British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Micromorphology of the Quaternary sediments exposed at Drumbeg Quarry, near Drymen, Loch Lomond, Scotland

Physical Hazards Programme

Open Report OR/07/028

BRITISH GEOLOGICAL SURVEY

PHYSICAL HARZARDS PROGRAMME

OPEN REPORT OR/07/028

Micromorphology of the Quaternary sediments exposed at Drumbeg Quarry, near Drymen, Loch Lomond, Scotland

Emrys Phillips

Keywords

Micromorphology, Loch Lomond Readvance, Drumbeg Quarry.

Bibliographical reference

E.R. PHILLIPS. 2007. Micromorphology of the Quaternary sediments exposed at Drumbeg Quarry, near Drymen, Loch Lomond, Scotland. *British Geological Survey Internal Report*, OR/07/028. 34pp.

Keyworth, Nottingham British Geological Survey 2007

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham, Edinburgh and London; see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

☎ 028-9038 8462 Fax 028-9038 8461

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff, CF15 7NE

☎ 029–2052 1962 Fax 029–2052 1963

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of their strategic Physical Hazards Programme. It describes the micromorphology of a suite of Quaternary glacial sediments exposed in Drumbeg Quarry, near Drymen, Loch Lomond, Scotland. The work forms part of the multidisciplinary Physical Properties and Behaviour of UK Rocks and Soils Project, Task 1: Tills Engineering Geology.

Contents

Figure 4. Poorly sorted, matrix-supported diamicton (sample N3769; Unit III) containing sub-angular to rounded locally derived fragments of sandstone (see Figure 2 for location of sample).

Figure 5. Laminated silt and very fine-grained sand overlain by pebbly diamicton (sample N3770) containing sub-angular to rounded locally derived fragments of sandstone. The laminated fine-grained sediments represent the 'high strain zone' which forms the contact between the diamicton (Unit III) and underlying subglacially deformed sediments (Unit II) (see Figure 2 for location of sample).

Figure 6. Highly disrupted silty clay containing lenticels of very fine-grained sand (sample N3771, Unit II)). This sample possesses a distinctive mottled appearance in thin section (see Figure 2 for location of sample).

Figure 7. Laminated silt and fine-grained sand in sample N3772 (Unit I) deformed by a well-developed crenulation cleavage (S1). Bedding is locally transposed by this locally pervasive glacitectonic fabric (see Figure 2 for location of sample).

Figure 8. Diagram showing the relationship between the S1 crenulation cleavage and F1 folds developed within the proglacially deformed part (Unit I) of the ice-proximal deltaic sequence exposed at Drumbeg Quarry: **(a)** F1 fold deforming interbedded clay, silt and sand. The fold is deformed by a set of low-angle to sub-horizontal thrusts and moderately dipping normal faults; **(b)** Diagram showing the relationships between small-scale S, M and Z-shaped parasitic folds to the main F1 synform; and **(c)** Detail of domainal S1 crenulation cleavage developed axial planar to the F1 fold.

Figure 9. The well-developed crenulation cleavage (S1) and associated microfolds in sample N3773 (Unit I) are off-set by a later, northeast-directed thrust and moderately dipping reverse faults. Bedding within these finely laminated sediments is locally transposed by the S1 glacitectonic fabric (see Figure 2 for location of sample).

Figure 10. The massive to weakly laminated sand and silt of sample N3774 (Unit I) are deformed by a moderately northeast-dipping normal fault (see Figure 2 for location of sample).

Figure 11. Highly disrupted sand containing patches of very fine-grained silt and clay (sample N3775, Unit II). This sample possesses a distinctive mottled appearance in thin section (see Figure 2 for location of sample).

TABLES

Table 1. Details of samples collected from Section A Drumbeg Quarry near Drymen.

Summary

This report describes the micromorphology of samples prepared from Quaternary glaciogenic sediments exposed in Drumbeg Quarry, near Drymen, Loch Lomond, Scotland. The work forms part of the Tills Engineering geology studies of the Physical Properties and Behaviour of UK Rocks and Soils Project within the Physical Hazards Programme.

The first part of the report provides the background information on the Quaternary geology of the Drymen area. This is followed by a section describing the detailed micromorphology of seven large format thin sections of the variably deformed sands, silts and diamictons exposed in Section A of Drumbeg Quarry.

1 Introduction

Drumbeg Quarry [NN 479 877] lies to the southeast of the village of Drymen east of Loch Lomond in central Scotland (Figure 1), within the limit of the Loch Lomond Readvance marked by its terminal moraine (Rose, 1981). The quarry cuts through one of a series of ridges formed by coalesced ice-contact subaqueous fans/deltas that prograded into Lake Blane during the recession of the eastern margin of the Loch Lomond glacier lobe from its readvance limit (Figure 1). The sequence of deltaic sands and gravels (Figure 2), and proximal subaqueous outwash gravels (Browne and McMillan 1989; Benn and Evans, 1996; Phillips et al., 2002; Phillips et al., 2005) were locally deformed during the active retreat of the Loch Lomond glacier. The sedimentology and deformation history recorded by these deltaic sediments are described in details by Phillips et al., (2002; also see Benn and Evans, 1996; Phillips et al., 2005) and are, therefore, only summarised here.

Phillips et al. (2002) provided macroscopic evidence that these sediments had undergone a polyphase deformation history interspersed with periods of erosion and deposition. The earliest deformation event (D1) was driven by the northeasterly readvance of the Loch Lomond lobe into the ice-contact slope of the fan/delta (Figure 3). This proglacial D1 deformation event, is restricted to the lower part of the sequence now exposed at Drumbeg Quarry (Unit I, see Figure 2). It resulted in tilting of bedding and tectonic thickening of the sequence by folding (F1) and thrusting. In the mid- to outer-parts of the fan/delta, however, sedimentation apparently continued uninterrupted during D1 deformation. As the ice retreated, the fan-delta was re-established, leading to a period of erosion of the lower parts of the succession (Figure 3), followed by deposition of a sequence of proximal sands and gravels (Unit II, see Figure 2) upon these underlying polydeformed sediments.

A second phase of readvance of the Loch Lomond ice-lobe resulted in ductile shearing and disruption of this proximal sedimentary sequence (Phillips et al., 2002). This northeast-directed, subglacial deformation event (D2, Figure 3) accompanied the deposition of a carapace of diamicton (2-3 m thick) (Unit III, see Figure 2) and affected a greater part of the fan-delta complex than D1. Folding and boudinage during D2 lead to the disruption of the originally well-bedded sediments and eventual disaggregation and homogenisation of the sand and gravel beds. Deformation within the sand, silty sand and clay-rich lenses is highly heterogeneous. In the most intensely deformed units, the sedimentary lamination is transposed by a well-developed, finely banded fabric. This apparently intense deformation is in marked contrast to that recorded by the adjacent sand lenses, in which primary sedimentary structures (lamination, grading, cross-bedding) are often preserved. Elsewhere, D2 resulted in soft-sediment deformation, accompanied by liquefaction and water escape. An anastomosing network of ductile shear zones formed during D2, locally tectonically excised parts of the underlying sequence. One of these shear zone forms the contact between this D2 deformed sequence and the overlying diamicton (Figure 2). Phillips et al. (2002) interpreted a southwest-dipping banding within this 'high strain zone' as a glacitectonic fabric. However, no obvious macroscopic kinematic indicators were recognised within it.

The subsequent retreat of the Loch Lomond ice-lobe, from the overridden part of the ice-contact delta, was accompanied by erosion and truncation of all the earlier developed deformation structures and partial removal of the diamicton (Figure 3). The underlying deformed sequence was unconformably overlain by sands and gravels (Unit IV, see Figure 2) as the fan-delta complex was re-established. Deposition of the locally channellised deltaic sequence was apparently terminated by the deposition of a thin diamicton which caps the sequence exposed in Drumbeg Quarry.

2 Micromorphology

Seven samples (N3769, N3770, N3771, N3772, N3773, N3774, N3775) of the glaciogenic sediments were collected from Section A in Drumbeg Quarry (Table 1). The samples were obtained using 10 cm square, aluminium kubiena tins which were either cut or pushed into the face of the exposure. Once the samples were removed from the exposed face they were double sealed in plastic bags and stored at 4°C to prevent drying out and bacterial alteration prior to sample preparation. The location of the samples collected for thin sectioning are shown in Figure 2.

Table 1. Details of samples collected from Section A, Drumbeg Quarry, near Drymen.

Sample Number	Location	Grid Reference	Description
N3769 (Db 1)	Section A, Drumbeg Quarry, southeast of Drymen	[NN 4787 8772]	massive diamicton collected from Unit III
N3770 (Db 2)	Section A, Drumbeg Quarry, southeast of Drymen	[NN 4787 8772]	deformed diamicton and laminated/banded silt and sand collected from the base of Unit III
N3771 (Db 3)	Section A, Drumbeg Quarry, southeast of Drymen	[NN 4789 8773]	highly disrupted and fluidised silty sand collected from a highly deformed sandy lens within Unit II
N3772 (Db 4)	Section A, Drumbeg Quarry, southeast of Drymen	[NN 4789 8773]	folded and faulted interlaminated silt and sand collected from the limb of a asymmetrical fold within Unit I
N3773 (Db 5)	Section A, Drumbeg Quarry, southeast of Drymen	[NN 4789 8773]	folded and faulted interbedded sand and silt collected from Unit I
N3774 (Db 6)	Section A, Drumbeg Quarry, southeast of Drymen	[NN 4789 8773]	normal fault deforming sand and silty sand, collected from Unit I
N3775 (Db 7)	Section A, Drumbeg Quarry, southeast of Drymen	[NN 4790 8774]	highly disrupted and fluidised sand and silty sand, collected from Unit II

Sample N3769 was taken from within the massive diamicton of Unit III. Sample N3770 was collected from the base of this diamicton and includes part of a prominent high strain zone which marks the boundary between this subglacial till and the structurally underlying sediments of Unit II. Samples N3772 and N3773 were collected from the limbs of a steeply inclined F1 fold which deforms the sands and silts of Unit I. Sample N3774 is of a normal fault which off-setting bedding within Unit I. Samples N3771 and N3775 were both taken from Unit II and comprise highly disrupted silt and sand.

2.1 ANALYTICAL TECHNIQUES

A total of 7 large format thin sections were prepared by Mr D. Oates at the British Geological Survey's Thin Sectioning Laboratory (Keyworth) following the procedures for sample preparation of unlithified 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. An annotated scanned image (Figures 4 to 11) of each thin section has been used to describe the main microscopic features developed within these Quaternary deposits.

2.2 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 and Vegers, 1994; Menzies, 2000). Although repetitive features have been recognised (see van der Meer, 1987, 1993 and references therein), a standard nomenclature has yet to be formalised. The terminology used in this report is that proposed by van der Meer (1987, 1993) and 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.

Plasmic fabric - The arrangement of high birefringent, optically aligned clay plasma/domains which are visible under the microscope (under cross polars). These fabrics are only observed when the sediment is clayey. Sediments containing little fines or a 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 typically defining discrete shears. 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. 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. 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. 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 - These include: the circular arrangement of clasts (skeleton grains) with or without a 'core stone', interpreted as having formed in response to rotation (van der Meer, 1993); pressure shadows 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 (e.g. lamination, cross-lamination….etc); water-escape structures associated with forceful dewatering; and crushing of clastic grains.

2.3 THIN SECTION DESCRIPTIONS

Collectors Number: Db 1. **Registered Number:** N3769. **Location:** [NN 4787 8772] Section A, Drumbeg Quarry, southeast of Drymen. **Lithology:** massive diamicton (Unit III).

