Plasmic fabric analysis of glacial sediments using quantitative image analysis methods and GIS techniques
Zaniewski, K.

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
A Second Look At Plasmic Fabrics In Glacial Sediments; Quantification Through Image Analysis

Kamil Zaniewski
Fysisch Geografisch en Bodemkundig Laboratorium, University of Amsterdam
Amsterdam, 1018 WV, The Netherlands

Abstract

A new method of image analysis was tested on digital micro-photographs of glacial sediments. The method incorporated multispectral image classification algorithm to identify and separate the major components of each image. The resulting 'maps' showing areas of matrix, void spaces, skeleton grains and birefringent plasma, were used to quantify texture and plasmic fabric information. Data collected showed discrepancy between visual descriptions and objective interpretations of plasmic fabric patterns. The results showed that the current qualitative approach to plasmic fabric descriptions may be too subjective.

Introduction

This paper concerns a test case evaluation of a new procedure for the analysis of plasmic fabric in glacial sediments using image analysis techniques. As such it is an attempt at implementing what was up until now only a theoretical method of analysis.

Observations, interpretations and conclusions available through macroscale field and laboratory studies of glacial sediments are usually insufficient in distinguishing between genetically different sediments (van der Meer, 1993). A micromorphological approach allows studies of glacial sediments at higher magnifications, providing information on a wholly different scale. Using thin sections and a low magnification (<X10) petroscopic microscope it is possible to see structures and features otherwise invisible to the naked eye. Most of the information used in micromorphology is gathered through direct observation of thin sections. Such observations yield information regarding skeleton (grain size, microfabric, shape patterns, lithology), plasma, plasmic fabric, voids and microstructures. This information is predominantly subjective in nature. The focus of this paper is the investigation of plasmic fabric or the arrangement of uniformly oriented, optically anisotropic clay minerals. As clays change their orientation in response to stress the resulting pattern of optical birefringence can be used to trace the depositional and deformational history of the sample as related to stress.

The new technique introduced in this paper undertakes to remove some of the subjectivity currently encountered in micromorphology and to provide an objective way of thin section characteristic evaluation. The method attempts to measure, and thus quantify, plasmic fabric strength and frequency, preferred orientation of the plasmic fabric
domains, skeleton grain size distribution and sorting. All these quantifications are of course subject to the usual limitations where 2-dimensional information is used to analyze 3-dimensional features.

Methodology

The method used in this study follows the technique for image analysis of plasmic fabric created by the author (see previous chapters). The practical application of the original method inspired several changes which will be duly noted.

Four thin sections were used in this study: R.756 from Moncydie, Scotland, Mi.315 from Mt. Provender, Shackleton Range in Antarctica, Mi.316 from the Nansen Ice-Shelf, North Victoria Land in Antarctica and C.116 from the McMurdo Dry Valleys area of Antarctica. These four were selected to compare the effectiveness of the technique for a variety of plasmic fabric patterns. R.756 was used most extensively due to the variety and the apparent strength of the plasmic fabrics found. Results of the analysis were compared to the already available qualitative evaluation: the same thin section was used earlier to help in the interpretation of a Late Devensian diamicton sequence from Moncydie, Scotland (Menzies and van der Meer, 1998). The remaining three thin sections were selected to represent diamictons containing less obvious examples of plasmic fabric. Mi.315 represents a sample of a till found in a valley SE of Mt. Provender. It was also described as a ‘geliflucted till’. Mi.316 is an example of a ‘medial moraine’ material from Inexpressible Island on the Nansen Ice-Shelf. These two samples were examined earlier by van der Meer et al. (1993) and Zaniewski (1996). Sample C.116 is a till sample described by Zaniewski (1996).

In order to evaluate results of the new technique it was important to compare them to the ‘subjective’ descriptions used in earlier studies. The descriptions found below focus on two descriptive concepts only - plasmic fabric and texture of each thin section sample.

Textural information in thin sections usually concentrates on visual estimation of sorting, size and shape and composition of skeleton grains and matrix. Matrix consists of material too small to be identified as individual entities. In practice, this generally means objects smaller than the thickness of the thin section (<20 μm diameter) but some larger objects may also be included under extreme circumstances. Skeleton grains include all singular solid visible objects larger than thin section thickness. Since the primary emphasis of the project is on plasmic fabric information the images selected for analysis will focus on more fine grained areas of each thin section. Subsequently, texture related results are likely to underestimate the presence of coarsest fractions such as gravel.

