Micromorphological analysis of deformation structures

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1. Introduction

Micromorphology is increasingly being used by glaciologists and Quaternary geologists as a primary tool for the analysis of glacial sediments. This type of analysis, which utilises a standard petrological microscope (van der Meer, 1983; Carr, 2004; van der Meer and Menzies, 2011), can provide far greater detail of the depositional and deformation histories recorded by these sediments than can be obtained from macro-scale studies alone. Published studies have used micromorphology to differentiate between diamictons deposited in different sedimentary environments (van der Meer, 1987; Harris, 1998; Lachniet *et al*., 1999, 2001; Carr *et al*., 2000; Carr, 2001; Menzies and Zaniewski, 2003; Carr *et al*., 2006; Phillips 2006; Menzies *et al*., 2006; Reinardy and Lukas, 2009; Kilfeather *et al*., 2010); as an aid to our understanding of the processes occurring beneath glaciers (Menzies and Maltman, 1992; van der Meer, 1997; Menzies *et al*., 1997; Khatwa and Tulaczyk, 2001; van der Meer *et al*., 2003; Roberts and Hart, 2005; Hiemstra *et al*., 2005; Baroni and Fasano, 2006; Larsen *et al*., 2006, 2007; Hart, 2007); unravelling the often complex deformation histories recorded by glacigenic sequences (van der Meer, 1993; Phillips and Auton, 2000; van der Wateren *et al*., 2000; Menzies, 2000; Phillips *et al*., 2007; Lee and Phillips, 2008; Denis *et al*., 2010); and investigating the role played by pressurised pore-water/melt water during these deformation events (Hiemstra and van der Meer, 1997; Phillips and Merritt, 2008; van der Meer *et al*., 2009; Denis *et al*., 2010). The terminology used in these studies to describe the various micro-textures observed in thin section typically follows that proposed by van der Meer (1987, 1993) and Menzies (2000). The recent development of a quantitative microstructural mapping method (Phillips *et al*., 2011) which utilises commercially available computer graphic software (e.g. Adobe Illustrator/CorelDraw) alongside these traditional methods, has the potential to further contribute to our understanding the processes occurring during the deformation of glacial sediments. During this process the relationships between successive generations of clast microfabrics and other microstructures (e.g. plasmic fabrics, turbate structures, folds, faults, shears…etc) are determined, allowing a detailed relative chronology of fabric development to be established, applying the terminology and approach typically used by structural geologists and metamorphic petrologists to unravel the often complex, polyphase deformation histories recorded by glacial deposits.

2. Methodology

Although micromorphology is a powerful tool in the glacial scientists armoury in the study of both modern and ancient glacigenic sedimentary sequences, such studies should not be used in isolation, but as part of a multidisciplinary approach, involving sedimentological, geomorphological and structural field techniques. In the case of marine and other cores, micromorphology should ideally be used in conjunction with detailed lithological logs of the borehole and, if available, engineering and geophysical test data. Such field and/or borehole data will provide the context for interpreting the range of micro-textures and microstructures present in thin section in terms of the depositional processes and glacitectonic history recorded by the sedimentary sequence

2.1 Field sampling and description

The laboratory preparation of thin sections from samples of unconsolidated sediments is a labour intensive process, so careful thought is required to develop an appropriate field sampling strategy (Liu *et al.,* 2002; Dungan *et al*., 2002; Carr, 2004). The nature of the field site selected for collecting samples for micromorphological analysis will be constrained by the level of exposure in the area being studied. Large exposures, such as coastal cliff sections and quarry faces orientated parallel to the main ice flow direction, are ideal as they allow glacitectonic structures and sedimentary facies to be examined at a range of scales. However, in poorly exposed areas, samples can be successfully obtained from trial pits, drainage ditches, road cuttings, or temporary exposures provided by excavations for the foundations of buildings or services such as electricity cables and gas pipe lines. Prior to sampling the sedimentary sequences should be logged and the macro-scale characteristics of the sequence (e.g. geometry of the units, lithology, macroscopic deformation structures....etc) described in detail. An excellent

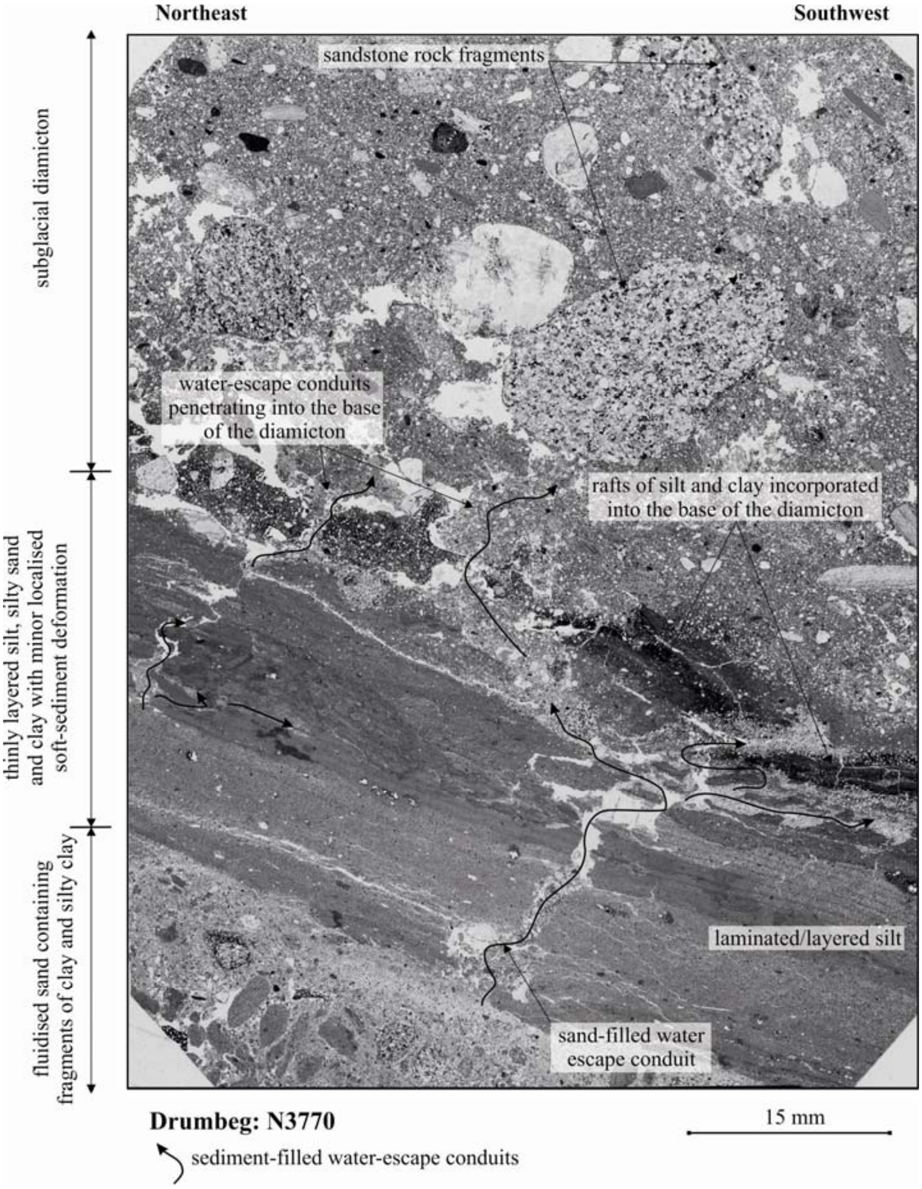

Figure 2.1. Thin section of the basal contact of a stratified diamicton from Drumbeg Quarry, Scotland (Phillips *et al*., 2007). The diamicton is underlain by a complex zone of laminated/layered silt and fluidised sand, interpreted as a water lubricated detachment. The contact is cross cut by a number of irregular, sediment-filled hydrofractures

practical guide to the analysis and description of glacial sediments in the field is provided by Evans and Benn (2004).