Description: This thin section is of a poorly sorted, open-packed, immature, matrix-supported, massive, sandy diamicton (Figure 4). Included detrital grains are angular, subangular to occasionally subrounded in shape with a low to moderate sphericity. The larger, coarse sand to pebble sized clasts are typically composed of rock fragments with the finer grained (fine- to medium-grade sand) being mainly of monocrystalline quartz with subordinate feldspar. There is a marked bimodal grain size distribution between the larger granule to pebble sized clasts and the finer sand grade detritus; the latter dominates the matrix of this sandy diamicton. Detrital grains are locally coated in a partial or complete rim of silt to clay grade material. The limited rounding of the sand grains is indicative of a limited period of transport within the sedimentary environment, suggesting that these clasts were derived from first cycle sands or direct from the sedimentary or metasedimentary bed rock. Occasional, diffuse till pebbles have been recognised within the diamicton. These till pebbles are internally massive (type 1 till pebbles of van der Meer 1993) and are distinguished by their slightly darker colour.

The lithic clasts are mainly composed of sedimentary and metasedimentary rock fragments. These include feldspathic meta-quartz-arenite (which possesses a sericitic matrix or cement), chert or cryptocrystalline quartzose rock, quartzose litharenite, polycrystalline quartz (possibly vein quartz), quartzofeldspathic mylonite, very fine-grained quartzose schist or phyllite, andesite, altered amygdaloidal basalt, very fine-grained chloritic phyllite, chlorite-quartz-schist, white mica-rich phyllite and sheared to protomylonitic fine-grained meta-quartz-arenite. The shape of the granule to pebble sized metamorphic lithic clasts suggests that they are polycyclic in nature and include broken fragments of much larger pebbles. Minor to accessory detrital components present within the matrix of the diamicton include plagioclase, microcline, white mica/muscovite, epidote, garnet, opaque minerals, chlorite, chloritic pseudomorphs after ferromagnesian minerals, apatite, chloritised biotite and rutile.

The mineralogy of the finely schistose to phyllitic metasedimentary rocks is dominated by chlorite and white mica (muscovite) indicating that they have undergone greenschist facies metamorphism and were probably derived from the Neoproterozoic Southern Highland Group (Dalradian). These polydeformed metasedimentary rocks are exposed to the north of Drumbeg and comprise a sequence of metamorphosed mudstones and siltstones, interbedded with quartzose to feldspathic metasandstones. These metasedimentary rocks are locally very highly deformed resulting in the development of a suite of protomylonitic to mylonitic rocks. Similar highly sheared ductile fault rocks are also exposed adjacent to, and within the Highland Boundary Fault Zone.

The sedimentary rock fragments are lithologically similar to the quartzose to lithic-rich alluvial to fluvial sandstones which dominate the Devonian in age Lower Old Red Sandstone facies rocks. These sedimentary rocks occur to the south of the Highland Boundary Fault and are widely exposed in the Drymen area. The andesitic and basaltic rock fragments present within the diamicton were probably derived from the Devonian basaltic to andesitic volcanic rocks which occur within the sandstone dominated sequence. The presence of andesite rock fragments clearly indicates that the Carboniferous Clyde Plateau Volcanic Formation, which form the Campsie Hills to the southeast of Drymen, were unlikely to be the source of these fine-grained igneous rocks. The Clyde Plateau lavas are petrographically and geochemically distinct from the older Devonian volcanic rocks, and are dominated by a suite of variably olivine-clinopyroxene-plagioclase porphyritic alkali basalts.

The diamicton is relatively undeformed (see Figure 4). No plasmic fabric(s) or any other deformation structures (folds, circular or galaxy structures) have been recognised. However, the lack of clay minerals within the silt- to clay-grade component of the matrix may, at least in part, explain the absence of a plasmic fabric. There is no obvious preferred shape alignment of the coarser grained clasts within the diamicton. This is in marked contrast to the well-developed clast macrofabric recorded by Phillips et al. (2002) within the till at the same structural/stratigraphical level within the diamicton as sample N3769 (see figure 12 of Phillips et al., 2002). Arcuate alignments or concentrations of sand grains are rarely developed/preserved within the matrix of the diamicton. These may represent partially formed or disrupted/overprinted galaxy or circular structures which have been previously interpreted as indicative of rotational deformation (van der Meer, 1993; Menzies, 2000).

Collectors Number: Db 2 **Registered Number:** N3770 **Location:** [NN 4787 8772] Section A, Drumbeg Quarry, southeast of Drymen. **Lithology:** deformed diamicton and laminated/banded silt and sand (Unit III).

Description: This thin section is composed of laminated or banded silt, silty clay and sand overlain by diamicton (Figure 5) and includes the upper boundary of the high strain zone which marks the base of Unit III (Figure 2). For ease of description this thin section is divided into three areas (see Figure 5).

The lower part of the thin section is composed of an approximately 20 mm thick layer of silty sand (minimum thickness as base of sand layer not seen). The sand is very poorly sorted with an open packed, matrix-supported texture. Low sphericity silt to sand grade clasts are angular to occasionally subrounded in shape and mainly composed of monocrystalline quartz. Detrital grains are locally enclosed within a fine-grained, brown coloured clayey coating. Minor to accessory detrital components present include plagioclase, polycrystalline quartz, amphibole, opaque minerals, felsite, quartz microporphyritic rhyolite rock fragments, chlorite and muscovite/white mica. The sand also contains granule to pebble-sized, angular to subangular, low sphericity lithic clasts which are, in general, composed of clayey silt. The larger of the pebble sized clasts are up to *c*. 4.0 mm in length. The fragments of clayey silt are lithologically similar to the overlying laminated silts and clays. Although mainly composed of silt, very fine-grained litharenite, fine-grained quartzose litharenite, very fine-grained schistose to phyllonitic metasedimentary rock, chlorite-schist or phyllite, schistose metasandstone and hematised sandstone lithic clasts are also present.

The matrix to the sand is lithological similar to, and may have been derived from, the silty ‘lithic’ clasts present within this sandy layer. The modal proportion of the matrix decreases upwards with the remaining sand becoming cleaner and possessing a more open packed texture with a higher intergranular porosity. This cleaner sand contains trace amounts of an orange-brown, highly birefringent clay cement. This cement is petrographically similar to clay cutan and is, therefore, thought to have formed due to the deposition of fines by percolating intergranular pore water. It is possible that this cement was formed shortly after, or even during the deposition of this sandy layer. The clean sand was also observed filling an irregular hydrofracture which cuts the overlying laminated silt and clay (Figure 5). Consequently, the sand is thought to have been injected into the predominantly silty sediments resulting in the local fragmentation of the adjacent clayey silt. These fragmented silts were incorporated into the fluidised sand. The locally developed clay cutan cement probably formed during the final stages of dewatering of this sandy sediment.

The silty sand is overlain by an approximately 20 to 25 mm thick layer of laminated/banded silt and silty clay (Figure 5). As previously stated, these laminated sediments are lithologically similar to the granule to pebble sized silt clasts present within the underlying sand. The boundary between the sand and the overlying laminated silt and clay is sharp, but irregular in form. Occasional, very fine sand grains within the silt laminae are angular in shape with a low to moderate sphericity. These clasts are mainly composed of monocrystalline quartz. Minor to accessory detrital white mica/muscovite, opaque minerals, epidote, garnet and chlorite have also present within the silts.

The laminated clay and silt is cut by two funnel-shaped water-escape features filled by homogeneous sand and silt (Figure 6). These structures are linked to a number of sub-horizontal hydrofractures which occur parallel to the lamination within the host silt and clay. These layer-parallel fractures occur immediately below a thick clay lamina. This thicker clay layer may have temporarily impeded the upward migration of the fluidised sand, forcing it to spread laterally until the cohesive strength of the clay was exceeded and upward fluid migration re-initiated. The larger of the hydrofractures is connected to the relatively thick sand present at the bottom of the thin section (see Figure 5). The same hydrofracture can be traced upwards where it cuts the base of the overlying diamicton (Unit III of Phillips et al., 2002). Brittle deformation associated with hydrofracturing resulted in localised brecciation and fragmentation of the laminated silt and clay in the walls of these sand-filled structures. These microstructural relationships indicate that hydrofracturing and injection of the fluidised sand occurred after the deposition of at least the basal part of the diamicton (Unit III).

No obvious macroscopic sedimentary structures (e.g. cross lamination) have been recognised within the laminated silt and silty clay, consistent with the banding/lamination within these fine-grained sediments being tectonic in origin. In outcrop, these laminated sediments occur within the upper part of the high-strain zone forming the base of the diamicton (Unit III of Phillips et al., 2002) separating it from the underlying highly disrupted sands and gravels of Unit II. However, in thin section, the silty laminae may be reverse graded indicating that they are waterlain. A fine-scale colour banding has subsequently been imposed onto these laminated sediments and is defined by the variation in hematitic staining. The pale brown hematitic stained bands are interpreted as representing palaeo-oxidation fronts within the sediments and were formed due to the fluctuation in the level of Fe-bearing pore water. Development of this staining may have occurred at any time after deposition (possibly recent) and, therefore, does not reflect groundwater conditions within the proglacial or fluvial/deltaic environment.

In the centre of the laminated silt and clay unit is a 3.0 to 5.0 mm thick layer of variably disrupted clay to silty clay (Figure 5). A fine lamination and bedding-parallel plasmic fabric present within this clay are deformed by a variety of structures including disharmonic folds, narrow shears and flame structures. The style of deformation within this clayey layer was clearly lithologically controlled, with the less cohesive silty partings having undergoing partial liquefaction and remobilisation. The complex, disharmonic nature of the folds and the apparently penecontemporaneous fluidisation of the silt suggests that the sediments were water saturated at the time of deformation. Two plasmic fabrics have been identified within the clay: **(a)** an early layer-parallel foliation (S1); and **(b)** a second fabric (S2) developed at approximately 45° to the lamination. The variation in intensity of these fabrics is at least in part due to the variation in the modal proportion of clay minerals. The layer-parallel S1 fabric is clearly cross-cut by the S2 fabric, with both foliations being defined by the preferred shape and optical alignment of the clay plasma. No obvious crenulation style folding of the S1 fabric by S2 has been noted. In the adjacent, silty laminae S1 is absent and S2 is defined by the preferred shape alignment of detrital phyllosilicate flakes (mainly muscovite). It is likely that S1 within the silts has been overprinted during liquefaction and remobilisation. The occurrence of the S2 fabric within the silt laminae indicates that the imposition of this second fabric post-dated liquefaction.

The upper part of the laminated clay and silt layer is composed of massive to weakly laminated silt (Figure 5). This silt possesses a distinctive mesh-textured fabric composed of two foliation planes orientated at approximately 90° and is morphologically similar to a lattisepic plasmic fabric developed in clay-rich sediments or pencil cleavage developed in metamorphic rocks. The silt is locally deformed by narrow shear bands which define a variably developed extensional crenulation cleavage (ECC) or SC-fabric geometry. The sense of shear recorded by this shear fabric is uncertain due to later disruption of the silt.

The laminated silt and clay unit is overlain by a very poorly sorted, immature, open to very open packed, matrix supported, massive diamicton (Figure 5). The silty matrix to the diamicton locally possesses a very poorly developed plasmic fabric. Angular to subangular, coarse silt to sand grade clasts within this matrix are mainly composed of monocrystalline quartz with subordinate polycrystalline quartz. Minor to accessory detrital components present within the matrix include plagioclase, opaque minerals, muscovite/white mica, chlorite, chloritic pseudomorphs after ferromagnesian minerals, garnet, microcline and epidote. Very coarse sand to pebble sized clasts included within the diamicton range up to 25 mm in length and are mainly composed of sandstone and metasedimentary rock fragments. The lithic clasts are typically very angular to subangular in shape with a low to moderate sphericity. However, occasional rounded clasts are present. Recognisable lithologies include: fine-grained quartzose litharenite, altered litharenite, feldspathic sandstone, schistose metasandstone rock, micaceous phyllonite, chlorite-schist or phyllite, quartz-chlorite vein material, and rare altered basaltic rock fragments as well as traces of hematised mudstone, hornfels and recrystallised microgranitic rock. Angular fragments of laminated silt and clay, and hematised till pebbles occur near to the base of the diamicton, immediately adjacent to the contact with the underlying laminated sediments. The composition of the lithic clasts indicates that they were mainly derived from the Silurian to Devonian Old Red Sandstone facies succession and Neoproterozoic Southern Highland Group.