Plasmic fabric refers to the order of organization of birefringent plasma. Any
material finer than 2 μm (clay sized) is considered to be plasma. Plasma is therefore a major component of matrix. Plasmic fabric is the visible effect of stacking of optically anisotropic clay minerals. When stacked (similar orientation) the clays become visibly birefringent. Birefringence is an optical condition which can be observed under cross-polarized light. Units of similarly oriented (birefringent) clays are frequently referred to as domains. It is the characteristics of and the relationship between the domains, which define the various types of plasmic fabric. These patterns were first classified by Brewer (1964) and were used in soil studies. The same terminology was also adopted in some glacial sediment studies (van der Meer, 1993; Hiemstra, 1999). Since the term ‘domain’ has been used differently by other authors (Menzies, 1998; Menzies et al., 1997), referring to the different types of plasmic material observed in close proximity, some confusion may arise. In this work, all references pertain to birefringent domains and follow the nomenclature of Brewer (1964) and van der Meer (1993).

Examples of the various types of plasmic fabrics and textures were digitally photographed for objective evaluations. Individual images were obtained using a digital photographic camera (Leica DC200) mounted on a petrological microscope (Leica Wild M420) capable of low magnifications (up to 10x). Each location was photographed using three different illumination types - plain light, cross-polarized and cross-polarized with gypsum wedge (1/4λ). The brightness of the light source remained constant for each photograph. All the images were taken using a 10x microscopic objective (6.4 mm width of view). Each image consisted of 1280 columns and 1024 rows (1.3 million pixels). This was used to calibrate the dimensions of individual pixels. The value remained constant at approximately 5 μm pixel width and height (2000 pixels/cm resolution) allowing for the resolution of detail as small as 25 μm² in area.

All images were imported into TNT-Mips (Maps and Images Processing System) for further processing. The first stage of the analysis involved application of a multispectral classification algorithm to identify the main components of each image. The procedure converts each original image into a simpler map of the same area.
Diagram 1. Cumulative Area Curves. Example of the texture related results available. The raw data requires processing for the purpose of graphic display.

Diagram 2. Directional data can be displayed using rose diagrams. Examples of the results obtained in this study. All data is bidirectional and shows plasmic fabric domain orientation.

This new image shows skeleton grains, plasma and voids. Plasma was further subdivided into birefringent and non-birefringent zones facilitating plasmic fabric quantification. The birefringent areas of the plasma (plasmic fabric domains) were then quantified. Skeleton grain related information was used to quantify the texture of each sample. Unlike the original method (Chapter 4), an unsupervised method was used (Minimum Distribution Angle algorithm) to eliminate the problem of training site definitions in a highly varied imagery typical in micromorphology. Supervised classification methods require a detailed and exact a priori knowledge of the classified imagery. The accuracy depends on the number and the accuracy of the training sites used to define the many different classes (ex. various minerals) of objects in the image. In the highly varied imagery found in glacial sediments the training site definition proved to be impractical. An unsupervised method automatically divides a source image into groups of pixels of similar appearance. The groups are then labeled as belonging to a known material type.

The image analysis procedure can provide a very wide range of information for each image. The set produced in this study was narrowed to include only those characteristics relating to plasmic fabric and texture. More specifically, texture evaluation includes a grain size distribution curve (Diagram 1), overall sorting value, percentage of skeleton grains and their sorting value. Plasmic fabric information includes the overall anisotropism in percentage of the overall image area, average birefringence strength, frequency of oriented domains percentage, a rose diagram of orientated domains (Diagram 2), frequency of unistrial domains percentage, and the frequency of skelsepic plasmic fabric domains expressed as a percentage of all the domains. This information is displayed
in Table 1. This table also includes two additional columns containing the name of the plasmic fabric type identified and the type described in the original visual descriptions. The decision regarding plasmic fabric type is based on a set of diagnostic criteria defined in chapter 3. These diagnostic values are founded on the original fabric definitions of Brewer (1964, 1976), FitzPatrick (1984) and Bullock et al. (1985) but were quantified (based on practical experience with thin section descriptions) to allow for an objective identification (see below).

The analysis was limited to the plasmic fabric patterns found most commonly in glacial sediments. Each image analysed was first evaluated in terms of overall optical anisotropism of the plasma. If the result obtained falls below 2% the fabric should be listed as asepic (showing no plasma separations). Based on the texture of the matrix this could be either an argillasepic fabric (if clay sized material dominates) or silasepic fabric (if there is more silt in the matrix).

If the anisotropism frequency exceeds 2%, then one of the sepic fabrics is present. Skelsepic plasmic fabric is recognized whenever plasma separations appear to concentrate around skeleton grains. This concentration is measured by comparing the number of domains in close proximity of skeleton grains to the total number of all the domains. The diagnostic concentration level set for this study was 40%.

Other types of plasmic fabric are evaluated based on the frequency of oriented domains. An oriented domain is any domain whose shape allows for measurement of orientation. This is usually the case where sufficient elongation is obtained (generally a minimum of 1.5 axial ratio between a and b axis of the domain). Insepic plasmic fabric can be identified when less than 15% of the non-skelsepic domains are oriented.