Many micromorphological studies focus on elucidating the nature of the contacts between sedimentary facies or bounding structures (Figure 2.1) requiring careful sampling across these features. Micromorphology is also increasingly being used to examine in detail the development of small-scale glacitectonic structures, such as folds and faults (Figure 2.2), as well as hydrofracture systems (Figure 2.3). This approach is comparable to that employed in metamorphic and structural bedrock studies where thin sections of key structures are used to provide detailed insights into the processes occurring during deformation. In deformed glacial sequences this requires the targeted sampling of the deformation structures, for example systematic sample collection across a ductile shear zone or thrust to examine the progressive deformation history recorded by these detachments and their potential effect on fluid flow through the subglacial system.

Prior to sampling, the exposed section should be cleaned with a trowel or spade and the key structures and/or lithologies photographed as a reference. Individual samples are collected using square or oblong, aluminium Kubiena or 'mammoth' tins of different sizes, which are either cut or pushed into the face of each exposure in order to limit sample disturbance. The geographical position, orientation relative to magnetic north, depth and way-up of the sample should be marked on the outside of the tin during collection (Phillips *et al*., 2007; van der Meer and Menzies, 2011). Prior to removal of the samples the Kubiena tins should be photographed *in situ*, as this will provide an important reference to the relative location of the samples when describing the thin sections in the laboratory. Each sample is then removed from the face, sealed in two plastic bags, and ideally stored in a cold store to prevent the material from drying out prior to sample preparation. It is critical that correctly orientated samples are collected for thin sectioning so that kinematic indicators (such as asymmetrical folds, faults, SC-fabrics…etc; see Chapter 1 and Passchier and Trouw, 1996) can be correctly used to provide information on the stress regime active during deformation and local ice movement directions. The orientation of the samples, relative to the presumed directions of ice advance and retreat needs to be established as only samples orientated parallel to the principal direction of ice movement will exhibit the most complete record of glacitectonic deformation and its intensity.

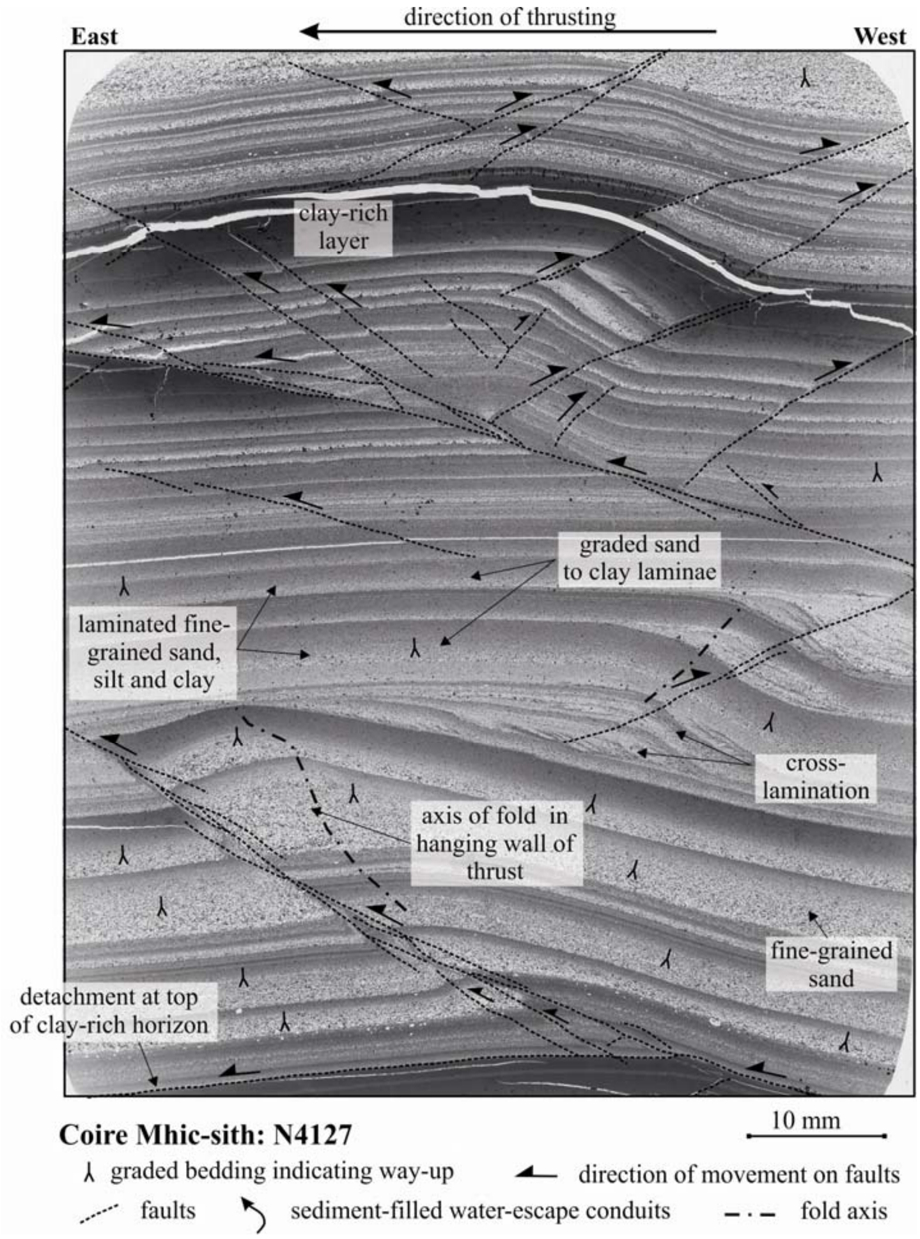

Figure 2.2. Thin section of glacially overridden lake sediments from Coire Mhic-sith, Scotland (Phillips *et al*., 2007). Deformation of these finely laminated sands, silts and clays resulted in easterly directed thrusting and the localised folding of bedding within the hanging walls of these brittle deformation structures