Finer grained clasts are locally enclosed within a fine clay or hematitic rim or coating. These coatings may have developed prior to the incorporation of the clasts into the diamicton or during the deposition or early diagenetic history of this glacial deposit. The larger clasts exhibit a variably developed preferred shape alignment (clast fabric) with their long axes occurring parallel to the base of the diamicton. No comparable clast fabric has been recognised within the matrix which is essentially massive in appearance. However, occasional to rare circular, arcuate and galaxy-like grain arrangements do occur within the matrix. A weakly developed stratification present near the base of the diamicton is highlighted by the variation in the modal fine silt and clay-grade material within the matrix. This stratification may result in the weakly developed fissility towards the base of the diamicton observed in outcrop.

The boundary between the underlying laminated sediments and diamicton is irregular and ranges from sharp to locally gradational (Figure 5). The laminated silt and clay immediately below the diamicton has locally been fragmented/brecciated. Fragmentation of the laminated silt and clay appears to be related to the introduction of a layer of matrix-poor sand along the boundary between the diamicton and underlying sediments. Injection of the sand resulted in the detachment of 1.0 to 5.0 mm thick tabular ‘slabs’ or ‘rafts’ of silt and clay, which are incorporated into the basal part of the diamicton. The diamicton also contains fragments of Fe-stained laminated silt and clay, as well as hematised till pebbles. These hematised till pebbles are compositionally similar to the host diamicton. However, hematisation is typically restricted to these clasts suggesting that Fe-oxidation occurred prior to there incorporation into the diamicton.

Macro- and microstructural observations clearly indicate that the sediments were water saturated at the time of deformation leading to hydrofracturing, disharmonic folding within the laminated silt and clay, and the variable fluidisation of the sands and silts. Although in the field the laminated silts and clays which underlie the diamicton appear to represent a high-strain zone and, therefore, purely tectonic in origin, it is clear that water played a significant role in the deposition/formation of these banded/laminated sediments. This interpretation is supported by the presence of reverse graded clay-silt laminae within this postulated ‘high-strain’ zone. An increase in pore water pressure during subglacial deformation and the deposition of Unit III could have acted as a hydrogeological jack, resulting in the decoupling of the diamicton from the underlying sediments. This decoupling may have assisted in the transport of the Loch Lomond glacier ice over its bed. The water lubricated detachment would have acted as a major ‘flow zone’ allowing the migration/escape of fluidised sediment and/or pore water. Reverse grading and the fine scale lamination within this apparent ‘high-strain’ zone record the fluctuation in pore water pressure during displacement. Deformation (folding, fabric development) of the laminated sediments within the ‘high-strain’ zone would have occurred during periods of relatively low pore water pressure.

Collectors Number: Db 3 **Registered Number:** N3771 **Location:** [NN 4789 8773] Section A, Drumbeg Quarry, southeast of Drymen. **Lithology:** highly disrupted and fluidised silty sand collected from a highly deformed sandy lens (Unit II).

Description: This thin section is of a highly disrupted silty clay which contains thin lenses of very fine-grained sand, and possesses a distinctive mottled or fragmented appearance (Figure 6). The original sediment was probably mainly composed of laminated fine sand, silt and clay. The boundaries between the coarse silt, sand and more clay-rich areas are highly irregular, lobate to locally flame-like indicating that these sediments have been strongly modified and disrupted due to liquefaction.

Angular, subangular to rarely subrounded, low sphericity clasts within the patches of silt and sand are mainly composed of monocrystalline quartz. The angular nature of the clasts is indicative of a limited period of transport in the fluvial/deltaic environment. The more rounded clasts may be inherited from the original sedimentary rock, or alternatively represent a minor component of wind-blown sand derived from the reworking of the sands on the exposed surface of the delta. Minor to accessory detrital components present within the slightly coarser grained sediments include muscovite/white mica, opaque minerals, chlorite, polycrystalline quartz, zircon, clinopyroxene, plagioclase and garnet. The variable shape alignment of the detrital micas defines a locally developed foliation within the coarser silty and sandy areas of the sediment.

The silt and sand varies in texture from very open packed with a distinctive cement supported appearance, through to moderately or closely packed in which individual clastic grains are in contact (i.e. clast or grain supported). The cement is composed of a distinctive orange-brown, highly birefringent clay which is petrographically similar to the clay cutan filling irregular to vein-like water-escape features. It is possible that the clay cement was formed when the silts and sands were in a highly dilated, possibly even fluidised state leading to the preservation of the very open packed, cement supported texture. In one irregular sand lens present within this sample the clay cutan cement is restricted to the basal part or the lens resulting is geopetal-like feature/structure. It is possible that in this instance cementation occurred during waining or low-magnitude flow where intergranular, clay-bearing water was concentrated at the base of the sandy lens. There is no evidence to suggest that the clay settled out of suspension from standing water (e.g. capping of sand grains by clay throughout the sand lens).

A well-developed plasmic fabric present within the clay cement locally forms concentric ‘shells’ upon detrital grains. Elsewhere, this fabric is disrupted or brecciated. Fragmentation may have occurred during compaction, or in response to an increase in intergranular pore water pressure during fluid flow. The latter may have been enough to fragment the partially formed clay cutan cement, but not to re-dilate/fluidise the partially cemented sand. The areas or patches of fine silt and clay are grey to brown in colour and possess a variably developed plasmic fabric. This fabric predates disruption of the clay and silt which are deformed by small-scale disharmonic to convolute folds. Elsewhere, these fine-grained sediments are laminated with individual laminae preserving a moderately to well-developed graded bedding, and are locally ‘capped’ by a thin veneer of highly birefringent clay (?cutan). In some cases this clay veneer grades into thicker patches of clay cutan. The intensity of the plasmic fabric present within the silt and clay increases towards the cutan. Consequently, it is unclear if this lamination and associated grain size grading is a primary sedimentary feature, or secondary in origin, forming in response to waining flow during subsequent liquefaction and remobilisation.

Migration of pore water though the sediment is recorded by wispy, irregular to flame-like clay cutan lined water-escape features, as well as larger areas or patches of highly birefringent clay cutan. The clay fill to a number of these water-escape features is finely laminated suggesting that they remained active over a prolonged period of time and accommodated several phases of fluid flow. A well-developed plasmic fabric within the cutan occurs parallel to the lamination and probably formed as a result of the ‘plating’ of the clay plasma along the margins of the water-escape conduit, rather than any subsequent deformation event. The clay cutan filled water-escape conduits are typically associated with the fine silty to clayey areas of the sediment. Fluid flow through the coarser sandy areas appears to have been intergranular in nature, with these coarser grained sediments having undergone liquefaction and remobilisation. In contrast, the more clay-rich areas within the sediment would have been relatively cohesive, leading to hydrofracturing.

Collectors Number: Db 4 **Registered Number:** N3772 **Location:** [NN 4789 8773] Section A, Drumbeg Quarry, southeast of Drymen. **Lithology:** folded and faulted interlaminated silt and sand collected from the limb of an asymmetrical fold (Unit I).

Description: This thin section is of a highly deformed interlaminated silt, silty clay and very fine sand which contains a lens of matrix-poor, clean fine- to medium-grained sand (Figure 7). The sample was collected from the overturned limb of an F1 fold (see Figure 2). A fine-scale sedimentary lamination within the silt, silty clay and very fine sandy silt has been crenulated and variably overprinted/transposed by a new compositional banding which is tectonic in origin. This fabric is morphologically similar to a well-developed domainal crenulation cleavage developed within polydeformed metamorphic rocks (Figure 8). The earlier foliations and/or bedding are preserved within apparently lower strain or ‘Q-domains’. In these domains the earlier developed foliation or lamination may be deformed by small-scale crenulation-style folds (Figure 8).

In sample N3772, the sedimentary lamination (S0) is preserved within the lower strain Q-domains of the domainal (S1) crenulation fabric. In these domains S0 is deformed by a small-scale, tight to isoclinal, asymmetrical folds that are truncated against the adjacent S1 M-domains (Figures 7 and 8). The sense of shear recorded by these asymmetrical fold structures is consistent with an overall sense of displacement towards the northeast. A locally developed fine-scale axial planar to weakly fanning foliation (S1) is developed associated with these microscopic scale F1 folds. This fabric is defined by very narrow, clay-rich shears which possess a weakly to moderately developed planar (unistrial) plasmic fabric. Elsewhere within the Q-domains the sedimentary lamination (S0) is apparently unfolded at occurs at a high angle (ranging from 45° to 90°) to S1. The variation in the orientation of S0 within the S1 Q-domains is the result of F1 folding. These folds have been dissected and variably overprinted during the progressive development of the new tectonic fabric.

The M-domains of the S1 fabric represent the limbs of the crenulation-style folds (see Figure 8) in which S0 has been progressively rotated and sheared out into a new, finely banded tectonic fabric. A fine foliation within the M-domains is defined by shape-aligned detrital white mica flakes. This fabric occurs parallel to the margins of the M-domains and is axial planar to the F1 folds preserved within the adjacent Q-domains. The boundaries between the Q- and M-domains are sharp and may have accommodated minor amounts of displacement in response to flexural slip.

The centre and upper part of sample N3772 is dominated by a lens of very fine-grained, matrix-poor sand (Figure 7). Internally the bulk of this sandy lens is essentially massive. However, a weak sedimentary lamination is preserved by a number of thin, laterally impersistant heavy mineral bands. These bands are mainly composed of granular-looking opaque minerals. The massive appearance of the sand suggests that the original sedimentary lamination has been largely overprinted, possibly due to liquefaction and remobilisation of the sediment. Water may have preferentially migrated into the sand lens as the adjacent silt and clay dewatered during deformation and crenulation cleavage development. The sand is composed of angular to subangular, low sphericity clasts of monocrystalline quartz and minor plagioclase. Other minor to accessory detrital components include muscovite/white mica, plagioclase, opaque minerals, microcline, chlorite, epidote, clinozoisite, Mg-chlorite and apatite. Structurally above the sand, bedding within the silt and clay has been transposed by the S1 fabric (Figure 7). Below the sand lens the lamination is preserved and is deformed by open, low amplitude F1 folds. This area may represented a ‘pressure shadow’, which partially protected the silts and clays from folding during deformation.

Collectors Number: Db 5 **Registered Number:** N3773 **Location:** [NN 4789 8773] Section A, Drumbeg Quarry, southeast of Drymen. **Lithology:** folded and faulted interbedded sand and silt (Unit I).

Description: This sample was collected from the steep limb of a mesoscale F1 fold, immediately adjacent to a pale blue-grey coloured high-strain zone within the polydeformed sand-dominated sequence of Unit I (Figure 2). The sample is composed of finely inter-laminated or banded silt, clayey silt and very fine-grained sand (Figure 9), and is lithologically similar to sample N3772. The original sedimentary lamination has been variably overprinted/transposed by a well-developed tectonic fabric (S1). This fabric is composed of alternating, 5 to 30 mm wide, Q- and M-domains (Figures 8 and 9). Bedding (S0) within the M-domains has been overprinted by the S1 fabric which comprises narrow, alternating bands of silt and clayey-silt. Although similar to the sedimentary lamination, this tectonic banding lacks any obvious internal sedimentary structures (e.g. grading). The boundaries between the individual bands are sharp and may have accommodated minor amounts of slip (displacement). Detrital micas within the silt and clayey silt are aligned parallel to S1 and were probably passively rotated into this foliation during deformation.

In the adjacent, apparently lower strain, Q-domains the sedimentary lamination is deformed by open to tight, asymmetrical to weakly symmetrical, crenulation-style folds (Figure 9). The foliation within the M-domains is axial planar to these folds. The sense of shear recorded by the asymmetrical crenulations is consistent with folding having occurred in response to layer-parallel flexural-slip on the limb of a larger scale synform (see Figure 8). The Q-domains, in general, are slightly coarser grained than the M-domains and contain a greater number of coarse silt to very fine sand laminae. This slight variation in the number/density of silt and sand laminae may, at least in part, have controlled the scale of partitioning of deformation and hence the location and thickness of the developing Q and M-domains.