If more than 15% of the domains were oriented, then one of the following plasmic fabric types may be present: masepic, bimasepic, trimasepic, multisepic (see below for definition) or omniseptic. These are exclusive; only one may be present at a time. The decision as to which pattern is present is based on the number of preferred orientation directions found. This can be obtained in a traditional manner through rose diagram interpretation. However, rose diagrams may prove to be unreliable and may be misleading in showing a predominant orientation (Wells, 2000). Furthermore, any use of rose diagrams would introduce a degree of subjectivity through qualitative orientation evaluations.

In this study, preferred domain directions are established through observation of predominant frequencies. Orientation values are grouped and their frequency is calculated. Class centres are located at every 5° (between 0° and 175°). Frequency of occurrence is established for each class centre and if the value exceeds a certain critical minimum it is then considered to be a preferred orientation direction. The frequencies are measured for 10°, 20° and 30° class intervals with 15%, 20% and 25% critical values respectively.

Fabric type is based on the number of preferred modes of orientation found (1 for masepic, 2 for bimasepic and 3 for trimasepic). An omniseptic plasmic fabric is identified...
when no preferred orientation mode was identified but there were also no class intervals
with frequencies below 10% (for 30° intervals) 4% (for 20° intervals) or 1% (for 10°
intervals). This assures a more or less even distribution in all directions and fits with the
definition of omnisepic plasmic fabric. An additional type of fabric, not described in
previous classifications but necessary in quantitative studies, is the multisepic pattern. It
is a default pattern used whenever none of the previous oriented fabric types can be
applied.

Lattisepic plasmic fabric is a variant of the bimasepic pattern and can be identified
when the two preferred modes of orientation differ by approximately 90°. In visual
analysis, lattisepic plasmic fabric appears as a lattice-like pattern. The critical value was
set between 80° and 100° to allow for some variation.

Unistrial plasmic fabric can be defined as a form of masepic plasmic fabric.
Unistrial domains are long and narrow streaks of birefringent plasma. Their diagnostic
definition is set by the length to width axial ratio of 20:1. The ratio is a tentative value
based on visual observations of unistrial domains in glacial sediments (van der Meer, pers.
comm.).

Thin Section Descriptions

Texture descriptions of thin sections include a general estimation of the range of grain sizes
found and occasionally include visual evaluation of the degree of sorting. It is important
to note that the descriptions usually refer to the sorting of the skeleton grains only.

In addition to the general listing of the features found in each thin section, each of the
photographed sample sites is also described to provide more specific details. The sites
selected were chosen to represent various types of plasmic fabric as well as different
degrees of birefringence and optical anisotropism frequency.

*Moneydie Sample. R.756*

Menzies and van der Meer (1998) found that the sample shows a wide variety of
plasmic fabrics. Included were domains of strongly anisotropic omnisepic plasmic fabric,
equally strong lattisepic and skelsepic domains as well as many examples of cross-cutting
unistrial domains. In addition, the sample was found to contain some gravel but to
generally lack in skeleton grains with the majority of the sample being clay-sized. The thin
section sample could be divided into three distinct zones. These are parallel bedded units
of diamicton showing textural and colour differences with clearly delineated inter-unit
boundaries. The thin section orientation is unknown.
This is the lowest diamicton unit. This part of the thin section contains examples of unistrial plasmic fabric which frequently intersect. There were two unspecified dominant plasmic fabric orientation directions.

Based on the information provided and direct observation of the sample, six images (numbered 2-7) were selected for analysis. These included examples of omniseptic plasmic fabric (2,4), unistrial plasmic fabric (multiple Riedel shears) (2,4,5,6), lattiseptic plasmic fabric (5) and what appeared to be masepic plasmic fabric pattern (3,7).

This is the middle layer in the sequence. It was described as a diamicton. It contains more gravel than the other zones. Examples of lattiseptic and skelseptic plasmic fabric were found. Plasmic fabric strength was described as uniform throughout the zone.

Only two images were obtained from this portion of the thin section. These included examples of possibly insepic plasmic fabric (8) and what was described as lattiskelsepic (predominantly lattiseptic with some skelseptic presence) plasmic fabric (9).

This is the top layer in the sequence. Although it did not appear to differ from the material contained in zone 1 it appeared to show examples of cross-cutting unistrial domains - not apparently found elsewhere in the sample.

All three sample images show unistrial domains (10, 11, 12). Image 12 also shows an apparent masepic plasmic fabric.

The thin section orientation is unknown. The sample showed only a minimum degree of plasma orientation. This was evidenced by skelsepic plasmic fabric around some of the skeleton grains (van der Meer et al., 1993) and weak insepic to lattiseptic plasmic fabric (Zaniewski, 1996). No other types of plasmic fabric were observed at the low magnifications used in this study. The sample also contains a full range of skeleton grain sizes - up to 1.5 cm (pebble-sized) - with no sorting and a clayey plasma. Although most voids and fractures are very likely due to sample shrinking during drying, some contain laminated cutans (typically a highly birefringent structure).

