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Sedimentology, deformation and micromorphology of the stratified diamictons exposed at Bacton Green, north Norfolk

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Sedimentology, deformation and micromorphology of the stratified diamictons exposed at Bacton Green, north Norfolk

Emrys Phillips and Jonathan R. Lee

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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
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☎ 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 the strategic Geology and Landscape South Programme. It describes the sedimentology, deformation and micromorphology of a sequence of stratified diamictons exposed at Bacton Green, North Norfolk coast. The work forms part of a multidisciplinary Quaternary Palaeogeography Landscapes (Thetford) Project.

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This report describes the sedimentology, deformation and micromorphology of the Quaternary glaciogenic sediments exposed at Bacton Green on the north Norfolk coast. The work forms part of the Quaternary Palaeogeography Landscapes (Thetford) Project of the Geology and Landscape South Programme.

The first part of the report provides the background information on the Quaternary geology of the Bacton Green area, north Norfolk. This is followed by sections describing the sedimentology, macro- and micro-scale structures of a diamicton complex at Bacton Green. The results are used to develop a model for the deposition of these stratified glacigenic sediments.

1 Introduction

This report describes the sedimentology, macro-scale deformation structures and micromorphology of a sequence of deformed sands, silts and diamictons which form part of the Pleistocene glaciogenic sequence exposed at Bacton Green on the north Norfolk coast, England (Figure 1). Micromorphology is a relatively new and, currently, still developing technique, and refers to the examination of unlithified Quaternary deposits and other glacial sediments in thin section (see van der Meer, 1987, 1993; Menzies, 2000). A total of eight large format thin sections of the stratified diamictons and intercalated, laminated sands and silts from the Bacton Green coastal section have been examined during this study.

The deposits at this site, which form a highly deformed stratified till complex, contain sedimentological and structural elements that enable their original mode of deposition and subsequent phases of deformation to be reconstructed. Developing models of deposition, and particularly their subsequent deformation history provide an invaluable insight into the range of ‘depositional’ and ‘tectonic’ features that can develop within stratified tills. This knowledge can be utilised in the future genetic interpretation of tills within the Pleistocene record – an area of research that has historically courted a high degree of ambiguity and controversy (Eyles *et al*., 1989; McCarroll and Harris, 1992; Hart and Roberts, 1994). In addition, this study contributes to the debate surrounding whether subglacial deformation occurs spatially throughout the entire subglacial bed (e.g. van der Meer *et al*., 2003; Menzies *et al*., 2006), or whether the spatial pattern of deformation resembles a ‘mosaic’ of deforming and stable areas (e.g. Piotrowski *et al*., 2004). Understanding and attempting to resolve this issue, is integral to understanding the dynamics of glaciers and ice sheets which in-turn strongly influence ice sheet models.

2 Location and Geological Context

Bacton Green (Figure 1) is located on the north Norfolk coast between Mundesley and Happisburgh. The study site is located 1.5 km north of the village adjacent to the Bacton Gas Terminal. The cliffs increase in height northwards, but are approximately 16m at the site of investigation. The geology of the cliff sections between Bacton and Mundesley was first examined by Reid (1882). More recent investigations have recognised a sequence consisting of two tills separated by sands, overlain in-turn by sands and gravels (Banham, 1966; Lunkka, 1994; Lee, 2003). Following modern stratigraphic nomenclature, these units correspond to the

Walcott Till Member (subglacial), Mundesley Sand Member (deltaic), Bacton Green Till Member and Stow Hill Sand and Gravel Member (glaciofluvial) (Lee *et al*., 2004). The whole glacial sequence overlies pre-glacial sands and muds (West, 1980) that form part of the Wroxham Crag Formation (Lee, 2003).

West and Banham (1968)	**Lunkka (1994)**	**Lee (2003), Lee *et al*. (2004)**
Gimingham Sands	Stow Hill Sands and Gravels	Stow Hill Sand and Gravel Member
Third Cromer Till	Mundesley Diamicton	Bacton Green Till Member
Mundesley Sands	Mundesley Sands	Mundesley Sand Member
Second Cromer Till	Walcott Diamicton	Walcott Till Member
		Wroxham Crag Formation
Cromer Forest Formation		Cromer Forest Formation

Table 1. Early and Middle Pleistocene stratigraphy at Bacton Green, north Norfolk.

The focus of this research is on the Bacton Green Till Member of the Sheringham Cliffs Formation (Lee *et al*., 2004). Bacton Green represents the most southern and eastern outcrop of the till, and from here it can be traced northwards through coastal sections to Weybourne via Trimingham, Overstrand, and West Runton. Inland, the Sheringham Cliffs Formation has been mapped extensively across northern Norfolk on Cromer (131), Aylsham (147) and Wells-Next-The-Sea (130) 1:50,000 geological map sheets.

The primary origin of the till is thought by many to be subglacial (Banham, 1988; Hart, 1987; Hart and Boulton, 1991a; Hart and Roberts, 1994; Roberts and Hart, 1994), being deposited by grounded Scandinavian ice entering north Norfolk from the area of the North Sea Basin (Banham, 1988; Ehlers and Gibbard, 1991). Alternative genetic interpretations have been presented by several other authors including Eyles *et al*. (1989) who suggested that the till throughout Norfolk was subaqueous in origin, and Lunkka (1994) and Lee (2003) who argued that it was subaqueous in places.

Detailed examination of the provenance of the till reveals that it is not Scandinavian as previously considered, but was deposited by British ice flowing down the east coast of England from central Scotland (Lee, 2003 and references therein). This interpretation is based upon the presence of key diagnostic lithologies such as Magnesian Limestone and Carboniferous coal that crop out extensively in northern Britain.

3 Primary mode of deposition

The Bacton Green Till crops out at beach level in the vicinity of the study site and the base of the lithofacies is obscured by modern beach material. Five hundred metres northwest of the study site, the base of the till rises northwards above the level of the foreshore, exposing beneath it, a thick sequence of stratified silty sand. The contact between the two units is typically gradational comprising alternate beds of diamicton and rippled sand. Elsewhere, the contact between the two units is sharp and planar with flame and convolute structures commonly developed within the upper horizons of the sand.

The till consists of a complex sequence of diamicton interbedded with silty sand and sand. Deformation along the length of the section is laterally variable, with in places, the diamicton and sorted sediments being intensely folded and faulted, whereas in others, the level of deformation is minimal and the primary sedimentary features are still observable. The sedimentary description detailed below is based upon data collected from the undeformed parts of the section. The styles and significance of the deformation structures are discussed below.

The basal seven metres of Bacton Green Till within the sections are composed of alternate beds of diamicton and silty sand and sand. Beds of clast-poor diamicton are matrix-supported, dark olive-brown (2.5Y 3/3) to dark grey (5Y 4/1), containing only rare clasts of flint, vein quartz and shell debris. Typically they are highly consolidated and massive in structure, although thin horizontal stringers of graded sand are locally present. Intervening beds of sand can often be traced laterally for several tens of metres into zones of deformation, and range in thickness from thick laminae (< 1 cm) to sets of sand, silty sand and poorly sorted clayey sand ranging between 8 and 40 cm thick. Individual sets of sand are often massive, but both normal and reversed graded bedding are preserved within the more poorly sorted sands. The lower boundary of the sands with the underlying diamicton is typically sharp and sub-horizontal. Rare, small rounded intraclasts of diamicton occur just above this junction. The top four metres of the till consists of a contorted mélange of diamicton, identical to that described above, with thin beds of sands and large pods of sand and sandy gravel. The highly deformed nature means that primary sedimentary features are either poorly preserved or absent.

The association of sedimentary features within this till point to a complex primary mode of formation. The highly consolidated and massive beds of diamicton containing a mixture of local and far-travelled materials are typical of materials mixed together and homogenised subglacially. The thin sandy stringers present within the beds of diamicton have been interpreted as lenses of sand incorporated locally and progressively attenuated during shearing (Hart and Roberts, 1994). However, the presence of graded bedding implies that these lenses are sedimentary rather than tectonic features. An alternative mechanism for the formation of these sandy stringers is the remobilisation and subsequent resettling of material by subaqueous traction currents (Eyles and Eyles, 1983). Such a mechanism implies that the beds of diamicton, although originally deposited as subglacial till, were reworked subaqueously as cohesive mass flows. Lending support to this theory is the geometry and nature of the boundary between the till and underlying sands, where features diagnostic of subglacial deformation such as planes of decollement, low angle thrusts and folding are absent. Instead, the gradational and sometimes sharp but conformable nature of the boundary is more typical of a subaqueous style of sedimentation with alternate beds of diamicton and sand reflecting pulses of diamicton being introduced into a standing body of water (Eyles *et al*., 1985; Hart and Roberts, 1994). A subaqueous origin for the intra-formational sand beds is also suggested by the field characteristics. Reverse and normal graded bedding correspond to sedimentation from accelerating and waning turbidity flows. Small-scale scouring associated with the turbidity flows is indicated by the small intra-clasts of diamicton aligned in places along the base of the sandy beds.

In summary, the sedimentary features where preserved, indicate that the Bacton Green Till was deposited originally within water and represents part of a gradational continuum with the underlying Mundesley Sands reflecting an ice advance into a glaciolacustrine basin and delta. The advance of ice into this standing body of water resulted in cohesive masses of poorly sorted sediment (i.e. subglacial till) being introduced onto the delta surface and then reworked down-delta by gravitational and subaqueous processes. Sorted sand beds record the introduction of pulses of well-sorted sediment down the delta front as turbidity currents. The upwards transition within the till to a more pebbly facies probably represents the input of coarse glacial outwash into the lacustrine basin.

4 Glacitectonic deformation structures

The lower part of the section exposed at Bacton Green is shown in Figure 2. This stratified diamicton and sand sequence locally show evidence of intense deformation including recumbent to asymmetrical folds, thrusts, normal and reverse faults, as well as sand-filled hydrofractures.

4.1 RECUMBENT FOLDS

Beds of sand and diamicton are locally deformed by a number of tight to isoclinal, locally flame-like folds (Figure 3). These folds are typically developed in the hanging walls of very gently dipping to subhorizontal thrusts (Figure 3). The thrusts and limbs of the recumbent to gently inclined folds locally occur parallel to the layering developed within the remainder of the sequence. The amplitude of the recumbent folds ranges from a few tens of centimetres up to several metres. The smaller scale folds locally exhibit a marked asymmetry and verge towards the north to northwest. The limbs of the folds are highly attenuated, thinning rapidly away from the hinge. These attenuated limbs have locally undergone boudinage leading to fragmentation of the fold and the formation of isolated rootless fold structures. In contrast to the attenuated limbs, sand layers within the hinges of the folds are thicker and deformed by small-scale S, M and Z-shaped parasitic structures. Small-scale thrusts and gently to moderately dipping reverse faults are also present within the hinges of the folds.

The geometry of these highly attenuated to rootless recumbent folds is typical of structures in ductile shear zones in response to relatively high shear strains. However, the disharmonic nature of the parasitic folds associated with these larger scale structures suggests that the sediments had a relatively high pore water content (and/or pressure) at the time of deformation. This would have lowered the cohesive strength of the sediment pile allowing the formation of the isoclinal, locally rootless folds at much lower strains. The sense of displacement on the associated thrusts and reverse faults is towards the north. This coupled with the overall shape of the folds suggests that folding developed in response to northerly directed shear.

4.2 NORMAL FAULTS AND EXTENSIONAL SHEARS

At the southwestern end of the section (see Figure 2) the interlaminated sands and diamictons are deformed by a number of gently to moderately northerly dipping normal faults and associated extensional shears (Figures 3b and 4a). The shears and normal faults are closely associated (see Figure 3a) and record the same sense of offset with a downthrow towards the north to northwest. The amount of displacement on the faults ranges from c. 1 cm up to 30 cm. Minor ductile folding and drag folding occurs immediately adjacent to the normal faults. Consequently, associated shears are thought to have developed in response to, and during an ‘early’ ductile phase prior to brittle faulting.

4.3 SAND LENSES OR AUGEN

The deformed sequence at Bacton Green contains a number of symmetrical to asymmetrical, eye-shaped lenses or augen of sand (Figures 4b, 5 and 6; also see Figure 2). Similar shaped lenses of rafts of diamicton also occur within the sequence (Figure 6a). The sand lenses range from a few tens of centimetres to over 2 metres in length and are elongated parallel to the layering within the host sequence. The layering and fine-scale lamination within the host sands and diamictons clearly wraps around the sand lenses (Figure 6b) showing that they form an integral part of the sequence and were not deposited in tunnel-like features (e.g. sub-glacial channels) eroded into the sequence. The sand lenses possess distinct tails which are streaked out into the plane of the layering present within enveloping sands and diamictons. Smaller lenses or ribbons of sand detached from these tails can be traced up to several metres away from the larger sand lenses.

A number of the lenses are internally massive with the sand lacking any obvious internal structure (see Figure 6b). In other examples, the sand ranges from well-bedded to finely laminated with bedding being deformed by variably developed asymmetrical, northerly verging folds (Figure 5). These folds are enclosed within a variably developed carapace of more massive, structureless sand in which bedding has been overprinted. The hinges of the tight, gently inclined to recumbent folds, where developed, dominate the structure of the sand lens. The limbs of the fold are clearly truncated at the margins of the augen (Figure 5), which implies that these features are tectonic in origin. Associated with the main fold structures are a set of variably developed S, M and Z-shaped parasitic folds and small-scale reverse faults and thrusts. The faults are most common in the hinge area of the folds and probably developed to accommodate further shearing associated with the progressive tightening of these ductile structures. These smaller scale folds are locally disharmonic with flame-like projections extending from these folds defining a crude foliation parallel to the axial plane of the larger scale fold structure. The disharmonic nature of the folds and wispy, flame-like appearance of the axial planar foliation indicate that pore water content/pressure increased during folding resulting in localised liquefaction and remobilisation of the sandy layers.

The asymmetry of the folds, and shape of the sand lenses is consistent with them having formed in response to the same northerly directed shearing event. The folds preserved within the sands are interpreted as representing the detached, rootless hinges of originally much larger fold structures. The geometry of the original sand bodies is, however, uncertain. It is possible that the sand lenses form part of an originally laterally extensive body which was fragmented/dismembered during progressive shearing of the folds. Alternatively, the sands may have been deposited as lenticular channel-like units with the resultant augen-like shape of the sand bodies partially being inherited from the primary morphology of these clastic deposits. The morphology of the original sands, therefore, has important implications for the apparent intensity of deformation recorded by the sedimentary sequence exposed at Bacton Green. If the sands originally formed laterally extensive bodies the inferred intensity of deformation is significantly increased. During the initial stages of deformation the sands would have remained as relatively coherent units forming a series of ‘linked’ antiforms and synforms. Dismemberment of these folds would have occurred in response to continued ductile shearing, probably in response to subglacial deformation. However, this progressive change from a coherent series of folds to the observed ‘rootless’ fold structures is not preserved at Bacton Green. In the alternative model, the lenticular sand bodies simply need to be folded and do not require a prolonged period of intense ductile shear to form the observed fold geometries.

4.4 COMPOSITIONAL LAYERING

One distinctive feature of the sequence exposed at Bacton Green is the well-developed compositional layering (Figure 6b). This layering is highlighted by the pale yellow-brown, fine- to medium-grained sand which ranges from *c*. 1 cm up to 30 cm thick. These laterally extensive sands alternate with layers of a darker brown sandy diamicton, with individual layers being traceable for several metres across the section (see Figure 2). The margins of individual layers are sharp and typically highly planar, lacking any primary sedimentary features such as sole marks, load casts and/or ripples. Although some layers show a lateral variation in thickness, the majority maintain a relatively uniform thickness over several metres (Figure 6b).