The domainal S1 fabric is deformed by a number of low-angle to sub-horizontal reverse faults which clearly off-set both S1 and the sedimentary lamination (S0). These fault zones are locally lined by a thin layer of clayey silt suggesting that these brittle structures acted as a focus for fluid migration during deformation.

The upper left-hand part of the sample N3773 is dominated by a layer or lens of massive, matrix-poor, moderately to well-sorted, fine-grained sand (Figure 9). The sand is mainly composed of angular to subangular, low to moderate sphericity clasts of monocrystalline quartz. Minor to accessory detrital components include plagioclase, muscovite/white mica, chlorite, opaque minerals, apatite, epidote, amphibole, zircon, polycrystalline quartz and garnet. The sand contains irregular patches or bands of a red-brown coloured clay cement. This sand represents the margin of a ‘high-strain’ zone. Although, in the field, this zone clearly truncates a mesoscale F1 fold, in thin section the sand preserves very little evidence of deformation. It is possible that this sand was injected into a pre-existing structure (e.g. fault or shear zone) during the later stages of deformation. Consequently, this fluidised sand does not exhibit any of the deformation recorded by the adjacent laminated silt and clayey silt.

Collectors Number: Db 6 **Registered Number:** N3774 **Location:** [NN 4789 8773] Section A, Drumbeg Quarry, southeast of Drymen. **Lithology:** normal fault deforming sand and silty sand, (Unit I).

Description: This thin section is of a deformed clay to clayey silt lining to a moderately NE-dipping normal fault which deforms a massive to weakly laminated fine-grained sand (Figure 10). The poorly sorted, high porosity, matrix-poor, clean sand which dominates this thin section is massive to weakly laminated and possesses open packed texture. Detrital grains are angular to subangular with a low sphericity, indicative of a limited period within the fluvial/deltaic environment. However, rare subrounded, moderate sphericity clasts are also present. These more rounded grains may have been inherited from the source rock, or alternatively represent wind blow sand derived from the reworking of the sandy sediments exposed on the surface of the delta. The detrital assemblage is dominated by monocrystalline quartz with subordinate to minor plagioclase and lithic fragments. The lithic clast are mainly composed of very fine-grained sedimentary and metasedimentary rock fragments. Occasional fine-grained igneous rock (possibly volcanic) fragments have also been recorded. Minor to accessory detrital components include muscovite/white mica, opaque minerals, mica-rich phyllitic rock, altered biotite, chlorite, apatite, garnet, polycrystalline quartz, tourmaline, clinozoisite, zoisite, amphibole, biotite and rare pyroxene. Heavy minerals (e.g. garnet, opaque minerals, apatite) present within the sand locally form laterally impersistant to lenticular heavy mineral bands. The presence of apatite within the heavy mineral assemblage indicates that the sediment had a low residence time in the sedimentary environment, consistent with the texturally immature nature of the sediment.

Fine-scale hematitic or clay coatings are developed on some detrital grains and are thought to represent an early, poorly formed rim cement. Elongate detrital grains, in particular the detrital phyllosilicate minerals (muscovite, chlorite, biotite), are variably shape-aligned parallel to bedding. This layer-parallel foliation is thought to be sedimentary in origin and, therefore, completely unrelated to subsequent deformation.

The dominant feature present within sample N3774 is a *c*. 18 to 20 mm wide fault zone (Figure 10). This fault is lined by finely laminated to massive silt which has been ‘dragged’ into this structure from a prominent silty layer within the sand dominated sequence of Unit I. The lamination within the silt fault lining is deformed and defines a sigmoidal fabric geometry yielding a dextral (top to right) sense of shear. This sense of shear is consistent with a northeasterly downthrow on this normal fault (see Figure 10). In detail, the fault is composed of a network of smaller structures which off-set the lamination within the silt. The fault zone is bound by two moderate to steeply northeast-dipping fault planes. The smaller scale faults, although they exhibit the same sense of off-set as these bounding structures, dip at a steeper angle to the northeast (main bounding structures 37°, smaller scale faults 49°). The geometry of the small-scale faults is consistent with them having developed as Riedel shears within the main fault zone. These Riedel shears result in the observed thinning/attenuation of the silty layer observed in outcrop. All of the fault planes are marked by a pronounced preferred alignment of detrital micas which were passively rotated into parallelism with the fault during deformation. Fluid migration along the fault planes has resulted in localised yellow-brown to red-brown Fe-staining within and immediately adjacent to these brittle structures. Traces of a clay cutan are also developed along these extensional faults.

Collectors Number: Db 7 **Registered Number:** N3775 **Location:** [NN 4790 8774] Section A, Drumbeg Quarry, southeast of Drymen. **Lithology:** highly disrupted and fluidised sand and silty sand (Unit III).

Description: This thin section is of a highly disrupted and fluidised sand and silty sand which contains irregular patches and bands of clay and silty clay resulting in a distinctive mottled appearance to this sample (Figure 11). The patches of silt and clay are cut by irregular veinlets of orange-brown clay cutan. The sand and silty sand which dominates sample N3775 is massive, poorly sorted and matrix-poor with a high to very high porosity. The sand is locally very open packed with a cement supported texture. This cement is composed of a highly birefringent clay cutan. Angular, subangular to rarely subrounded, low sphericity sand grains are mainly composed of monocrystalline quartz as well as subordinate plagioclase and lithic fragments. Minor to accessory detrital components include muscovite, hematised mudstone, polycrystalline quartz, opaque minerals, chlorite, microcline, epidote, zircon, biotite, very fine-grained volcanic rock, amphibole, apatite, tourmaline, serpentine/serpentinite and rare pyroxene. The fragments of serpentinite or serpentine may have been derived from a suite of serpentinised ophiolitic (oceanic) rocks which occur in discrete pods or lenses along the Highland Boundary Fault Zone.

Sedimentary structures (e.g. grading, cross lamination, lamination) are poorly preserved or have been overprinted within sample N3775. A weakly preserved lamination is locally defined by laterally impersistant heavy mineral bands.

The patches of silty clay possess a variably developed plasmic fabric and coarser-scale foliation defined by shape aligned detrital micas. Both foliations are deformed and disrupted resulting in very complex internal fabric relationships. In the most highly disrupted areas the plasmic fabric occurs as randomly orientated, discontinuous domains of aligned clay plasma or mica. Plasmic fabrics are most clearly developed within the clay cutan lined water-escape conduits where they define and a locally anastomosing fabric geometry. The development of the plasmic fabric within these flow zones occurred in response to the 'plating' of the clay plasma onto the margins of these features. The plating of fines to the walls of veins would have helped to stabilise these water-escape features. An increase in pore water pressure during a subsequent phases of fluid flow may have resulted in the observed disruption and fragmentation of the plasmic fabrics within the silty clay and/or clay cutan.

3 Discussion

The micromorphological analysis confirms the field observations of Phillips et al. (2002) that there is a marked contrast in the style of proglacial D1 and subglacial D2 deformation recorded by the glacigenic sediments at Drumbeg Quarry (see Figure 2). The predominantly sandy sediments deformed during D1 have undergone folding and thrusting (Figure 2). F1 folding was accompanied by the imposition of an axial planar, domainal S1 crenulation to transposition fabric within the finer grained units (Figures 7, 8 and 9). The morphology of this fabric is similar to crenulation cleavages developed within polydeformed metamorphic rocks (Bell and Rubenach, 1983; Vernon, 1989; Passchier and Trouw, 1996) with crenulation-style folding of bedding being preserved within lower strain domains (see Figure 9). Sand-filled water-escape conduits occur parallel to, and locally cross-cut S1. In detail, these sand-filled features developed along the lower strain domains of the S1 cleavage (Figure 9). This microtextural relationship indicates that S1 locally controlled the sites of water-escape and that dewatering occurred during D1.

In contrast to the proglacial D1 event, microstructures developed during the later subglacial D2 deformation of the overlying ice-proximal sands and gravels, are consistent with the soft-sediment deformation. The composition of the sediments affected by D1 and D2 are similar, so any differences in the style of deformation are probably related to water content and pore water pressure at the time of deformation. Both D1 and D2 were caused by the advance of the Loch Lomond ice-lobe northeastwards into Lake Blane. Consequently, it is likely during both readvance phases, the deltaic sediments were water saturated. Differences in water content and pore pressure during D1 and D2 may, therefore, have been affected by the setting of these deformation events. For instance, during proglacial D1 deformation the relatively high porosity and permeability of these unconsolidated sands would have initially allowed water to escape, keeping the effected pore-water pressure relatively low. However, tectonic thickening of the sedimentary pile during subglacial deformation (D1), would have resulted in the consolidation of the sediments. This may have led to a reduction in permeability and an increase in pore-water pressure. The result would have been the localised liquefaction and fluidisation of the sands during the later stages of D1. The presence of thin silt and clay interbeds also formed temporary barriers, locally impeding water-escape. The progressive development of the domainal S1 cleavage within these clayey sediments, however, provided an ideal fluid pathway allowing trapped pore-water to escape.

During subglacial D2 deformation, the ice-proximal sands and gravels were completely overridden by ice, leading to deposition of a carapace of diamicton covering these water-saturated sediments. The diamicton would have formed a relatively impermeable cap, retarding water-escape and causing an increase in pore-water pressure. Loading, exerted by the overriding ice, would have added to this pressure increase. Consequently, subglacial D2 deformation of these water saturated sediments was characterised by liquefaction and soft-sediment deformation. The large-scale disruption of this part of the Drumbeg glacigenic sequence is therefore interpreted as having been largely due to elevated water pressures and liquefaction, rather than high shear strains produced by the overriding ice. Hiemstra et al. (2005) suggested that till deposition at Drumbeg was incremental and associated with an seasonally oscillating ice margin. These seasonal oscillations in the ice margin would have accompanied a fluctuation in pore water content and pressure within the underlying sedimentary sequence.

The shear zones, recognised by Phillips et al. (2002), which locally tectonically excised parts of the already disrupted sequence, developed at a later stage of D2. At the time, dewatering of the sedimentary pile would have allowed an increase in the amount of shear transmitted into the glacier bed, where it was partitioned into discrete shear zones. One of these shear zones is developed along the contact between the ice-proximal sands and gravels, and the overlying diamicton (Figures 2 and 5). Microstructures developed within this shear zone include banded foliation, layer-parallel plasmic fabric in the clays; narrow shear bands defining ECC or SC fabrics and disharmonic folds; as well as sand-filled hydrofractures that post-date the imposition of the main foliation. However, a number of the more silty bands within this apparently highly deformed zone are reverse-graded or homogenised due to localised liquefaction. The presence of soft-sediment deformation and liquefaction features within this shear zone suggest that pore-water pressure continued to fluctuate and that the shear zones presented preferential sites for fluid pathways to develop allowing water to escape. The injection of fluidised silt and sand into these actively deforming zones may also have acted as a lubricant aiding displacement. The increase in pore-water pressure during injection of this fluidised material into the shear zones could also have acted as a ‘hydraulic jack’, resulting in the decoupling of the diamicton from the underlying sediments. One potential effect of this decoupling would be the rafting and imbrication of the diamicton during the later stages of D2 subglacial deformation.

Glossary

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

Plasmic fabric – The optical arrangement of high birefringent clay plasma/domains which are visible under crossed polarised light using a petrological microscope.

Unistrial plasmic fabric – A planar plasmic fabric defined by relatively continuous domains which is typically observed defining discrete shears (van der Meer, 1993).

Skelsepic plasmic fabric – A plasmic fabric in which the orientated domains occur parallel to the surface of large grains (van der Meer, 1993).

Lattisepic plasmic fabric – A plasmic fabric defined by short orientated domains in two perpendicular directions (van der Meer, 1993).

Omnisepic plasmic fabric – A plasmic fabric in which all the domains have been reoriented (van der Meer, 1993).

