Micromorphology of the Quaternary sediments from the Dounreay area, Caithness, Scotland

Integrated Geological Survey (North)

Internal Report IR/03/045

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/03/045

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Key words

Quaternary, micromorphology, Caithness, Scotland.

Front cover

Cover picture details, delete if no cover picture.

Bibliographical reference

E. R. PHILLIPS. 2003. The micromorphology of the Quaternary sediments from the Dounreay area, Caithness, Scotland. *British Geological Survey Internal Report*, IR/03/045. 37pp.

Keyworth, Nottingham British Geological Survey 2002

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of their regional geological mapping programme. It contains descriptions of the micromorphology of three samples of diamicton exposed in the Reay District, Caithness, Scotland. The work forms part of a multidisciplinary Caithness Devonian and Quaternary Project.

The a main aim of this project is to investigate the Devonian and Quaternary geology of the far North East of Scotland, represents an important component of the onshore geology of the UK that has a crucial role in understanding the evolution of the West Orkney and Northern North Sea basins. In addition, formulation of local planning policies on landfill, hard rock extraction and groundwater protection, in this sparsely populated but environmentally sensitive region, has demonstrated a requirement for modern geospatial data throughout the project area. This involves the resurvey of the solid and drift geology of the onshore eastern margin of the Orcadian basin (1: 50 000 Sheets 83E, 94W, 110, 115 E 116W & 116E) concentrating on the nature and distribution of the Quaternary and Devonian strata.

Acknowledgements

David Oates is acknowledged for his expertise in making high quality large format thin sections, even of out the most poorly consolidated of materials.

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Summary

This report describes the micromorphology of the Quaternary sediments exposed in the Dounreay area of Caithness, northeastern Scotland. The work forms part of the Devonian and Quaternary of Caithness Project of the Integrated Geological Survey (North) Programme.

The report provides detailed descriptions of the micromorphology of three large format thin sections of the Quaternary sediments exposed at several locations within the project area.

1 Introduction

This report describes the micromorphology of a suite of Quaternary sediments exposed in the Dounreay area of Caithness, northern Scotland. Micromorphology is a relatively new and still developing technique and refers to the examination of Quaternary and other glacial sediments in thin section. (see van der Meer 1987, 1993; Menzies 2000). A total of three large format thin sections of unconsolidated sediment from Dounreay area have been examined.

Three samples (PY705; PY706; PY708) of a variety of unconsolidated diamictons (Quaternary in age) were collected from the following locations: Shuttered Trial Pit Number 3, Dounreay (Buldoo) [ND 00284 66876] (two samples), Shuttered Trial Pit Number 5, Upper Dounreay [ND 00251 65942] (one sample). The samples were collected using 10 cm square, aluminium kubiena tins which were either cut or pushed into the face of the exposure. The samples were then removed and sealed into two plastic bags and stored within the BGS cold store at Murchison House (Edinburgh) to prevent the material from drying out prior to sample preparation.

2 Analytical techniques

A total of three samples were prepared by Mr D. Oates at the British Geological Survey, Thin Sectioning Laboratory (Keyworth) as large format covered thin sections following the procedures for sample preparation of unconsolidated or poorly lithified materials. The thin sections were examined using a standard Zeiss petrological microscope and Zeiss projector enabling the analysis of both large and small scale microscopic textures and fabrics. A photomicrograph and detailed, annotated scanned images of each thin section have been used to describe the main microscopic features developed within these Quaternary deposits.

3 Terminology

The description and interpretation of the micromorphology and deformation structures developed within glacial deposits is a relatively recent and still developing technique (see van der Meer 1987, 1993; Seret 1993; van der Meer *et al*. 1990; van der Meer *et al*. 1992; van der Meer *et al*. 1994, Phillips & Auton 2001; Menzies 2000; Rose & Harte 2001). Although repetitive features have been recognised by several workers (see van der Meer 1987, 1993 and references therein) no standard nomenclature has yet to be formalised. The terminology used in this report is that proposed by van der Meer (1987, 1993) (also see Menzies 2000) and is based upon nomenclature developed by pedologists (for references see van der Meer 1993). A definition of the terms used for the various textures and fabrics, and their proposed mode of formation is given below and summarised in Fig. 1 (also see the glossary at the end of this report).

Plasmic fabric - The arrangement of high birefringent clay plasma/domains which are visible under the microscope (under cross polars) because of the similar extinction of similarly orientated domains. These fabrics are only observed when the diamicton is clayey. Diamictons which contain a limited amount of fines or relatively high proportion of carbonate within the matrix do not exhibit a well developed plasmic fabric.

Unistrial plasmic fabric - A planar plasmic fabric defined by relatively continuous domains which is typically observed defining discrete shears (Fig. 1). Interpreted as developing in response to planar movement (van der Meer 1993).

Skelsepic plasmic fabric - A plasmic fabric in which the orientated domains occur parallel to the surface of large grains (Fig. 1). Interpreted as developing in response to rotational movement (van der Meer 1993).

Lattisepic plasmic fabric - A plasmic fabric defined by short orientated domains in two perpendicular directions. In many cases this fabric is found associated with a skelsepic plasmic fabric (Fig. 1). Therefore, lattisepic plasmic fabrics are also interpreted as having developed in response to rotational movement (van der Meer 1993).

Omnisepic plasmic fabric - A plasmic fabric in which all the domains have been reoriented (Fig. 1). Interpreted as developing in response to rotational movement (van der Meer 1993).

Till 'pebbles' - Formed by rotational movement (van der Meer 1993). They are subdivided into three types: Type (1) consists of till which lack an internal plasmic fabric. They are defined by encircling voids and the shape of the 'pebbles' becomes progressively angular and flatter with depth; Type (2) is characterised by 'pebbles' of fine-grained material which were part of the original sediment host. They are recognised by an internal plasmic structure and are not defined by voids; Type (3) form isolated 'pebbles' of either till or fine-grained sediments and are usually interpreted as having formed by reworking of the till. They may or may not contain internal plasmic fabrics.

Other microscopic features - Include: the ***circular arrangement of clasts*** (skeleton grains) with or with out a 'core stone' (Fig. 1), interpreted as having formed in response to rotation (van der Meer 1993); ***pressure shadows*** (Fig. 1) which are also interpreted as having formed in response to rotation (van der Meer 1993); ***dewatering structures*** associated with shearing; ***microboudinage***; microscopic scale ***primary sedimentary structures*** (lamination, cross lamination……etc.); ***water escape structures*** associated with forceful dewatering; and crushing of clastic grains (Fig. 1).

4 Thin section descriptions

Detailed descriptions of each thin section examined during this study are presented below.

4.1 SAMPLE N4108

Sample Number: PY 705. **Registered Number:** N4018. **Location:** 2.30 m depth, shuttered trial pit number 3, Dounreay (Buldoo). **Lithology:** yellow brown diamicton (till), Unit 4. Broubster Till.

Description: This thin section is of a poorly sorted, coarse-grained, matrix to clast supported, immature, till pebble-rich diamicton which possesses a silty looking matrix (Fig. 2). The bulk of the sample (*c*. 60 to 70 % of the total sample) is composed of subangular, subrounded to rounded in shape sand to pebble sized clasts of diamicton (Plate 1a, b and c). The till pebbles are internally massive (type 1 till pebbles of van der Meer 1993) and are distinguished from the matrix of the diamicton by their slightly darker colour and slightly coarser grain size. The till pebbles are composed of medium yellow-brown silty looking diamicton (Plate 1b and c). A very weakly developed plasmic fabric has been recorded in some till pebbles. However, in general plasmic fabrics are absent possibly due to the lack of clay minerals and/or the presence of finely disseminated carbonate minerals (limestone lithic clasts noted in this diamicton, see below). Textural evidence, coupled with the high modal proportion of till pebbles within the diamicton suggests that it was formed due to the reworking of a pre-existing till deposit. Rounding of the till pebbles (Plate 1c) clearly indicates that there has been some transport of these fragments and that they were not formed due to *in situ* hydrofracturing.

The lithic clasts included within the diamicton are angular, subangular to subrounded in shape with a low sphericity. These lithic clasts are mainly composed of sedimentary rock fragments (Plate 1b and d) which appear to have been primarily derived from the Devonian sedimentary strata which dominate the solid geology of the Reay area. Recognisable lithologies present include: micaceous siltstone; laminated siltstone and mudstone with ptygmatically folded veinlets of fluidised very fine-grained sandstone to coarse siltstone (Plate 1d); limestone; granitic rock; calcareous silty mudstone; immature fine-grained lithic-rich sandstone; hematised fine siltstone; and inter laminated fine-grained sandstone and micaceous siltstone. No obvious metamorphic rock fragments (e.g. Moine Supergroup) have been recognised within this diamicton and granitic lithic clasts are rare. The lithic clasts range up to *c*. 45 mm in length. Finer grained clasts range from coarse sand to granule in size and are variably enclosed within a rim or coating of slightly darker coloured matrix. These coatings are lithologically similar to the till pebbles which dominate this diamicton. Finer grained rock fragments were also noted included within recognisable till pebbles (Plate 1b). The rounding of the lithic clasts suggests that they have undergone a prolonged period of transport and may be polycyclic in nature.

The finer grained clasts within the till pebbles and matrix of the diamicton are range from fine silt to medium sand-grade in size (see Plate 1c). They are typically angular in shape with a low sphericity, however occasional subrounded grains have been noted. The clast assemblage within the matrix is dominated by monocrystalline quartz and subordinate to minor sedimentary rock fragments; the latter includes the same range of lithologies as the coarser grained lithic clasts. Other minor to accessory detrital components present include plagioclase, opaque minerals, chlorite, carbonate, muscovite, white mica, polycrystalline quartz and amphibole. The range of fine-grained detrital components within the diamicton and till pebbles are comparable to the detrital assemblage within the Devonian sedimentary strata (see Phillips 2002). Consequently, the matrix of the diamicton is possibly derived from disaggregated sedimentary bedrock.

The matrix to the diamicton is lithologically similar to the till pebbles but is finer grained and a very pale yellow-grey to yellow-brown colour.

4.2 SAMPLE N4019

Sample Number: PY 706. **Registered Number:** N4019. **Location:** 0.80 m depth, shuttered trial pit number 3, Dounreay (Buldoo). **Lithology:** blue-grey diamicton (till), Unit 2. Forss Till (shelly).

Description: This thin section is of a coarse-grained, very poorly sorted, matrix supported, very open packed, lithic/clast-rich diamicton with a sandy looking matrix (Fig. 3 and Plate 2a). This diamicton possesses a distinct bimodal grain size distribution with a marked break between the granule to pebble sized clasts and the finer grained silt to medium-grained sand-grade clasts present within the matrix.

The large clasts in this diamicton are typically angular, subangular to subrounded in shape with a low sphericity (Plates 2 and 3). However, rare to occasional well rounded pebbles have also been noted. The clast are mainly composed of sedimentary rock fragments with rare granite and monocrystalline quartz fragments; the latter were only noted forming the smaller granule sized clasts. Recognisable lithologies present include: fine-grained sandstone (Plate 2a); micaceous, very fine-grained sandstone; dark coloured mudstone and silty mudstone (Plate 3c); limestone (Plate 2c) with diagenetic quartz or carbonate replaced siltstone; feldspathic metasandstone/psammite (Plate 3a); weakly foliated psammite; bedded mudstone and fine-grained sandstone; immature, fine-grained, lithic-rich or feldspathic sandstone (Plate 3b); coarse siltstone; polycrystalline carbonate minerals or limestone; hematised very fine-grained sandstone or siltstone; biotite granitic rock or gneiss; calcareous siltstone; laminated mudstone; dark brown mudstone; and altered biotite granite. Sandstone lithic fragments may show minor carbonate replacement, which occurred prior to their incorporation within the diamicton. Carbonate replacement during diagenesis is a common feature within the Devonian sedimentary rocks of the Reay district. A number of the larger, typically more well rounded clasts appear to represent broken fragments of larger pebbles and are, therefore, interpreted as being polycyclic in origin. A weakly to patchily developed preferred, subvertical shape alignment of elongate clasts has been noted within this diamicton. The rock fragments are locally fractured.

The sandy looking matrix to the diamicton is fine-grained and contains angular, subangular to occasionally rounded in shape, low to moderate sphericity clasts (see Plates 2a, 2d and 3c). The detrital assemblage within the matrix is dominated by monocrystalline quartz with subordinate plagioclase and rock fragments. The latter are composed of the same range of sedimentary rocks noted forming the granule to pebble sized lithic clasts. Other minor to accessory detrital components present within the matrix include muscovite/white mica, opaque minerals, polycrystalline quartz, amphibole, carbonate, chlorite, zircon, altered biotite and garnet. Rare hematised basaltic rock fragments have also been recorded. Weakly to crudely developed circular arrangements and clustering of the fine-grained sand-grade clasts have been noted associated with some of the larger lithic clasts. The clay to very fine silt grade component of the matrix is a dusty grey-brown colour and exhibits traces of alteration to an opaque mineral. The matrix to the diamicton is compositionally similar to the siltstones and silty sandstones present within the Devonian sedimentary bed rock. No obvious plasmic fabric(s) have been recognised within the matrix to the diamicton. This may be due to a lack of deformation, or alternatively either a lack of clay minerals and/or the presence of finely disseminated carbonate within the matrix.