Due to the locally intense deformation recorded at Bacton Green the origin and preservation of this layering is uncertain. It is possible that the layering is purely sedimentary in origin. The partitioning of deformation into discrete horizons within the sedimentary pile may have resulted in the preservation of this sedimentary layering in the essentially undeformed parts of the sequence. However, the layering occurs throughout, even wrapping around the detached, rootless folds present within the previously described lenses/augen of sand, without any obvious signs of disturbance (see Figures 3b and 5a). An alternative origin for the compositional layering is that it is tectonic and represents transposed bedding.

4.5 THRUSTS

The layering within the Bacton Green sequence is locally cut out by a number of subhorizontal to gently southerly dipping thrust faults (Figure 7a). These thrusts occur parallel to, and locally cross-cut the layering and record a northerly directed sense of displacement. Similar thrusts are also observed at the southern end of the section associated with the tight to isoclinal recumbent folds (Figure 3). The thrusts are located within the diamicton layers and clearly truncate the compositional layering present within the Bacton Green sequence. This relationship indicates that thrusting post-dates the development of this layering. Thin lenses or augen of sand locally occur within the immediate hanging walls of the thrusts (Figure 7a). These sand layers represent fragments detached from the larger sand augen.

The northerly sense of displacement recorded by the thrusts is consistent with the sense of shear obtained from the previously described folds and sand augen, indicated that all these structures developed during the same northerly directed deformation event.

4.6 ASYMMETRICAL ANGULAR FOLDS AND ASSOCIATED FAULTS

At the northern end of the section (see Figure 2) the sand layers are deformed by a number of angular, open, asymmetrical folds (Figures 7b and 8). The axial surfaces of these kink-like folds dip steeply towards the south. The folds verge towards the north and are associated with a set of moderately southerly dipping reverse faults (Figures 8a and b). The sense of displacement on these faults is towards the north with faulting typically occurring within the hinge or on the steeply inclined short limb of the folds (Figure 8b). It is likely that faulting occurred in response to brittle failure as the earlier formed folds began to tighten.

An angular box-like fold structure developed immediately adjacent to an augen of coarse-grained sand (Figure 8a) is apparently related to the kink-like folds.

4.7 SAND-FILLED HYDROFRACTURES

Sand-filled hydrofractures (Figure 9a) are only recognised within the structurally higher parts of the sequence exposed at Bacton Green. These subvertical to steeply dipping water-escape structures are filled by fine- to medium-grained sand which is similar in composition to the sand layers present elsewhere within the sequence. The hydrofractures cross-cut the stratification present within the diamicton and the large-scale recumbent fold structures indicating that this phase of liquefaction and water-escape post-dated the folding.

5 Micromorphology

Eight samples of the stratified glaciogenic sediments were collected from Bacton Green by one of the authors (J.R. Lee) whilst studying for his doctorate (PhD) at the Department of Geography, Royal Holloway, University of London (Lee, 2003). The samples were obtained using 10 cm square, aluminium Kubiena tins which were cut into the face of the exposure. The location of the samples are shown in Figure 9b. Samples BG4/E and BG4/F were taken from an elongate lens of diamicton located towards the centre of the exposed section (see Figure 2). The remaining samples were collected from different structural levels within the surrounding interlayered sand and diamicton.

5.1 ANALYTICAL TECHNIQUES

A total of 8 large format thin sections were prepared at the Department of Geography, Royal Holloway, University of London. Following removal from the exposed face, they were orientated and labelled, and double sealed in plastic bags and stored at 4°C to prevent drying-out and bacterial alteration. Samples were subsequently dried by a mixture of air-drying and acetone replacement, impregnated with a polyester resin and cut and polished into thin sections following standard procedures (Carr and Lee, 1988).

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 10 to 17) of each thin section has been used to describe the main microscopic features developed.

5.2 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 in the glossary at the end of this report.

5.3 THIN SECTION DESCRIPTIONS

Collectors Number: BG4/A. **Thin Section Number:** 2982. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** laminated silty sand.

Description: This thin section is of a laminated, matrix-rich, poorly sorted, immature, silty sand which possesses an open packed, matrix-supported texture and contains scattered very coarse-grained sand, granule to pebble sized clasts (Figure10). A parallel lamination or banding is defined by a variation in grain size and modal proportion of matrix within the sandy laminae. The individual laminae are massive with no obvious grading or any other internal sedimentary structures.

The sand laminae are clast supported with an open-packed texture. The variation in modal matrix content within the sand results in a variably developed/preserved intergranular porosity. The more silty/matrix-rich laminae exhibit a more open packing leading to a locally developed matrix-supported texture. Angular, subangular to subrounded, fine to medium sand grains possess a low to moderate sphericity. The coarser grained sand and granule sized clasts tend to be more rounded in shape. Locally these clasts are broken and represent fragments of much larger well-rounded grains. These well-rounded clasts are clearly polycyclic in origin with the textural maturity of the grains having been inherited from the source rock and/or sediment. Sand grains are mainly composed of monocrystalline quartz. Minor to accessory detrital components include polycrystalline quartz, carbonate, plagioclase, amphibole, opaque minerals, garnet, chlorite, epidote, tourmaline, zircon, perthitic K-feldspar and muscovite. Recognisable lithic clasts are composed of chert, rhyolitic rock, felsite, micritic limestone, mudstone and a very fine-grained metamorphic or igneous rock. Bioclastic debris forms a minor component within the silty sand and includes shelly fragments (molluscs, gastropods), calcispheres and microfossils including possible foraminifera and/or algae. No obvious fracturing, cataclasis, grain boundary etching or pressure solution of unstable detrital grains has been recognised within this thin section.

Collectors Number: BG4/B. **Thin Section Number:** 2983. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** very weakly laminated to massive, fine- to medium-grained sand.

Description: This thin section is of a weakly laminated to massive, poorly sorted, immature, matrix-rich, fine- to medium-grained sand (Figure 11) with an open to very open-packed, matrix supported texture. This typically fine-grained sand also contains occasional coarse to very coarse sand grade detrital grains. Detrital grains are angular, subangular to subrounded in shape with a low to moderate sphericity. Rare well-rounded sand grains are also present. The broken edges to some of these well-rounded grains suggest that the latter are polycyclic with the rounding being inherited from the source sediment or sandstone.

Clasts are mainly composed of monocrystalline quartz. Minor to accessory detrital components include shell fragments, opaque minerals, plagioclase/feldspar, epidote, carbonate, calcispheres, zircon, a very fine-grained ?metasedimentary rock, polycrystalline quartz, muscovite, , garnet, amphibole, glauconite, chlorite, biotite, oxidised mica/opaque foils, tourmaline, microcline, very fine-grained schistose to phyllitic rock. Very small ?gastropods, foraminifera/algae and possible plant fragments are also present. Rare mud/silt clasts and rounded ‘till pebbles’ which are similar in composition to the matrix of the sand.

The sand possesses a turbid, brown calcareous matrix which contains traces of a Fe oxide stain. Lithic clasts have also locally undergone minor alteration to, or staining by ferric oxide. There is very little to no evidence of deformation within this sample. Although clay grade, the matrix contains very little obvious clay minerals; possibly explaining the absence of plasmic fabric within this sample. The absence of deformation and fragmentation of delicate bioclasts, kinking of detrital micas or pressure solution and grain boundary etching of carbonate grains, however, all indicate very little loading and compaction of the sand. In contrast the apparent clustering and crude circular arrangements of the larger sand grains suggests that some ‘rotational’ movement or deformation has occurred.

An early, dark coloured, clay-grade rim cement is variably developed on detrital grains with the sand possessing a patchily developed/preserved intergranular porosity.

Collectors Number: BG4/C. **Thin Section Number:** 2984. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** laminated fine- to medium-grained sand in which the lamination is offset by two normal (extensional) faults.

Description: This thin section is of a laminated, immature, matrix-rich, fine- to medium-grained sand (Figure 11) with an open-packed, clast- to matrix-supported texture. Scattered very coarse-grained sand, granule and small pebble sized clasts also occur within this typically fine-grained sediment. The lamination is defined by the variation in grain size, modal proportion of matrix and colour of this clay-grade component. This apparently primary sedimentary lamination is offset by two, moderately inclined normal (extensional) faults (Figure 12).

Sand grains are angular, subangular to occasionally rounded in shape with a typically low to moderate sphericity. Occasional well-rounded grains may represent included wind-blown clasts. Alternatively, such grains may be polycyclic with the grain shape being inherited from the source sediment or rock. These sand-grade clasts are mainly composed of monocrystalline quartz. Minor to accessory detrital components include plagioclase, opaque minerals, carbonate, polycrystalline quartz, amphibole, calcispheres, glauconite, chlorite, muscovite, microcline, biotite, epidote, garnet, oxidised mica, apatite, possible staurolite and possible kyanite. Minor to trace bioclastic debris includes shell fragments, foraminifera, algae and small gastropod fragments. Lithic clasts are a minor component within the sand and are composed of a very fine-grained volcanic/igneous rock, siliceous rock/chert, micritic mud (similar in composition to the matrix), silt, haematised ?basaltic rock, radiolarian chert and chalcedony. Mud and silt clasts are embayed against neighbouring more rigid quartzose grains.

The clay-grade to micritic calcareous matrix forms irregular rims and coatings upon detrital grains. A silt cap was noted on one coarse-grained clast only. Silt caps are typically equated with the migration of pore water through a porous, permeable sediment after deposition. No obvious clay minerals have been recognised within the matrix. The darker, more matrix-rich laminae possess a distinctive matrix-supported texture. A number of the sand laminae, however, are clean and lack any obvious matrix component. Apart from the lamination, no other sedimentary structures (for example grading, cross lamination) have been recognised within this sandy sediment. Elongate detrital grains are variably shape aligned parallel to the lamination.

The most distinctive feature of this sample is the presence of two, moderately inclined faults which offset the earlier formed lamination (Figure 12). The laminae adjacent to the faults are attenuated and have undergone localised drag folding. The geometry of these drag folds and correlation of relatively distinct marker laminae across the faults indicates a normal/extensional offset. No obvious crushing of grains adjacent to the fault planes has been recognised. Movement along the faults appears to have simply resulted in the passive rotation of elongate clasts into alignment along the plane of the fault. Individual fault planes are lines by either clay grade material or clean, matrix-poor sand. The latter appears to have been derived by the dragging of sand laminae in the adjacent walls into these faults during extensional movement. Such movement would have created space along the fault plane to accommodate this material. Individual faults are composed of several discrete planes. The structurally lower of the two faults (Figure 12) is more diffuse in nature and marked by a 5 to 8 mm-wide zone of deformation.

Collectors Number: BG4/D. **Thin Section Number:** 2985. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** massive fine- to medium-grained sand.

Description: This thin section is of a massive, poorly sorted, immature, matrix-rich, fine- to medium-grained sand (Figure 13) with an open to very open-packed texture. The packing of the sand is variable and lacks any obvious signs of compaction, such as the kinking of detrital micas or fragmentation of delicate bioclasts. This typically fine-grained sand also contains scattered coarse-grained sand to granule sized clasts.

Sand grains are angular, subangular, subrounded to occasionally rounded in shape with a typically low sphericity. The well-rounded grains are locally broken and represent fragments of much larger grains. The texturally variable sand grains are mainly composed of monocrystalline quartz. Minor to accessory detrital components include polycrystalline quartz, muscovite, biotite, opaque minerals, chlorite, carbonate, glauconitic material, epidote, plagioclase, amphibole, zircon, sericitised feldspar, foraminifera/small gastropod fragments, algae, calcispheres and garnet. Lithic clasts are a very minor component within the sand and are composed of felsite/recrystallised chert, haematitic mudstone/ironstone and a very fine-grained pilotaxitic igneous rock.

The matrix of the sand is a turbid, brown colour and is composed of a clay-grade material and micritic carbonate, but apparently lacks clay minerals. Clustering and crude arcuate grain arrangements of the coarser grained clasts have been noted, otherwise the sand is undeformed. A slightly paler coloured subvertical, branching feature has been noted towards the left hand side of the thin section. The origin of this feature if uncertain, but it may represent some form of water-escape feature/conduit.

Collectors Number: BG4/E. **Thin Section Number:** 2987. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** weakly laminated silty sand (diamicton).

Description: This thin section is of a disturbed, weakly laminated silty sand (diamicton) (Figure 14) containing scattered coarse-grained sand, granule to small pebble sized clasts. The sediment possesses a distinctive mottled appearance in thin section and is cut by an irregular veinlet of fine- to coarse-grained, matrix-poor sand (Figure 14). The sand within this vein is compositionally similar to the sandy laminae within the host sediment.

The lamination present within this silty sand is diffuse in nature (see Figure 14) and has been variably disrupted and overprinted during deformation and apparently associated liquefaction and remobilisation of the sediment. The lamination, where present, is defined by the variation in grain size and modal proportion of a silt- to clay-grade, grey-brown matrix. Although relatively sharp at very low magnification, in detail the sand laminae appear to grade into the adjacent silts. This gradation is recorded by an increase in the modal proportion of matrix within the sand, rather than an overall decrease in grain size of the sand laminae. Although clay-grade, this matrix is carbonate-rich (micritic) and lacking in clay minerals. Rare dolomite rhombs (?diagenetic in origin) have been noted within the matrix. The absence of clay minerals may explain the lack of plasmic fabrics within the matrix to this deformed sandy sediment.

The sand laminae are clast supported with an open-packed texture. The variation in modal matrix content within the sand results in a variably developed/preserved intergranular porosity. The more silty/matrix-rich laminae exhibit a more open packing leading to a locally developed matrix-supported texture. Angular, subangular to rarely rounded sand grains possess a low to occasionally moderate sphericity. These clasts are enclosed within a variably developed cryptocrystalline to micritic carbonate rim, forming an apparently ‘early’ cement. the coarser grained sand and granule sized clasts tend to be more rounded in shape and locally represent broken fragments of much larger well-rounded grains. Sand grains are mainly composed of monocrystalline quartz. Minor to accessory detrital components include carbonate, plagioclase, amphibole, opaque minerals, garnet, kyanite, epidote, polycrystalline quartz, zoisite/clinozoisite, tourmaline, zircon, microcline and muscovite. Recognisable lithic clasts are composed of chert, rhyolite, felsite, micritic limestone, mudstone and a very fine-grained (originally glassy) igneous rock. Bioclastic debris forms a minor component within the silty sand and includes shelly fragments (molluscs, gastropods) and microfossils including possible foraminifera and/or algae. No obvious fracturing, cataclasis, grain boundary etching or pressure solution of unstable detrital grains has been recognised within this thin section.

In the lower right-hand part of the thin section, the fine-scale lamination is distorted around an elongate lithic clast (Figure 14). The geometry of this distorted lamination records a possible sinistral (anticlockwise) sense of rotation of the included lithic fragment. In the same area of the thin section, the larger elongate, detrital grains exhibit a variably developed preferred shape alignment with their long axes occurring at a moderate to high angle to the preserved lamination. This preferred grain alignment has not been recognised within the finer grained clasts.

Elsewhere within the thin section the lamination is off-set by a number of subhorizontal to moderately dipping faults (Figure 14). In detail, the individual fault planes are poorly defined to diffuse in nature and are defined by a narrow zone of shear in which the individual laminae are highly attenuated. Three types of fault have been recognised: **(1)** normal (extensional) faults dipping at approximately 30° to 40°; **(2)** moderate to gently inclined reverse faults dipping at approximately 25° to 35°; and **(3)** a set of low-angle to subhorizontal thrusts (Figure 13). No cross-cutting relationships have been identified between the fault sets, consequently the relative age relationships between these structures is uncertain. However, the sense of displacement (sinistral) on all of these faults is consistent with them having formed during the same deformation event. The normal and reverse faults possibly formed as Reidel shears and developed during the same deformation event which resulted in thrusting. The sinistral sense of off-set displayed by the faults is comparable with the sense of rotation recorded by the small pebble sized clasts present in the lower part of the thin section. All three fault sets are cut by the irregular veinlet of clean sand, indicating that liquefaction, remobilisation and injection of this matrix-poor sand post-dated faulting.