Grain size – (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.

Rounded – Describes the smoothness of the surface of a grain. 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.

Sphericity – Describes how closely a detrital grain 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.

Sorting – Well sorted describes a 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.

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.

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

Clay cutan – a modified texture, structure or fabric of an unconsolidated material (e.g. soil) caused by the concentration of optically aligned, highly birefringent clay plasma.

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

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.

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

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.

Detritus – A general term for fragmentary material, such as gravel, sand, clay, worn from rock by disintegration. Detrital grains in clastic sediments or 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.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

Bell, T.H. and Rubenach, M.J. 1983. Sequential porphyroblast growth and crenulation cleavage development during progressive deformation. *Tectonophysics*. **92,** 171 - 94.

Benn, D.I. and Evans, D.J.A. 1996. The interpretation and classification of subglacially-deformed materials. *Quaternary Science Reviews*. **15,** 23-52.

Browne, M..A.E. and MacMillan, A.A. 1989. *Quaternary Geology of the Clyde Valley*. British Geological Survey Research Report SA/89/1, Onshore Geology Series. HMSO, London.

Hiemstra, J.F., Evans, D.J.A. and Benn, D.I. 2005. Drumbeg: zooming in on Unit III (an alternative scenario for deformation phase D2). In Evans, D.J.A. (ed.) *The Quaternary of the Western Highland Boundary: Field Guide*. Quaternary Research Association. 104-110.

Menzies, J. 2000. Micromorphological analyses of microfabrics and microstructures indicative of deformation processes in glacial sediments. *In* Maltman, A. J., Hubbard, B. and Hambrey, J. M. (eds) *Deformation of Glacial Materials. Geological Society, London, Special Publication*. **176,** 245-257.

Passchier, C.W. and Trouw, R.A.J. 1996. *Microtectonics*. Springer.

Phillips, E.R., Evans, D.J.A. and Auton, C.A. 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. *Sedimentary Geology*. **149,** 157-182.

Phillips, E.R., Auton, C.A., Evans, D.J.A. and Benn, D.I. 2005. Drumbeg glacial sedimentology and tectonostratigraphy. In Evans, D.J.A. (ed.) *The Quaternary of the Western Highland Boundary: Field Guide*. Quaternary Research Association. 88-103.

Rose, J. 1981. Field guide to the Quaternary geology of the south eastern part of the Loch Lomond basin. Proceedings of the Geological Society of Glasgow. 122/123, 12-28.

Seret, G. 1993. Microstructures in thin sections of several kinds of till. *Quaternary International*. **18,** 97-101.

van der Meer, J.J.M. 1987. Micromorphology of glacial sediments as a tool in distinguishing genetic varieties of till. In *INQUA Till Symposium, Finland 1985*. Kujansuu, R. and Saarnisto, M (editors). Geological Survey of Finland, Special Paper **3,** 77-89.

van der Meer, J.J.M. and Laban, C. 1990. Micromorphology of some North Sea till samples, a pilot study. *Journal of Quaternary Science*. **5,** 95-101.

van der Meer, J.J.M., Rabassa, J.O. and Evenson, E.B. 1992. Micromorphological aspects of glaciolacustrine sediments in northern Patagonia, Argentina. *Journal of Quaternary Science*. **7,** 31-44.

van der Meer, J.J.M. 1993. Microscopic evidence of subglacial deformation. *Quaternary Science Reviews*. **12,** 553-587.

van der Meer, J.J. M. and Vegers, A.L.L.M. 1994. The micromorphological character of the Ballycroneen Formation (Irish Sea Till): a first assessment. *In* Warren and Croot (eds.) *Formation and Deformation of Glacial Deposits*. Balkema, Rotterdam. 39-49.

Vernon, R.H. 1989. Porphyroblast-matrix microstructural relationships: recent approaches and problems. *In* Daly et al., (eds). *Evolution of metamorphic belts*. Geological Society of London Special Publication. **43,** 83-102.

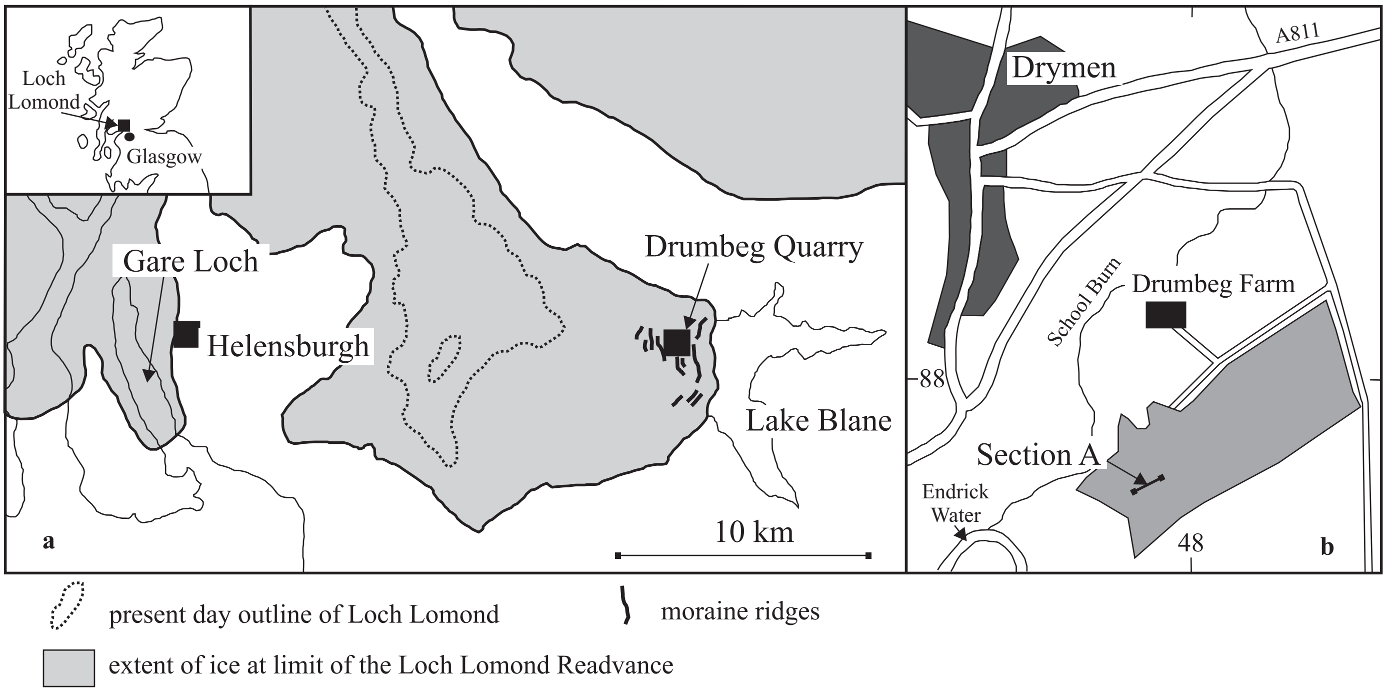

Figure 1. (a) Map showing the palaeogeography of the Loch Lomond Readvance and position of Drumbeg Quarry. (b) Location map of Drumbeg quarry, Drymen showing the position of section A (after Phillips et al. 2002).

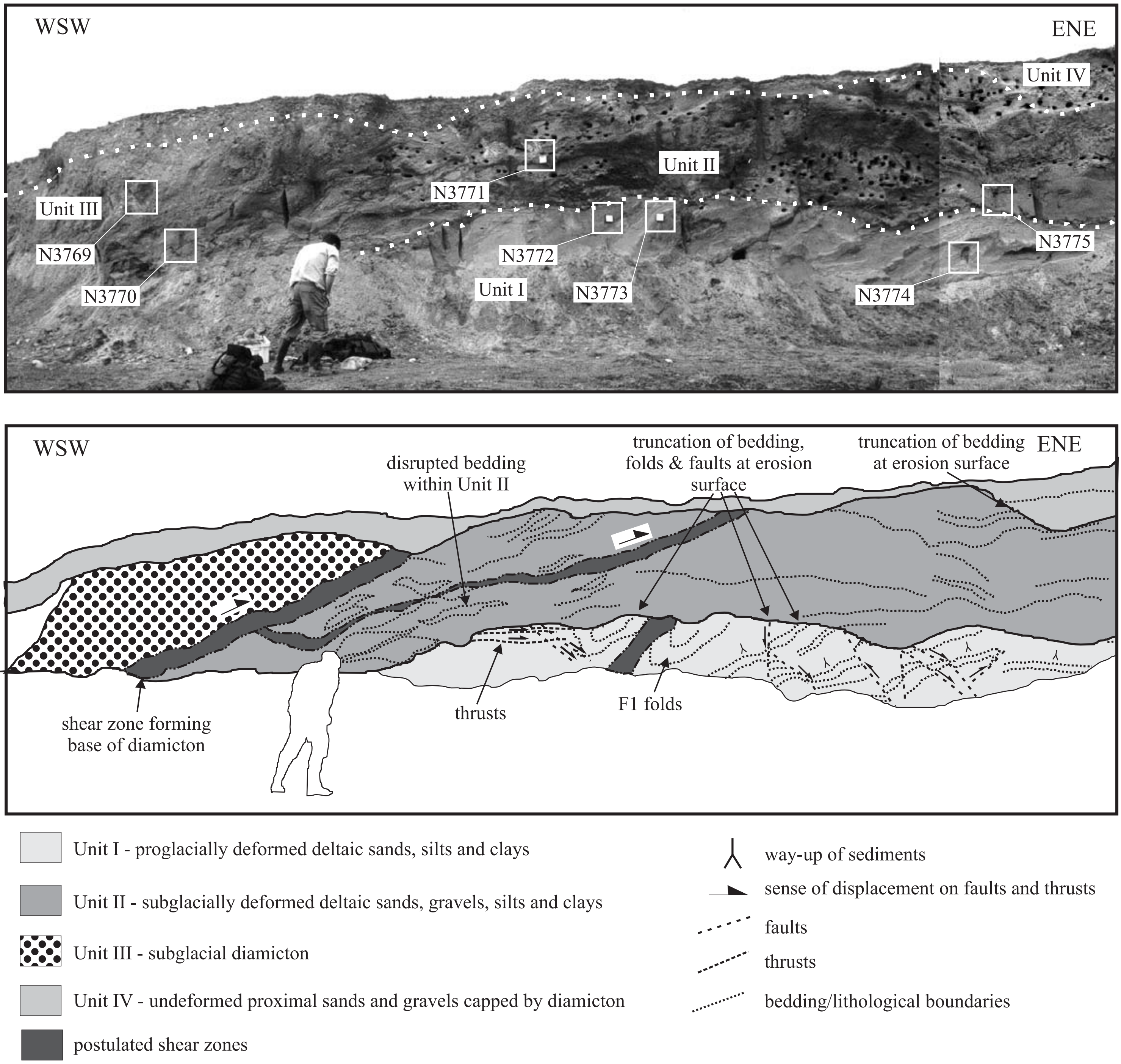

Figure 2. Photomosaic showing the main deformation structures and tectonostratigraphical units exposed at Drumbeg Quarry near Drymen (after Phillips et al., 2002). Also shown are the locations of samples N3769, N3770, N3771, N3772, N3773, N3774 and N3775 collected from both the proglacially and subglacially deformed parts of the sequence.