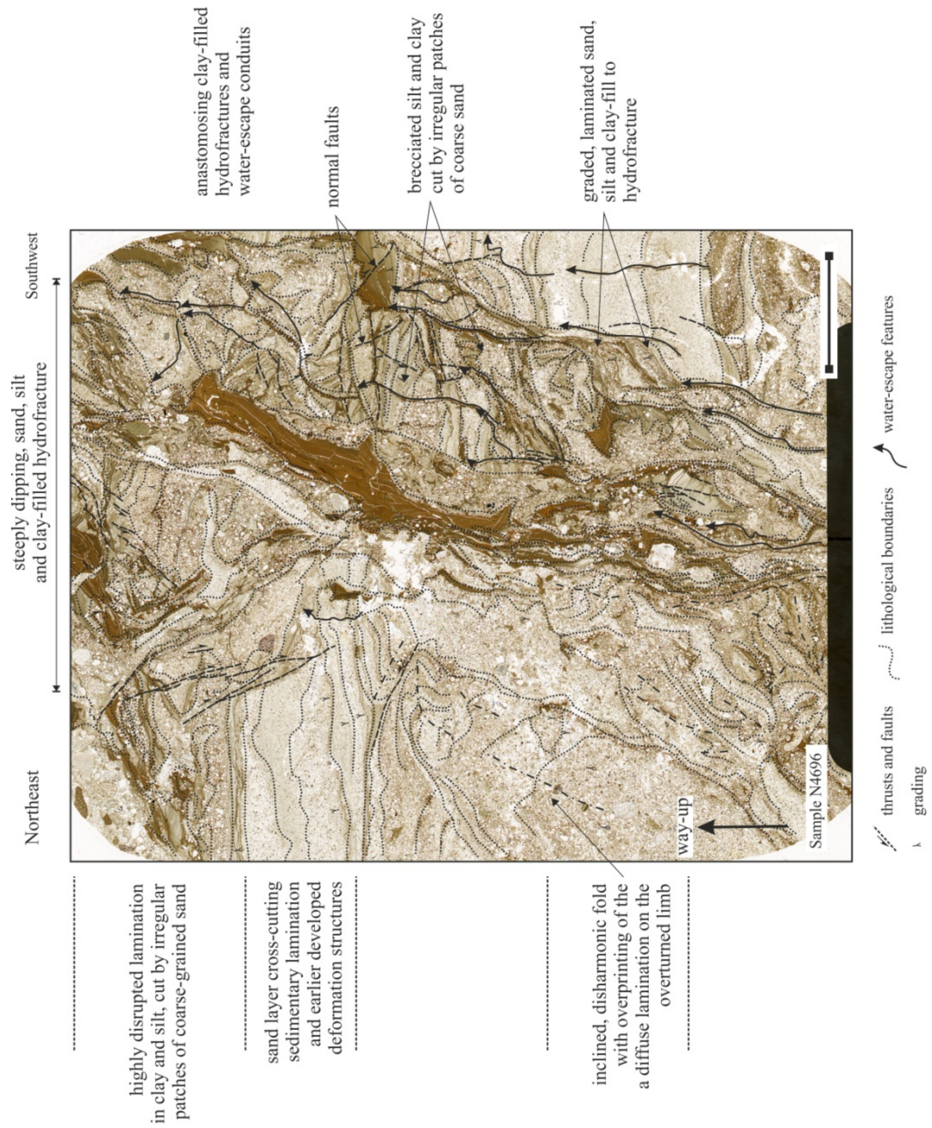

Figure 2.3. Thin section of a sediment-filled hydrofracture system cutting a raft of glaciomarine sediments from Clava, Scotland (Phillips and Merritt, 2007). The complex sediment fill present within the hydrofracture indicate that this system was active over a prolonged period of time and accommodated several phases of water-escape

2.2 Sample preparation and thin section production

The preparation of thin sections from unconsolidated glacial sediments (total time up to 10-12 months) comprises three main stages; *(i)* removal of pore water, *(ii)* impregnation by resin and curing, and *(iii)* thin section production (Fitzpatrick, 1984; Murphy, 1986; Lee and Kemp, 1992; Carr, 2004). A detailed description of this process can be found in Carr and Lee (1998) and is only briefly described here. The removal of the pore water within the sample is achieved by either air drying, or by the much slower process of acetone replacement where the intergranular pore water is gradually replaced by acetone (Lee and Kemp, 1992; Phillips *et al*., 2007). The acetone is changed regularly over a six week period (every day for five days then once a week for the next five weeks) to allow for all the water to be removed. Air drying of samples, in particular clay-rich sediments, can lead to the development of shrinkage cracks during sample preparation, potentially affecting the quality of the thin section and/or the degree of confidence which can be applied to the interpretation of open fracture systems within the sediment. Once 'dry' the sample is impregnated with an epoxy resin (Lee and Kemp, 1992) and placed into a fume cupboard to cure (harden). A number of thin section laboratories carry out the resin impregnation within a vacuum chamber, increasing the pressure over a period of six hours to encourage the resin to fill all the pore spaces in the sample. However, care must be taken as this may lead to the disaggregation of friable/delicate samples. Once impregnated with resin the samples are then left to cure for a minimum of six weeks prior to cutting. Problems with incomplete resin impregnation of glacial sediments do occur, especially in samples with high clay contents as this can prevent the resin penetrating fully through the sample. One way to avoid this problem is to replaced the acetone used in the sample drying stage with a resin-acetone mix, progressively increasing the resin content up to 100%. This approach does increase the preparation time, but does lead to an increase in the quality of sample impregnation. Alternatively, sample impregnation can be improved by carrying out surface impregnation with epoxy resin (Carr and Lee, 1998).

Once hardened large format, orientated thin sections are cut from the centre of each of the impregnated sediment blocks, avoiding artefacts associated with sample collection or preparation. Each thin section should be cut orthogonal to the main deformation structures evident from the field investigation. The cut block is attached to a glass slide with a thin film (zero bond) of adhesive. Once dry the excess sample is cut away using a rock saw, and the thin section ground down to a thickness of 20-30µm, either by hand or specialist grinding machine, prior to being covered by a thin, protective glass cover-slip (Carr and Lee, 1998).

2.3 Description of thin section micromorphology

Thin sections are typically examined using a standard petrological microscope under plane and cross-polarised light allowing the identification and detailed study of the range of micro-textural and structural characteristics present within the sample. High resolution digital scans of the whole thin section can be used to identify larger-scale structures within the sample (e.g. folds, faults....etc) and/or as an aid to locating the position of key features observed at higher magnifications. Photomicrographs of these structures can be captured using a specialised camera and digital imaging software attached to the microscope. Traditionally the terminology used to describe the various micro-textures developed in glacial sediments (in particular tills) was developed by van der Meer (1987, 1993) and Menzies (2000) (Figures 2.4 and 2.5), and derived from soil micromorphology (Brewer, 1976).

Published work on systematically recording the type and frequency of microstructures developed within diamictons has largely focused upon attempts to establish their depositional setting (Carr, 2001; Carr *et al*., 2001; Menzies *et al*., 2006; Menzies and Whiteman, 2009; Kilfeather *et al*., 2010). The resultant summary tables have been used to compare the range of microfabrics and structures present within diamictons laid down in radically different sedimentary environments. One drawback to this type of approach is that the relationships between the various microstructures are not recorded. Consequently, such summary tables cannot be used as an aid to unravelling the polyphase deformation histories recorded by diamictons and, therefore, do not shed any light on the series of events/processes that led to the formation of these complex deposits. Furthermore, sediment composition can have a profound effect on the range of microstructures developed within a diamicton, for example plasmic fabrics will only develop where clay minerals are present within the matrix, potentially leading to the miss identification/characterisation of depositional setting.