In the upper right-hand to central part of the thin section the lamination is deformed by a number of recumbent to gently inclined, tight, asymmetrical folds (Figure 14). Small-scale parasitic structures associated with these folds are disharmonic indicative of a high pore water content and/or pressure during deformation; a conclusion supported by the diffuse nature of the lamination in this area. The lamination on the limbs of the folds is locally highly attenuated and disrupted. The folds are dissected by the thrusts and normal faults indicating that ductile folding occurred prior to faulting.

Collectors Number: BG4/F. **Thin Section Number:** 2988. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** weakly laminated, folded and faulted, fine- to medium-grained sand (diamicton).

Description: This thin section is of a deformed (folded and faulted), weakly laminated, poorly sorted, immature, fine- to medium-grained sand (diamicton) (Figure 15). The weakly developed or preserved lamination is defined by both a variation in grain size and the modal proportion of matrix. The matrix-rich laminae possess an open packed matrix-supported texture resulting in a highly 'dilated' appearance to the sediment. In contrast, the matrix-poor laminae are more closely packed with a clast-supported texture, with a locally developed/preserved intergranular porosity. The turbid, brown coloured, clay grade to micritic carbonate-rich matrix has a low clay content, resulting in the general absence of a plasmic fabric(s). However, traces of a very weakly developed fabric wrapping the larger detrital grains has locally been recognised within the matrix. A crude skelsepic to turbate-like fabric has also been recognised enclosing some detrital grains.

Detrital grains are angular, subangular to occasionally subrounded in shape with a low sphericity. Occasional well-rounded grains are probably polycyclic in origin with the shape of the clasts being inherited from the source sediment or rock. The largely texturally immature clasts are mainly composed of monocrystalline quartz. The typically fine- to medium-grained sand also contains scattered coarse- to very coarse-sand grade clasts. Minor to accessory detrital components polycrystalline quartz, plagioclase, chlorite, opaque minerals, muscovite, epidote, amphibole, carbonate, zircon, glauconite, calcispheres, polycrystalline carbonate, zoisite/clinozoisite, foraminifera or small gastropod tests, garnet, ?pyroxene, shell fragments, apatite, microcline and tourmaline. Bioclastic debris is a less common accessory component within this sample. Lithic clasts also form a minor to accessory component in the detrital assemblage and include a very fine-grained basaltic rock, very fine-grained volcanic rock and chalcedony.

The lamination is deformed by a number of open to tight, inclined to recumbent, disharmonic folds and smaller scale parasitic structures. These folds are most clearly developed within the upper right hand part of the thin section (Figure 15). At least three sets of faults have been recognised within this sample: **(1)** a set of subhorizontal thrusts; **(2)** a set of low-angle normal faults which appear to link into the thrusts; and **(3)** a set of gently to moderately inclined reverse faults which locally offset the earlier developed thrusts (Figure 15). All of these faults offset the lamination and fold structures indicating that faulting largely post-dated folding. The faults record a consistent sinistral sense of displacement which is comparable to the sense of asymmetry recorded by the earlier formed fold structures (Figure 15). At low magnification the fault planes are easily recognised and clearly truncate and offset the lamination. However, at higher magnifications, the individual fault planes are less distinct and marked by a narrow, diffuse zone of shear rather than a discrete planar discontinuity.

The disharmonic nature of the folds suggests that the sediment possessed a relatively high pore water content and/or pressure during at least the early stages of deformation. This was apparently followed by a fall in pore water content and/or pressure after folding had ceased allowing faulting to take place. In the centre and towards the left hand side of the thin section, the lamination is very poorly preserved and diffuse in nature. It is possible that the sand underwent localised liquefaction during folding resulting in the homogenisation of the sand and overprinting of the lamination. The cross-cutting nature of the relatively matrix-poor sand which occupies the central part of the thin section (Figure 15) may record the localised remobilisation of this liquefied sand. Although this sand vein cross-cuts and, therefore, post-dates the folding, the relationship of liquefaction to later faulting remains equivocal. However, there is no evidence of liquefied sand having been injected along any of the fault sets (see Figure 15), indicating that liquefaction pre-dated faulting possibly resulting in the rapid dewatering of the sand allowing brittle faulting to take place.

Collectors Number: BG4/G. **Thin Section Number:** 2986. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** laminated, fine- to medium-grained sand.

Description: This thin section is of a laminated, very poorly sorted, matrix-rich, immature fine- to medium-grained sand (Figure 16) with a clast- to matrix-supported texture. Although typically fine to medium-grained, the sample also contains scattered coarse-grained sand to granule sized clasts. The lamination present within the sample is defined by a variation in grain size and the modal proportion and colour of the matrix. The clay grade matrix ranges from grey-brown to red-brown and is calcareous, lacking significant proportions of clay minerals. The matrix locally forms slightly darker rims around the clasts.

Sand grains are angular, subangular, subrounded to occasionally well-round in shape with a low sphericity. The well-rounded grains are locally broken suggesting that they are polycyclic in origin. The shape of these grains may, therefore, have been inherited from the source sediment or rock. The clasts are mainly composed of monocrystalline quartz. However, minor to accessory detrital components include carbonate, polycrystalline quartz, opaque minerals, garnet, amphibole, shell fragments, algae, muscovite, calcispheres, glauconite, chlorite, epidote, zircon, tourmaline, microcline and possible plant debris. Lithic clasts are also present and include haematised mudstone/ironstone, micritic bioclastic limestone, cherts and a very fine-grained igneous/volcanic rock.

A very weakly developed foliation present within the matrix occurs parallel to the lamination. This fabric is defined by shape-aligned silt-grade detrital grains. This sample exhibits very little evidence of deformation or compaction with no obvious pressure solution of carbonate grains or kinking of detrital micas. Furthermore, complete foraminifera or small gastropods tests are present. These delicate bioclasts would have been crushed if the sample had undergone significant compaction/loading during deformation. The microfossils are locally associated with thin, ribbon-like calcareous laminae.

Collectors Number: BG3/?9. **Thin Section Number:** 2983. **Location:** [TG 335 348] Bacton Green, north Norfolk. **Lithology:** weakly laminated, fine- to medium-grained sand.

Description: This thin section is of a weakly laminated to massive, poorly sorted, immature, matrix-rich, fine- to medium-grained sand (Figure 17) with a very open-packed, clast- to matrix-supported texture. Although relatively fine-grained this sand also contains scattered coarse sand to granule sized clasts. These larger clasts are variable enclosed within a dark grey-brown rim of matrix material. The lamination, where present, is defined by the variation in the colour and proportion of matrix. The matrix is calcareous and lacks any obvious plasmic fabric. The matrix-rich laminae possess a very open packing and exhibit a matrix-supported texture.

Sand grains are angular, subangular to subrounded in shape with a low sphericity. Occasional well-rounded grains are also present. Sand grains are mainly composed of monocrystalline quartz. Minor to accessory detrital components include microcline, polycrystalline quartz, muscovite, opaque minerals, garnet, rutile, plagioclase, glauconitic material, epidote, carbonate, amphibole, calcispheres, foraminifera or small gastropod tests, algae, biotite, Mg-chlorite and shell fragments. Lithic clasts also occur as a very minor component and are composed of altered ?volcanic rock, silt/mud, micritic limestone, bioclastic micritic limestone and very fine-grained pilotaxitic volcanic rock, as well as one large (*c*. 5 mm across), rounded clast of an indurated, fine-grained sandstone.

Lenses and laminae of matrix-poor sand contain a rim or stain of Fe-oxide. A similar stain is developed along fractures (Figure 17) and probably developed as a result of oxidation during later ground water flow.

6 Deformation of the glaciogenic sequence at Bacton Green: the formation of a subglacial shear zone

The stratified sands and diamictons exposed at Bacton Green are locally intensely deformed. Deformation resulted in folding, (Figures 3, 7 and 8) thrusting (Figures 3 and 7a), normal and reverse faulting (Figures 7 and 8), as well as hydrofracturing (Figure 8a). The geometry of the various folds, thrusts and faults are consistent with these various structures having been developed during the same northerly directed shearing event (Figure 18). The style of deformation recorded by the Bacton Green sediments is more reminiscent of subglacial rather than proglacial deformation. This is supported by the consolidated nature of the diamictons, even though they represent mass flow deposits laid down in a proglacial environment.

The geometry of the highly attenuated to rootless recumbent folds is typical of structures in ductile shear zones formed as a result of relatively high shear strains. Such conditions may be developed within a subglacial shear zone (Figure 18) developed beneath overriding glacier ice (*c.f.* van der Wateren *et al*., 2000). This style of ductile deformation effects all of the glacigenic sequence exposed at Bacton Green suggesting that the postulated subglacial shear zone may have been up to *c*. 20 m thick. It is likely that shear was not uniformly distributed throughout the sequence with deformation being partitioned into discrete horizons within the large shear zone. This pattern of deformation partitioning would not have been 'fixed' with the actively deforming zones moving position within the sequence with time. The recumbent, locally flame-like folds are more commonly developed in the structurally higher parts of the sequence (see Figure 18). This is consistent with an overall increase in the intensity of deformation towards the base of the overriding glacier ice (Figure 18); as predicted by the deforming bed model (Boulton & Hindmarsh, 1987; Evans *et al*., 2006 and references therein).

The disharmonic nature of parasitic structures associated with the larger scale folds present at Bacton Green indicates that the sediments had a relatively high pore water content (and/or pressure) at the time of deformation. This may have dramatically reduced the cohesive strength of the sediment pile allowing the formation of the locally rootless folds at much lower shear strains. Micromorphological evidence supports the view that pore water content and/or pressure varied during folding. Thin sections (BG4/E; BG4/F) from a deformed lens of fine-grained sandy diamicton show that the fine-scale layering or lamination is deformed by a number of asymmetrical, gently inclined to recumbent disharmonic folds (Figures 14 and 15) which are cut by irregular veinlets (Figure 14) and patches (Figure 15) of fine- to coarse-grained sand. Cross-cutting relationships between the disharmonic folds, thrusts and later sand-filled veinlets indicate that pore water content fluctuated during deformation. The diffuse, variably disrupted nature of the stratification and disharmonic nature of the folds are consistent with an increase in pore water pressure during folding leading to localised liquefaction and remobilisation of the sediment. This was followed by a fall in pore water content, leading to an increase in the cohesive strength of the sediment enabling brittle faulting to occur. The geometry of the folds and sense of displacement on the later brittle faults indicate that they were formed in response to the same northerly directed shear event. Continued deformation would have resulted in the progressive loading of the Bacton Green sediments leading to hydrofracturing and the injection of fluidised sand-filled veins (Figure 14) and more diffuse patches (Figure 15). On a larger scale, fluctuations in pore water content in the sediment pile may have controlled the pattern of deformation partitioning within the postulated subglacial shear zone, with deformation being preferentially focused into the relatively weaker 'water-rich' parts of the sequence. Water escape from one of these zones would have resulted in an increase in the strength of the sediment and the potential 'switching' of deformation to another ('weaker') part of the sediment pile.

The lenticular augen of sand (Figures 4b, 5 and 8a), which form a distinctive feature of the deformed sequence at Bacton Green, represent the detached hinges of tight to very tight, asymmetrical folds which formed in response to northerly directed shear (Figure 18). The style of deformation recorded by these folds is typically associated with high shear strains. However, a high pore water content and/or pressure during deformation would have aided the formation of these rootless fold structures even at relatively low shear strains. Liquefaction and remobilisation of the sand during deformation would have aided the attenuation and boudinage of the fold limbs, leading to the detachment of the fold hinges.

The well-developed compositional layering (Figure 7b) present within the glacigenic sediments at Bacton Green may also owe its origins to deformation within the proposed subglacial shear zone. The laterally extensive, alternating layers of sand and diamicton typically lack any obvious sedimentary structures and show very little lateral variation in thickness (Figure 7b). This layering also wraps around the sand augen without any obvious signs of disturbance (Figures 4b and 6a). Consequently, this layering may be partially tectonic in origin, representing transposed bedding. Sedimentary structures, where preserved, would mark the low strain zones/domains within the subglacial shear zone. In thin section, however, neither the matrix-rich sand or diamicton layers exhibit a well-developed plasmic fabric, which would be expected if the layering was tectonic in origin. The mineralogy of the matrix, although clay-grade, is dominated by very fine-grained to micritic carbonate and lacking in clay minerals. The lack of clay plasma within the matrix component of both the sands and diamictons explains the lack of a plasmic fabric within these sediments. The presence of highly birefringent carbonate within these sediments would also 'mask' such fabrics if present.

The presence of angular, kink-like folds, thrusts and normal and reverse faults within the subglacial shear zone developed at Bacton Green apparently formed later in the deformation history. Field and microscopic observations show that faulting occurred at several stages during deformation. Three sets of faults have been recognised: **(1)** a set of low-angle to subhorizontal thrusts; **(2)** moderate to steeply inclined normal (extensional) faults dipping; and **(3)** moderate to gently inclined reverse faults (Figures 3, 4a, 7, 8, 12, 14 and 15). Displacement on both the normal and reverse faults, and spatially related extensional shears (Figure 4a) is consistent with these structures having developed as Reidel shears (see inset Figure 18). In general, the later structures developed within the proposed subglacial shear zone at Bacton Green are brittle in nature, consistent with a fall in pore water content during the later stages of deformation. This suggests that there was a marked change in the hydrodynamic system beneath the overriding glacier ice, allowing pore water to escape and leading to the ‘locking’ of the subglacial shear zone. During the earlier stages of the deformational history, drainage was impeded allowing the pore water pressure to rise, assisting the formation of highly ductile deformation structures within the subglacial shear zone, even at relatively low shear strains. This restricted drainage system may have resulted from the common occurrence of relatively impermeable, fine-grained diamicton layers within the sequence coupled with an impervious cap of the overriding glacier ice. Water-escape may have been partially facilitated by hydrofracturing. Sand-filled hydrofractures (Figure 9a) are present within the upper part of the sequence exposed at Bacton Green. However, such features are not widely developed suggesting that hydrofracturing was not solely responsible for the dewatering of the subglacial shear zone. Alternatively, dewatering of the sediment pile may have only began to occur during the retreat of the glacier ice and unloading of the Bacton Green sedimentary sequence.

7 Conclusions

A number of conclusions can be made regarding the primary depositional setting and subsequent deformation of the Early to Middle Pleistocene glacial sediments exposed at Bacton Green, north Norfolk:

- Sedimentary features, where preserved, indicate that the Bacton Green Till was deposited originally within water and represents part of a gradational continuum with the underlying Mundesley Sands. This gradational sequence records the advance of a glacier into a glaciolacustrine basin and delta. The advance of ice into this standing body of water resulted in the deposition of subglacial till onto the surface of the delta. This diamicton was then reworked and transported down-delta by gravitational (mass flow) and subaqueous processes. Sorted sand beds within the Bacton Green sequence record the introduction of pulses of well-sorted sediment down the delta front as turbidity currents. The upwards transition within the till to a more pebbly facies is thought to record the input of coarse glacial outwash into the lacustrine basin.