A minor, but distinctive feature of this diamicton is the presence of included plant material (Plate 2a, b and d). This plant material is orange-brown in colour (under plane polarised light) and isotropic under crossed polarised light. Internally the plant material varies from amorphous through to some fragments which preserve a well developed cell structure (Plate 2b and d). The absence of any compaction/collapse of these plant remains suggests that they post-date the deposition of the diamicton and probably represent rootlets. The plant remains are locally associated with fractures that are partially filled by very fine-grained clay-grade material.

Fracturing of the diamicton may have been associated with growth of plant roots or alternatively allowed the penetration of the rootlets.

4.3 SAMPLE N4020

Sample Number: PY 707. **Registered Number:** N4020. **Location:** 0.40 m depth, shuttered trial pit number 5, Upper Dounreay. **Lithology:** weathered diamicton (till), Unit 2. Forss Till (shelly).

Description: This thin section is of a poorly sorted, coarse-grained, matrix supported, open packed, clast/lithic-rich, immature diamicton (Fig. 4, Plates 4 and 5) in which the rock fragments exhibit a pronounced vertical to subvertical preferred shape alignment (Plate 5b, also see section 5). This diamicton possesses a distinct bimodal grain size distribution comprising very coarse-grained sand to pebble sized (up to *c*. 22mm in size) set within a fine sand to silt-grade matrix. The larger clasts are angular, subangular to occasionally rounded in shape with a low sphericity. These large clasts are mainly composed of sedimentary rock fragments, dominated by mudstone and siltstone (Plate 5b). Other recognisable lithologies include hematised siltstone; laminated fine-grained sandstone and siltstone; fine- to very fine-grained sandstone; silty mudstone; biotite granitic rock; dark brown coloured mudstone. The coarse- to very coarse-grained sand grains may also be composed of variably strained monocrystalline quartz. The elongate nature of the large clasts is partially controlled by the finely laminated nature of the sedimentary bedrock. A number of these larger clasts also appear to be broken fragments of much larger pebbles. These suggest that the coarse-grained detritus may be partially polycyclic in origin.

The sandy to silty matrix contains angular to subangular in shape low to moderate sphericity clasts which are mainly composed of monocrystalline quartz and subordinate sedimentary rock fragments. These lithic clasts are composed of a similar range of lithologies as the larger, pebble sized rock fragments. Other minor to accessory detrital components present within the matrix include: polycrystalline quartz, plagioclase, muscovite/white mica, chlorite, amphibole, opaque minerals, altered biotite, zircon and apatite.

The migration of water through the diamicton is recorded by: (a) Diffuse patches of yellow-brown to honey brown clay cutan cement and the associated winnowing/removal of finer grained material from the matrix of the diamicton (Plates 4a, b and 5a). Winnowing of the fines from the matrix was probably contemporaneous with the deposition of the clay cutan cement.; and (b) The presence of clay cutan line/filled veinlets which represent fluid pathways or water-escape conduits (Plate 4c and d). These cutan filled water-escape features are closely associated with the diffuse patches of clay cement. The diffuse patches are interpreted as recording intergranular, ‘unconfined’ flow of water. However, as the permeability of the matrix decreased, possibly due to the deposition of the clay cement, water flow became concentrated into discrete zones or fluid pathways. These conduits were then filled by clay cutan to form the observed veinlets. The clay cutan is strongly birefringent and locally possesses a well developed plasmic fabric which occurs parallel to the margins of the veinlets. Geopetal-like clay cutan infillings of the water-escape conduits have also been noted. The clay lining to the conduits probably resulted in the stabilisation of these open features, which may have had a prolonged history of water migration. Clay cutan filled veinlets and water escape conduits have also been noted developed along the margins of the granule to pebble sized clasts (see bottom of Plate 4d). The diffuse patches of clay cutan cement show a weakly developed subvertical arrangement and forms a poorly developed network preserving the original pattern of water migration through the diamicton. These areas of intergranular water migration are associated with the zones of subvertically aligned elongate clasts. Traces of hematitic rusty brown oxide have been noted associated with late stage water migration.

5 Clast Shape Analysis

The clast-rich diamictons from the Dounreay area have also been used as part of a preliminary study to investigate the development of a preferred clast orientation within glacigenic sediments. The approach used here is similar to the Rf/θ method (Ramsay 1967) of strain analysis used by structural geologists and till clast macrofabric analysis used by glaciologists and Quaternary geologists (see Benn & Evans 1998). However, unlike the Rf/θ method the approach used her can not be used to estimate strain as in many cases the markers (i.e. clastic grains) are undeformed and acted as rigid bodies during deposition/deformation. Any preferred alignment of these markers is, therefore, considered to be due to the passive rotation of these clasts within an actively deforming matrix. Alignment of clasts may occur as a result of either primary sedimentary processes and/or subsequent deformation. The role of inheritance of a preferred shape alignment within diamictons has been largely overlooked in studies of till macrofabrics, with such fabrics being interpreted as having developed in response to an imposed deformation rather than resulting from an earlier sedimentary process (*c.f.* imbrication of pebbles in a fluvial deposit).

The aspect ratio (Rf) and orientation (θ in degrees) of coarse sand to pebble sized clasts within three samples (N4018, N4019, N4020) of diamicton have been measured in thin section under low magnification. Rf is the ratio of the short axis and long axis of the clast and θ the angle between the long axis and a datum (e.g. bedding or horizontal). The data obtained is displayed graphically (Figs. 5 to 7) and on a series of diagrammatic representations of the thin sections (Figs. 8 to 10). If a preferred shape alignment of elongate clasts is developed then the data should form a cluster on a plot of aspect ratio (Rf) versus long axis orientation (θ) (e.g. see Fig. 7a). The degree of clustering of the data broadly reflects the intensity of the this preferred alignment. The greater the spread or scatter in the data on the Rf/θ plot (e.g. Fig. 5a) records either a weakly developed or no fabric. The preferential alignment of clasts can also be established using histograms of long axis orientation (e.g. Fig. 7d). These graphical methods will also show if the clasts exhibit more than one direction of long axis orientation.

Sample N4018 is of a poorly sorted, coarse-grained, matrix to clast supported, immature, till pebble-rich diamicton which possesses a silty looking matrix (see Fig. 2). Sand to pebble sized till pebble clasts (type 1 till pebbles of van der Meer 1993) have not been included in the analysis of the clast fabric within this sample. However, the orientation of the main axes of these till pebbles are shown on Fig. 8 (dotted lines on Fig. 8a and b).

Data obtained for sample N4018 shows that the clasts in general possess an aspect ratio of < 2.8 (Figs. 5a and b), with a mean Rf of 2.03 (Table 1).

Table 1. Statistical data calculated for the aspect ratio of coarse sand to pebble sized clasts included within Sample N4018.

Mean	2.028267

Standard Error	0.068395
Median	1.83
Mode	2
Standard Deviation	0.687365
Sample Variance	0.472471
Kurtosis	3.233431
Skew	1.487591
Range	3.75
Minimum	1
Maximum	4.75
Sum	204.855
Count	101

The data do not show any obvious clustering on the plot of aspect ratio versus long axis orientation (Fig. 5a). However, a weakly developed alignment can recognised at -40° on Figs. 5c and d. The bulk of the clasts appear to exhibit a positive value of θ, forming a broad peak between 25° and 50° on Fig. 5d. Figure 8a shows the orientation and length of both the long and short axes of the clasts measured in sample N4018 and there relationship to a horizontal datum. Orientation data for the long axes of these clasts were then extracted in order to establish if there is a consistent pattern of long axis orientation within the sample (Fig. 8b). The resultant pattern (black dotted lines of Fig. 8b) shows two preferred alignments of the clasts between 30° to 40° and a second at approximately -40°. The first fabric locally appears to have a crudely domainal appearance (e.g. bottom right-hand corner of Figs. 8b and 11) consisting of discrete zones in which the clasts show a pronounced alignment. The relationship between the two clast alignment fabrics is uncertain.

In the upper right-hand quadrant of the thin section the clasts define a foliation which wraps around a large lithic clast (Figs. 8b and 11). This large rock fragment probably formed a rigid object within the deforming finer grained matrix of the diamicton.

Sample N4019 is of a coarse-grained, very poorly sorted, matrix supported, very open packed, clast-rich diamicton with a sandy looking matrix (see Fig. 3). Data obtained for this sample shows that the clasts in general possess an aspect ratio of < 3.0 (Figs. 6a and b), with a mean Rf of 2.06 (Table 2).

Table 2. Statistical data calculated for the aspect ratio of coarse sand to pebble sized clasts included within Sample N4019.

Mean	2.05809
Standard Error	0.09658
Median	1.8
Mode	2
Standard Deviation	0.93638
Sample Variance	0.8768
Kurtosis	12.4355

Skew	2.74788
Range	6.5
Minimum	1
Maximum	7.5
Sum	193.46
Count	94

The data does not show any obvious preferred shape alignment of the clasts (Figs. 6c and d). The absence of a single preferred clast alignment fabric is show on Fig. 9a. However, detailed analysis of clast orientation within sample N4019 suggests that this diamicton possesses a complex pattern of alignment (Figs. 9b and 12). In the lower right-hand corner on Figs. 9b and 12 the smaller clast define a fabric which appears to wrap around the larger rock fragments. In contrast, in the lower left-hand corner (Figs. 9b and 12) the long axes of the finer grained clasts define a crude circular arrangement, similar to the smaller scale 'galaxy' structures defined by van der Meer (1993). Elsewhere, the diamicton possesses a domainal-like fabric with discrete zones of preferred clast alignment, separated by areas either lacking in larger included grains or no obvious clast alignment (see Fig. 12). This complex, locally cross-cutting pattern of clast alignment is considered to reflect a prolong history of movement/displacement accommodated by this subglacial diamicton. Early formed alignments are progressively modified and/or overprinted as the diamicton continues to 'flow'. The complexity of the clast fabrics and the presence of circular clast arrangements is indicative of turbulent flow with the large included boulders within the diamicton probably providing the mechanical instability required to initiate turbulent flow.

Sample N4020 is of a poorly sorted, coarse-grained, matrix supported, open packed, clast/lithic-rich, immature diamicton (Fig. 4). Visual examination of this thin section at low magnification revealed that the elongate rock fragments exhibit a pronounced vertical to subvertical preferred shape alignment. Data obtained for this sample shows that, in general, the clasts possess an aspect ratio of < 2.8 (Figs. 7a and b), with a mean Rf of 2.15 (Table 3). The elongate nature of the clasts is partially controlled by the presence of a well-developed sedimentary lamination within the siltstone and mudstone rock fragments which dominate the clast assemblage within this diamicton.

Table 3. Statistical data calculated for the aspect ratio of coarse sand to pebble sized clasts included within Sample N4020.

Mean	2.152727
Standard Error	0.107539
Median	2
Mode	2
Standard Deviation	0.79753
Sample Variance	0.636054
Kurtosis	2.744923
Skew	1.583994
Range	3.65
Minimum	1.08

Maximum	4.73
Sum	118.4
Count	55

The data for the lower part of the thin section exhibits a moderately developed cluster at a value of θ of approximately 70° to 90° on Fig. 7a. A second, weaker cluster in the data can be recognised between 60° and 85° (see Fig. 7a). This pronounced high-angle to subvertical alignment of clasts can also be seen on Figs. 7c and d. Figure 10a shows the orientation and length of both the long and short axes of the clasts measured in sample N4020 and there relationship to a horizontal datum. The long axes of these clasts and the pattern of alignment (black dotted lines of Figs. 10b and 13) clearly highlights the subvertical nature of the clast alignment fabric within this sample. In outcrop comparable subvertical clast alignments are interpreted as being indicative of cryoturbation. However, it is clear from Figs. 10b and 13 that this subvertical alignment is not developed throughout the sample and is concentrated within particular zones. Also these 'zones' locally display cross-cutting relationships (see Fig. 13) indicating that this diamicton has undergone several phases/periods of modification during cryoturbation.

6 Conclusions and Interpretations

A number of conclusions/interpretations can be made based upon the detailed examination of these large format thin sections of the Quaternary sediments exposed in the Reay District of Caithness:

1. Sample N4018 is of a poorly sorted, coarse-grained, matrix to clast supported diamicton which is characterised by the presence of subangular to rounded till pebbles (type 1 till pebbles of van der Meer 1993). Microtextural evidence, coupled with the high modal proportion of till pebbles within the diamicton suggests that it was formed due to the reworking of a pre-existing till deposit. Rounding of the till pebbles clearly indicates that there has been some transport of these fragments and that they were not formed due to *in situ* hydrofracturing.

2. Lithic clasts included within samples N4018, N4019 and N4020 are mainly composed of sedimentary rock fragments (siltstone; mudstone; very fine-grained sandstone to coarse siltstone; limestone; calcareous mudstone; fine-grained lithic-rich sandstone) and were derived from the Devonian strata which dominates the solid geology of the Reay area. Metamorphic (e.g. weakly foliated psammite from the Moine Supergroup) and granitic rock fragments (e.g. Strath Halladale Granite) are rare. The rounding of the lithic clasts suggests that they have undergone a prolonged period of transport and may be polycyclic in nature.

3. Finer grained detritus within matrix of the diamictons is predominantly composed of monocrystalline quartz and subordinate to minor sedimentary rock fragments; the latter includes the same range of lithologies as the coarser grained lithic clasts. Minor to

accessory detrital components include plagioclase, opaque minerals, chlorite, carbonate, muscovite, white mica, polycrystalline quartz, amphibole, altered biotite, zircon and apatite. The similarity in composition between the matrix of the diamicton and the Devonian sedimentary strata (see Phillips 2002) suggests that these glacial deposits are composed of locally derived disaggregated sedimentary bedrock.

