounding smaller grains. This is the process by which turbine structures form.

Moving particles will naturally seek out the path of least resistance. Pore spaces will be the paths of least resistance, so particles will rapidly fill available voids (Fig. 12A). Consequently, rotational deformation will cause an increase in till density, making it more difficult for rotation to occur within this group of particles. This explains why aggregates, which look the same as the surrounding till mass, form nuclei of some turbate structures: a patch of sediment, which becomes more dense than the surrounding material is less mobile than the surrounding sediment and will behave like a pebble and rotate en masse, forming a turbate nucleus. All turbates may increase in size as pores at their outer edges are filled by surrounding particles, or clay and silt particles become aligned to their sides. This process explains the association of many or well-developed turbates in tills with low porosities, as described in Section 4.3.

Shearing and the production of lineations may only occur after rotational deformation has increased the density of till to such a degree that rotational deformation can no longer easily occur. Shear strain may then build up until it results in discrete failure along lineations or fissile partings. This may occur in some parts of a till bed while rotational deformation is continuing elsewhere. In the case of lineations it may result in the infilling of pore spaces along these shear zones (Fig. 12B), as grains migrate towards the zone of shear. However, in the case of fissile partings porosity is increased by the creation of planes of weakness and anisotropy. It has been suggested by van der Meer et al. (2003) that fissility is caused by water in the subglacial system developing pathways through the till leading to interconnected shear planes accommodating both deformation of the sediment and evacuation of water (Fig. 12C). If water is successfully transported through till during or soon after deposition, this pore system may remain open and hydraulically active long after the glacier has gone.

The formation of a marble bed increases the degree of porosity and results in interconnected planar pores, though the till within the individual aggregates tends to be very dense (Fig. 12D). Marble bed formation may result from an initial subglacial compression and de-watering of the sediments followed by brittle failure along sub-horizontal planes, brecciation and rotation of aggregates caused by shearing (Hiemstra and van der Meer, 1997). Alternatively, the high density of the till in individual aggregates may result from a period of plastic deformation preceding break up of the till into aggregates. However, it is interesting to note that none of the till samples in this study, which contains a marble bed structure, contains well-developed turbates or lineations. It is not clear why this is the case, but it could be postulated that the process of marble bed formation destroyed turbine and linear structures by breaking them apart, thereby leaving them unrecognisable, though this would seem unlikely, because if turbates or lineations had existed some of them should survive. Therefore, we suggest that the marble bed forms under different subglacial conditions than those that exist during the formation of turbates and lineations. While fissility may develop by a combination of high water pressure and shear as suggested by van der Meer et al. (2003), the marble bed may develop when shear is the dominant deforming factor in the subglacial system, and water pressures are not high.

Sorted sediment bands and beds in the thin sections, whether formed by water-escape, by inclusion of pre-existing sorted sediments, or by sub- or pro-glacial melt-water deposition, are important for the formation of continuous pore systems. The incorporation and survival of these bands depends on the type of deformation the till bed undergoes and whether pervasive deformation continues following their inclusion.

Those tills that show little sign of deformation are some of the most porous, which supports the hypothesis that it is
Fig. 12. The development and removal of pores in the deforming till bed. (i) Examples of structures that affect the development of pores, as seen in thin sections in plain light (and on a flat-bed scanner for image C); (ii) the same images annotated; (iii) cartoons illustrating the initial state of sediment prior to subglacial deformation; (iv) cartoons illustrating the interpreted forms of deformation that result in the development and destruction of pores and other microstructures. In (Aiv) the long axes of elongate small grains (clay/silt/fine sand) align along the sides of a rotating pebble. Particles in this bed find the paths of least resistance, resulting in infill of pores. In (Biv) shearing of till to form lineations of grains or plasma may occur where till is too dense for rotational deformation to occur. Porosity may decrease along these zones of shear as particles migrate towards the shear zone and, finding the paths of least resistance, infill pores. In (Civ) Brittle break-up of the bed during shearing, possibly associated with water-escape, forms fissile partings that increase a till’s porosity. In (Civ) break-up of a dense and dry till bed during high shear stress and rotation of individual aggregates, forms the marble-bed, increasing porosity.