- This stratified sedimentary sequence locally shows evidence of intense deformation including recumbent to asymmetrical (locally flame-like) folds, thrusts, normal and reverse faults, as well as sand-filled hydrofractures. The geometry of the highly attenuated to rootless recumbent folds is typical of structures in ductile shear zones in response to relatively high shear strains. However, the disharmonic nature of the parasitic folds associated with these larger scale structures suggests that the sediments had a relatively high pore water content (and/or pressure) at the time of deformation.

- The geometry of the folds and sense of displacement recorded by the thrusts and various normal and reverse faults are consistent with these structures having developed in response to the same northerly directed shear event. The style of deformation recorded by the Bacton Green sediments is more reminiscent of subglacial rather than proglacial deformation. This is supported by the consolidated nature of the diamictons, even though they represent mass flow deposits laid down in a proglacial environment.

- The symmetrical to asymmetrical lenses or augen of sand present within the lower parts of the deformed sequence exposed at Bacton Green are glacitectonic, rather than sedimentary in origin. These sand lenses represent the detached hinges of larger, northerly verging asymmetrical folds. Dismemberment of these folds is thought to have occurred in response to progressive ductile shearing, with the shape of the augen recording an overall northerly directed sense of shear during this subglacial deformation event.

- The well-developed compositional layering present within the mot intensely deformed parts of the glacigenic sediments at Bacton Green is thought to be tectonic in origin, representing transposed bedding.
- Sand-filled hydrofractures have only been recognised within the structurally higher parts of the sequence exposed at Bacton Green. These water-escape structures cross-cut the stratification present within the diamicton, as well as the large-scale recumbent folds indicating that liquefaction and water-escape post-dated folding.
- In thin section the Bacton Green sediments are composed of finely laminated to massive, fine to medium-grained sand interlayered with a relatively matrix-rich, poorly sorted, silty sandy diamicton. These texturally immature sediments are mainly composed of angular to subrounded monocrystalline quartz fragments.
- The turbid, calcareous matrix to the sands and diamictons typically lacks a plasmic fabric. The absence of such fabrics in thin section may, at least in part, reflect the lack clay minerals and/or presence of carbonate within the matrix;
- Micromorphological evidence of deformation has only been recognised in three of the thin sections. In sample BG4/C the lamination is deformed by two, moderately inclined normal (extensional) faults which resulted in localised attenuation and drag folding of the laminae. Individual faults are composed of several discrete planes that are lined by either clay grade material or clean, matrix-poor sand;
- In samples BG4/E and BG4/F the sediment possesses a distinctive mottled appearance and is cut by an irregular veinlets of fine- to coarse-grained, matrix-poor sand. These sand-filled water-escape features cross-cut a number of earlier developed faults and recumbent to gently inclined, tight, asymmetrical folds which deform the lamination preserved elsewhere within the thin sections. The disharmonic nature of the folds and the diffuse nature of the lamination preserved within this sample are consistent within these sediments possessing a relatively high pore water content and/or pressure during deformation;
- The geometry of the highly attenuated to rootless recumbent folds is typical of structures in ductile shear zones formed as a result of relatively high shear strains. Such conditions may be developed within a subglacial shear zone developed beneath overriding glacier ice (*c.f.* van der Wateren *et al*., 2000). This style of deformation effects all of the glacigenic sequence exposed at Bacton Green indicating that the proposed subglacial shear zone may have been up to *c*. 20 m thick;
- It is likely that shear was heterogeneous with deformation being partitioned into discrete horizons within the larger scale shear zone. The recumbent, locally flame-like folds are more commonly developed in the structurally higher parts of the sequence; consistent with an overall increase in the intensity of deformation towards the base of the overriding glacier ice. The disharmonic to flame-like nature of the folds coupled with the macro- and microstructural evidence for liquefaction and water-escape indicate that the Bacton Green sediments possessed a relatively high pore water content at the time of deformation. This may have dramatically reduced the cohesive strength of the sediment pile allowing the formation of structures typically equated with intense ductile deformation at much lower shear strains.

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 a 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.

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.

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.

ALLEY, R.B. 1989. Water-pressure coupling of sliding and bed deformation. *Journal of Glaciology*. **35,** 108-139.

BANHAM, P.H. 1988. Polyphase glaciotectonic deformation in the Contorted Drift of Norfolk. In: CROOT, D.G.(ed). *Glaciotectonics: Forms and Processes.* Balkema, Rotterdam, 27-32.

BOULTON, G.S. & HINDMARSH, R.C.A. 1987. Sediment deformation beneath glaciers: rheology and geological consequences. *Journal of Geophysical Research*. **92,** 9059-9082.

EHLERS, J. & GIBBARD, P.L. 1991. Anglian glacial deposits in Britain and the adjoining offshore regions. In: EHLERS, J., GIBBARD, P. L. & ROSE, J.(eds). *Glacial Deposits of Great Britain and Ireland*, Balkema, Rotterdam, 17-24.

EVANS, D.J.A., PHILLIPS, E.R., HIEMSTRA, J.F. & AUTON, C.A. 2006. Subglacial till: formation, sedimentary characteristics and classification. *Earth Science Reviews*. **78,** 115-176.

EYLES, C.H. & EYLES, N. 1983. Sedimentation in a large lake: a reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada. *Geology*, **11**, 146-152.

EYLES, C.H., EYLES, N. & MIALL, A.D. 1985. Models of glaciomarine sedimentation and their application to their interpretation of ancient glacial sequences. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **51**, 15-84.

EYLES, N., EYLES, C.H. & MCCABE, A.M. 1989. Sedimentation in an ice-contact subaqueous setting: the mid-Pleistocene 'North Sea Drifts' of Norfolk, U.K. *Quaternary Science Reviews*, **8**, 57-74.

HART, J.K. 1987. *The genesis of the north east Norfolk Drift*. Unpublished PhD thesis, University of East Anglia.

HART, J.K. & BOULTON, G.S. 1991a. The glacial drifts of Norfolk. In: EHLERS, J., GIBBARD, P. L. & ROSE, J. (eds). *Glacial Deposits of Great Britain and Ireland.* Balkema, Rotterdam, 233-243.

HART, J.K. & ROBERTS, D.H. 1994. Criteria to distinguish between subglacial glaciotectonic and glaciomarine deformation. I. Deformation styles and sedimentology. *Sedimentary Geology*, **91**, 191-213.

LEE, J.R. 2003. *Early and Middle Pleistocene lithostratigraphy and palaeoenvironments in northern East Anglia, UK.* Unpublished PhD Thesis, Royal Holloway University of London.

LEE J.R., BOOTH S.J., HAMBLIN R.J.O., JARROW A.M., KESSLER H., MOORLOCK B.S.P., MORIGI A.N., PALMER, A., PAWLEY S.J., RIDING J.B. & ROSE J. 2004. A new stratigraphy for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham and Cromer, East Anglia, UK. *Bulletin of the Geological Society of Norfolk*, **53**, 3-60.

LUNKKA, J.P. 1994. Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of northeast Norfolk, England. *Journal of Quaternary Science*, **9**, 209-233.

McCARROLL, D. & HARRIS, C. 1992. The glacigenic deposits of western Lleyn, north Wales: terrestrial or marine. *Journal of Quaternary Science*, **7**, 19-29.

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

MENZIES, J., VAN DER MEER, J.J.M. & ROSE, J. 2006. Till – as a glacial "tectomict", its internal architecture, and the development of a "typing" method for till differentiation. *Geomorphology*, **75**, 172-200.

PASSCHIER, C.W. & TROUW, R.A.J. 1996. *Microtectonics*. Springer.

PIOTROWSKI, J., LARSEN, N.K. & JUNGE, F.W. 2004. Soft subglacial beds: a mosaic of deforming and stable spots. *Quaternary Science Reviews*, **93**, 993-1000.

REID, C. 1882. *The Geology of the Country around Cromer*. Memoirs of the Geological Survey of England and Wales.

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. & SAARNISTO, M (editors). Geological Survey of Finland, Special Paper **3,** 77-89.

VAN DER MEER, J.J.M. & 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. & 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., MENZIES, J. & ROSE, J. 2003. Subglacial till: the deforming glacier bed. *Quaternary Science Reviews*, **22**, 1659-1685.

VAN DER MEER, J.J.M. 1993. Microscopic evidence of subglacial deformation. *Quaternary Science Reviews*. **12,** 553-587.

VAN DER MEER, J.J. M. & VEGERS, A.L.L.M. 1994. The micromorphological character of the Ballycroneen Formation (Irish Sea Till): a first assessment. *In* WARREN & CROOT (eds.) *Formation and Deformation of Glacial Deposits*. Balkema, Rotterdam. 39-49.

VAN DER WATEREN, F.M., KLUIVING, S.J. & BARTEK, L.R. 2000. Kinematic indicators of subglacial shearing. *In* MALTMAN, A.J., HUBBARD, B., HAMBREY, J.M. (eds). *Deformation of Glacial Materials*. Geological Society, London, Special Publications. **176,** 259-291.

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.

WEST, R.G. 1980. *The pre-glacial Pleistocene of the Norfolk and Suffolk coasts*. Cambridge University Press, Cambridge.

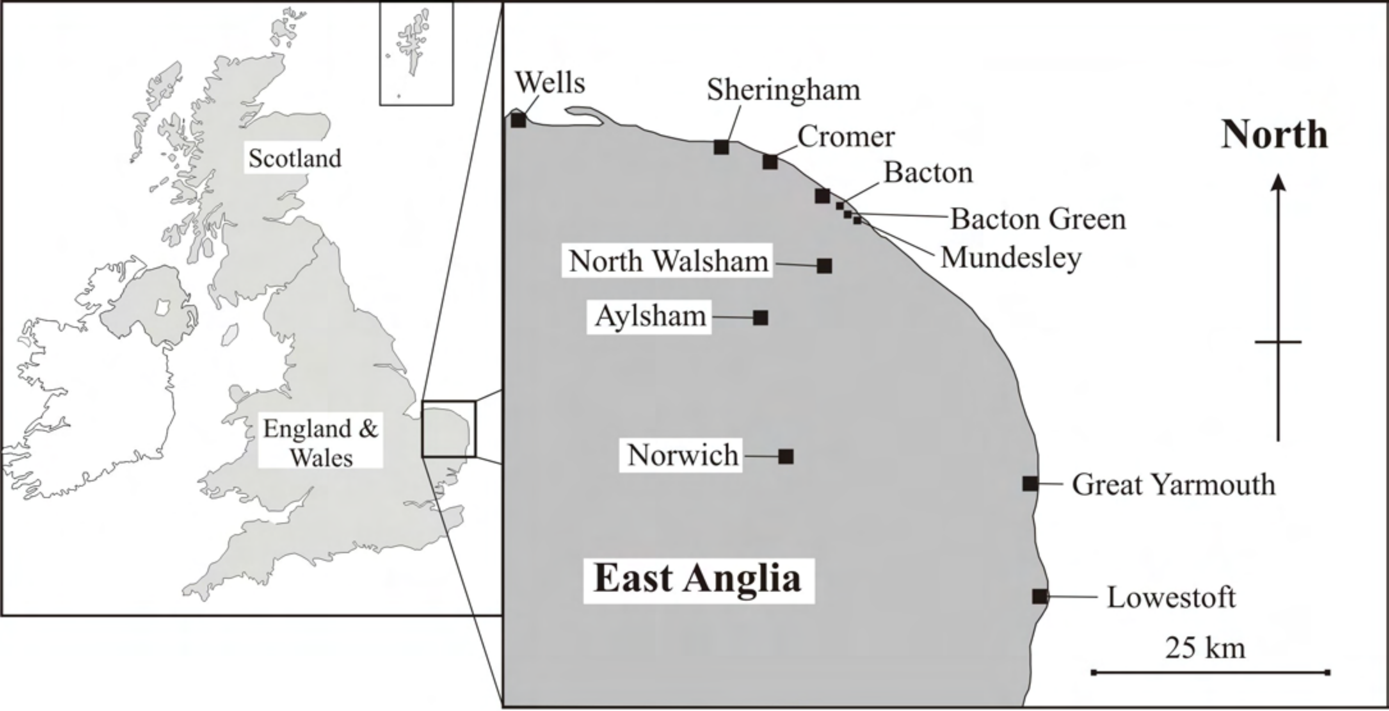

Figure 1. Map showing the location of Bacton Green, north Norfolk.

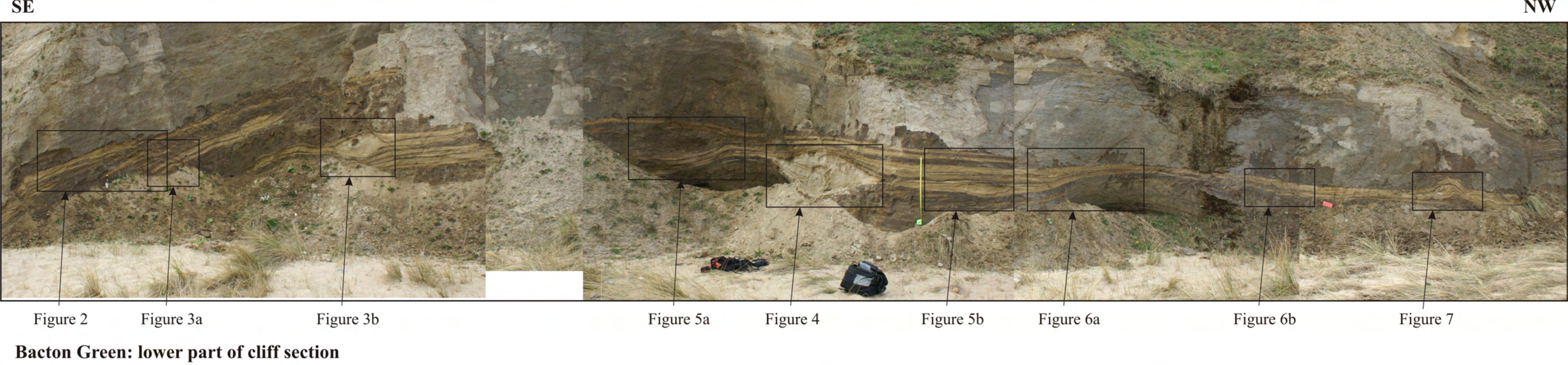

Figure 2. Photomosaic of the exposed section through the glaciogenic sequence at Bacton Green, north Norfolk. The location of the photographs in Figures 3 to 8 are also shown.