The image selected from this sample includes no apparent plasma separations - potentially an aseptic plasmic fabric (more specifically an argillaseptic plasmic fabric).

It is a poorly-sorted diamicton composed in part of ‘welded’ till pebbles (Zaniewski, 1996).
Plasma varies between silty clay and clay. The skeleton grains range between 30 μm and just over 1 cm (pebble sized). The thin section orientation in the field is not known. Plasmic fabric patterns identified included weak insepic plasmic fabric, weak (thin) skelsepic domains around some of the skeleton grains, a few examples of unistrial plasmic fabric domains and a weakly developed lattisepic plasmic fabric. Earlier work by van der Meer et al. (1993) described the same plasmic fabric patterns (except for the insepic) but did not refer to the fabric as weak.

The images selected for analysis included examples of lattisepic (1), skelsepic (1,2) and insepic (2) plasmic fabrics.

Dry Valleys Sample. C.116

This sample was described as a poorly sorted diamicton with skeleton grain diameters of up to 4 mm. No orientation was indicated for the thin section. The majority of all skeleton grains appeared to be smaller than 2.5 mm. The matrix consists predominantly of clay and some fine silt. The plasmic fabric was found to be a mix of lattisepic, insepic and occasionally omniseptic domains (Zaniewski, 1996).

Weak lattisepic(1,2) and skelsepic(1,2) plasmic fabrics were photographed for analysis. Since no skelsepic domains were mentioned in the earlier qualitative studies this may be treated as an example of the equivocal nature of the subjective thin section descriptions.

Observations

Table 1 includes the summary of the results and is partly based on the information available directly from the image analysis routine. In addition, the results also include rose diagrams and the associated direction data, cumulative size distribution curves and plasmic fabric birefringence strength listing for each domain.

For each image evaluated, texture information included grain size distribution, overall sorting values and skeleton grain sorting values (silt- and sand-sized material). This type of information is, of course, limited in accuracy due to the 2-dimensional nature of thin sections. Furthermore, inaccuracies will occur within both the finest (less than 20 μm) and coarsest (over 2 mm) grain size ranges. The former is due to the decreasing ability to resolve objects smaller than the thickness of thin section - matrix being composed of clay-sized and fine silt-sized material. The latter limitation is due to illegal object limitation of image analysis procedures restricting measurements to only those objects contained wholly within the image (Thompson et al., 1992). Any object in contact with the image edge has an external component. As such its complete shape and size remain unknown. Larger
objects are more likely to come in contact with the edge and therefore be excluded from size measurements. More accurate results can be expected for sand sized material.

Because of the limitations placed on textural information the results should therefore be used as a general reference only. Diagram 1 shows three examples of cumulative area curve obtained in this study.

Interpretations

Texture

Texture-related measurements showed that the sorting evaluations provided by visual evaluations clearly overestimate the degree of sorting actually present. Skeleton sorting values for all of the images tested showed “extremely poorly-sorted material” while the visual descriptions refer only to poor sorting.

When the formula included clay content the sorting values improved to “very poorly-sorted” or even “poorly-sorted” (R.756(6)(7)). This change is not surprising considering the very high clay content estimates obtained. However, some silt-size grains may potentially remain buried within the thickness of the thin section (i.e. undetectable). There may therefore be a degree of overestimation in favor of the clay fraction.

Comparison of the size distribution information also shows some inconsistency between visual descriptions and the image analysis results. R.756 description for Zone 2 indicates an increase in gravel content. Although the measured values did not show any gravel the very coarse sand fraction appeared to be higher in this part of the thin section (3.0 and 3.8 %) while most of the other images examined showed no coarse sand present. The only evidence for the presence of a gravel fraction was measured in R.756 (12) representing Zone 3 material (2.7%).

Measurements of the clay fraction content for R.756 showed very high values ranging from 62.8 to 85.2 %. Even taking into consideration that some overestimation is expected, the results agree with the visual estimate of clayey plasma.

The results for sample C.116 analysis generally agreed with visual descriptions. The sample contained approximately 50% clay and 8% silt. Texture analysis also recognized up to 13.8 % of the skeleton grains as ‘very coarse sand’ and up to 6.3% as gravel. This agrees in principle with the observed upper limit of 4mm (granules).

Even though both Mi.315 and Mi.316 samples are described as containing pebble-sized grains, none were reported. However, “very coarse sand” was observed in all three samples used. The lack of large gravel grains may be explained by their size, the limited width of view of the images analysed (6.4 mm ) and the limit placed on illegal objects.
Examination of the plasma related information revealed an even closer agreement. Mi.316 plasma varied in texture between clay (1) and silty clay (2). In Mi.316(1) clay-sized material reached 79.1 % while the silt fraction represented only 4.7% (the absolute minimum of all the images analysed). Mi.316(2) showed a relatively reversed trend of only 59% clay and 12.5 % silt (maximum value observed in the study). In case of Mi.315 the fit is only marginal in that the clay content was found to be only 50.5% with the silt fraction representing 9.9%.