Researchers with a geological background have employed structural geological terminology to describe the successive generations of fabrics (S1, S2……Sn), folds (F1, F2…..Fn), rotational structures, shears and faults present deformed glacial sediments, including diamictons (Roberts 1995; Phillips and Auton, 2000; van der Wateren *et al.,* 2000; Phillips *et al*., 2007; Denis *et al*., 2010; Phillips *et al*., 2011). The interrelationships between the successive

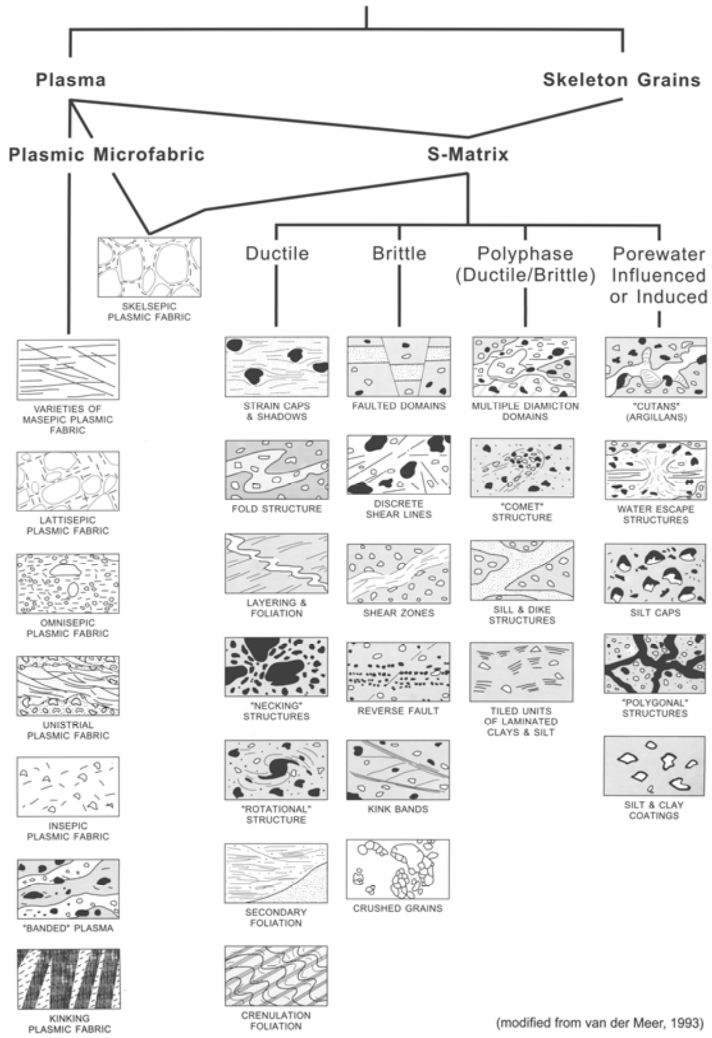

Figure 2.4. An example of the relationship between observed micromorphological structures and suggested form of depositional processes within a subglacial environment (Menzies, 2000)

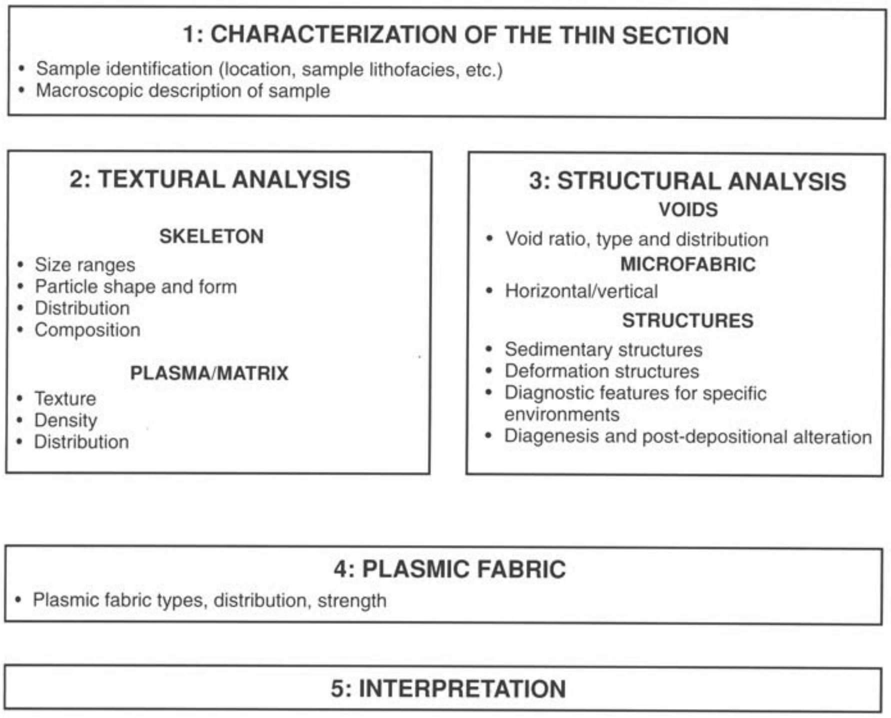

Figure 2.5. Format for describing thin sections (Carr, 2004)

generations of deformation structures are, typically, more clearly observed in thin section than at outcrop and can be used to understand the deformation histories recorded by polydeformed glacigenic sequences.

Clast microfabric analysis using thin sections of diamictons, typically integrated with macrofabric analysis, has been used to provide evidence of palaeo-ice flow directions and to model the response of tills to subglacial deformation (Sitler and Chapman, 1955; Ostry and Deane, 1963; Evenson, 1970; 1971; Johnson, 1983; Carr 1999, 2001; Carr *et al*., 2000; Lee, 2001; Carr and Rose, 2003). Work by Carr (2001) has indicated that clasts microfabrics may potentially be used to discriminate between diamictons deposited in differing sedimentary environments (also see Carr 2004).

2.4 Microstructural analysis of thin section

Phillips *et al*. (2011) have recently published a new method for the analysis of polydeformed diamictons that utilises high resolution digital scans of orientated thin sections imported into a standard computer graphics package to measure the orientation of long axes of detrital (skeleton) grains included within a glacial deposit. These data are then used to identify the main clast microfabrics present within the sediment, allowing the delineation of microfabric domains in which elongate grains share a similar preferred orientation (Figure 2.6). This process leads to the identification, characterisation and, most importantly, a greater understanding of the interrelationships between the various generations of microfabrics developed within polydeformed glacial deposits. The relationships between the clast microfabrics and other microstructures (e.g. plasmic fabrics, turbate structures, shears, folds, faults…etc) are examined, in conjunction with examination of thin sections under a petrological microscope. Clast long axis orientation data collected for different parts of a thin section are plotted on a series of rose diagrams allowing the variation in clast microfabric orientation to be displayed graphically.

This relatively simple graphical technique is illustrated in Figure 2.6 and can be summarised in the following 5 stages:

Stage 1 – *import a high resolution scan of the thin section into the graphics package;*

Stage 2 – *enlarge (zoom in) the image so that the fine sand grains (down to c. 0.05 mm in diameter depending on the quality of the scan) are clearly visible and, on a separate layer, digitise the long axes of the included detrital grains working systematically across the thin section. Data can be obtained for all clasts with aspect ratio >1.1, over a wide range of grain sizes (very fine sand to small pebble);*

Stage 3 – *long axis orientation data for either the whole thin section, or key areas of the thin section, are plotted on a series of rose diagrams allowing the identification of the principle clast microfabrics within the sample. Plotting a series of diagrams for different parts of the thin section and/or from different lithological units within the glacial deposit allow any systematic variations in the orientation of the main clast microfabrics to be established and the effect of till composition on these microfabrics to be assessed;*

Stage 4 – *using a different line style, highlight/define the main clast microfabrics in the thin section. These microfabrics are defined by the preferred alignment of the long axes of the clasts, so it is a simple case of drawing lines to pick out the 'trains' of aligned grains;*