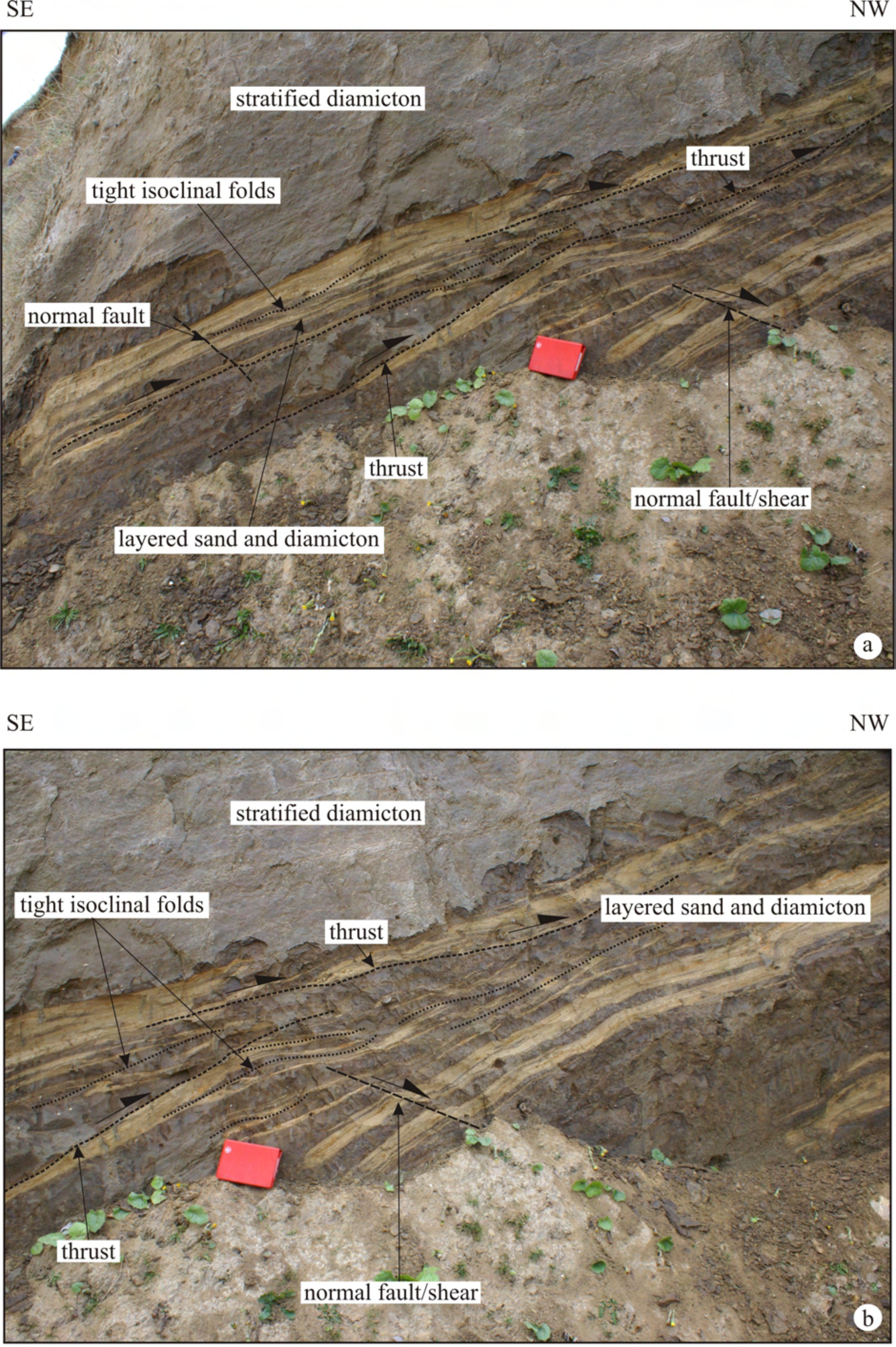

Figure 3. (a) and **(b)** Photographs showing the tight to isoclinal folding and thrusting of the sand layers exposed at the southwestern end of the Bacton Green section. Notebook is 19 cm in length.

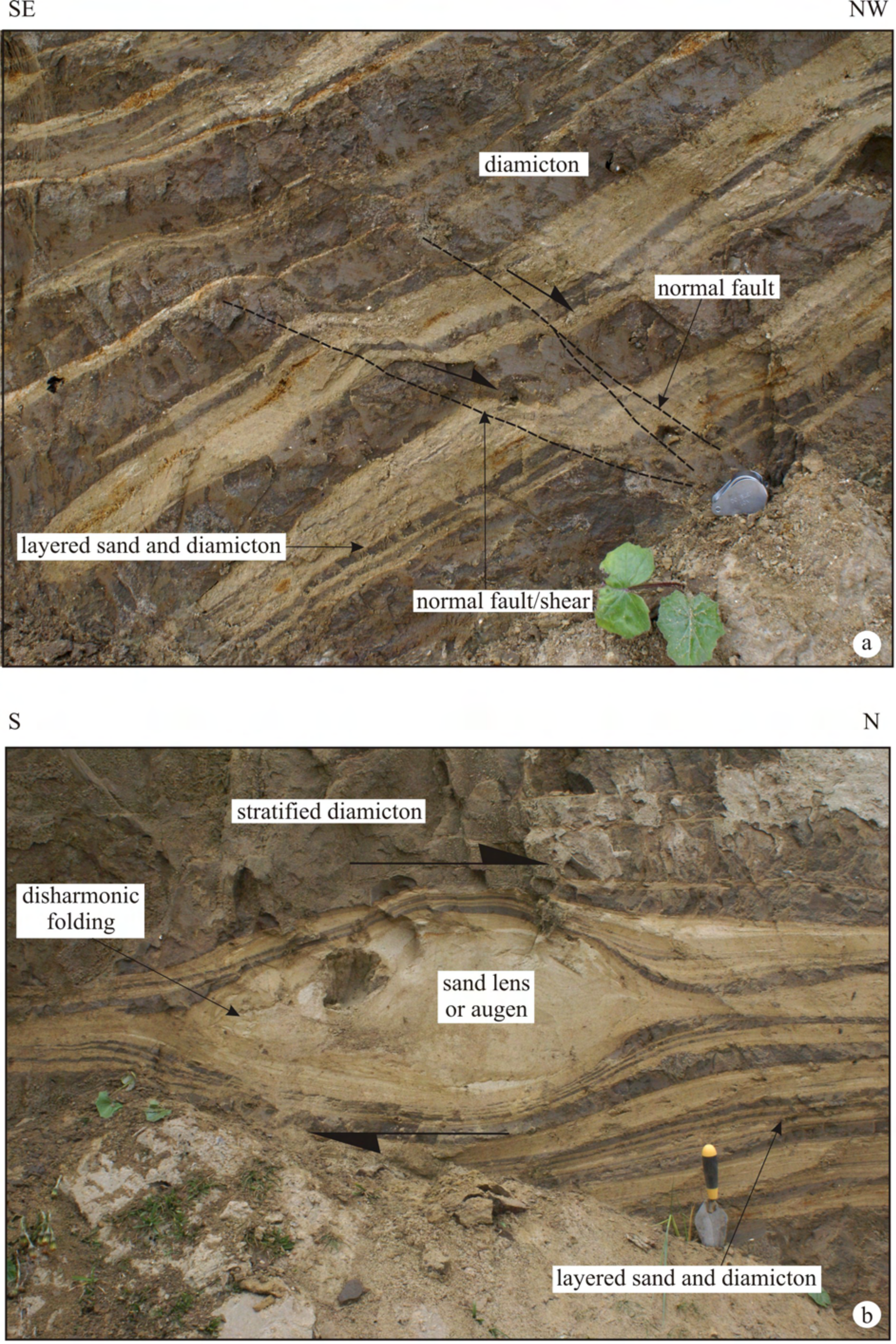

Figure 4. (a) Northerly dipping normal fault and associated extensional shear band offsetting the sand laminae. **(b)** Symmetrical to weakly asymmetrical augen or lens of massive to weakly laminated sand. The lamination, where preserved is deformed by small-scale disharmonic folds. The shape of the augen indicates a northerly directed sense of shear. Trowel is 15 cm in length.

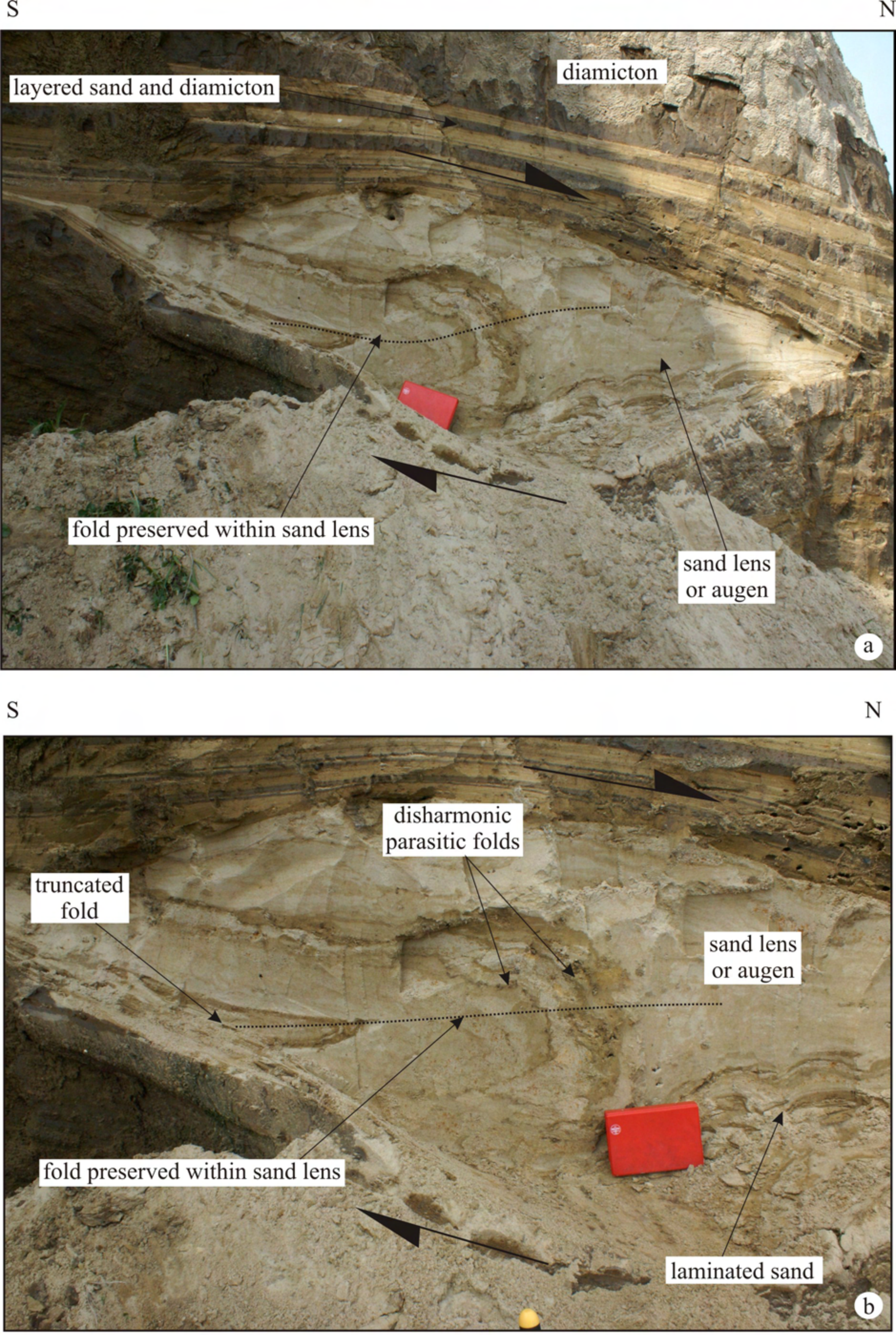

Figure 5. (a) and **(b)** Symmetrical to weakly asymmetrical augen or lens of laminated sand. The lamination is deformed by an asymmetrical, northerly verging fold which is truncated at the margins of the sand lens. The lamination in the hinge area of the fold is deformed by small-scale disharmonic, parasitic folds. The shape of the augen and asymmetry of the fold record a northerly directed sense of shear. Notebook is 19 cm in length.

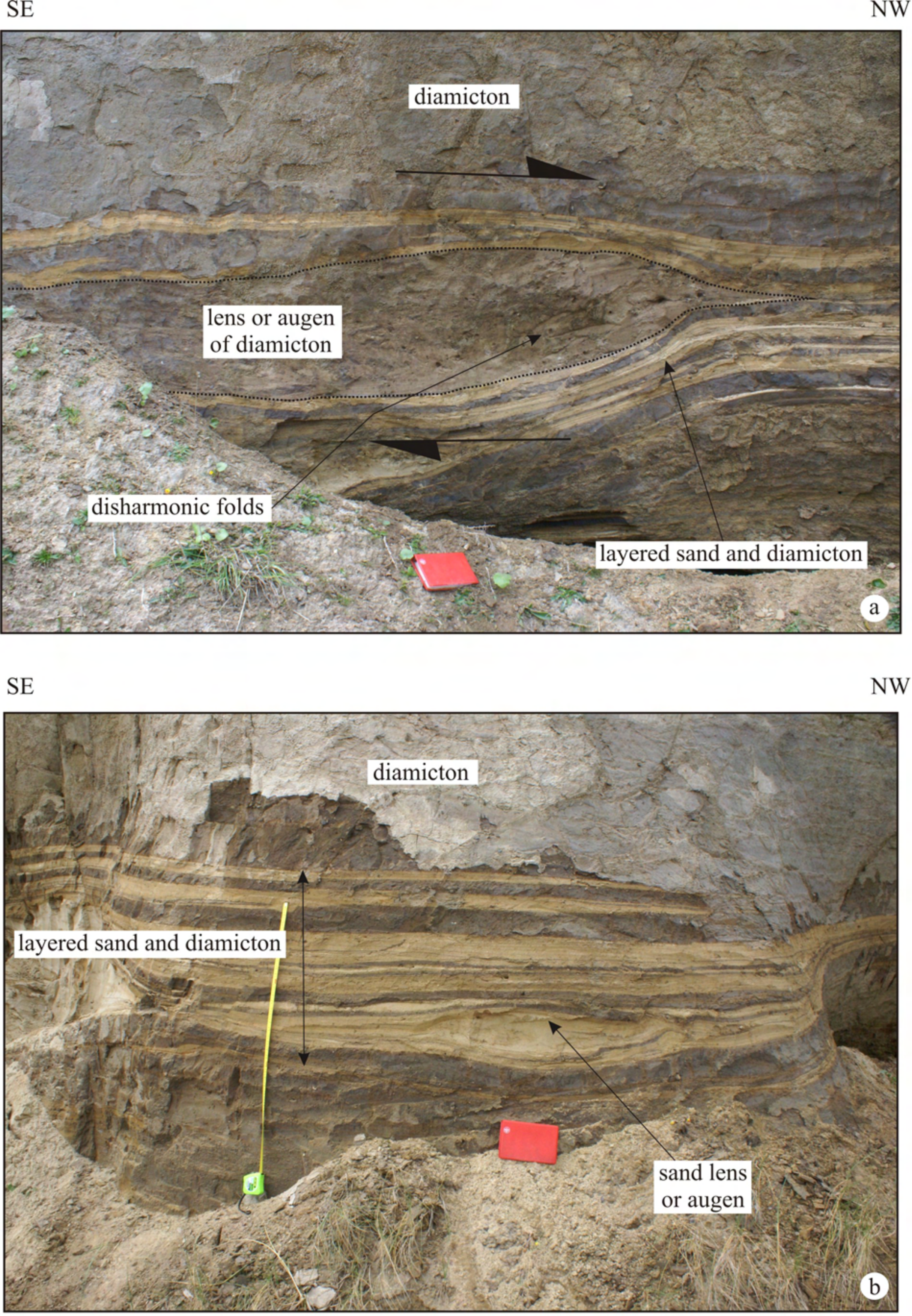

Figure 6. (a) Elongate lens or augen of weakly stratified diamicton. This raft-like lens is wrapped by the layering within the adjacent host sediments. The fine stratification or layering within the diamicton is deformed by locally complex disharmonic folds. **(b)** Well-developed compositional layering defined by alternating layers of sand and sandy diamicton. Notebook is 19 cm in length.