Asepic Plasmic Fabrics

The only image tested which included an example of an asepic (argillasepic) plasmic fabric closely agreed with the initial qualitative evaluation. Although not completely lacking plasma separations the results showed only very rare anisotropism. This is not unexpected as the field of view may include a few small birefringent domains without them being observed during sample descriptions. Sample Mi.315 does contain plasmic fabric domains and it is likely that the image tested overlapped an area of sepic plasmic fabric (Plate 2). This argument is supported by other evidence (see Table 1). It was found that the image contained 3776 sepic domains (a very small value as compared to other images tested) of which 55 % were listed as skelsepic (one of the highest proportions). The close proximity of the skelsepic domains to the skeleton grains (very often also optically anisotropic) and their remarkably small size (average domain size of less than 35 μm or just over a pixel in area) may explain why they were not noted in the initial visual description. It is worth noting that the original description of Mi.315 includes references to skelsepic plasmic fabric being present (van der Meer et al., 1993).

Skelsepic Plasmic Fabric

Although identified frequently in this study and in visual observations it was only rarely that the results matched. This type of fabric appears more difficult to identify.
subjectively than anticipated.

Samples R.756(9) and Mi.316(1) did not match well with the expected pattern. Skelsepic domains represented only a very small portion of all domains. For image Mi.316(2) the results appeared to match the visual descriptions well. The observed value for ‘frequency of anisotropism’ of only 3.8% indicates a weak fabric. Although the average birefringent intensity value (b) seems to be high it is more closely linked to the average domain size (see discussion).

Both C.116(1) and (2) clearly showed a presence of skelsepic plasmic fabric. However, only C.116(2) confirmed the visual description of a weak pattern (anisotropism of only 2.6%). In C.116(1) this appeared to be strong (anisotropism value of 9.2%) while only a weak pattern was described.

Previously unobserved skelsepic domains were identified in sample R.756(3),(10) and(12).

Insepic Plasmic Fabric

A number of unexpected examples of this type were found in R.756(5), (12) and C.116(2). In these images, where a fabric showing preferred orientation was first described, now an insepic pattern was found. However, the very low percentage of oriented domains found in these images makes any conclusion regarding overall preferred orientation highly ambiguous.

When insepic plasmic fabric was expected, only Mi.316(2) agreed well with the visual description. In R.756(8) strong masepic plasmic fabric was observed.

Lattisepic Plasmic Fabric

All images tested (R.756(9),C.116(1),(2) and Mi.316(1)) failed to confirm the presence of this type of fabric. In C.116(2) and R.756(5), there are not enough oriented domains to consider any type of preferred orientation. In R.756(9) and C.116(1), only one preferred orientation direction was detected. In Mi.316(1), there were multiple modes of orientation. This type of fabric appears to be more rare than expected. It may be that the subjective identification of this pattern is affected by an optical illusion. It should be noted from the table just how often the combination of skelsepic and lattisepic plasmic fabric was described. In practice, objective studies may identify this fabric far less frequently due to the highly restrictive diagnostic requirements.

Masepic Plasmic Fabric

Masepic plasmic fabric was identified more frequently than any other type of fabric considered in this study. Besides the expected examples in R.756(3) and (7), the procedure
also led to identification of masepic fabric in R.756(6,8,9,10,11) and C.116(1). Only one example of expected masepic fabric (R.756(12)) failed to show evidence of masepic plasmic fabric. This was due to an insufficient number of oriented domains.

**Multisepic Plasmic Fabric**

This type of plasmic fabric was encountered in two cases. Since this is a new pattern it was not used in any of the visual descriptions used here. As it is a default format, its presence indicates conditions where none of the other types of fabric could be diagnosed. The two examples involved sample R.756(4), previously thought to have shown an omnisepic plasmic fabric with unistrial domains, and Mi.316(1), originally described as a skel-lattisepic example.

**Unistrial Plasmic Fabric**

None of the images chosen as examples of unistrial plasmic fabric (R.756(2,4,5,6,10, 11,12)) provided information supporting its presence. As evidenced by the number of images used, unistrial fabric is observed very frequently in visual descriptions. Each image used in this study was tested for frequency of the highly elongated domain shapes typical for unistrial fabric. In none of the images did this frequency exceed 0.2 %. Furthermore, in none of the images was this type of domain completely absent. Based on these results it appears that the criteria defining this fabric may have to be relaxed or redefined in the future.