Stage 5 – *identification of clast microfabric domains and microstructural interpretation of the glacial deposit. These are defined as areas in which the included detrital grains exhibit the same preferred alignment. This is a simple process of drawing a polygon around the area. Comparison of these domains with the orientation data plotted on the rose diagrams (plotted during Stage 4) allows the identification/characterisation of the main clast microfabrics developed within the specimen. Different coloured fills can be used to identify these different clast microfabrics. Particular care should be taken to clearly represent any cross-cutting or similar relationships between the various clast microfabrics and other microstructures identified within the thin section. This information forms the basis on which the relative age of the successive generations of microfabrics and structures can be established. Once completed the diagram represents a microtextural-microstructural 'map' of the entire thin section.*

Terminology	**Definition**
Spaced foliation	Microfabric is spaced; clast alignment preferentially developed within discrete zones of domains
Continuous foliation	Microfabric is continuous; clast alignment homogeneously developed throughout the thin section
Microfabric domains	Spaced microfabrics in which clasts show a pronounced preferred shape alignment
Microlithons	Microfabric which have a weak or no preferred fabric, or contain relicts of earlier formed microfabrics oblique to the later microfabric domains
Crenulation foliation	Crenulation style microfolds deforming earlier formed clast microfabric, can be recognised in the microlithons
Disjunctive foliation	No crenulations can be recognised in the microlithons

Table 2.1. Definitions of key terminologies for the microstructural mapping method (Phillips *et al*., 2011)

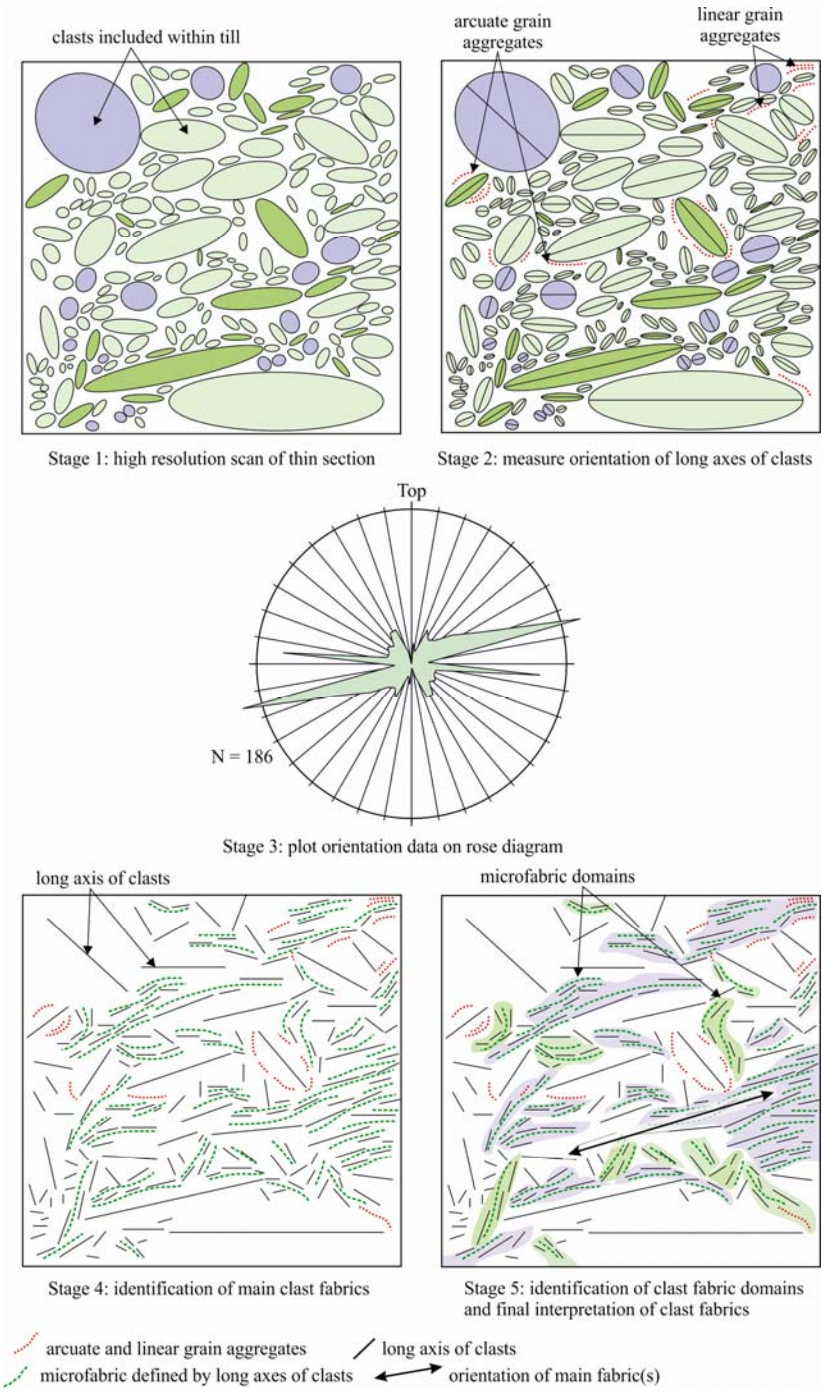

Figure 2.6 (previous page). Diagram showing the five stages involved in the proposed graphical approach to the identification and analysis of clast microfabrics in glacial sediments: **Stage 1** – import high resolution scan of thin section into graphics package; **Stage 2** – measure the orientation of the long axes of the clasts; **Stage 3** – plot orientation data on a rose diagram; **Stage 4** – identification of main clast microfabrics; and **Stage 5** – identification of clast microfabric domains and final interpretation of clast microfabrics (Phillips *et al*., 2011)

The terminology proposed for the description of the clast microfabrics in glacial sediments follows the system used by petrologists (Powell, 1979; Borradaile *et al*., 1982; Passchier and Trouw, 1996) for the description of cleavage and/or schistosity developed in metamorphic rocks. The main terms used in this method have been summarised in Table 2.1 and a full description can be found in Phillips *et al*., (2011).

The 'microstructural mapping' method potentially represents a powerful new tool for the identification, description and analysis of the microstructures and clast microfabrics developed in polydeformed glacial sediments. The detailed microstructural maps of thin sections generated by this approach allow the relationships between successive generations of clast microfabrics and other microstructures (e.g. plasmic fabrics, turbate structures, folds, faults, shears…etc) to be determined, allowing a detailed relative chronology of fabric development to be established. This level of micromorphological detail is necessary when attempting to unravel the often complex polyphase deformation histories recorded by glacigenic deposits. This method enhances traditional methods of thin section analysis and increases the detail we can obtain from a thin section.

The ease of application of both methods is clearly demonstrated using two case studies: *(i)* a sample of stratified chalk-rich till from West Runton, North Norfolk (Eastern England); and *(ii)* a sample of faulted gravel from Dinas Dinlle, North Wales.

3. Case Study 1 – stratified chalk-rich diamicton from West Runton

An orientated sample of diamicton (sample number WR01/01; orientation 259°-079°) was taken from a thinly stratified chalk–rich till exposed at the base of a prominent sea stack on the beach at West Runton, North Norfolk (Figure 2.7; the stack was subsequently removed during a severe storm during the winter of 2010-2011). The sample included two discrete shears or reverse faults which off-set the stratification in the till (apparent sense of displacement towards the west, inset Figure 2.7), as well as evidence for the potential mixing of two lithologically distinct diamictons; a very pale grey, chalk-rich diamicton and a medium-grey till. The stratified chalk-rich till structurally underlies a thick unit of polydeformed, brown sandy diamicton (correlated with the Bacton Green Till exposed in the nearby cliff face) which possesses a pervasively developed glacitectonic banding or foliation that is itself deformed by several generations of open to tight, asymmetrical folds. The top of the stack was capped by a thin unit of chalk (Figure 2.7), possibly representing a small bedrock raft contained within the highly deformed Bacton Green Till.