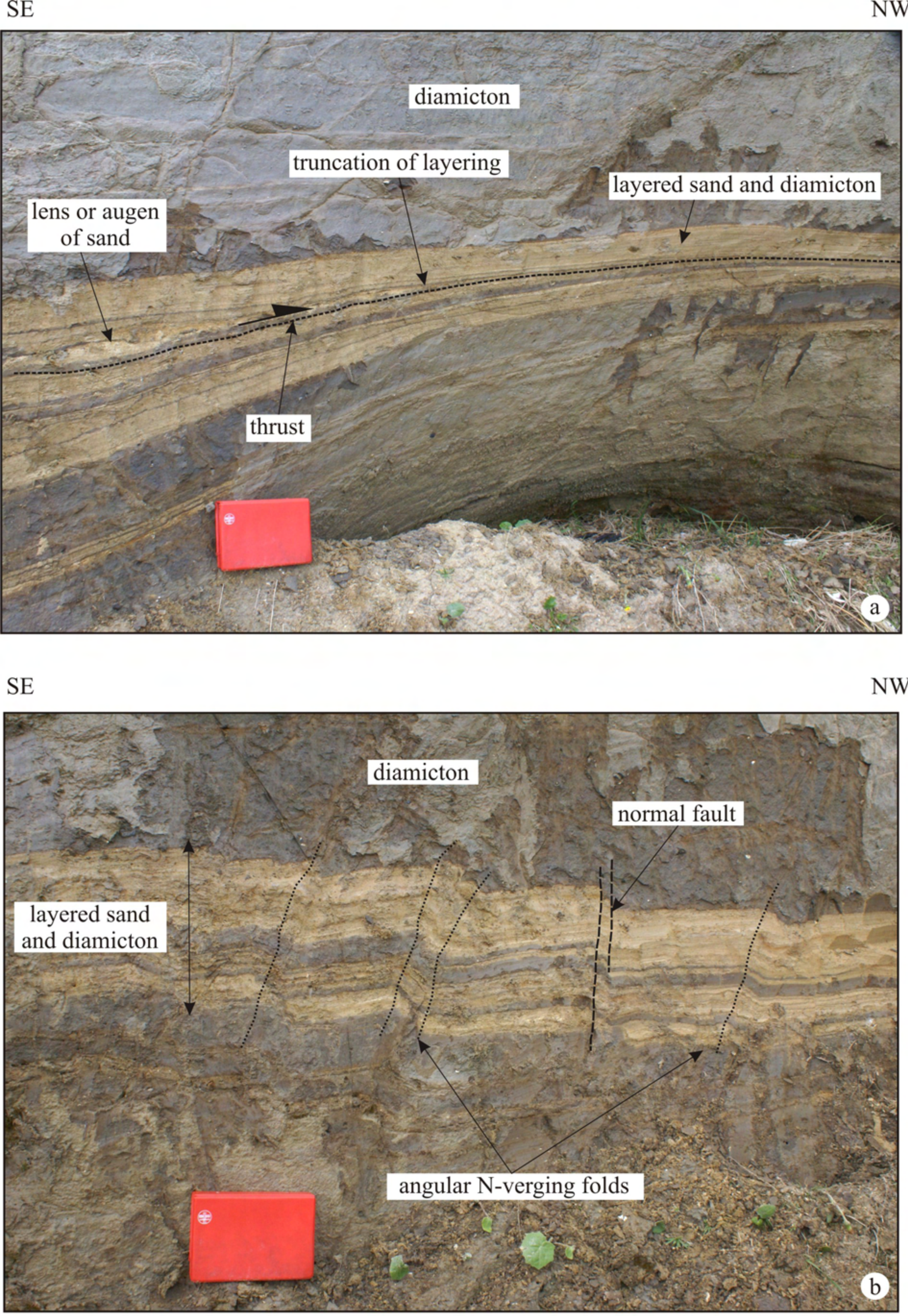

Figure 7. (a) Gently southerly dipping thrust fault deforming the thinly interlayered sand and diamicton. **(b)** Thinly layered to laminated sand and diamicton deformed by angular, steeply inclined, northerly verging kink-like folds. Notebook is 19 cm in length.

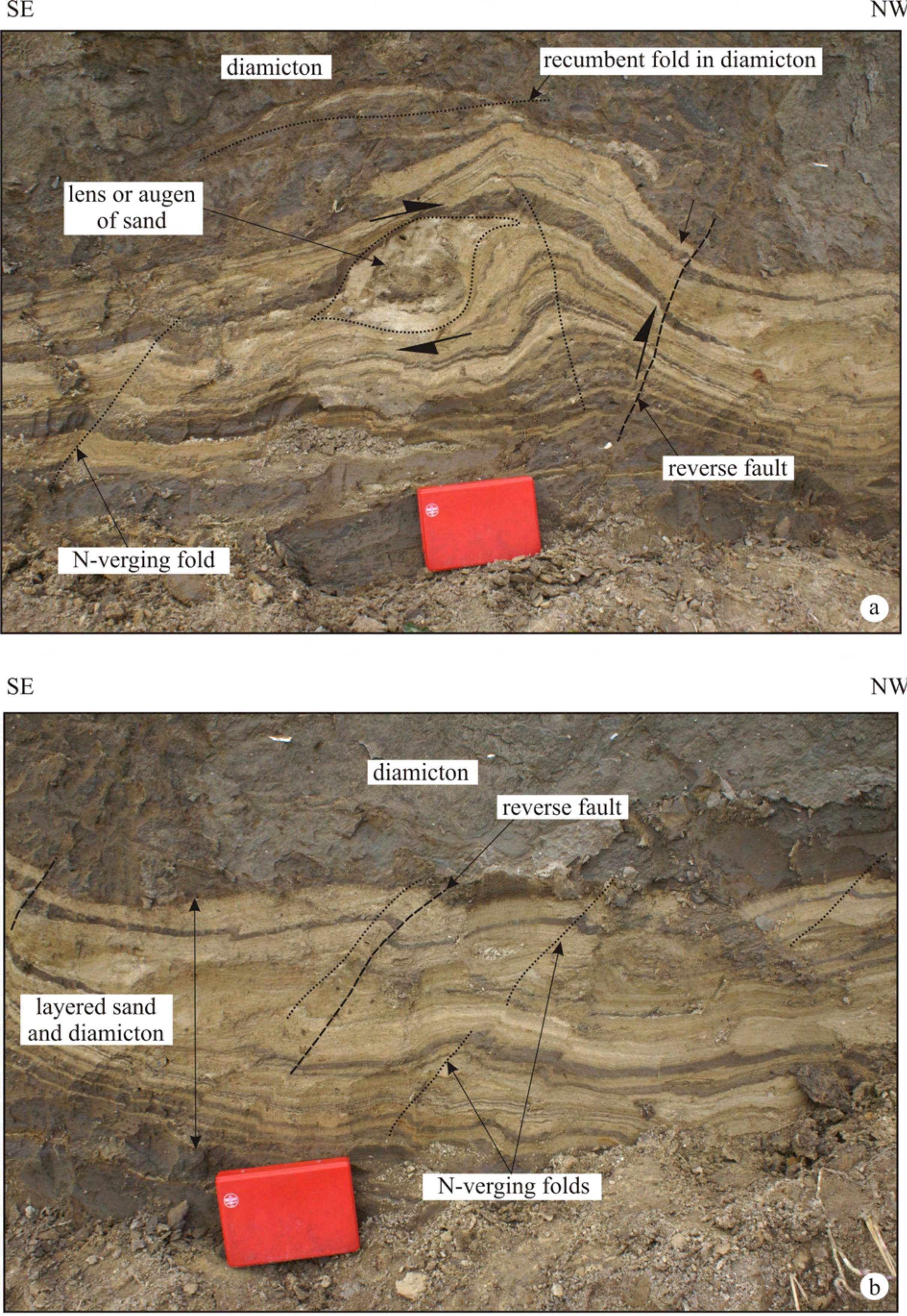

Figure 8. (a) Open, box-like fold deforming thinly layered sand and diamicton. Also present is a well developed augen of coarse sand. The shape of the augen clearly records a northerly directed sense of shear. **(b)** Thinly layered to laminated sand and diamicton deformed by angular, steeply inclined, northerly verging kink-like folds and associated reverse faults. Notebook is 19 cm in length.

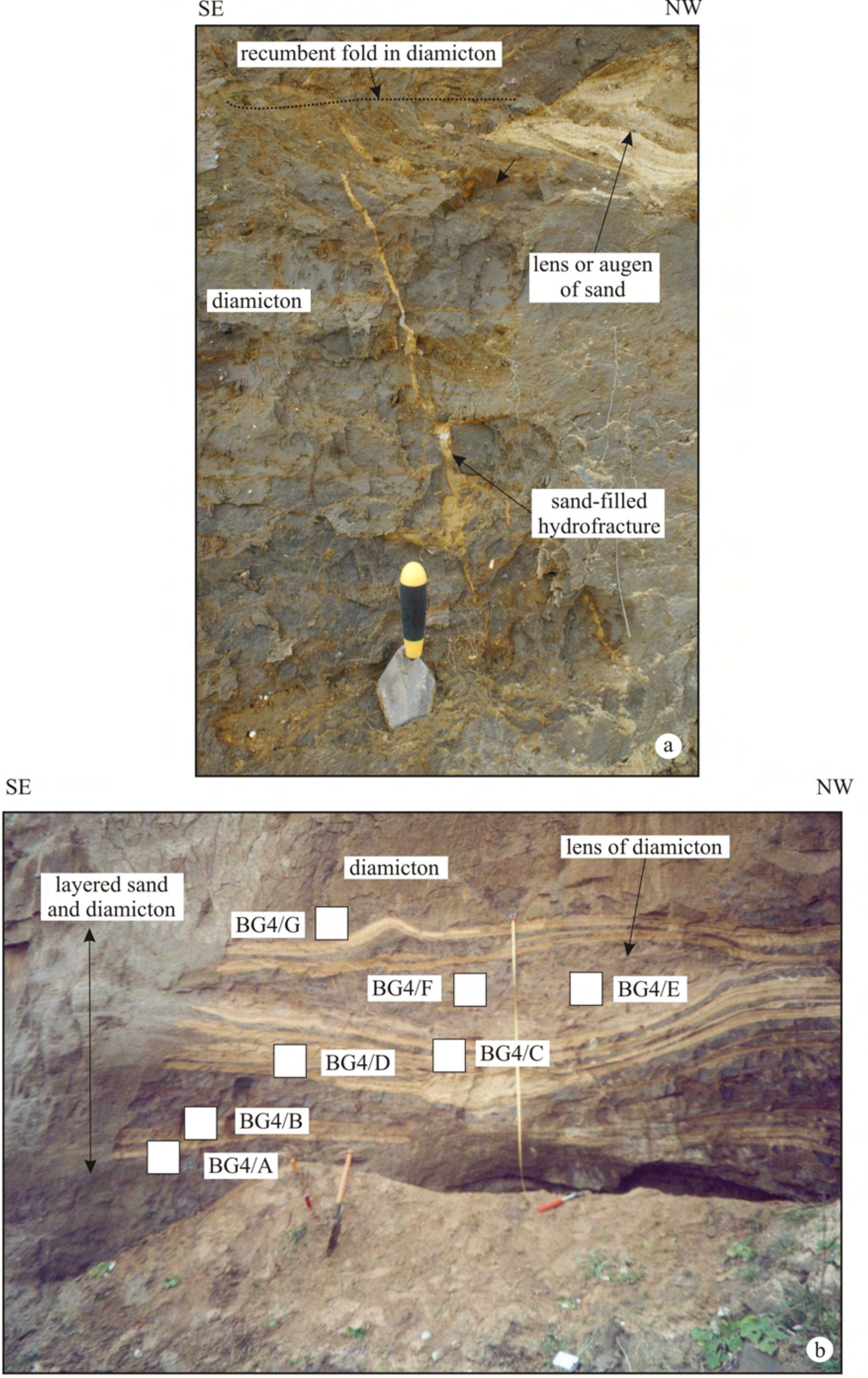

Figure 9. (a) Sand-filled hydrofracture cutting a stratified diamicton exposed at a higher structural/stratigraphic level within the Bacton Green sequence. Trowel is 15 cm in length. **(b)** Photograph of part of the section exposed at Bacton Green showing the relative position of the samples collected for micromorphological analysis.

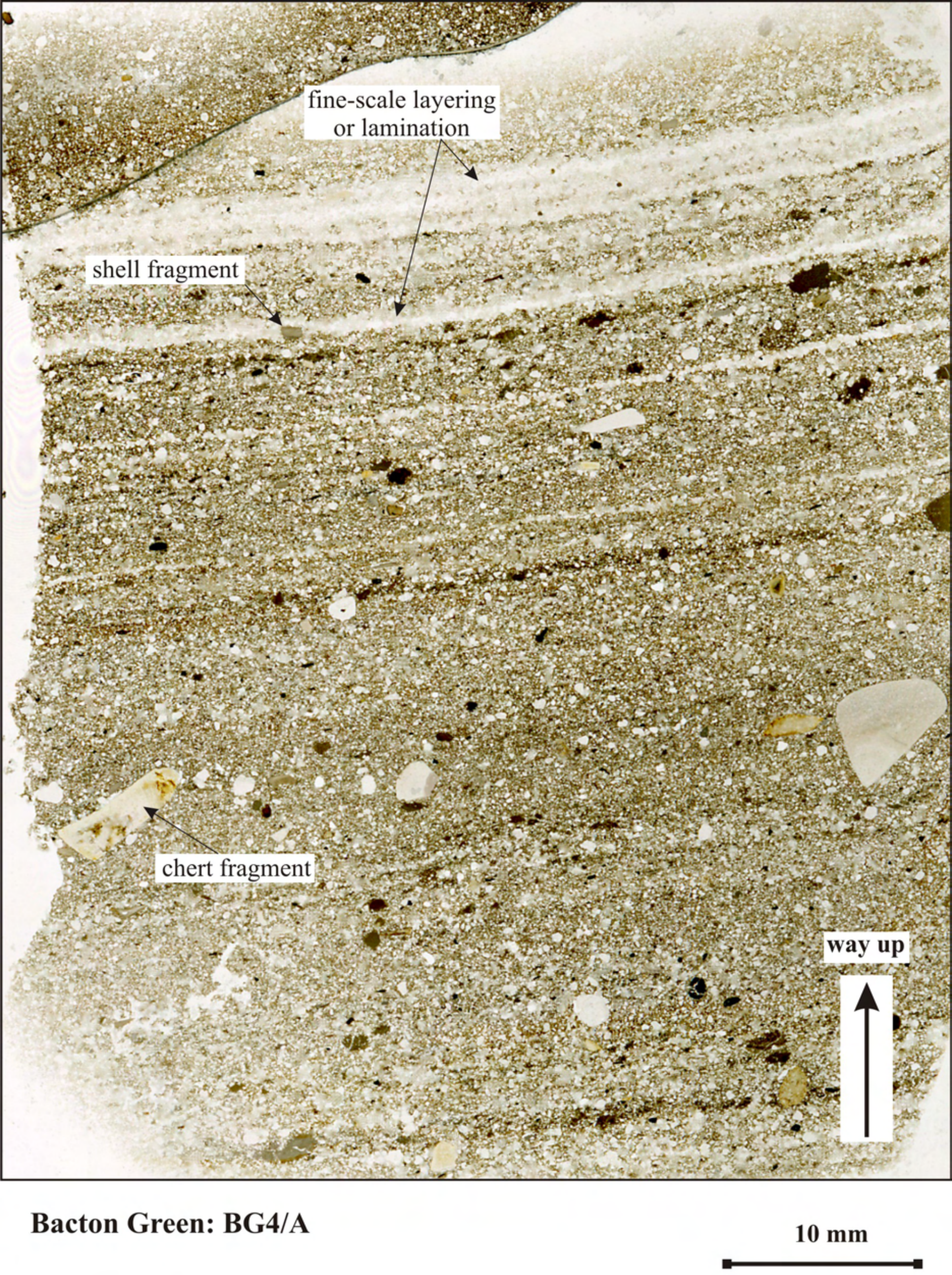

Figure 10. Annotated scan of thin section BG4/A.