4. Sample N4019 is of a coarse-grained, very poorly sorted, matrix supported, very open packed, clast-rich diamicton which possesses a sandy looking matrix.

5. No obvious plasmic fabric(s) have been recognised within the matrix of the diamicton. This may be due to a lack of clay minerals within the matrix and/or the presence of finely disseminated carbonate within the matrix.

6. A distinctive feature of sample N4019 is the presence of included plant material. Internally the plant material may be either amorphous or preserve a well-developed cell structure. The absence of any compaction/collapse of these plant remains suggests that they post-date the deposition of the diamicton and probably represent rootlets.

7. Sample N4020 is of a poorly sorted, coarse-grained, matrix supported, open packed, clast-rich, immature diamicton in which the rock fragments exhibit a pronounced vertical to subvertical preferred shape alignment.

8. Sample N4020 contains clear evidence recording the migration of water through the diamicton during its post-depositional history. This resulted in: (a) the development of a diffuse patchy clay cutan cement and contemporaneous winnowing/removal of fines within the matrix; and (b) the formation of clay cutan line or filled veinlets representing abandoned water-escape conduits. The patches of clay cement are interpreted as recording ‘unconfined’ intergranular flow of water. However, as the permeability of the matrix decreased in response to the deposition of the clay cement, water flow became concentrated into discrete zones or fluid pathways, now represented by the clay cutan filled veinlets. The clay cutan filled veinlets and patches of clay cement form a subvertical network preserving the original pattern of water migration through the diamicton. Importantly, these zones of water migration are closely associated with the subvertically aligned clasts and may record the pattern of water flow during cryoturbation.

9. Clast orientation data from sample N4018 reveal only weakly developed preferred alignments. The main fabric present within the sample locally possesses a crudely domainal appearance consisting of discrete zones in which the clasts show a pronounced alignment. These clast fabrics can locally be observed wrapping around the large lithic clasts.

10. Clast orientation data for sample N4019 does not show any obvious preferred shape alignment of the clasts. However, detailed analysis of clast orientation within this diamicton revealed a complex pattern of alignment, including clast fabrics which wrap around the larger rock fragments, circular clast arrangements (*cf*. ‘galaxy’ structures of van der Meer 1993), and domainal-like fabrics with discrete zones of preferred clast

alignment, separated by areas either lacking in larger included grains or no obvious clast alignment. This complex pattern of clast alignment fabrics is considered to reflect a prolong history of movement/displacement accommodated by turbulent ‘flow’ within this subglacial diamicton.

11. Clast orientation data for sample N4020 reveal a pronounced vertical to subvertical preferred shape alignment of elongate rock fragments. The elongate nature of the clasts is partially controlled by the presence of a well-developed sedimentary lamination within the siltstone and mudstone rock fragments which dominate the clast assemblage. This subvertical clast alignment occurs within discrete zones within the diamicton and is interpreted as having formed due to cryoturbation. The cross-cutting relationships between these ‘zones’ indicating that the diamicton has undergone several phases/periods of modification during cryoturbation.

Glossary

Cement supported – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within the cement.

Cement – The material bonding the fragments of clastic sedimentary rocks together and which was precipitated between the grains after deposition.

Clast supported – Describes a fragmentary deposit where all the detrital grains are in contact.

Detritus – A general term for fragmentary material, such as gravel, sand, clay, worn from rock by disintegration. Detrital grains in clastic sedimentary rocks may be composed of single mineral grains (e.g. monocrystalline quartz, plagioclase), polycrystalline mineral grains (e.g. polycrystalline quartz) or lithic fragments including sedimentary, igneous and metamorphic rock fragments.

Grain size – Refers to the size of fragmentary material present in unconsolidated sediments and sedimentary rocks: (a) clay < 0.0039 mm in size; (b) silt, 0.0039 to 0.0625 mm in size; (c) fine sand, 0.0625 to 0.25 mm in size; (d) medium sand, 0.25 to 0.5 mm in size; (e) coarse sand, 0.5 to 1.0 mm in size; (f) very coarse sand, 1.0 to 2.0 mm in size; (g) granules 2.0 to 4.0 mm in size; (h) pebbles 4.0 to 64 mm in size.

Lattisepic plasmic fabric – A term used to describe a plasmic fabric developed within an unconsolidated sediment defined by short orientated domains in two perpendicular directions (van der Meer 1993).

Matrix – Material, usually clay minerals or micas, forming a bonding substance to grains in a clastic sedimentary rock. The matrix material was deposited with the other grains or developed authogenically by diagenesis or slight metamorphism. Also used more generally for finer grained material in any rock in which large components are set.

Matrix supported – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within a finer grained matrix.

Micromorphology – A term used to describe the study of unconsolidated glacial sediments in thin section using a petrological microscope.

Omnisepic plasmic fabric – A term used to describe a plasmic fabric developed in an unconsolidated sediment in which all the domains have been reoriented (van der Meer 1993).

Packing – Describes, as the term suggests, how closely the individual detrital grains are packed together within a fragmentary deposit. The term closely packed is used where all the grains are in contact and there is very little obvious matrix or cement; moderately packed and open packed are used with an increase in the porosity, matrix and/or cement.

Plasmic fabric – A term used to describe the optical arrangement of high birefringent clay plasma/domains within an unconsolidated sediment which are visible under crossed polarised light using a petrological microscope.

Porosity – The volume of voids expressed as a percentage of the total volume of the sediment or sedimentary rock.

Pressure shadow – A region of low strain developed immediately adjacent to a rigid or competent object in a rock (e.g. a garnet porphyroblast).

Pseudomorph – A mineral or aggregate of minerals having taken the form/shape of another mineral phase that it/they have replaced.

Rounded – Describes the smoothness of the surface of a detrital grain present within a sediment or sedimentary rock. The terms *well-rounded*, *rounded*, *subrounded*, *subangular*, *angular*, *very angular* are used to describe the increasingly angular/irregular/rough nature of the surface of detrital grains.

Skelsepic plasmic fabric – A term used to describe a plasmic fabric developed within an unconsolidated sediment in which the orientated domains occur parallel to the surface of large grains (van der Meer 1993).

Sorting – Well sorted describes a fragmentary deposit in which all the detrital grains are of approximately uniform size. In reality most fragmentary deposits contain a range of grain sizes and can be described as moderately sorted, poorly sorted or in extreme cases unsorted.

Sphericity – Describes the how closely a detrital grains present within a sediment or sedimentary rock approximates to a sphere. The terms low sphericity, moderate sphericity and high sphericity are used to describe how spherical (ball-like) the detrital grains are.

Schist – A metamorphic rock of broadly pelitic composition (i.e. a metamorphosed mudstone) with a well-developed schistosity.

Schistosity – A planar structure developed in a metamorphic rock defined by the alignment of elongate minerals such as micas and amphibole.

Unistrial plasmic fabric – A term used to describe a planar plasmic fabric developed with an unconsolidated sediment defined by relatively continuous domains which is typically observed defining discrete shears (van der Meer 1993).

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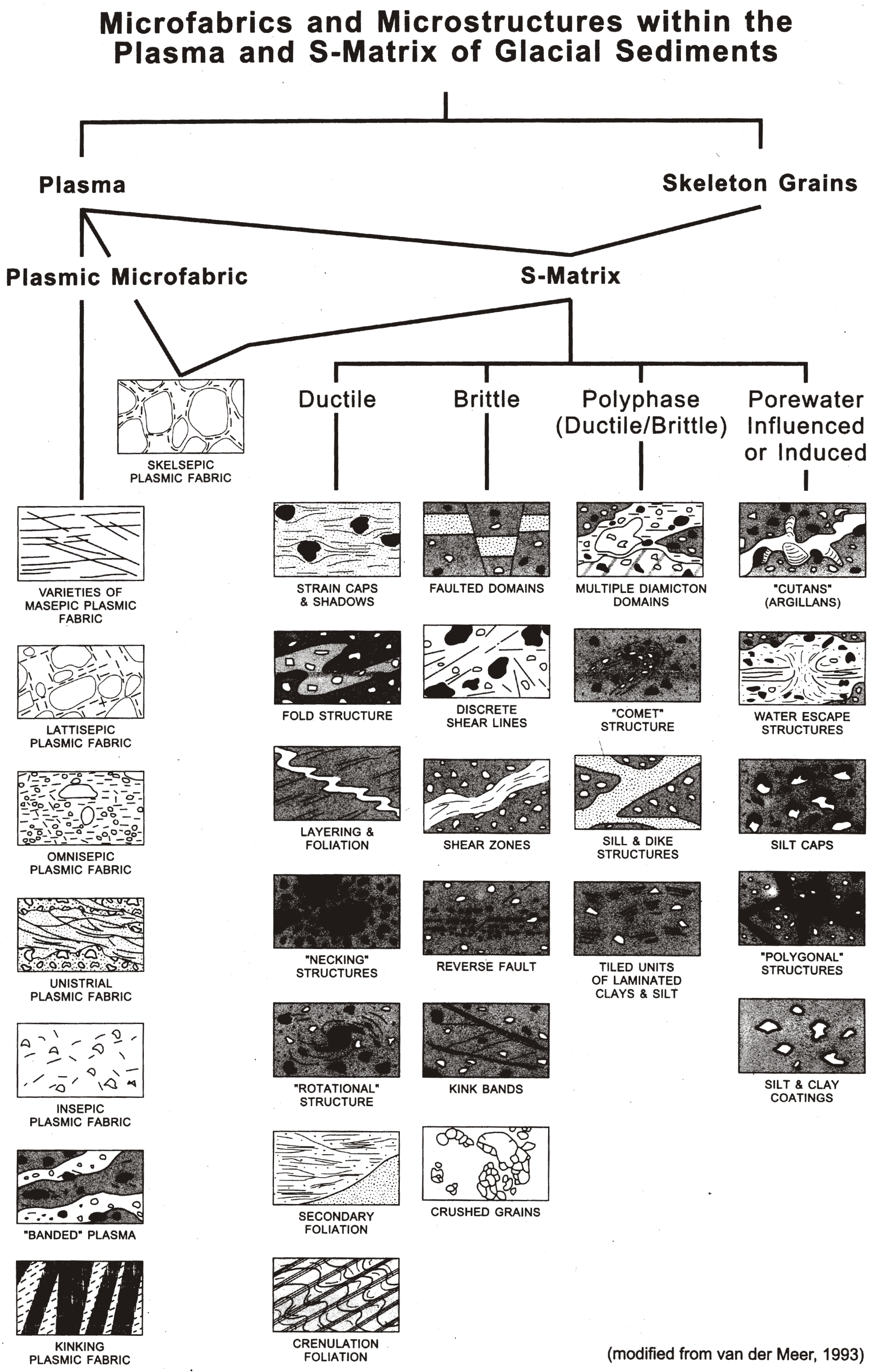


Fig. 1. Microfabrics and microstructures developed within glacial deposits (taken from Menzies 2000).