The thin section is composed of a stratified or layered, matrix-supported, fine silty clay (Figure 2.8a) which contains sub-rounded chalk clasts (<20mm in diameter) and rare flints. Traces of opaque minerals and some bioclastic material are also present. The wispy-looking compositional banding is defined by alternating chalk-rich and relatively chalk-poor layers. At lower magnification, the margins of the individual layers appear sharp and irregular in form (see Figure 2.8a). At higher magnifications, however, these contacts are more gradational in nature and marked by a rapid change in the modal proportions of included chalk fragments. In the central, right-hand side of the thin section is a wedge-shaped unit or layer of silty clay containing a higher concentration of detrital quartz grains. A fine-scale layering present within this quartzose unit is folded by a sub-horizontal to recumbent open fold.

Vertical and sub-horizontal, irregular, open fissures are concentrated in the lower middle part of the thin section. These structures do not appear to follow any pre-existing planes of weakness or the layering present within the diamicton and may have been induced during sample preparation. An easterly dipping, diagonal band of haematic staining which runs across the in central part of the thin section, cuts across and therefore post-dates the development the compositional layering present within the diamicton. This zone of haematic staining is interpreted as having formed as a result of Fe oxidation associated with the movement (post-depositional) of groundwater through the till.

Micro-scale deformation structures developed within the till include pressure shadows adjacent to the larger chalk clasts and variably developed arcuate grain to liner grain alignments.

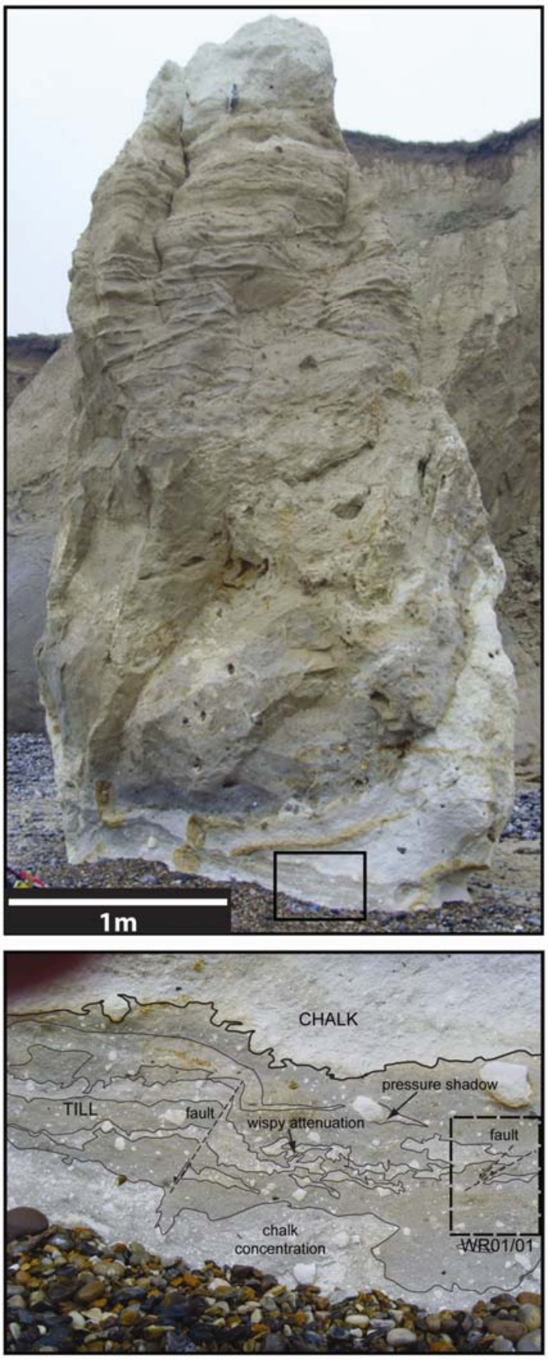

Figure 2.7. Photograph of coastal stack and zoomed-in region at the base highlighting the macro-scale structures

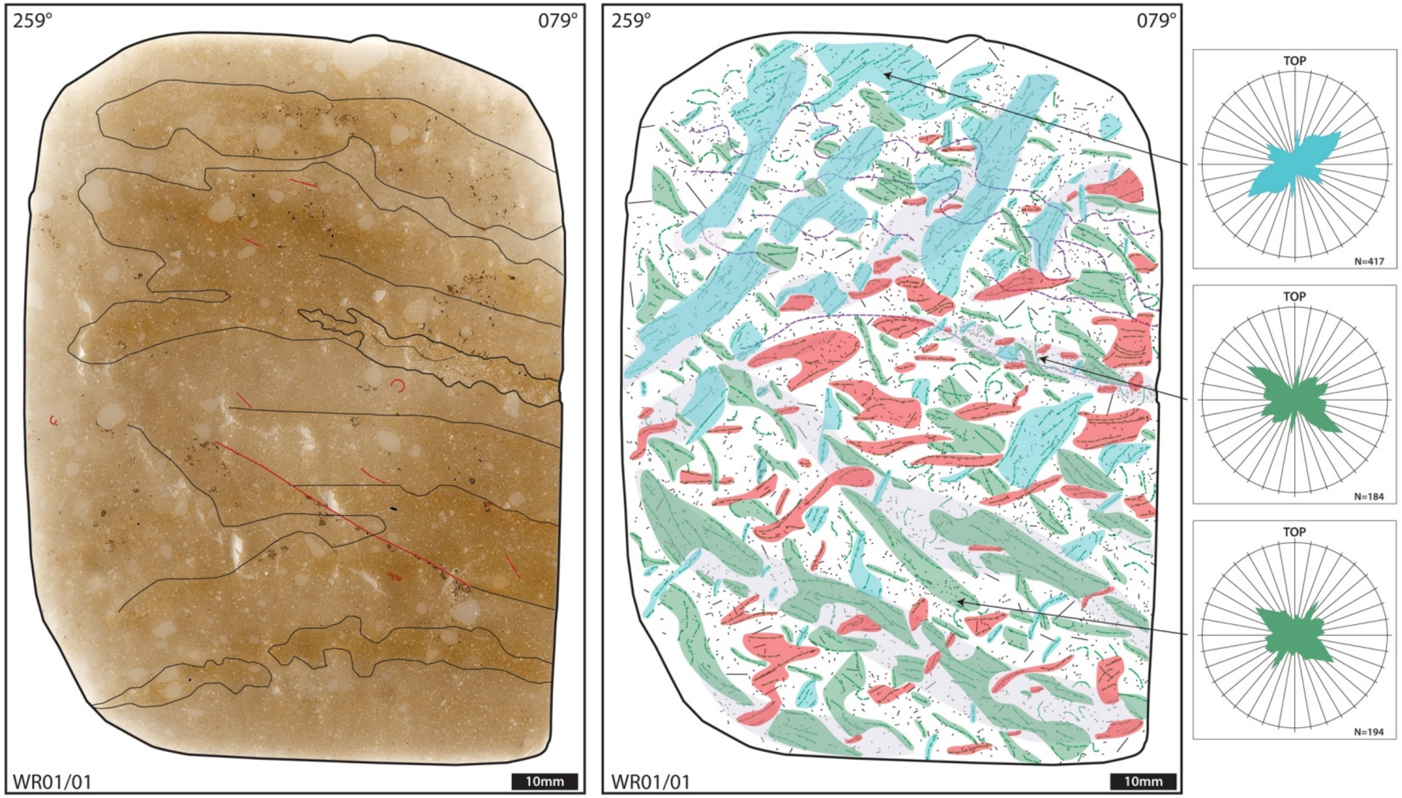

Figure 2.8. Example of a completed microstructural map of a polydeformed glacial deposits at West Runton, Norfolk