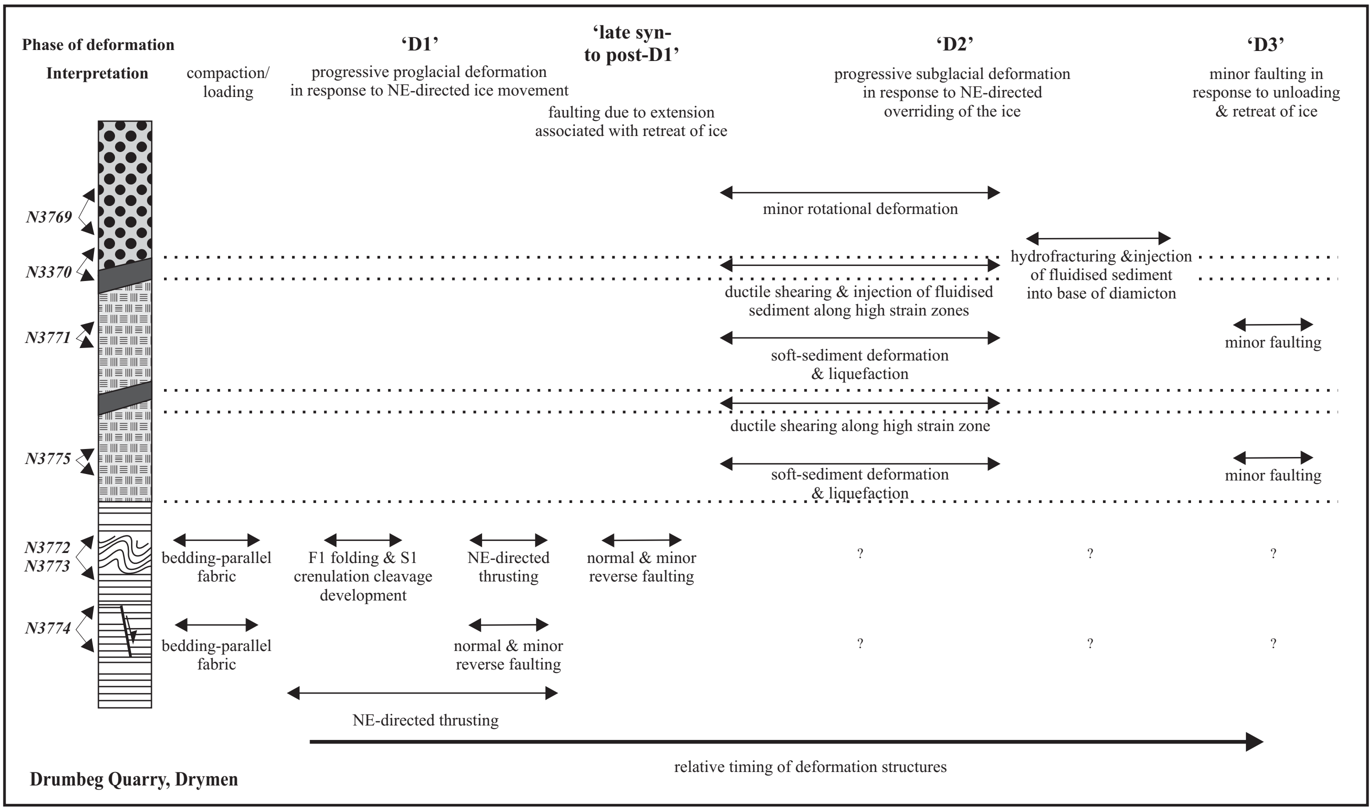

Figure 3. Diagram summarising the relative age relationships (based upon macro- and microstructural evidence) of structures developed during proglacial (D1) and subglacial (D2) deformation of the deltaic sequence exposed at Drumbeg Quarry.

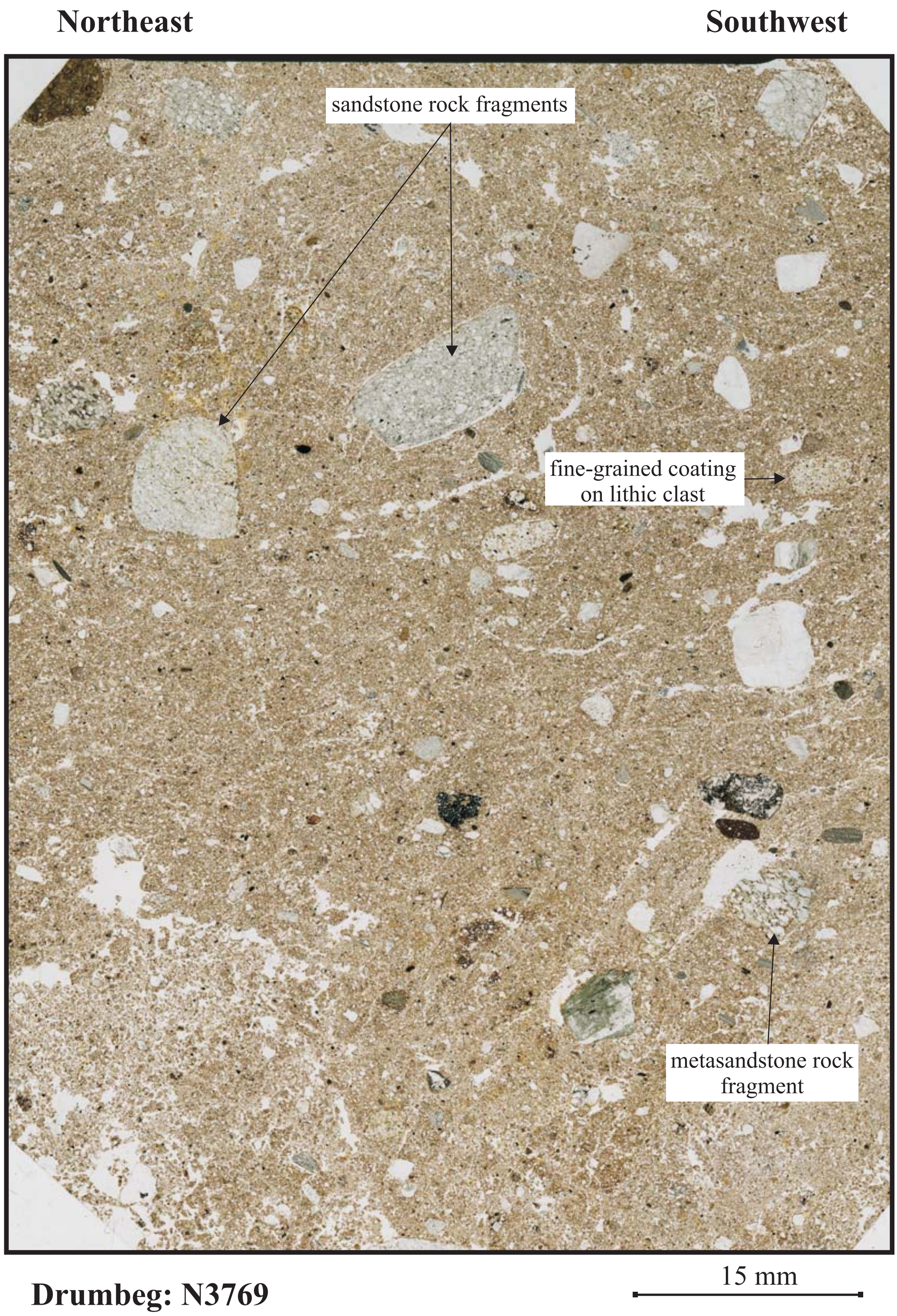

Figure 4. Poorly sorted, matrix-supported diamicton (sample N3769; Unit III) containing sub-angular to rounded locally derived fragments of sandstone (see Figure 2 for location of sample).

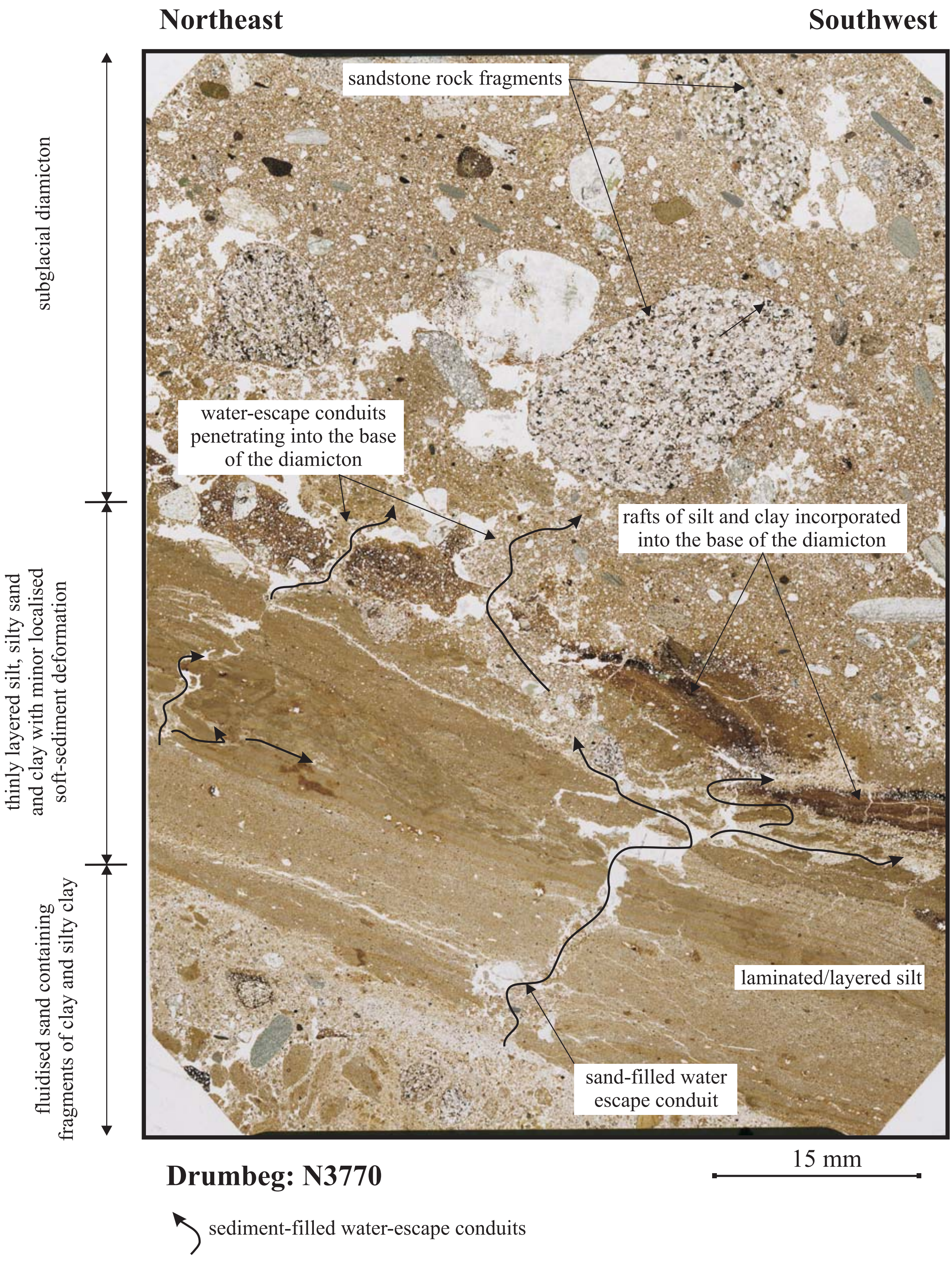

Figure 5. Laminated silt and very fine-grained sand overlain by pebbly diamicton (sample N3770) containing sub-angular to rounded locally derived fragments of sandstone. The laminated fine-grained sediments represent the 'high strain zone' which forms the contact between the diamicton (Unit III) and underlying subglacially deformed sediments (Unit II) (see Figure 2 for location of sample).