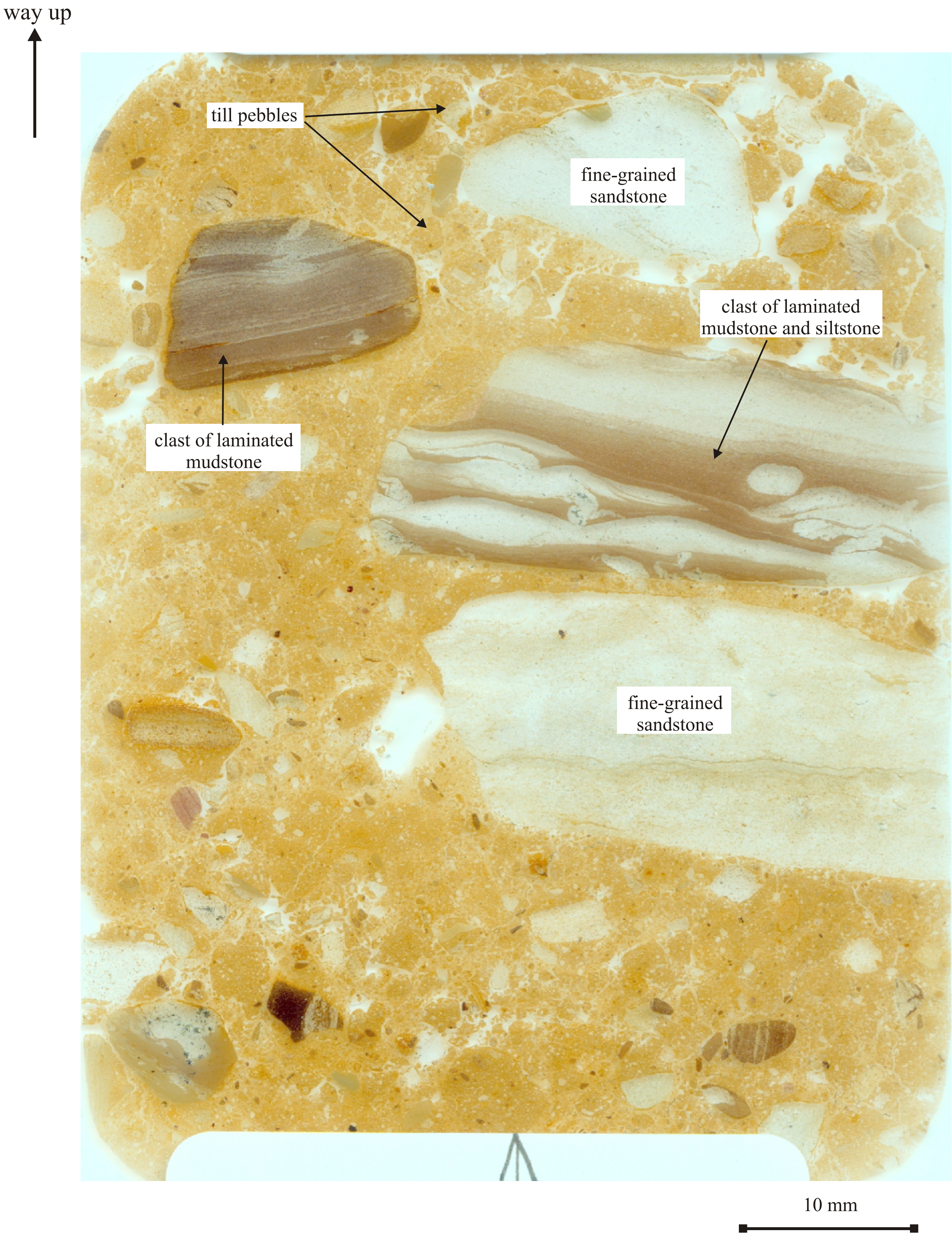
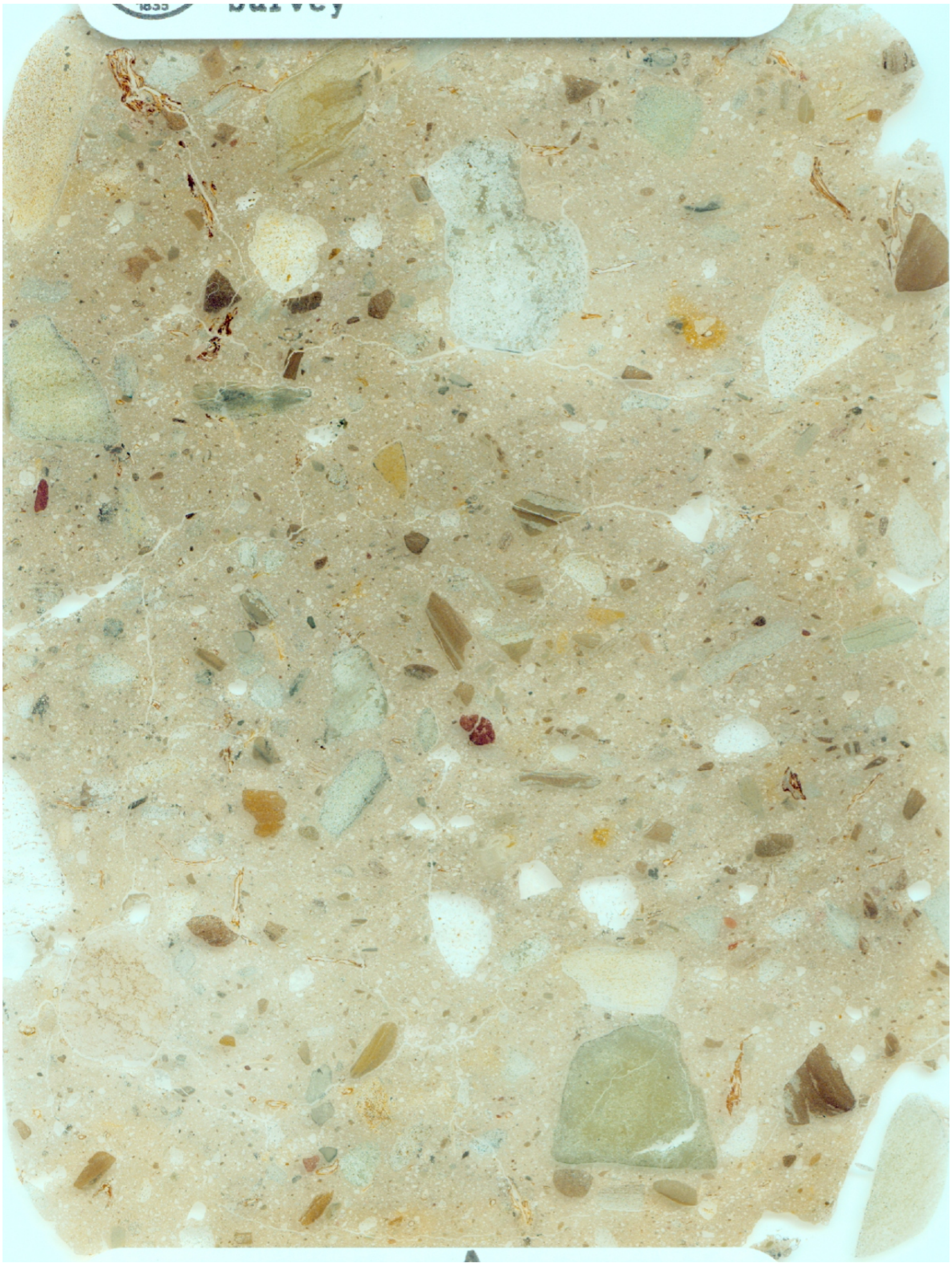


Fig. 2. Annotated scanned image of sample N4018.

way up



10 mm

Fig. 3. Annotated scanned image of sample N4019.

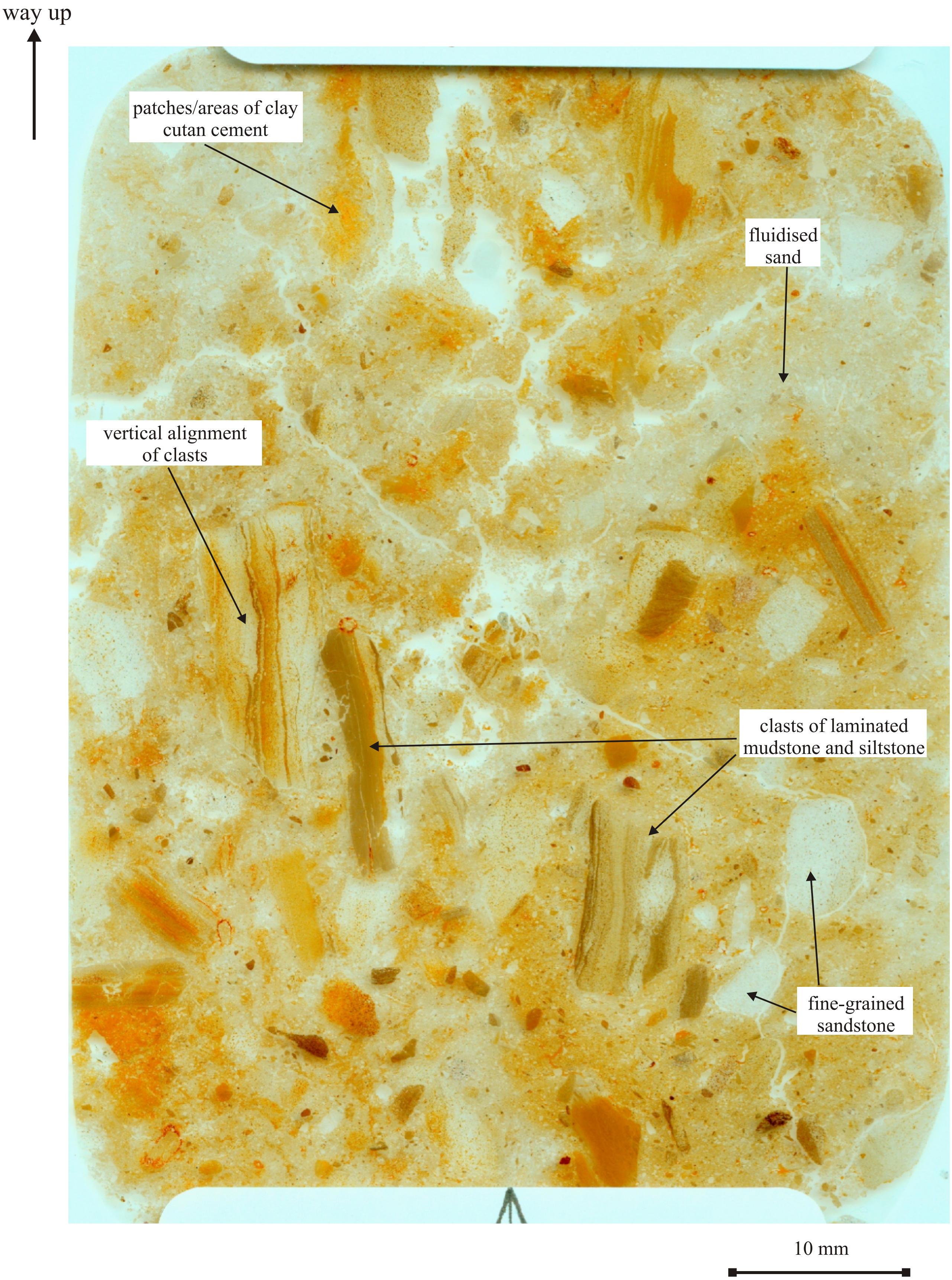


Fig. 4. Annotated scanned image of sample N4020.

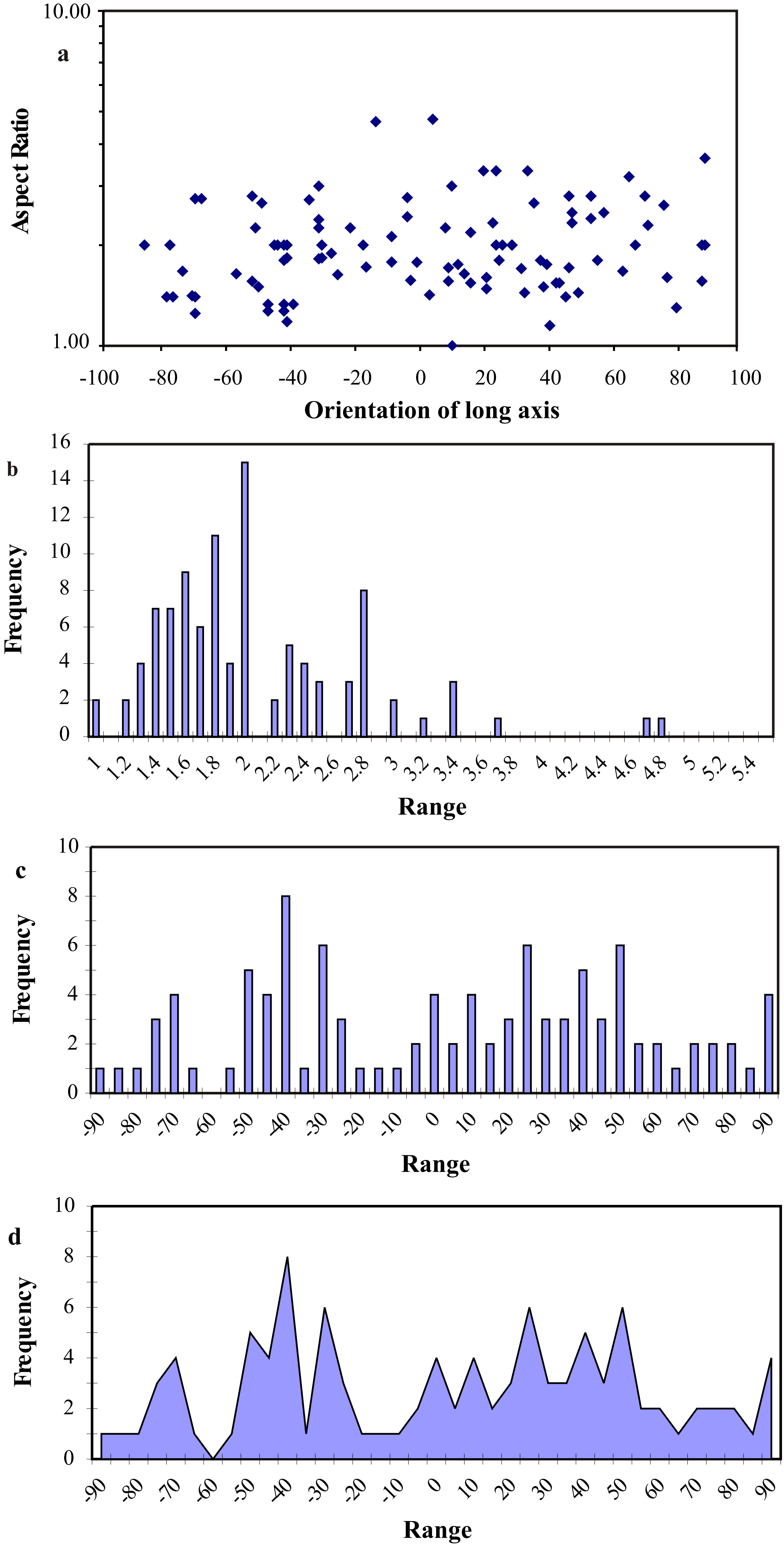


Fig. 5. Diagram showing clast orientation data for sample N4018. (a) plot of aspect ratio versus orientation of long axis. (b) histogram showing variation in clast aspect ratio. (c and d) plots showing variation in long axis orientation.