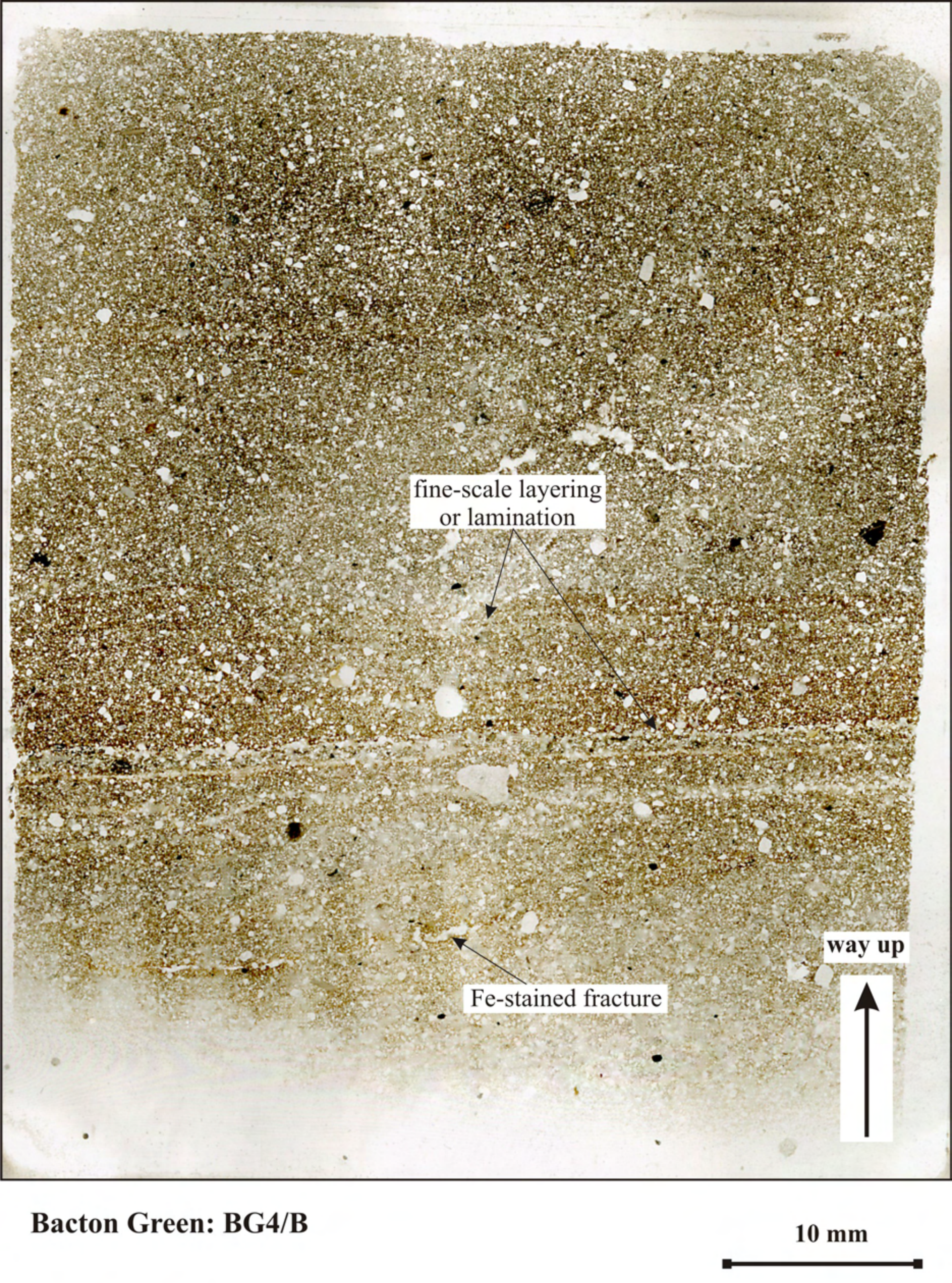

Figure 11. Annotated scan of thin section BG4/B.

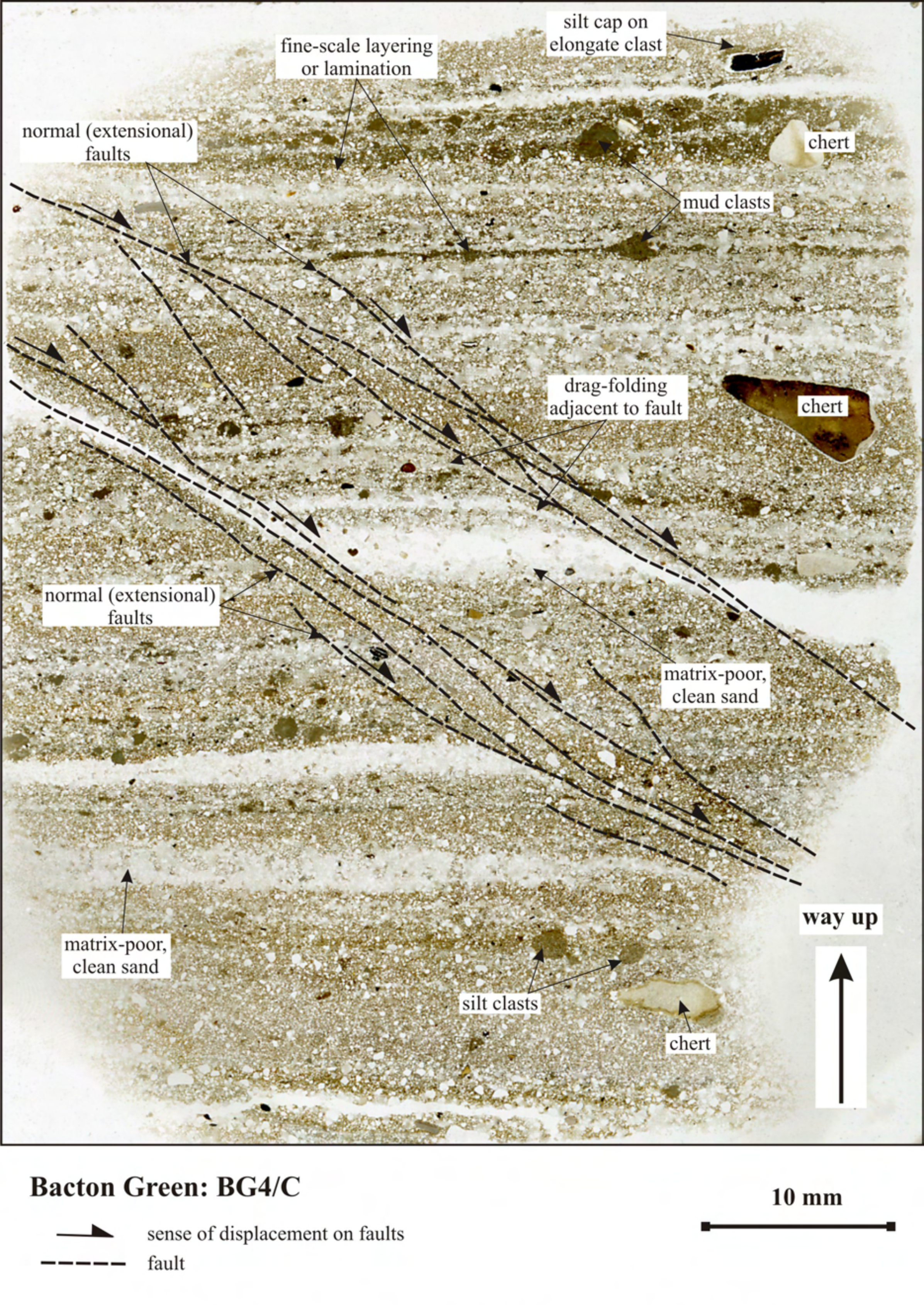

Figure 12. Annotated scan of thin section BG4/C showing main structures developed within this deformed, laminated fine- to medium-grained sand.

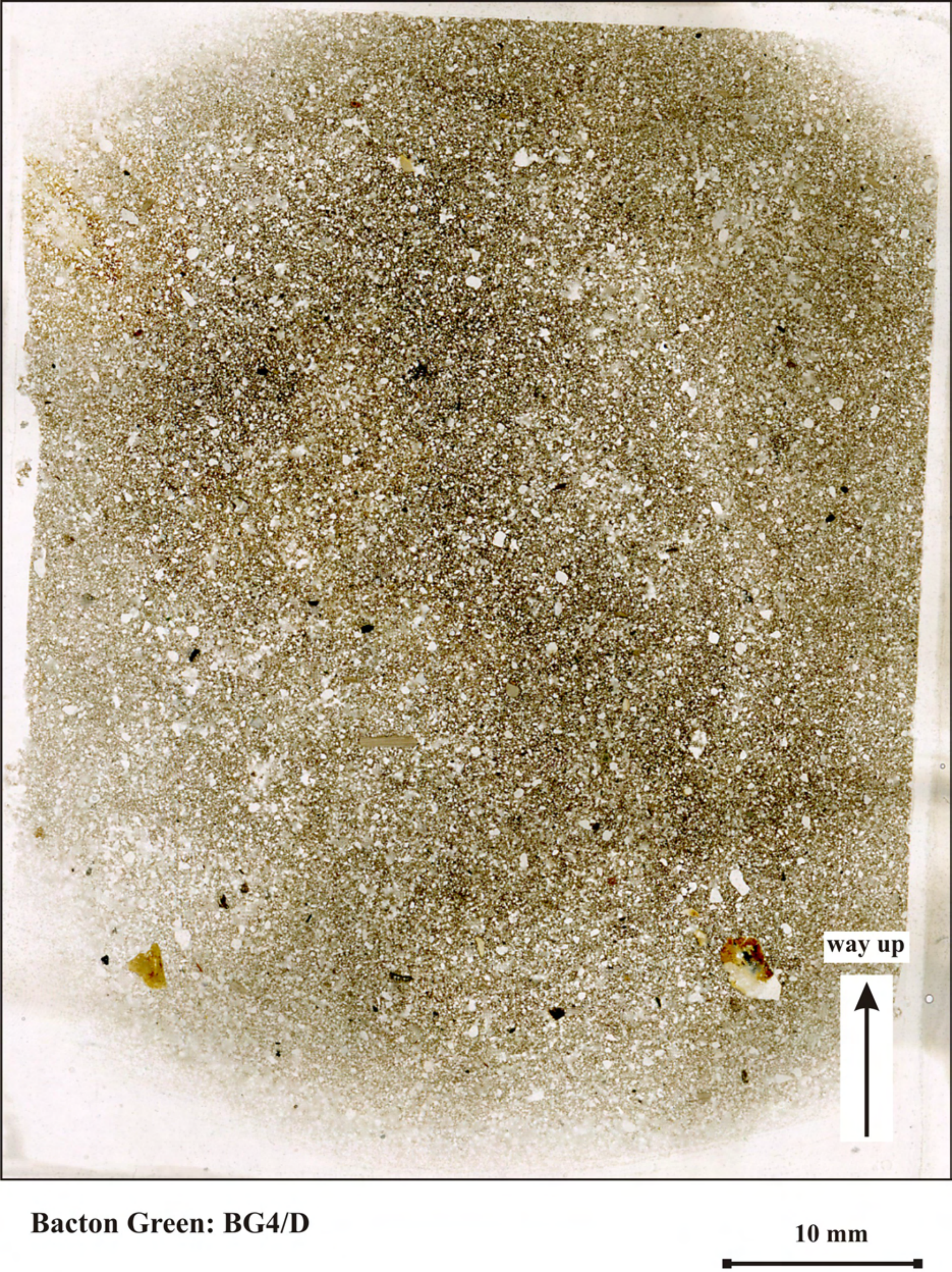

Figure 13. Scan of thin section BG4/D.

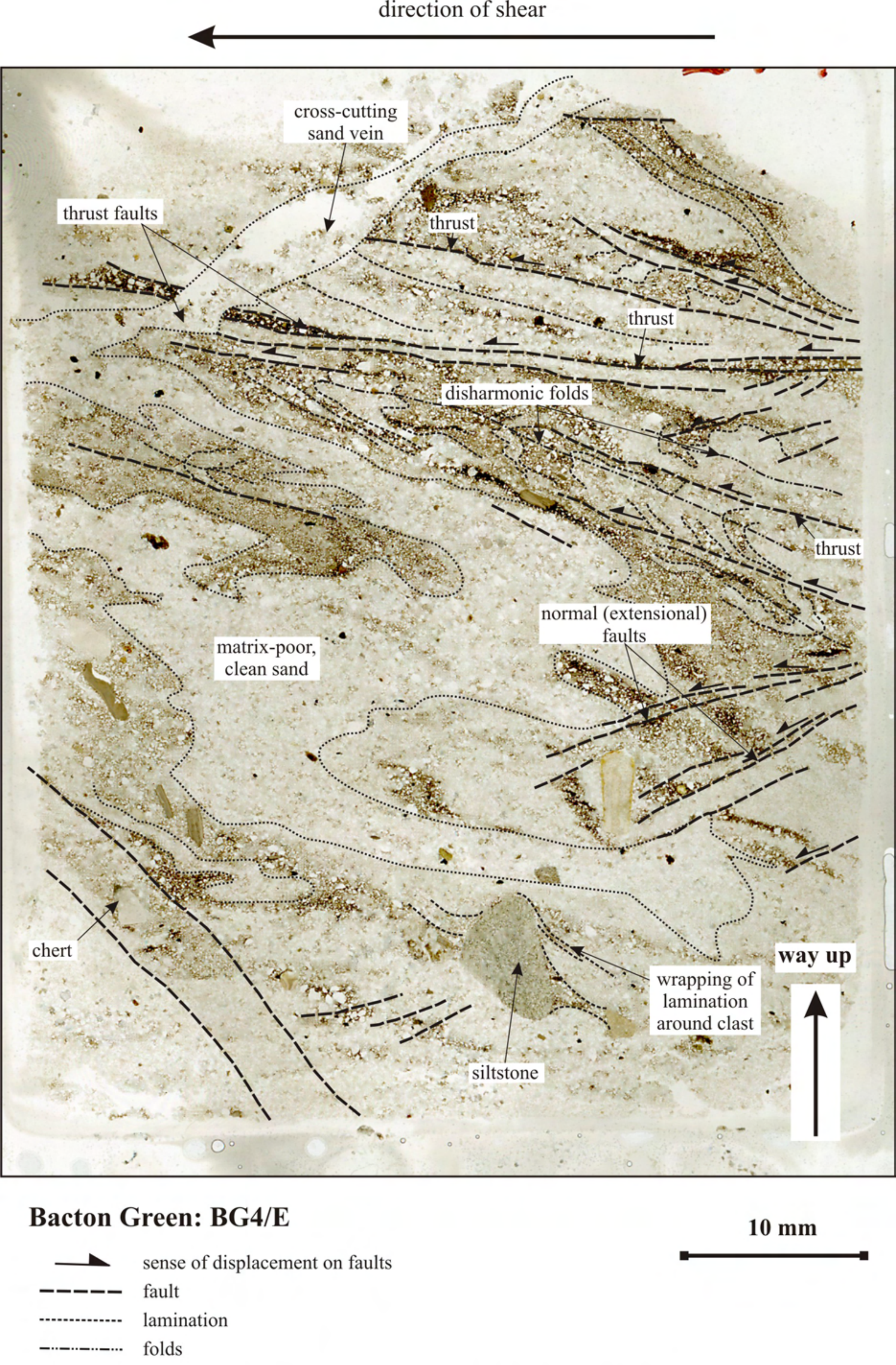

Figure 14. Annotated scan of thin section BG4/E showing main structures developed within this deformed, weakly laminated sand.