**Omnisepic Plasmic Fabric**

Only two images were described as having an omnisepic plasmic fabric (R.756(2) and (4)). Image analysis of R.756(2) confirmed the accuracy of the visual evaluation. Testing of R.756(4), however, only resulted in identification of a multisepic fabric.

**Discussion**

Although most texture results matched well with qualitative descriptions, the lack of detail and ambiguity of the original texture observations must be recognized. It should be emphasized that the descriptions focused on plasmic fabric and structures while the textural information is meant to give a general impression only. In selecting images for analysis, the highest importance was placed on plasmic fabric. Textural information was therefore limited to the areas showing a high degree of birefringence - mostly clayey plasma. This resulted in an inherent bias towards clay-rich samples - clearly reflected in the results.
obtained.

The visual descriptions were also further limited to a statement regarding skeleton grain sorting and perhaps maximum observed grain size. The advantage of the image analysis routine lies in the availability of detailed size information for the full range of textures. For the finer fractions the accuracy is naturally limited by the thin section thickness. The sand fraction appears most suitable for this type of analysis. The measurements on the coarser fraction can be improved by using lower magnifications. This would result in a larger coverage (over 2.5 cm width of view), with a minimum pixel width of 20 μm per pixel side. The use of larger images reduces the effect of “illegal object” limitation on larger skeleton grains. Increasing the minimum pixel size from 5 to 20 μm will have a limited effect on the measurements of the finer fraction since all skeleton grains smaller than the thickness of the thin section would be listed as plasma (combined clay-, fine silt-sized).

Even if the textural information provides fairly accurate results when compared to visual evaluations, the information available should not replace the more direct techniques currently applied in sediment texture studies. Sieving or settling tube studies provide much more accurate results over the full grain size range. Although some attempts have been made to evaluate 3-dimensional textural information from thin sections (Friedman, 1958), such extrapolations may prove to be more complicated in glacial tills where till micro- and macrofabric studies show that skeleton grain/clast orientation patterns can vary substantially within the same till beds (Derbyshire, 1978; Derbyshire et al., 1985; Menzies, 1990; Kjær and Krüger, 1998). The samples tested in this study also showed very poor sorting, another uncertain factor in 3-dimensional size projections based on 2-dimensional information (Friedman, 1958). Image analysis, however, remains perhaps the best way of evaluating texture in laminated sediments or when the only available sample is in form of a thin section. Furthermore, some aspects of texture-related information, such as sorting or angularity may prove to be very accurate, although more studies are needed. Where image analysis fails to match the accuracy of visual descriptions is in evaluation of changes in plasma density and skeleton grain distribution. Gradual changes within each image are not measured. The results provide data regarding each image as a homogenous picture with uniform plasma density and skeleton distribution patterns. In addition, visual descriptions include the entire thin section while this study only analyzed a few selected points of interest. This second problem may perhaps be overcome with a complete, partially overlapping photo coverage of the entire thin section. Some overlap is necessary in order to minimize the effects of ‘illegal objects’. Ultimately, a single image of the entire thin section would best serve the purposes of image analysis. The first issue, that of gradual distribution and density changes, was not addressed in this study but may have to be considered in any future development of the technique.

Plasmic fabric results show several interesting and unexpected trends. The most
startling observation was perhaps the fact that the described fabric patterns rarely found support in objective data obtained via image analysis.

Masepic plasmic fabric appeared more frequent than would be expected from subjective descriptions. Based on the measurements performed in this study it would appear that this type of plasmic fabric should have been described far more often. The sedimentary genetic implications of this are that sediment deformation along a single shear plane, usually evidenced by a masepic fabric (Jim, 1990) is far more prevalent in glacial sediments than previously thought.

Bimasepic and trimasepic domains and their variants (lattisepic) were not identified at all. This was surprising in that these types of plasmic fabric are frequently described in visual evaluations. Whereas many images clearly showed a single dominant domain orientation direction (masepic fabric) finding a second or third direction was nearly impossible. The possibility exists that the criteria used to identify the secondary direction were too stringent. It is also possible that the use of cross-polarized viewing conditions seriously limited the number of visible birefringent domains and their orientation. The use of circularly polarized light should be considered in any future analysis to overcome this type of bias (Chapter 3.1). Finally, the possibility that bimasepic or trimasepic fabrics are the result of optical illusion must be acknowledged.

Skelsepic plasmic fabric identification was based purely on the frequency of occurrence of skelsepic domains. Although the results appeared to be accurate there is perhaps a need to expand the diagnostic criteria to include the frequency of skeleton grains. This would provide a more flexible decision rule based on an expected frequency of skelsepic domains at a known skeleton grain content level.

Although skel-lattisepic plasmic fabric (skelsepic and lattisepic pattern observed together) is common in visual descriptions, it was not observed in any of the images tested. The results appear to indicate that under some circumstances, the presence of skelsepic domains may result in a visual suggestion of a lattisepic plasmic fabric. This would account for the complete lack of objective evidence for lattisepic plasmic fabric even though a skelsepic pattern is present.