deformation of till that decreases porosity. This includes flow tills and immature basal tills. Immature basal tills do show evidence of deformation but only for a relatively short period so that there was a lack of comminution of the till, which is very local in origin. The banded till in Sleave Bloom is also more porous than most other basal till samples; this may be due to this till having undergone deformation for a shorter period of time (thus preserving the banding) and being overlain by thinner ice than the lowland tills.
5.6. Summary

The porosity of the 12 Pleistocene till samples in this study tended to be low, with effective porosity ranging from 1% to 19%. The highest porosities are for immature grain dominated to grain supported tills and for sorted sediment pockets in till, which can have porosities greater than four times that of the surrounding till. Fissile partings may increase porosity by two to three times; marble bed structures also increase porosity significantly. Planar and packing voids frequently contain precipitated iron or manganese indicating that they are hydraulically active.

Pores are created and destroyed in the till bed as it deforms beneath the glacier. Samples containing well-developed turbate structures and lineations contain few and small pores, as particles rotating in the deforming till bed, or migrating towards and along shear zones, seek the path of least resistance and fill pores. On the other hand shear deformation may result in the creation of fissile partings, or the break up of the till bed into a marble bed structure, thus increasing porosity. Those tills that show little sign of deformation are most porous.

In conclusion:

- Deriving porosity estimates from particle size analyses seems unreliable, though very coarse grained, class dominated till will, contrary to particle packing theories, be very porous.
- Microstructure of tills is a far more important controlling factor for porosity in most, matrix supported, tills.
- The variable consolidations and structural and textural complexities of tills mean that detailed descriptions and analyses must be obtained for estimates of bulk porosity and pore connectivity.
- Both fissile partings and sorted sediment bands are easily recognisable in the field. This indicates that detailed field descriptions of tills, together with strategic thin section sampling, should allow till porosities to be estimated on maps, for instance at the scale of a landfill site or similar development.
- These results, together with hydrogeological investigations and knowledge could give a much better indication of probable permeabilities than has been the case to date.
- Pore types and percentage porosity give an indication of the nature and extent of deformation towards the end of till formation.

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References


Glossary

Birefringence: birefringence is one of the three factors that determine the interference colours seen between crossed polarisers under the microscope. It is the numerical difference between the highest and lowest refractive index of a mineral.

Cutan: a coating of clay material on or against structural elements such as walls of pores; can be the result of illuviation or crystallisation.

Effective porosity: the porosity that plays an effective part in the storage and movement water, which equates to pores with diameters of about 15-25μm and greater.

Intrackst: a distinct aggregate or sediment: pocket within the till.

Interference colours: the colours that are formed when a birefringent mineral, or domains of clays in parallel orientation, is examined between crossed polarisers or with circularly polarised light.

Lineations: an arrangement of skeleton grains or plasma into lines.

Marble bed structure: till forms separate aggregates delineated by voids, with no difference in structure or composition between the aggregates; it has been interpreted as resulting from brecciation of relatively dry till due to subglacial deformation, followed by rotation and rounding of the aggregates.

Microfabric: orientation of the (apparent) long axis of elongate skeleton grains in thin section.

Neoformation: a new substance formed in situ. Clay coating, or cutans, and precipitated iron or manganese are typical examples. (Also called authigenic formations.)

Omnisepic plasma fabric: plasma domains are oriented in all directions.

Petroscope: an adapted microfiche reader for examining thin sections.

Plasma: in micromorphology it is synonymous with matrix, which is all material smaller than the thickness of the thin section; consequently, individual particles cannot be distinguished.

Plasma: an optical effect of clays when they are closely packed, oriented parallel to each other and viewed in thin section between crossed polarisers. These zones or domains of clay particles display interference colours (orientation birefringence). This optical property allows indirect description of the fabric of clay particles. (Also called b-fabric.)

Skeletale (granae): single grains which are larger than the thickness of a thin section.

Skeletale plasma fabric: plasma particles are oriented around a skeleton grain.

Torbate: an arrangement of relatively fine grains around a larger grain or an aggregate; the long axes of the small grains tend to be aligned parallel to the sides of the larger grain; they have been interpreted as indicating rotational movement of particles within the deforming till bed. They have also been called ‘rotational structures’ and ‘comet structures’.