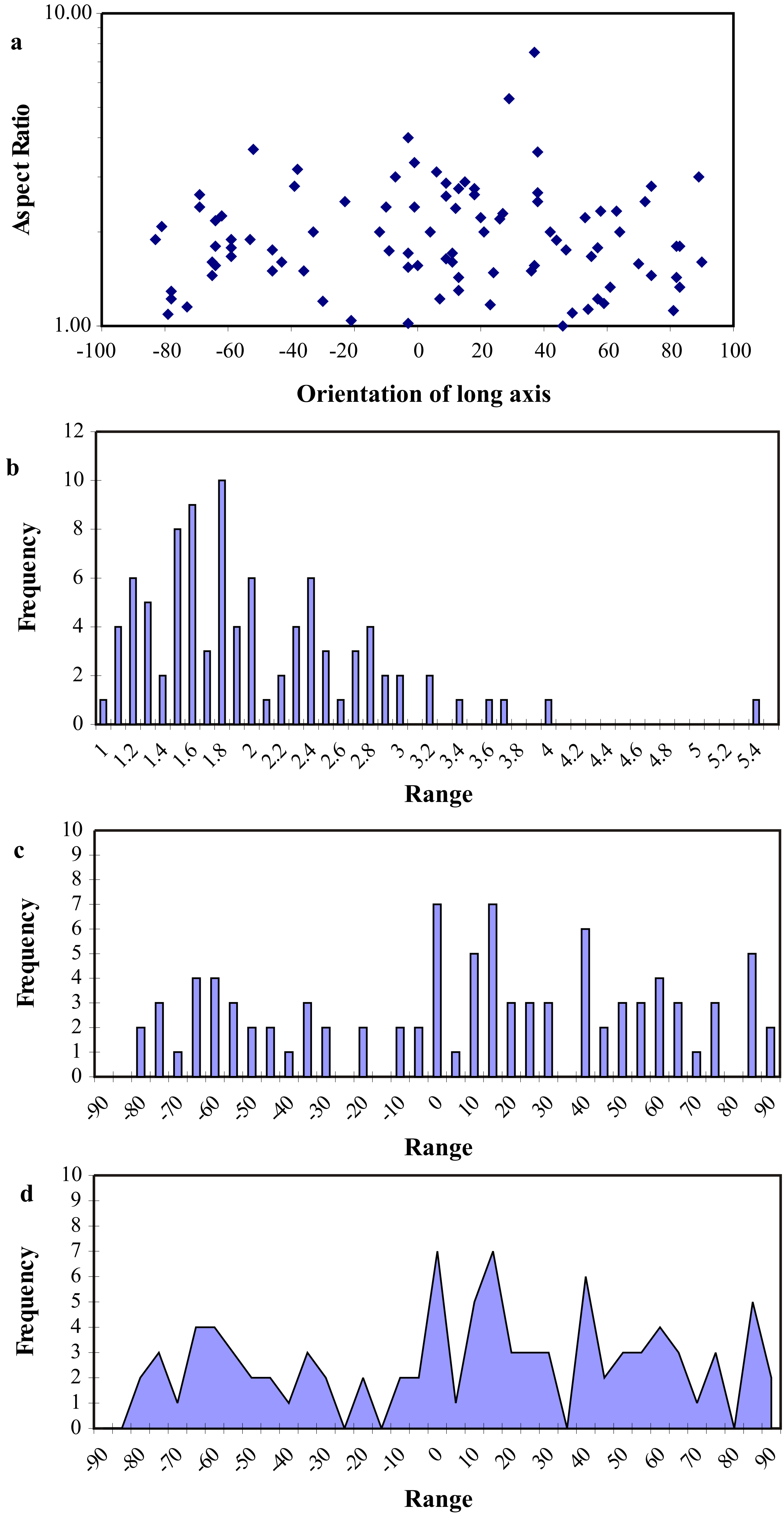


Fig. 6. Diagram showing clast orientation data for sample N4019. (a) plot of aspect ratio versus orientation of long axis. (b) histogram showing variation in clast aspect ratio. (c and d) plots showing variation in long axis orientation.

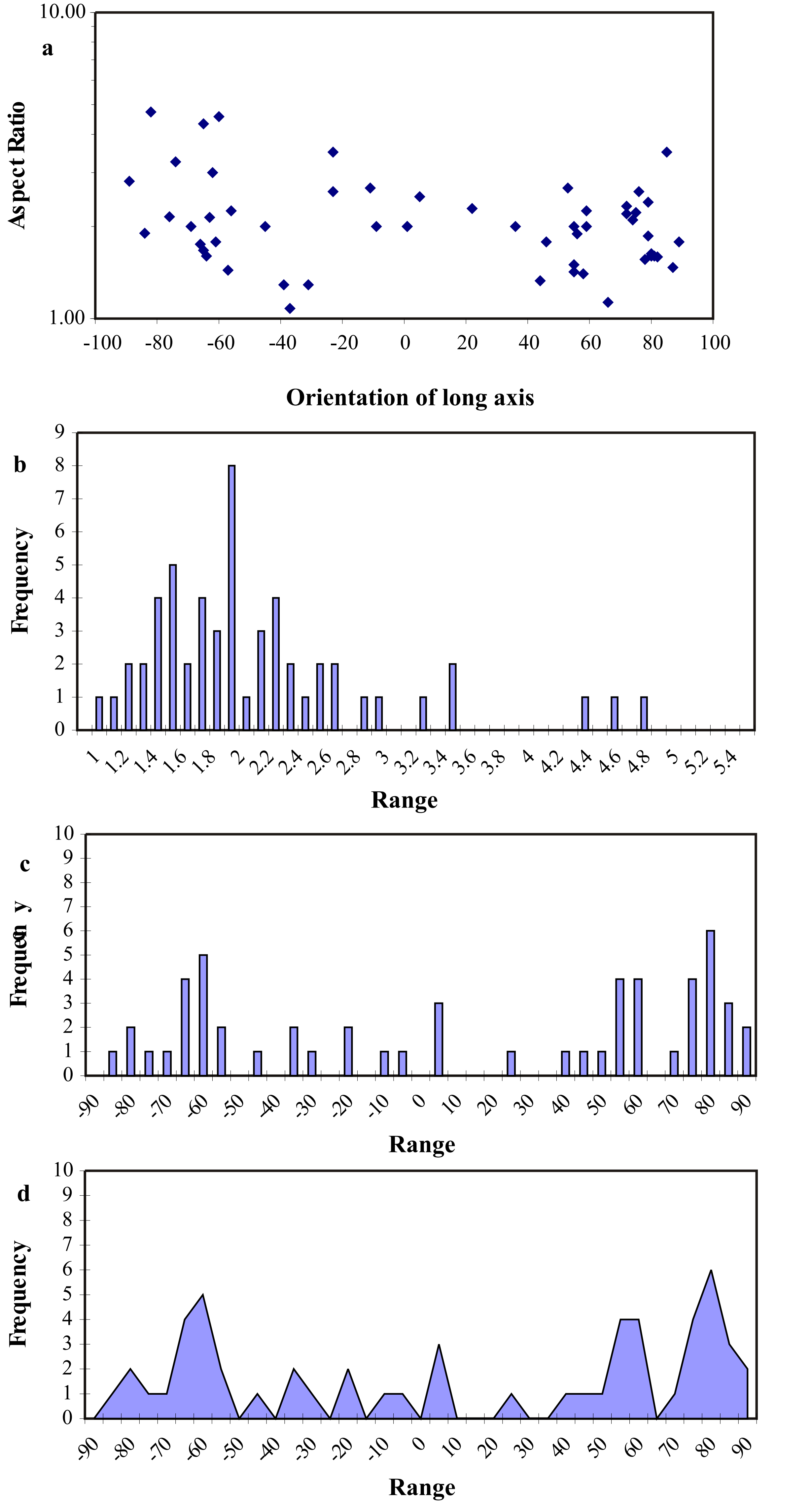
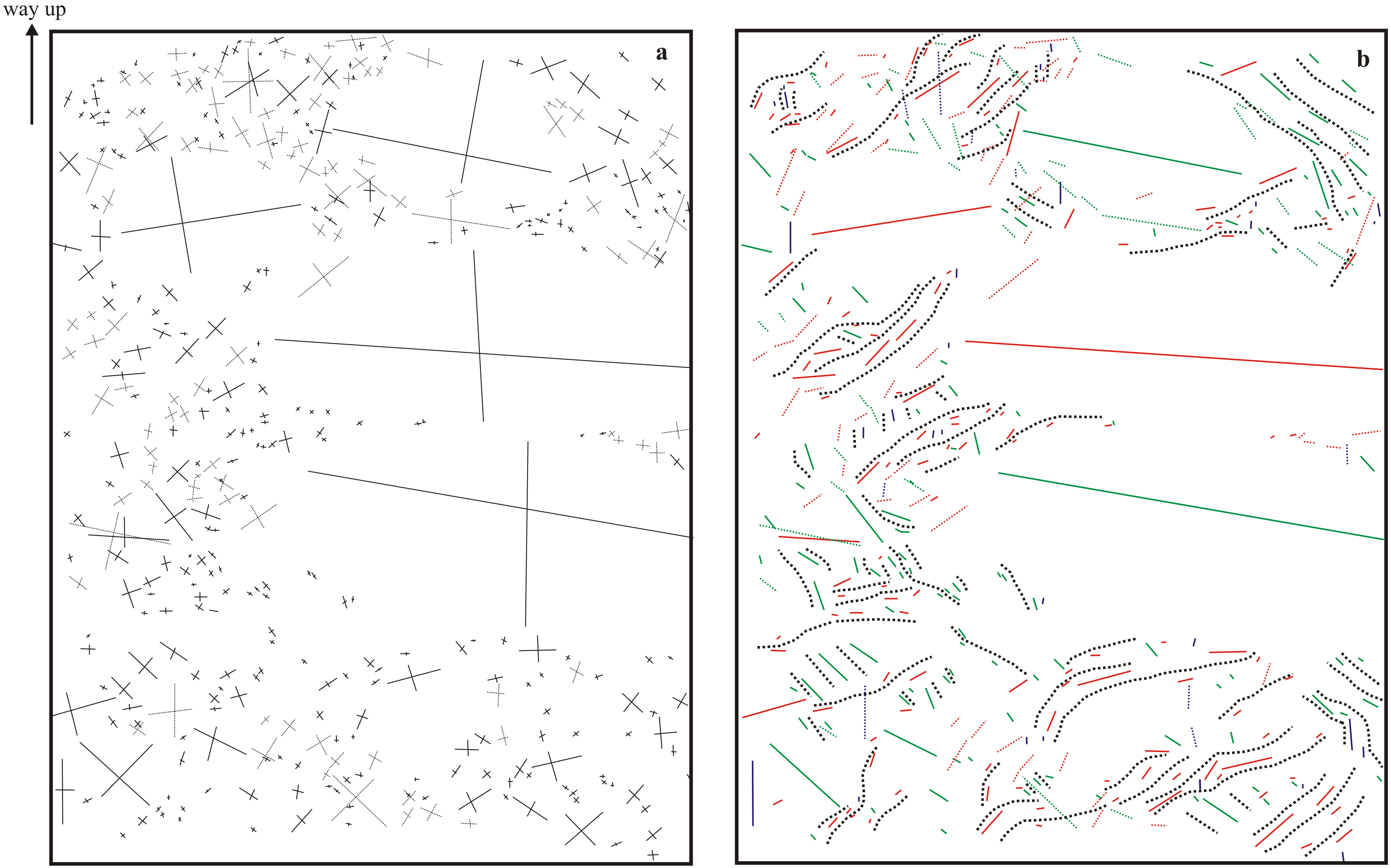


Fig. 7. Diagram showing clast orientation data for sample N4020. (a) plot of aspect ratio versus orientation of long axis. (b) histogram showing variation in clast aspect ratio. (c and d) plots showing variation in long axis orientation.



Sample PY705

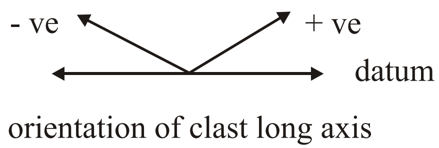


Fig. 8. (a) Diagram showing the orientation of the main axes of coarse sand to pebble sized clasts within Sample N4018. (b) Interpreted pattern of long axis orientation within sample N4018.