The objective recognition of unistrial fabric represents a classic “catch 22” situation. Unistrial domains tend to be few in number but mostly extensive in area. Their frequency values would therefore be extremely low. In digital (pixel-based) images, each large domain would likely be broken up into a series of discontinuous end-to-end aligned domains. Although domains of this type (20:1 elongation ratio) appear to be very rare (less than 1% of all the domains) they were nevertheless found in similar proportion in all images tested, irrespective of the presence of identified unistrial domains. Since unistrial domains tend to be few in number and are easily identified with the naked eye, the solution may be to measure their orientation individually. In addition to plasmic fabric recognition and quantification, the study also attempted to test a new method of fabric strength evaluation (Chapter 5.3). This was performed at two levels, birefringence strength (the
Diagram 3. Relationship between domain size and birefringence intensity. Area values represent the average size for each of the images tested. Birefringence Intensity Value is a mean for each image.

Diagram 4. Effects of stacking and mineral content variations on plasma separation visibility. Where small domains (a) are highly birefringent due to uniform platelet orientation and mineralogy they will remain highly visible. Small domains (c) with lower birefringence represent lower contrast and are therefore not as likely to be detected. Larger domains (b) do not need to be as highly birefringent to be noticeable.

The frequency of optical anisotropism in the matrix seemed to closely match the qualitative descriptions. The results appear to indicate that the visual descriptions of strength were almost completely determined by the areal ‘dominance’ of the plasma separations. The advantage of the image analysis routine lies in the much more precise way
the frequency is measured. In combination with the birefringent strength value, plasma anisotropism frequency may be used to define fabric strength much more accurately and precisely.

Conclusions

The results showed that the image analysis approach to thin section analysis can be used effectively to extract information regarding texture and plasmic fabric patterns of glacial sediments. Although further development and fine tuning is still required, this new method clearly shows a great deal of promise. The information can be used to diagnose plasmic fabric types present, their strength expressed as birefringent intensity and areal frequency, provide rudimentary grain size distribution curves and orientation information in the form of rose diagrams.

In addition, the results showed that there is a need for a more objective approach to thin section descriptions. The degree of difference between visual descriptions and the image analysis interpretations speaks for itself.

There are, of course, a number of development directions which should be explored further. The most immediate issue may be to obtain plasmic fabric strength data under controlled conditions. This would provide a much more consistent and reliable set of diagnostic characteristics relating fabric strength values and patterns to changes in sediment texture, anisotropic clay content, stress magnitude, stress direction and duration. Once the relationships are known, the use of plasmic fabric information will likely play a major role in the identification of glacial sedimentary facies in the context of their (post)depositional history. Accuracy and consistency of the results should also be considered. Although addressed individually in earlier chapters the issue of accuracy may have to be explored further. One suggested way is through the use of ‘offsetting imagery’, where a series of closely overlapping images are analyzed and the results evaluated. Standardizing the many procedural variables encountered in digital image analysis of thin sections (illumination brightness, magnification, resolution, camera settings) must also be attempted in order to maximize the consistency of results in independent studies.

It is important to note that the technique can be expanded beyond its ability to quantify plasmic fabric patterns and strength. Its development is not limited to plasmic fabric or simple grain size studies. It may, for example, be applied to shape analysis of skeleton grains, voids, microfabric or lithology studies. Image analysis is a flexible process allowing for customization and therefore better focus on those aspects of the imagery which are of highest significance. The results presented here may very well represent only the tip of an information iceberg.
References