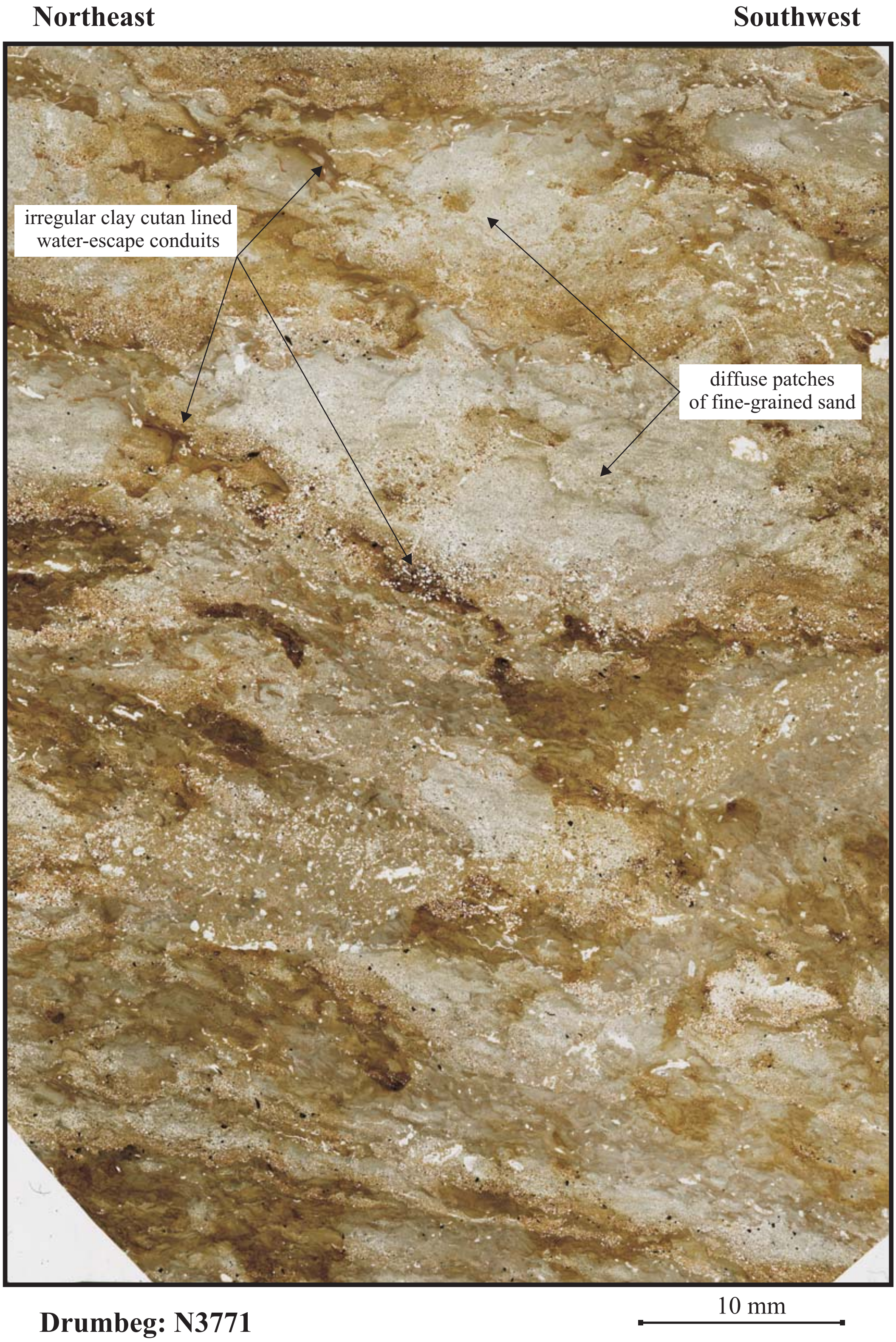

Figure 6. Highly disrupted silty clay containing lenticels of very fine-grained sand (sample N3771, Unit II)). This sample possesses a distinctive mottled appearance in thin section (see Figure 2 for location of sample).

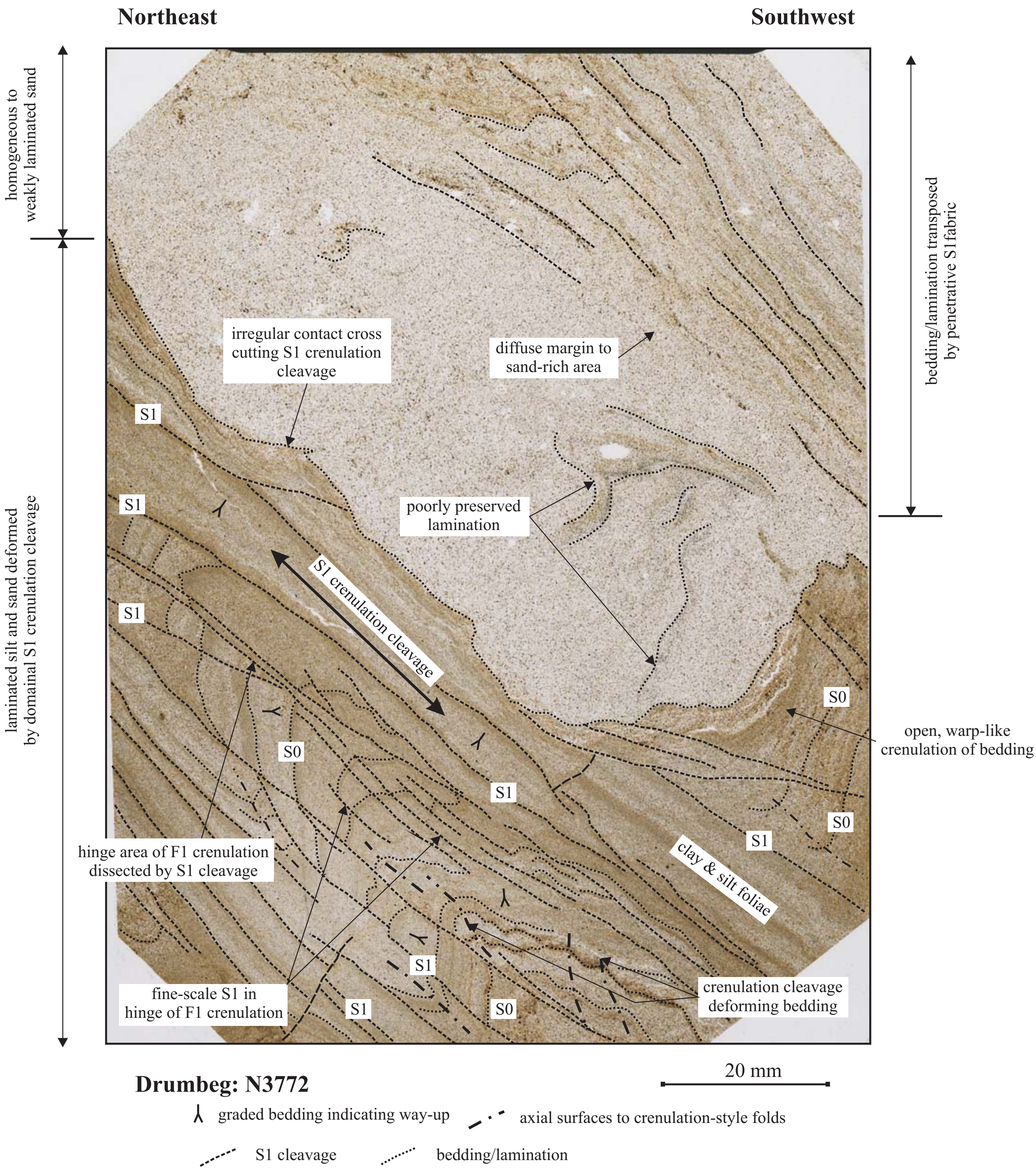

Figure 7. Laminated silt and fine-grained sand in sample N3772 (Unit I) deformed by a well-developed crenulation cleavage (S1). Bedding is locally transposed by this locally pervasive glacitectonic fabric (see Figure 2 for location of sample).

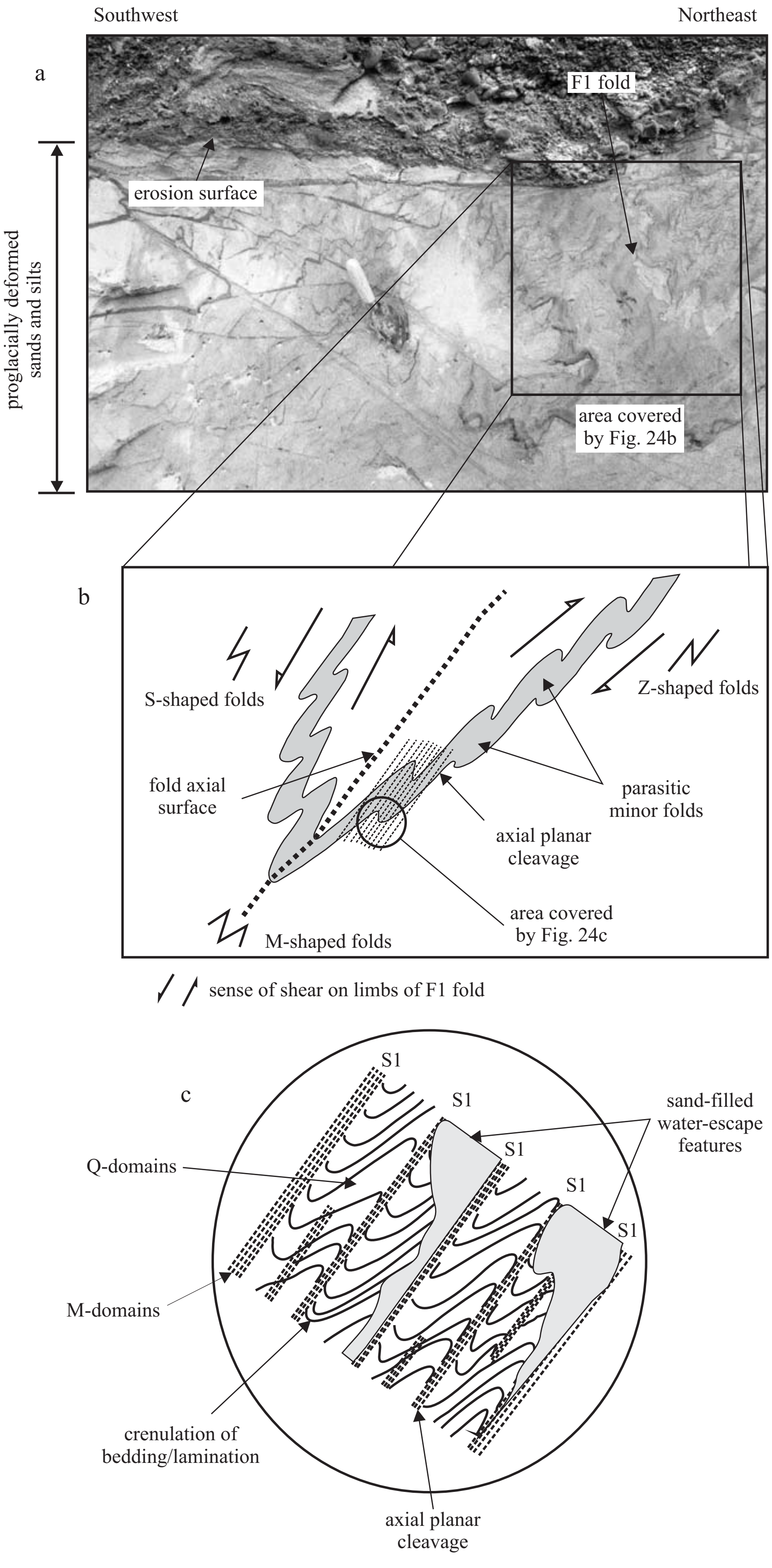

Figure 8. Diagram showing the relationship between the S1 crenulation cleavage and F1 folds developed within the proglacially deformed part (Unit I) of the ice-proximal deltaic sequence exposed at Drumbeg Quarry. (a) F1 fold deforming interbedded clay, silt and sand. The fold is deformed by a set of low-angle to sub-horizontal thrusts and moderately dipping normal faults; (b) Diagram showing the relationships between small-scale S, M and Z-shaped parasitic folds to the main F1 synform; and (c) Detail of domainal S1 crenulation cleavage developed axial planar to the F1 fold.