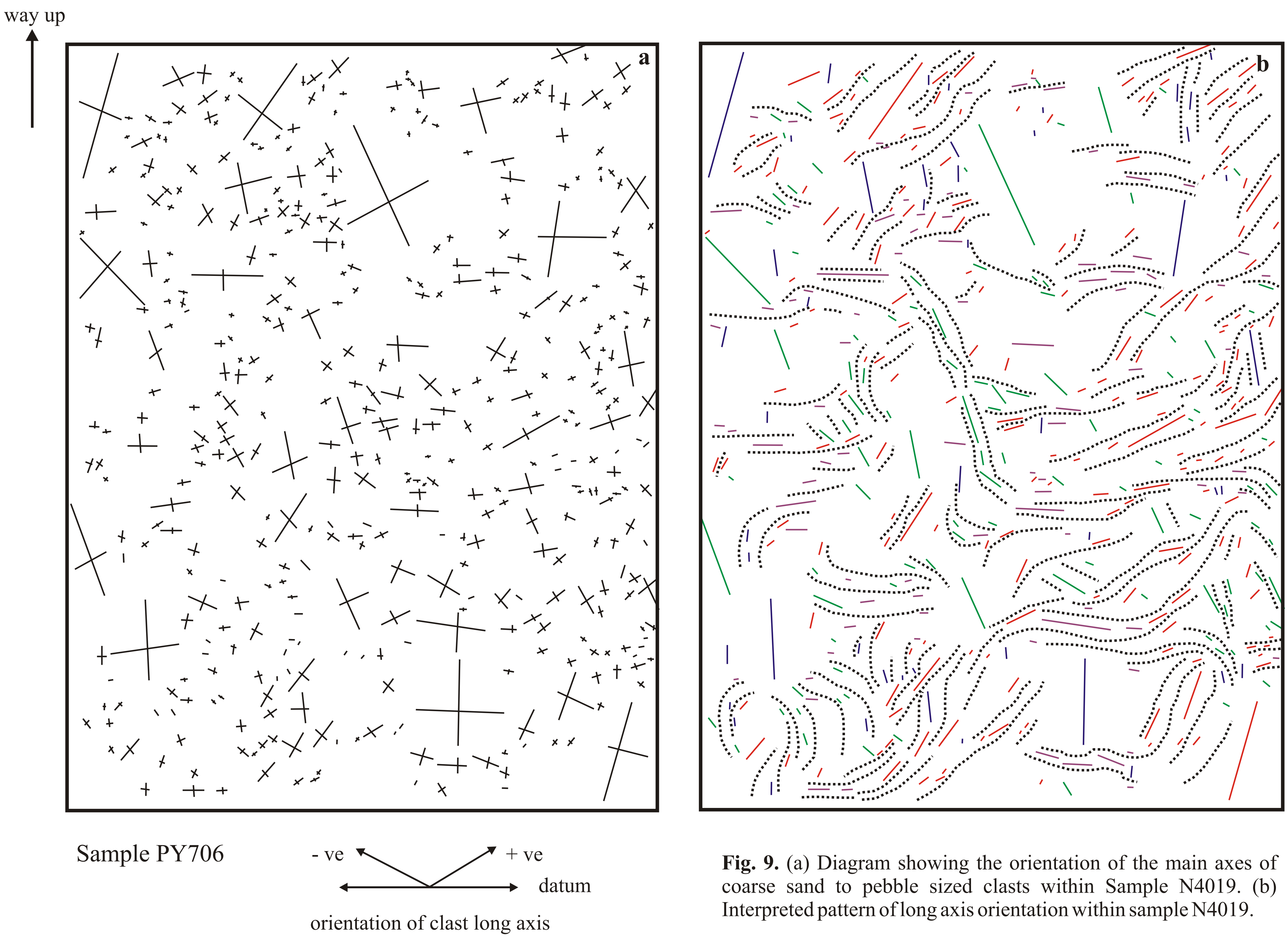
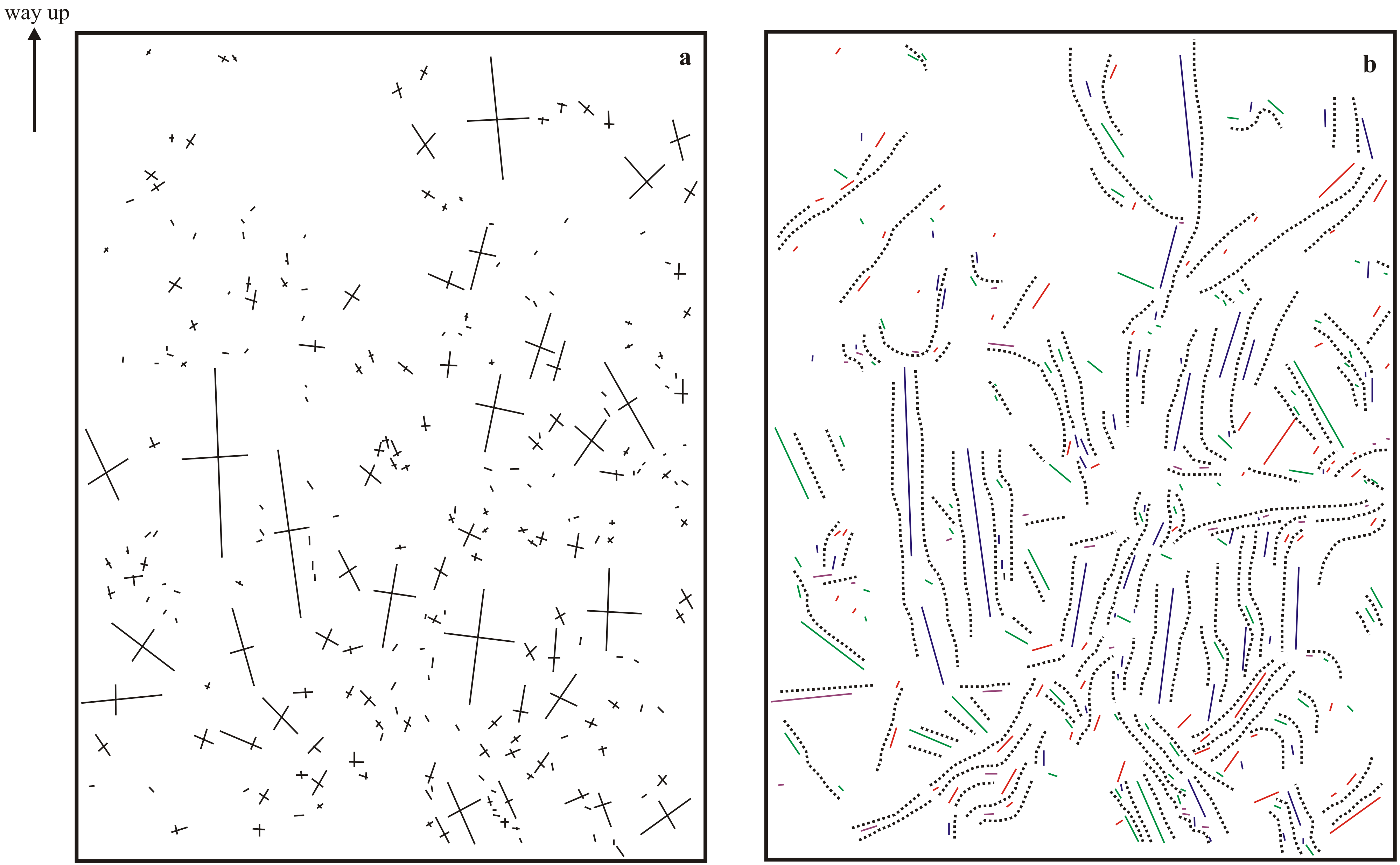


Fig. 9. (a) Diagram showing the orientation of the main axes of coarse sand to pebble sized clasts within Sample N4019. (b) Interpreted pattern of long axis orientation within sample N4019.



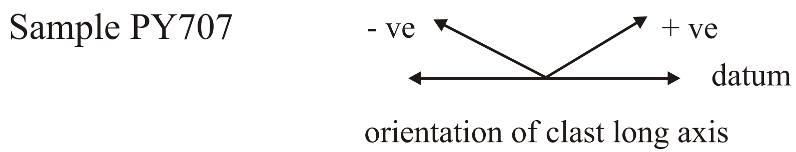


Fig. 10. (a) Diagram showing the orientation of the main axes of coarse sand to pebble sized clasts within Sample N4020. (b) Interpreted pattern of long axis orientation within sample N4020.

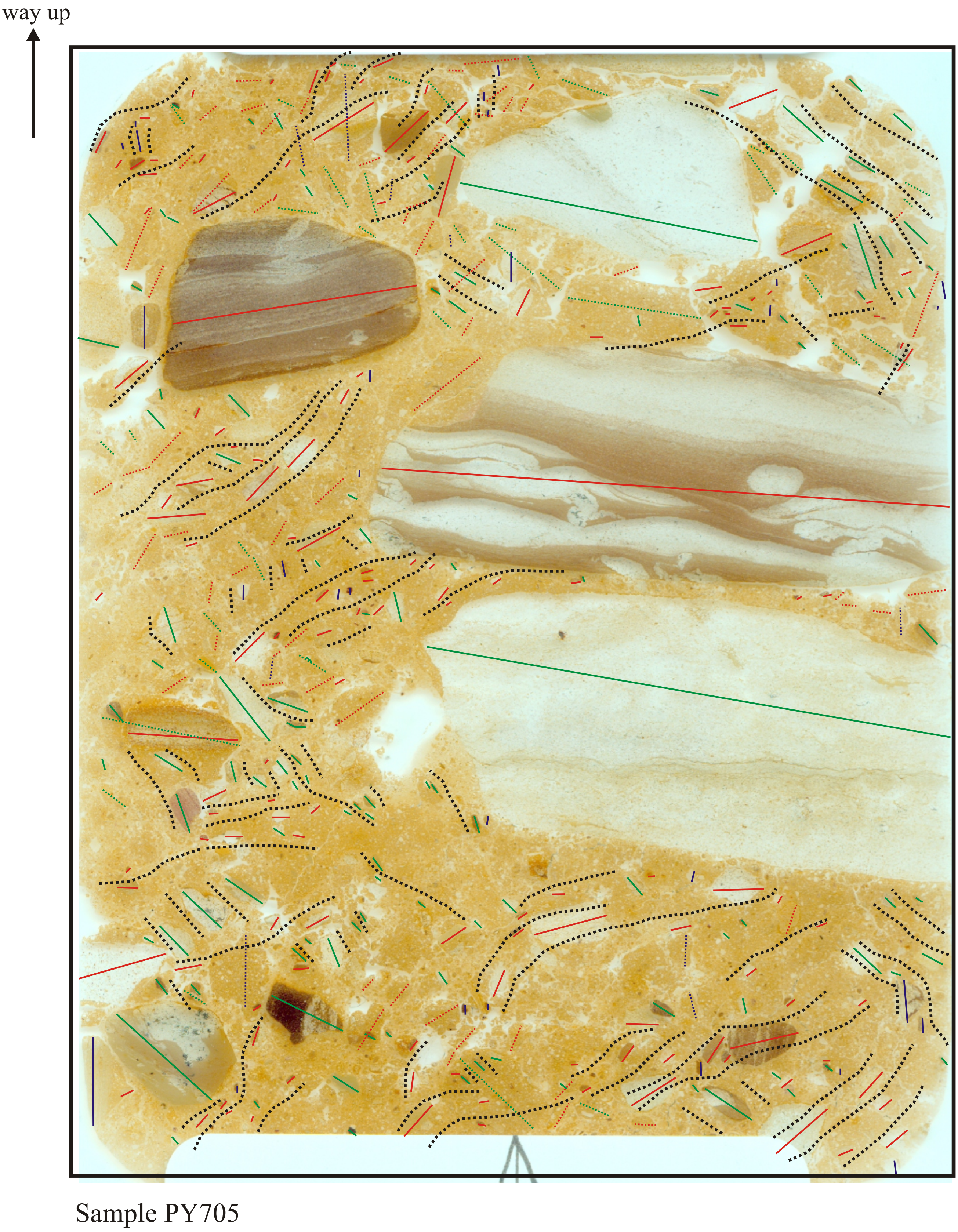
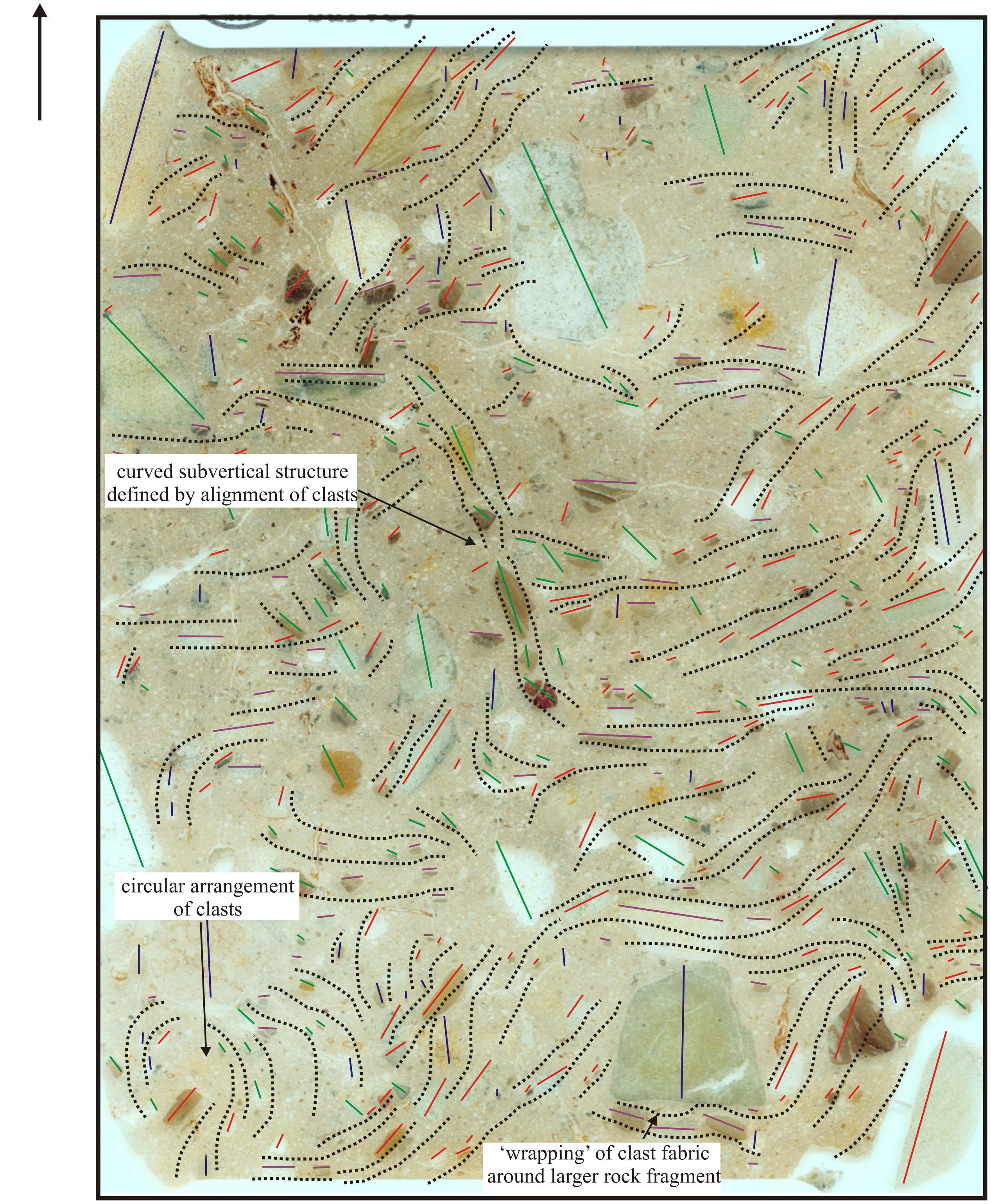


Fig. 11. Diagram showing the interpreted pattern of clast long axis orientation within sample N4018 overlain upon a scanned image of the thin section.

way up



Sample PY706

Fig. 12. Diagram showing the interpreted pattern of clast long axis orientation within sample N4019 overlain upon a scanned image of the thin section.