Three successive generations of clast microfabrics have been recognised within sample WR01/01 (Figure 2.8). The earliest fabric (S1, orange polygons on Figure 2.8) takes the form of an irregular, discontinuous spaced foliation and is developed throughout most of the sample, but is most pervasive within the central part of the thin section. S1 clearly cross cuts the compositional layering developed within this fine-grained chalk-rich till. This relationship indicates that the imposition of all three generations of clast macrofabric post-dated and are therefore unrelated to the formation of the stratification within the till. The second fabric (S2, green polygons on Figure 2.8) is a discontinuous, spaced foliation defined by irregular domains which cut across and, therefore, post-date both S1 and compositional layering. The earlier formed S1 fabric is preserved as a sigmoidal to locally crenulated fabric within the S2 microlithons. The heterogeneously developed S2 microfabric dominates the lower half of the thin section where it dips at a moderate angle towards the east. The relatively younger S3 fabric (blue polygons on Figure 2.8) is a weak zonal, relatively continuous, moderately to steeply westerly dipping discontinuous foliation and is most pervasively developed in the upper part of the thin section. This fabric defines a broad curve or arc becoming more steeply inclined towards the top of the thin section (Figure 2.8).

Clast microfabric data obtained from sample WR01/01 (see the rose diagrams on Figure 2.8) show that S2 and S3 are the most pervasively developed, suggesting that the imposition of these microfabrics may have resulted in the partial overprinting of the earlier developed S1 fabric. Although developed in different parts of the thin sections, highlighting the heterogeneous nature of deformation, S2 and S3 form a conjugate set, defining R and P-type Riedel shears (see Chapter 1) that formed during the later stages of deformation.

4. Case Study 2 – faulted gravel from Dinas Dinlle

An orientated sample (sample number DD09 3/1) of a faulted gravel was collected from polydeformed glacial sequence exposed at Dinas Dinlle on the western coast of Llyn Peninsula in North Wales (Phillips *et al*., 2011). The steeply inclined to subvertical, normal fault (downthrow to the north) occurs on the southern limb of a large-scale, asymmetrical anticline that deforms a thick, moderately well-bedded sequence of coarse sands and gravels. This brittle fault shows a pronounced displacement gradient with the amount of

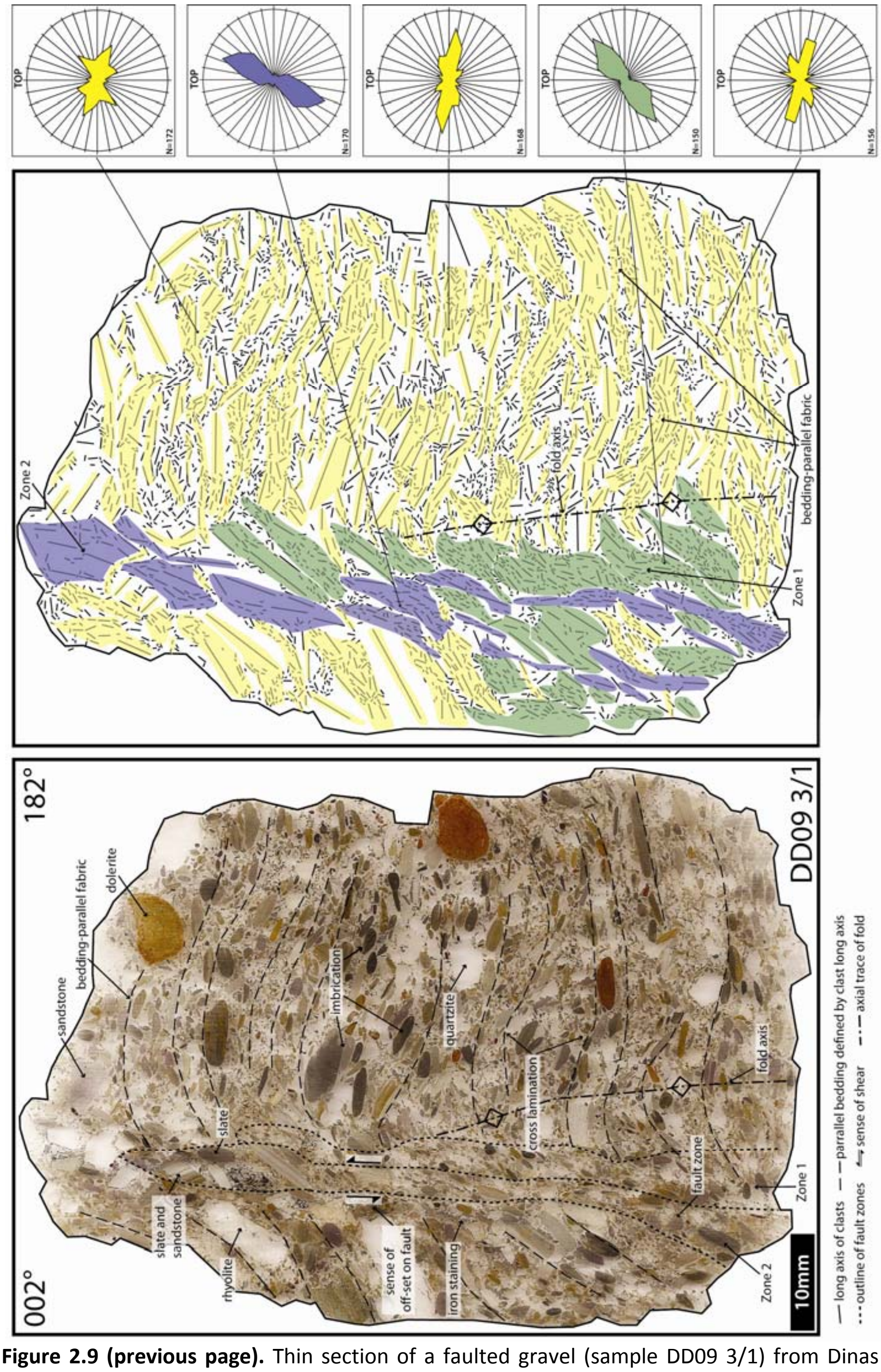

Figure 2.9 (previous page). Thin section of a faulted gravel (sample DD09 3/1) from Dinas Dinlle, Llyn Peninsula, North Wales. The gravel possesses a well-developed bedding-parallel clast microfabric which has been folded by an open, upright structure. This fold has been cut by a later steeply inclined normal fault (Phillips *et al*., 2011)

displacement decreasing upwards, from c. 12 cm near the centre of the exposed fault plane, to less than 6 cm towards its tip.