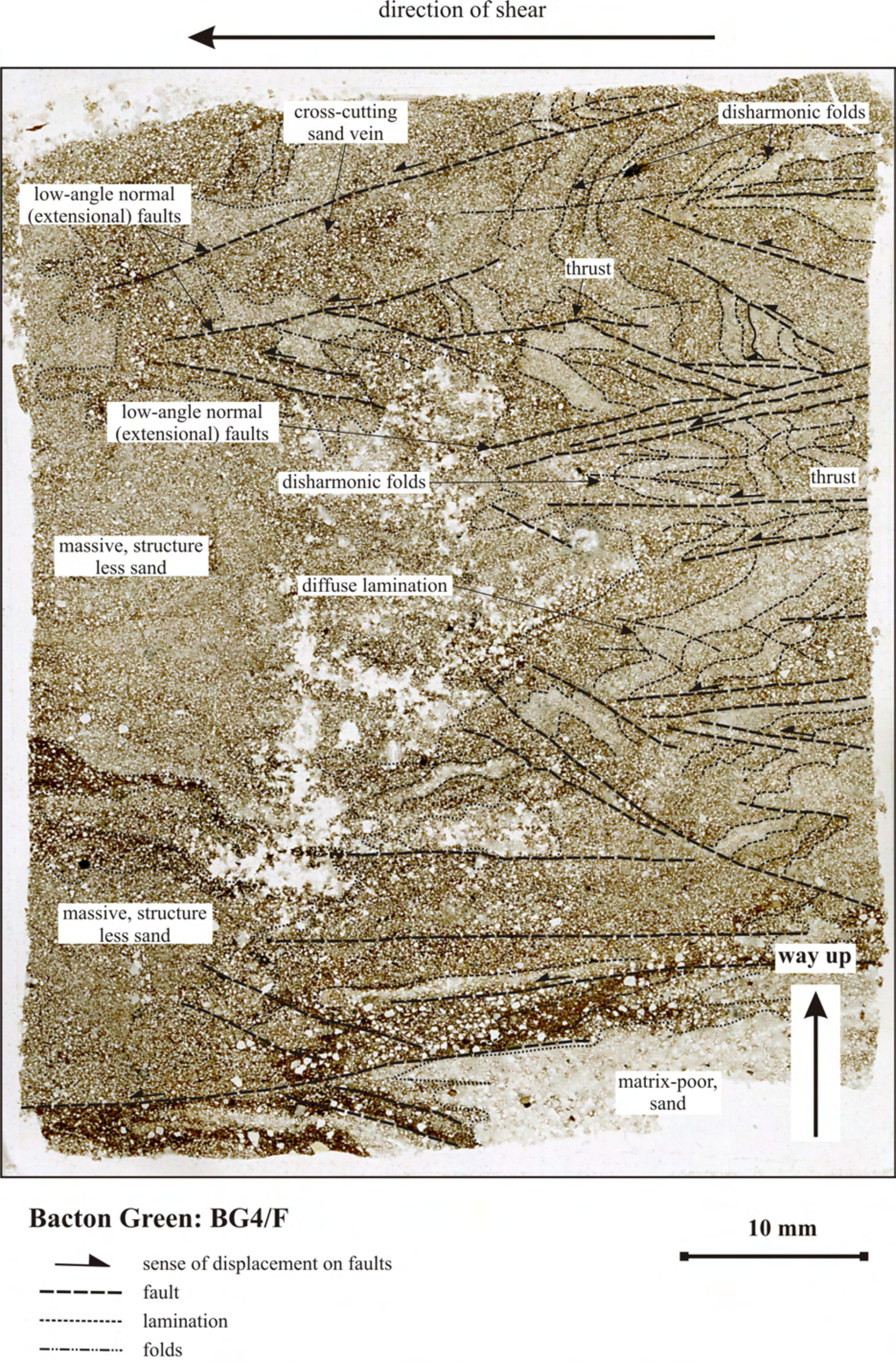

Figure 15. Annotated scan of thin section BG4/F showing main structures developed within this deformed, weakly laminated sand.

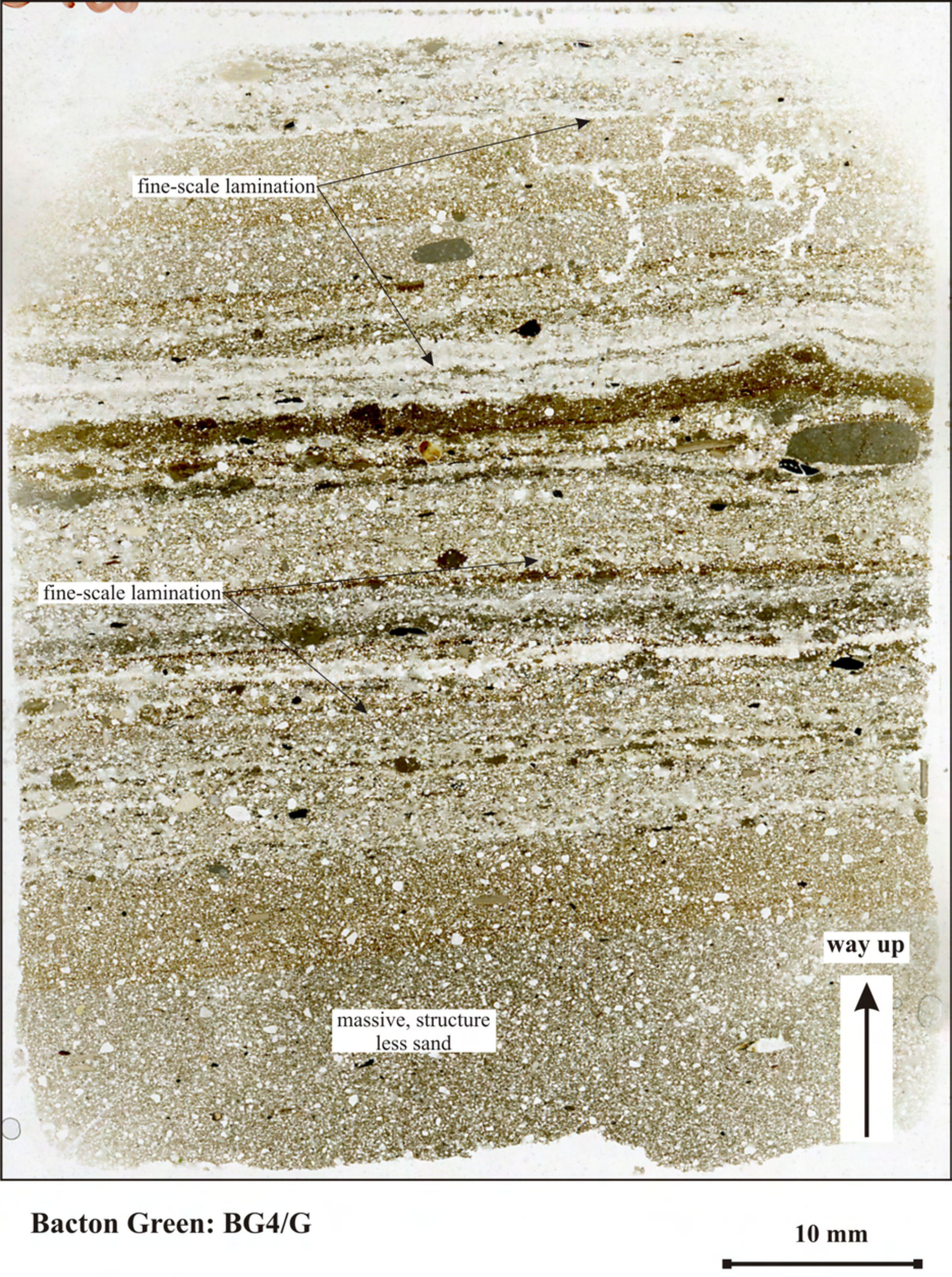

Figure 16. Annotated scan of thin section BG4/G.

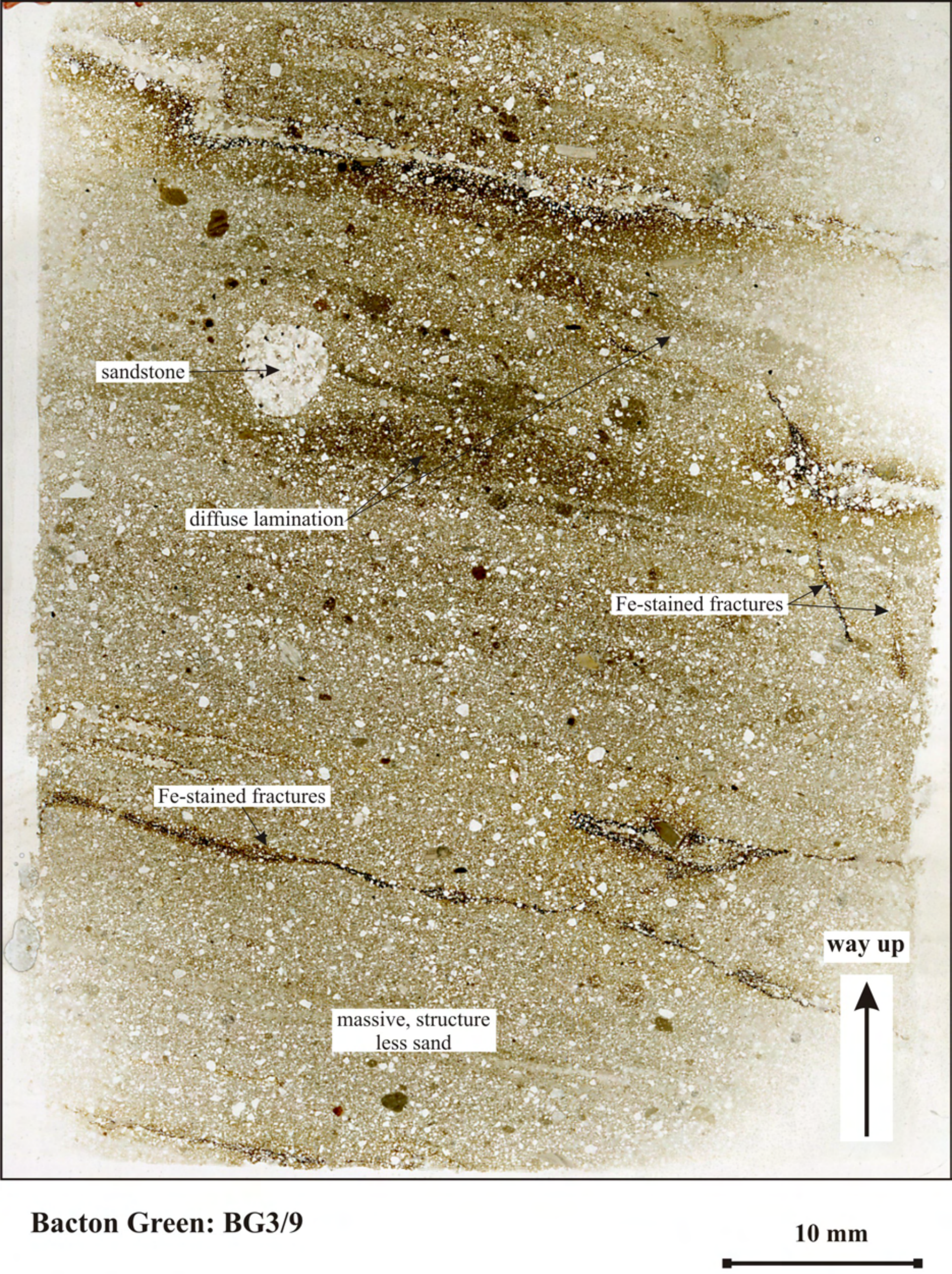

Figure 17. Annotated scan of thin section BG3/9.

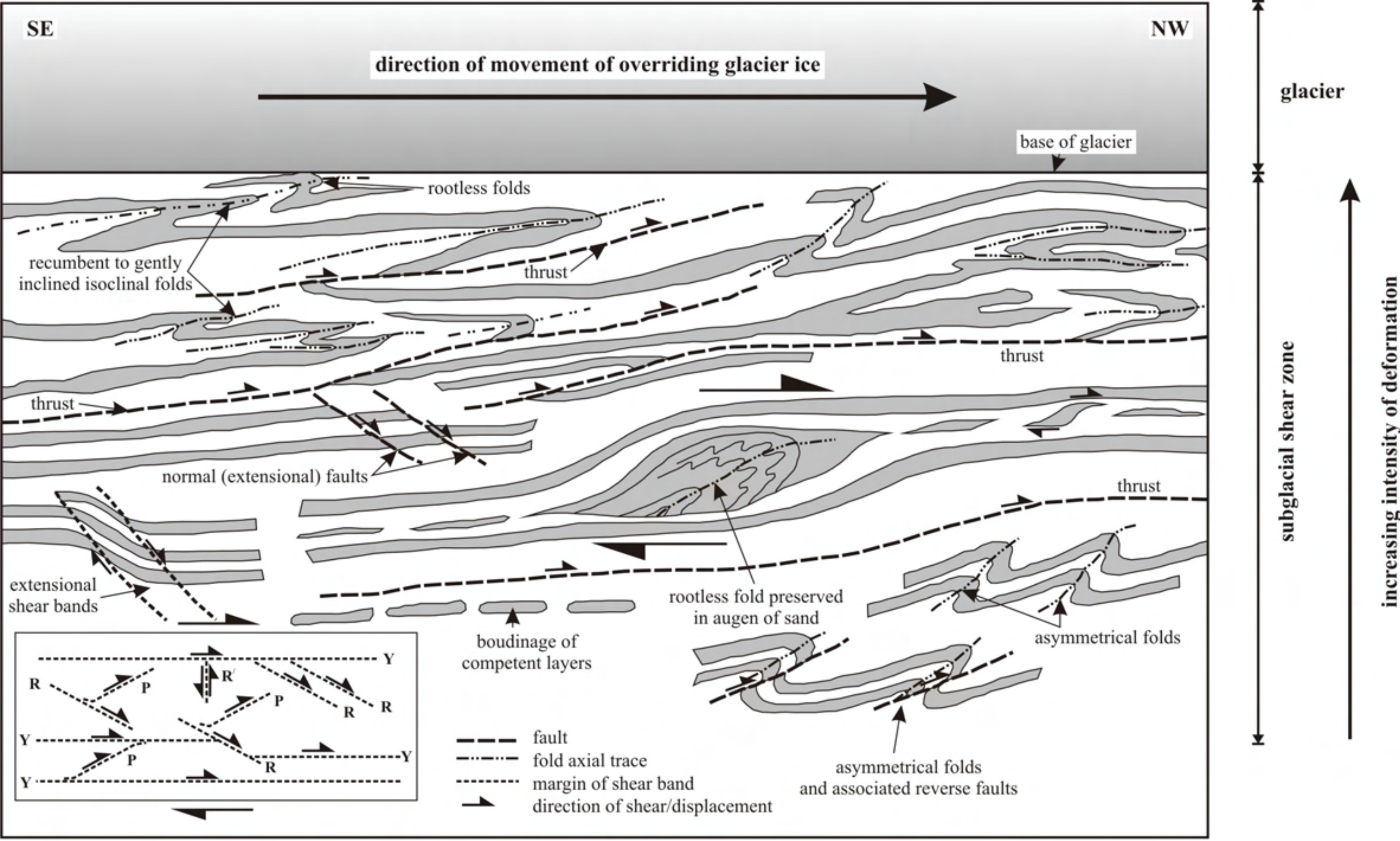

Figure 18. Diagram showing the range of deformation structures present at Bacton Green associated with the development of a 'subglacial shear zone'. Note that there is an over an increase in the apparent intensity of deformation upwards through the sequence.