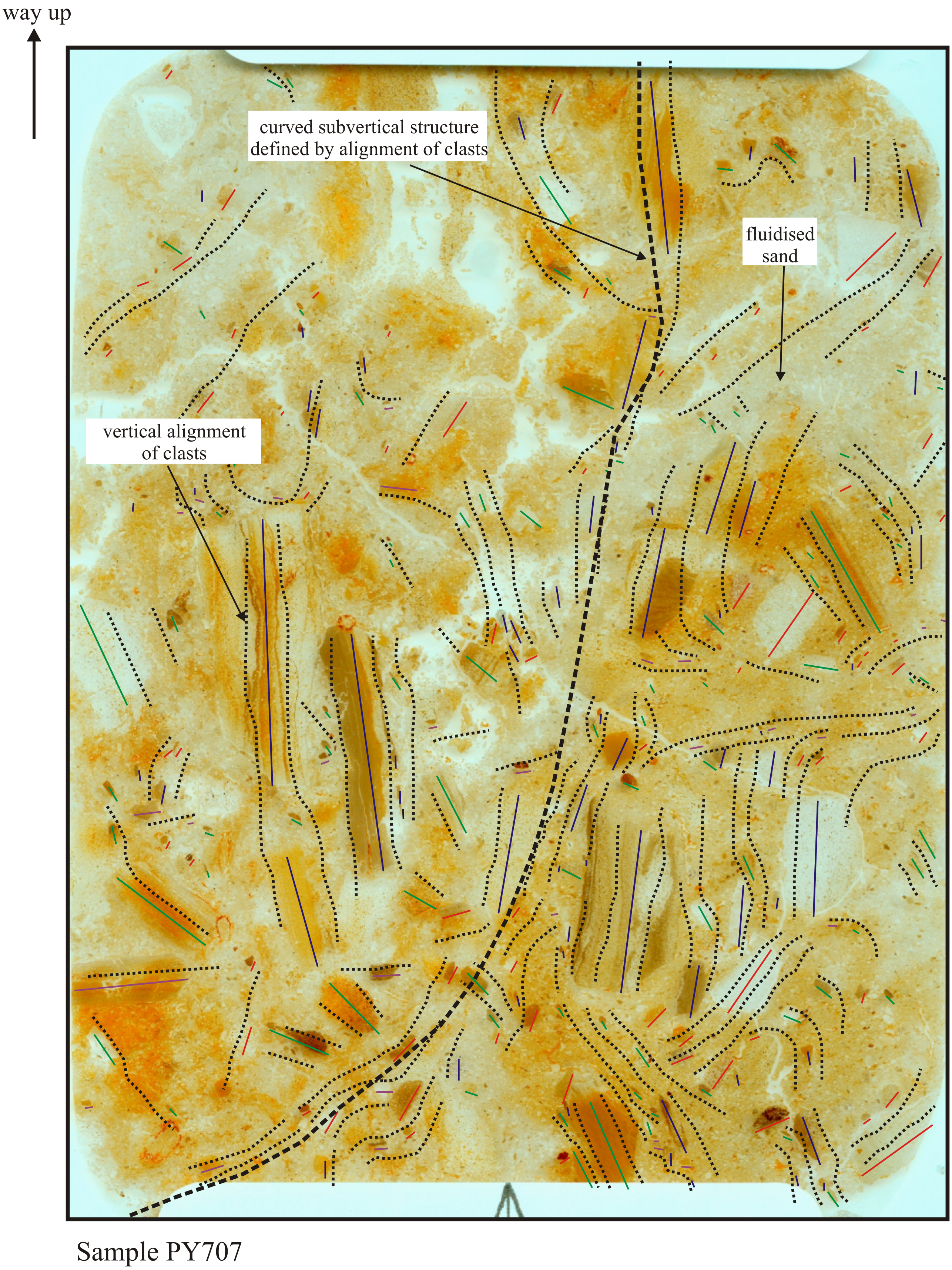


Fig. 13. Diagram showing the interpreted pattern of clast long axis orientation within sample N4020 overlain upon a scanned image of the thin section.

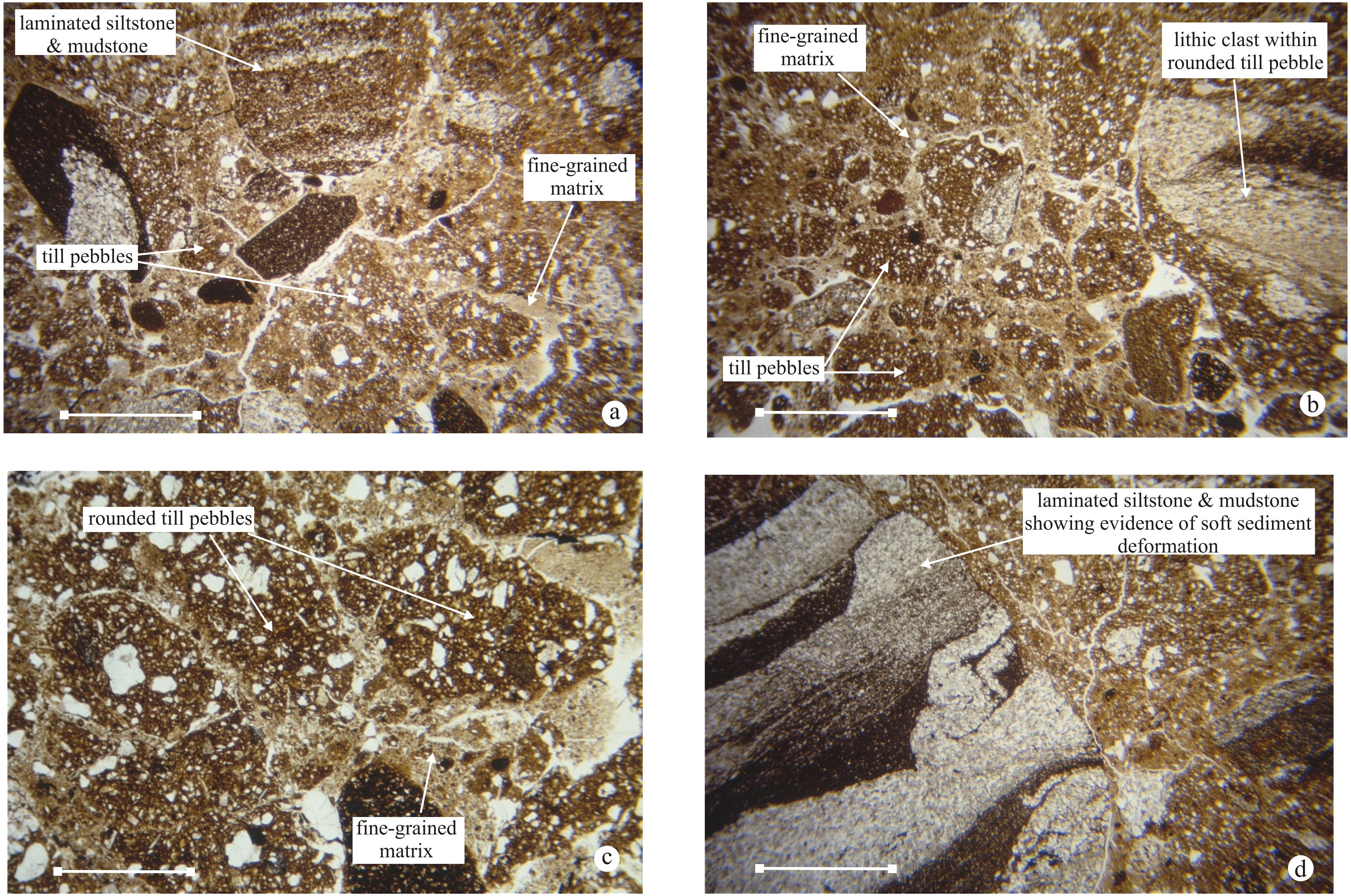


Plate 1. (a) Rounded to subangular till pebbles and rock fragments in a diamicton (Sample N4018, plane polarised light, scale bar = 4 mm). (b) Rounded to angular till pebbles with large pebbles containing broken lithic clasts (Sample N4018, plane polarised light, scale bar = 4 mm). (c) Internally massive rounded till pebbles (Sample N4018, plane polarised light, scale bar = 1 mm). (d) Large laminated siltstone and mudstone lithic clast within a diamicton. Note that the siltstone laminae are graded and show evidence of soft-sediment deformation (Sample N4018, plane polarised light, scale bar = 4 mm).

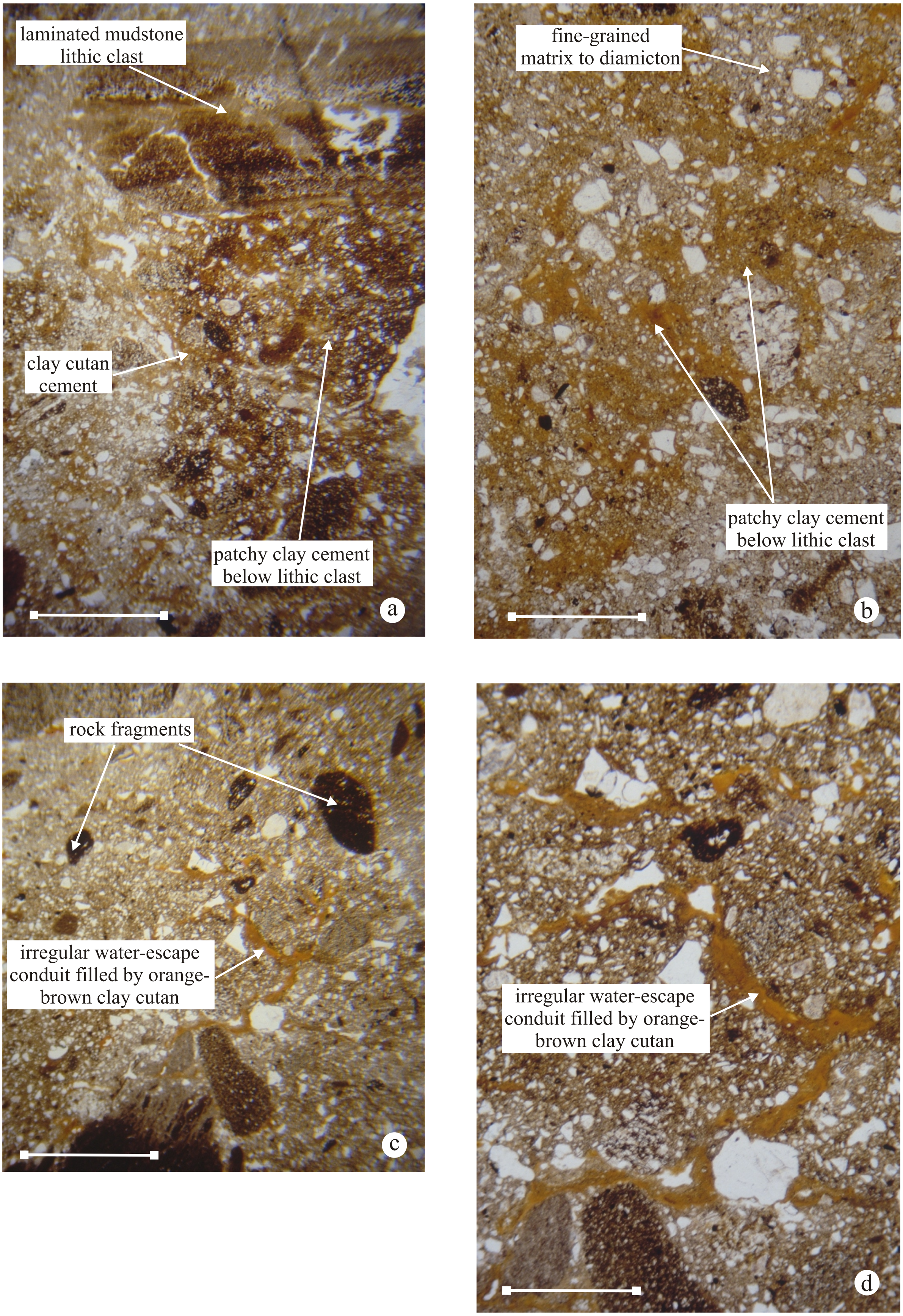


Plate 4. (a) Irregular patch of clay cutan cement developed below a large lithic clast (Sample N4020, plane polarised light, scale bar = 4 mm). (b) Patchy, orange-brown clay cutan cement associated with intergranular movement of pore water through diamicton and removal of fines (Sample N4020, plane polarised light, scale bar = 4 mm). (c) Irregular veinlet or water-escape conduit in diamicton filled by orange-brown clay cutan. (Sample N4020, plane polarised light, scale bar = 4 mm). (d) Irregular water-escape conduit filled by clay cutan. This type of feature is thought to have developed due to more 'confined' fluid flow during dewatering (Sample N4020, plane polarised light, scale bar = 1 mm).