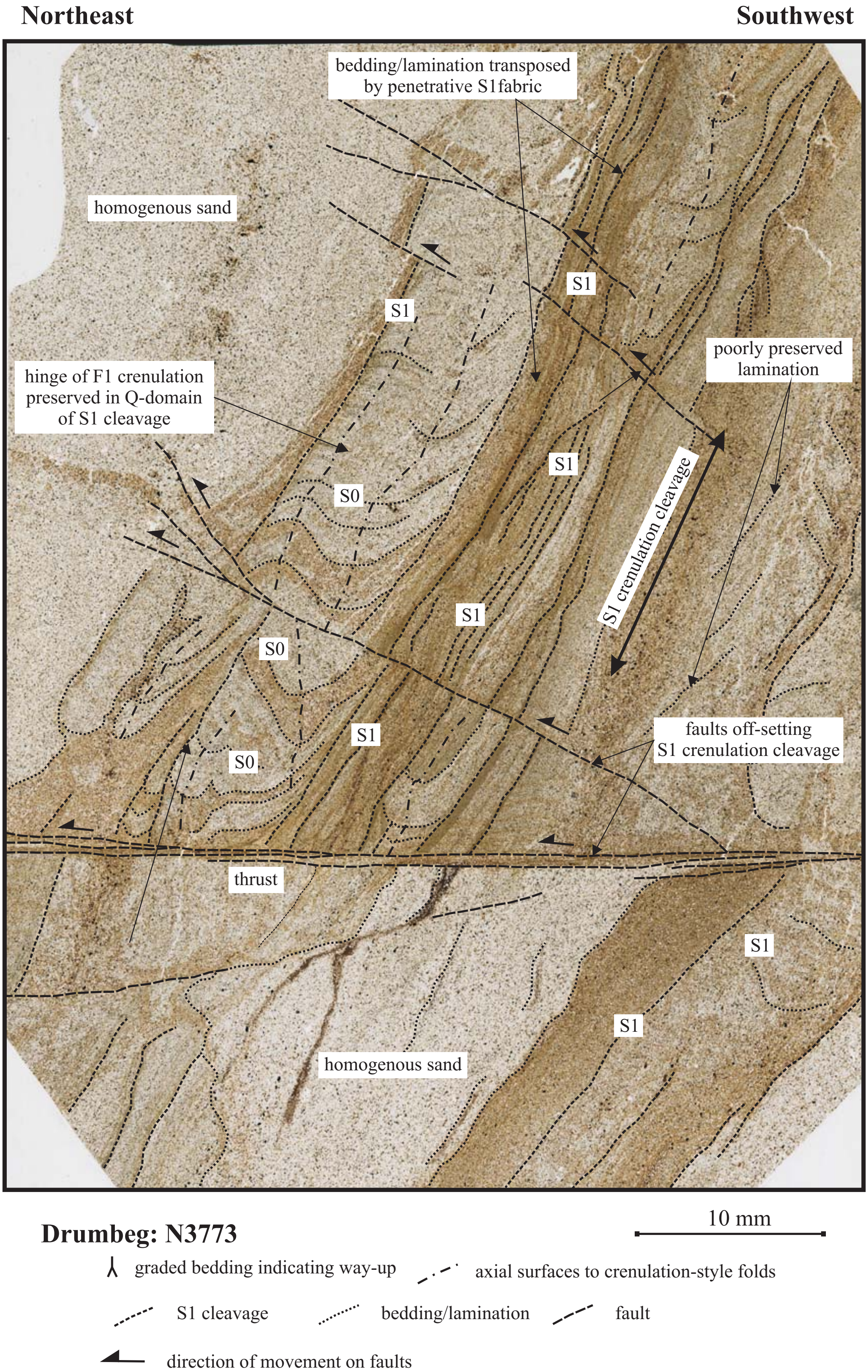

Figure 9. The well-developed crenulation cleavage (S1) and associated microfolds in sample N3773 (Unit I) are off-set by a later, northeast-directed thrust and moderately dipping reverse faults. Bedding within these finely laminated sediments is locally transposed by the S1 glacitectonic fabric (see Figure 2 for location of sample).

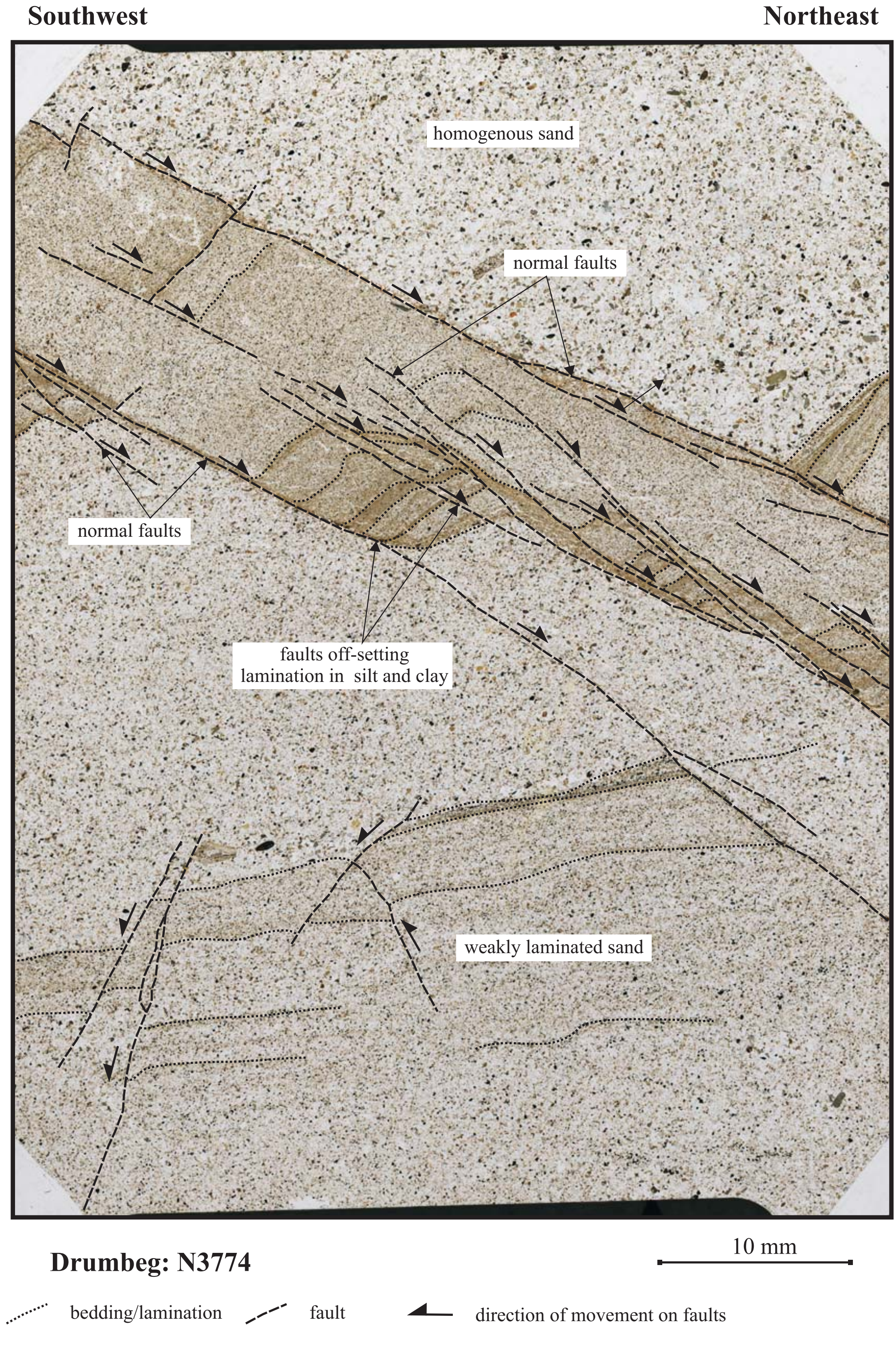

Figure 10. The massive to weakly laminated sand and silt of sample N3774 (Unit I) are deformed by a moderately northeast-dipping normal fault (see Figure 2 for location of sample).

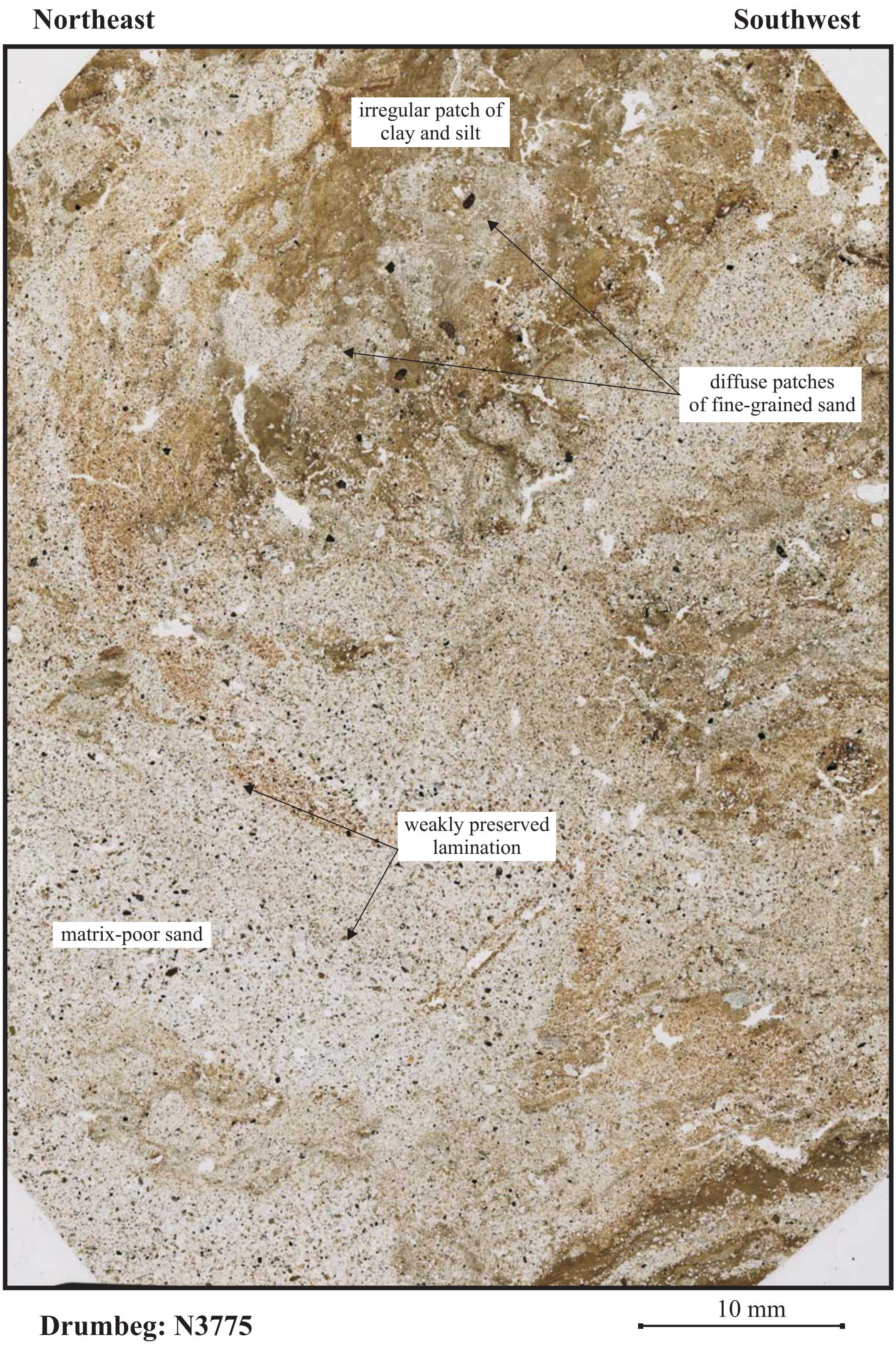

Figure 11. Highly disrupted silty clay containing thin lenses of very fine-grained sand (sample N3775, Unit II). This sample possesses a distinctive mottled appearance in thin section (see Figure 2 for location of sample).