In thin section (Figure 2.9) the fault deforms a moderately sorted, clast-supported gravel composed of subangular to subrounded, low sphericity clasts, dominated by mono- and polycrystalline quartz, slate and sandstone, within a coarse sand matrix. One of the most prominent features of this thin section is the presence of a very well-developed bedding-parallel clast microfabric (S0, yellow polygons on Figure 2.9) defined by the preferred shape-alignment of elongate coarse sand to small pebble sized clasts. This relatively smooth, zonal, spaced foliation is composed of elongate, parallel microfabric domains. In the intervening microlithons the clasts locally exhibit a pronounced alignment and stacking, thought to preserve the original sedimentary imbrication of the detrital grains formed as the gravel was being deposited.

The S0 bedding-parallel microfabric is folded by an open, upright, northerly verging asymmetrical fold, the hinge area of which has clearly been effected by deformation associated with a subvertical, 5 to 10 mm wide fault zone (Figure 2.9). The axial surface of the fold is coplanar with the normal fault. Deformation within the fault zone resulted in the reorientation of sand and pebble sized clasts leading to the overprinting of S0. In detail the fault is composed of several dislocations denoted by marked changes in the clast orientation. The fault is composed of two distinct zones: *(i)* a wedge-shaped outer zone (Zone 1) within the lower part of the fault (green zone in Figure 2.9) defined by a relatively pervasive, continuous clast microfabric in which the majority of the clasts exhibit a preferred alignment dipping at 38°-40° towards the north; and *(ii)* a central, narrower zone (Zone 2) characterised by a steeply inclined (c. 68°) northerly dipping, continuous clast microfabric (blue zone on Figure 2.9). The boundaries between the two zones are sharp, indicating that they represent at least two separate phases of movement on the fault, each accompanied by a phase of fabric development. The curved to sigmoidal nature of the fabric within the lower part of Zone 1 records a steeply inclined sinistral sense of shear, consistent with the normal sense of displacement on the fault (Figure 2.9). The more extensive Zone 2 cuts across Zone 1 (Figure 2.9), providing a clear relative age relationship between the phases of movement and fabric development

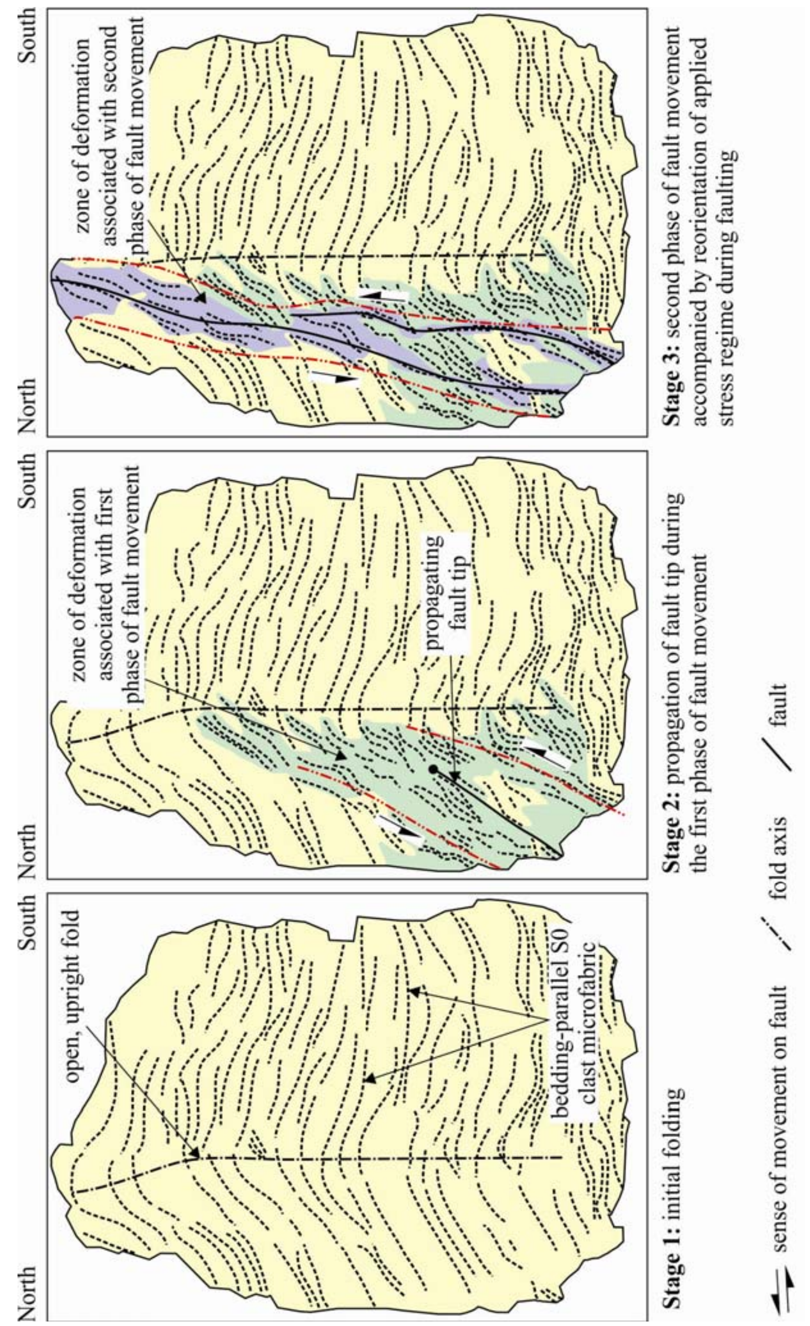

Figure 2.10. Model for the progressive development of the normal fault present within the thin section from Dinas Dinlle (Phillips *et al*., 2011)

along the fault (Zone 1 = S1, earlier; Zone 2 = S2, later), with the narrower Zone 2 recording a focusing of deformation during the later phase of fault movement. In the lower left-hand part of the thin section, Zone 2 bifurcates and encloses a lenticular area of Zone 1 microfabric which, itself, contains a relict of S0 (Figure 2.9).

Figure 2.10 is taken from Phillips *et al*. (2011) and shows a simple three stage model involving earlier folding followed by later brittle faulting to explain the deformation history recorded by the gravel. The earlier part of the deformation history (D1) resulted in the folding of a pre-existing bedding-parallel S0 fabric. S0 is thought to have formed during the deposition of the gravel, but was probably intensified as a result of compression during compaction of the sediment which also led to localised distortion and moulding of softer mudstone rock fragments around adjacent more rigid quartzose grains. Although the normal fault clearly cuts across and, therefore, post-dates folding, the axial surface of the fold is coplanar with this brittle structure indicating that they may have formed in response to the same overall stress regime. Folding is considered to have occurred immediately above the propagating fault tip (Stage 1 on Figure 2.10). As the fault propagated upwards, it progressively deformed the earlier fold, penetrating along the hinge of this structure. The fault zone clearly accommodated two phase of movement: *(i)* the earlier phase of movement, represented by Zone 1, led to a wedge-shaped zone of deformation immediately surrounding the fault tip (Stage 2 on Figure 2.10); and *(ii)* a later, second phase of movement, marked by the steeply inclined Zone 2, during which the fault tip cut through the remainder of the sediment and earlier formed Zone 1, and was accompanied by a much narrower zone of deformation (Stage 3 on Figure 2.10). The marked differences in the orientation and extent of Zones 1 and 2 can be used to suggest that there was a slight change in the stress regime being applied to the gravel during fault propagation, possibly with a cessation or pause in deformation separating Stages 1 and 2.

The detailed deformation history erected for the sample of faulted gravel from Dinas Dinlle clearly illustrates the potential of micromorphology as an aid to understanding the propagation of larger scale glacitectonic structures (e.g. folds, faults) through a deforming sedimentary sequence.