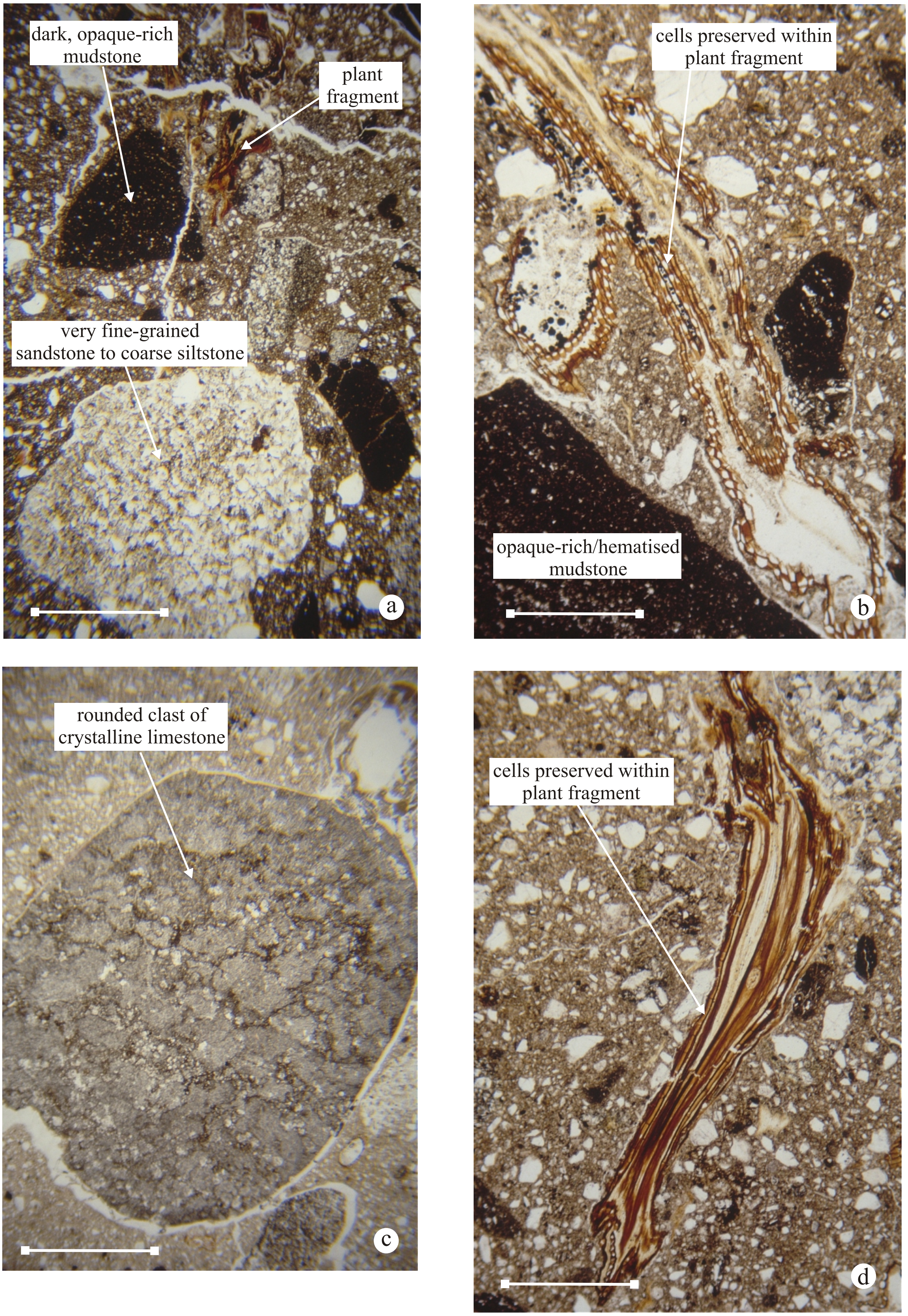
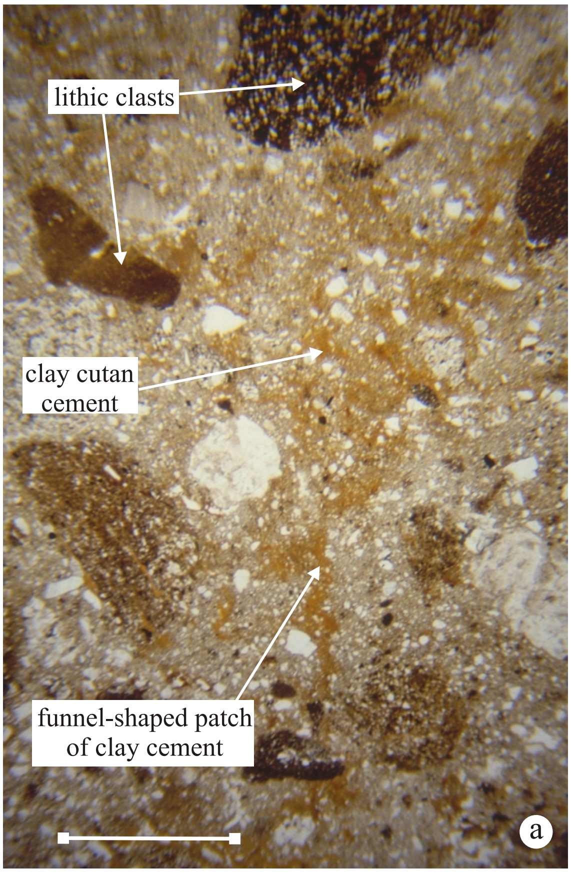


Plate 2. (a) Angular clasts of dark, opaque-rich mudstone, laminated siltstone and mudstone, and rounded clasts of very fine-grained sandstone to coarse siltstone within a coarse diamicton (Sample N4019, plane polarised light, scale bar = 4 mm). (b) Elongate plant fragments with well preserved internal cell structure (Sample N4019, plane polarised light, scale bar = 1 mm). (c) Rounded clast of crystalline limestone (Sample N4019, plane polarised light, scale bar = 1 mm). (d) Elongate plant fragment with well preserved internal cell structure and showing no evidence of compaction (Sample N4019, plane polarised light, scale bar = 1 mm).



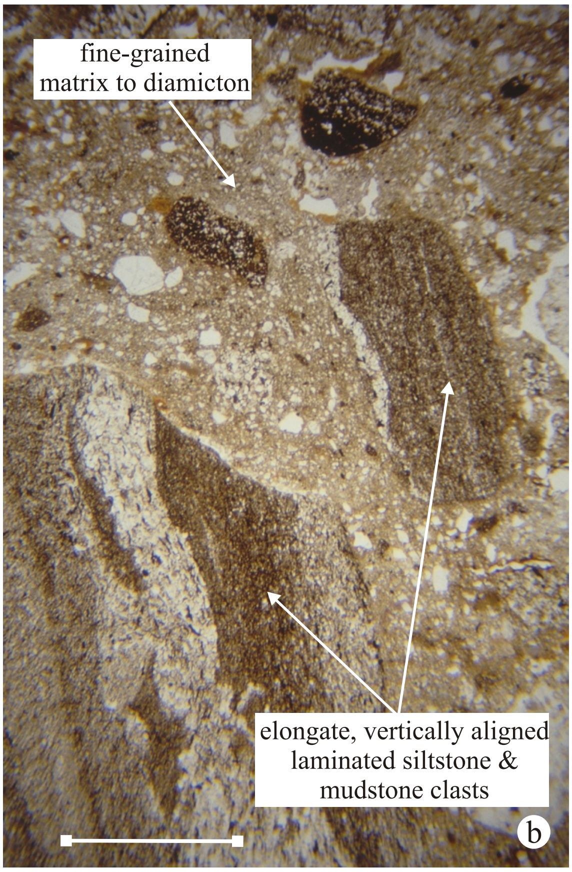


Plate 5. (a) Irregular patch of clay cutan cement developed due to intergranular migration of water through the diamicton and removal of fines (Sample N4020, plane polarised light, scale bar = 4 mm). (b) Elongate, vertically aligned clasts of laminated siltstone and mudstone. Note that the siltstone laminae within the largest clast (bottom left) show evidence of soft-sediment deformation (Sample N4020, plane polarised light, scale bar = 4 mm).

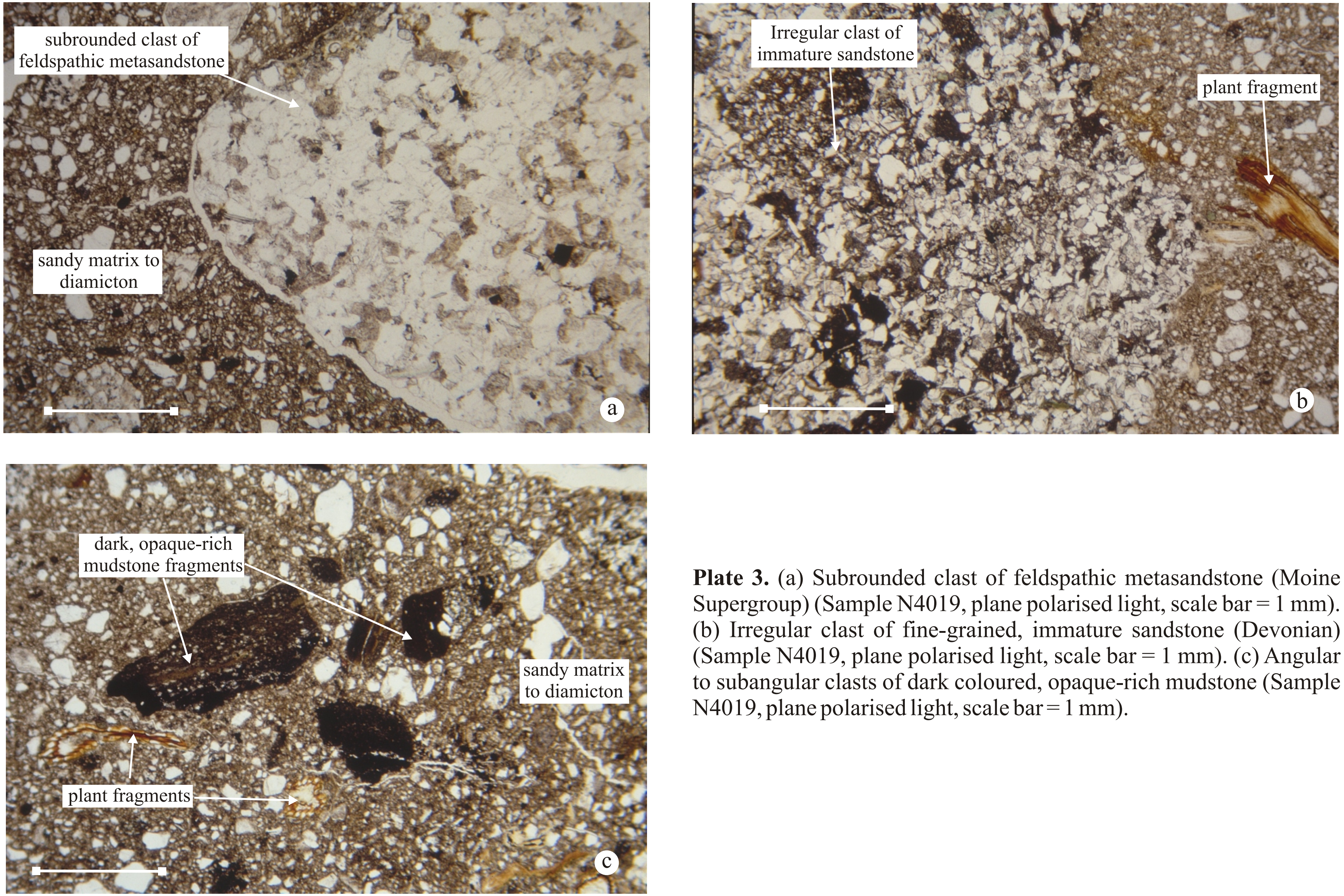


Plate 3. (a) Subrounded clast of feldspathic metasandstone (Moine Supergroup) (Sample N4019, plane polarised light, scale bar = 1 mm). (b) Irregular clast of fine-grained, immature sandstone (Devonian) (Sample N4019, plane polarised light, scale bar = 1 mm). (c) Angular to subangular clasts of dark coloured, opaque-rich mudstone (Sample N4019, plane polarised light, scale bar = 1 mm).