<table>
<thead>
<tr>
<th>Sample #</th>
<th>Skeleton Content (%)</th>
<th>Sorting (Overall)</th>
<th>Sorting (Skeleton)</th>
<th>Anisotropism (%)</th>
<th>Oriented Domains (%)</th>
<th>Average Plastic Fabric Strength</th>
<th>Average Domain Size (μm²)</th>
<th>Skelsepic Domains (%)</th>
<th>Orientation Modes</th>
<th>Described Plastic Fabric Pattern</th>
<th>Plastic Fabric Pattern in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.756(2)</td>
<td>36</td>
<td>1.99</td>
<td>5.52</td>
<td>29.5</td>
<td>17.3</td>
<td>149.9</td>
<td>544.1</td>
<td>38</td>
<td></td>
<td>Omnisepic, Unistratal</td>
<td>Omnisepic</td>
</tr>
<tr>
<td>R.756(3)</td>
<td>35</td>
<td>2.90</td>
<td>4.71</td>
<td>13.5</td>
<td>19.8</td>
<td>131.4</td>
<td>158.3</td>
<td>43</td>
<td>53</td>
<td>Masepic, Skelsepic</td>
<td></td>
</tr>
<tr>
<td>R.756(4)</td>
<td>21</td>
<td>2.37</td>
<td>4.89</td>
<td>21.0</td>
<td>18.6</td>
<td>121.6</td>
<td>281.0</td>
<td>36</td>
<td></td>
<td>Omnisepic, Unistratal</td>
<td>Multisepic</td>
</tr>
<tr>
<td>R.756(5)</td>
<td>32</td>
<td>2.38</td>
<td>5.60</td>
<td>13.5</td>
<td>10.5</td>
<td>158.6</td>
<td>122.6</td>
<td>37</td>
<td></td>
<td>Lattisepic, Unistratal</td>
<td>Insepic</td>
</tr>
<tr>
<td>R.756(6)</td>
<td>15</td>
<td>1.71</td>
<td>6.13</td>
<td>24.6</td>
<td>17.9</td>
<td>122.4</td>
<td>357.2</td>
<td>20</td>
<td></td>
<td>Unistratal</td>
<td>Masepic</td>
</tr>
<tr>
<td>R.756(7)</td>
<td>13</td>
<td>1.47</td>
<td>5.97</td>
<td>26.8</td>
<td>25.0</td>
<td>85.8</td>
<td>419.8</td>
<td>11</td>
<td></td>
<td>Masepic</td>
<td></td>
</tr>
<tr>
<td>R.756(8)</td>
<td>34</td>
<td>2.69</td>
<td>5.26</td>
<td>22.8</td>
<td>18.8</td>
<td>126.3</td>
<td>302.2</td>
<td>38</td>
<td></td>
<td>Insepic</td>
<td>Masepic</td>
</tr>
<tr>
<td>R.756(9)</td>
<td>33</td>
<td>2.96</td>
<td>5.12</td>
<td>13.0</td>
<td>16.7</td>
<td>125.3</td>
<td>152.2</td>
<td>35</td>
<td></td>
<td>Lattisepic, Skelsepic</td>
<td>Masepic</td>
</tr>
<tr>
<td>R.756(10)</td>
<td>08</td>
<td>2.84</td>
<td>5.19</td>
<td>9.5</td>
<td>15.5</td>
<td>142.7</td>
<td>135.3</td>
<td>47</td>
<td>130</td>
<td>Unistratal</td>
<td>Masepic, Skelsepic</td>
</tr>
<tr>
<td>R.756(11)</td>
<td>27</td>
<td>2.71</td>
<td>5.39</td>
<td>12.5</td>
<td>22.7</td>
<td>112.9</td>
<td>192.2</td>
<td>28</td>
<td>128</td>
<td>Unistratal</td>
<td>Masepic</td>
</tr>
<tr>
<td>R.756(12)</td>
<td>37</td>
<td>3.59</td>
<td>4.91</td>
<td>24.9</td>
<td>14.3</td>
<td>133.4</td>
<td>336.1</td>
<td>48</td>
<td></td>
<td>Masepic, Unistratal</td>
<td>Insepic, Skelsepic</td>
</tr>
<tr>
<td>C.116(1)</td>
<td>54</td>
<td>4.45</td>
<td>4.56</td>
<td>9.2</td>
<td>16.8</td>
<td>129.6</td>
<td>160.7</td>
<td>56</td>
<td>152</td>
<td>Skelsepic, Lattisepic</td>
<td>Skelsepic, Maspepic</td>
</tr>
<tr>
<td>C.116(2)</td>
<td>61</td>
<td>3.88</td>
<td>4.75</td>
<td>2.6</td>
<td>10.8</td>
<td>168.4</td>
<td>82.1</td>
<td>76</td>
<td></td>
<td>Skelsepic, Lattisepic</td>
<td>Skelsepic, Insepic</td>
</tr>
<tr>
<td>Mi.315(1)</td>
<td>50</td>
<td>3.59</td>
<td>4.72</td>
<td>0.5</td>
<td>1.5</td>
<td>220.1</td>
<td>39.3</td>
<td>55</td>
<td></td>
<td>Argillasepic</td>
<td>Argillasepic</td>
</tr>
<tr>
<td>Mi.316(1)</td>
<td>23</td>
<td>3.01</td>
<td>5.39</td>
<td>10.9</td>
<td>18.7</td>
<td>127.4</td>
<td>217.0</td>
<td>16</td>
<td></td>
<td>Lattisepic, Skelsepic</td>
<td>Multisepic</td>
</tr>
<tr>
<td>Mi.316(2)</td>
<td>36</td>
<td>3.45</td>
<td>5.32</td>
<td>3.8</td>
<td>11.8</td>
<td>158.3</td>
<td>71.4</td>
<td>42</td>
<td></td>
<td>Insepic, Skelsepic</td>
<td>Skelsepic, Insepic</td>
</tr>
</tbody>
</table>

Table 1. Summary of the image analysis results.