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A novel methodological approach for thin-section description and its application to periglacially disturbed Pleistocene deposits from Danbury, Essex, UK

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Abstract

Although micromorphological terminology has been evolving since 1960, there have been few attempts to create a systematic approach to the description of thin-sections which would serve as a guiding tool for inexperienced researchers, students, and all new to the field of micromorphology. In this paper we present a novel, decision tree based systematic approach for thin-section description. This new approach attempts to unify micromorphological descriptions of Quaternary deposits, regardless of the character of the deposit and the purpose of the analysis.

In this research project, named 'Hidden Ice Worlds', the micromorphology of an 8 m thick sequence of periglacially disturbed deposits from the Royal Oak Pit, Danbury hill, Essex, UK is described. This sequence is situated on the eastern side of Danbury hill, at c. 50 m OD. Based on micromorphological analyses, a new hypothesis for the evolution of this sequence is presented. Multiple phases of physical reworking associated with freezing and thawing of the deposit, subsequent to Elsterian (Anglian) glaciation (480-420 ka BP) is proposed as the main process responsible for the evolution of the sequence. As periglacially derived deposits are usually removed from such elevated locations on hill' slopes, inversion of the topography is proposed as a necessary factor for the formation and preservation of the sequence described in this atypical location.

Keywords: Micromorphology, Elsterian (Anglian), Periglacial deposits

Introduction and background

The two main aims of this paper are to present a novel decision tree-based systematic approach to thin-section description, and to illustrate its application using examples from the Hidden Ice Worlds research project. The first part of the paper gives an introduction to the study site and the methodology. This is followed by a discussion of the novel systematic approach to thin-section description. The subsequent presentation of results, interpretation and discussion illustrates the benefits of using the new approach to micromorphological description in Quaternary research.

Bullock et al. (1985, p. 45) defined micromorphology as a 'branch of soil science'. Similarly, Stoops (2003, p. 5) characterises it as 'a way of studying soil and regolith'. Micromorphology deals with the microscopic characterisation of soil constituents and their relationships in space and time (Bullock et al., 1985; Stoops, 2003). There are few inherent assumptions associated with the micromorphological analysis of Quaternary deposits. Firstly, it is assumed that the soil or sediment studied in thin-section occurs in its natural state and all constituents, inherited from the parent material, are preserved (Fedoroff et al., 1990). Secondly, all the features described from a thin-section are evidence for past environmental conditions (Drees and Wilding, 1987). Thirdly, a single component of a thin-section cannot be correctly interpreted without a full understanding of the other features present (Mucher and Morozova, 1981).

The dawn of the micromorphology dates back to the 1930's when Kubiena (1938) published the first micromorphological description of a soil in the form of a short paper and a handbook. Kubiena, later published another handbook of 'Micromorphology' in 1953 (after Stoops 2003). Since then, thin-section description has been recognised as a scientific method, and has been

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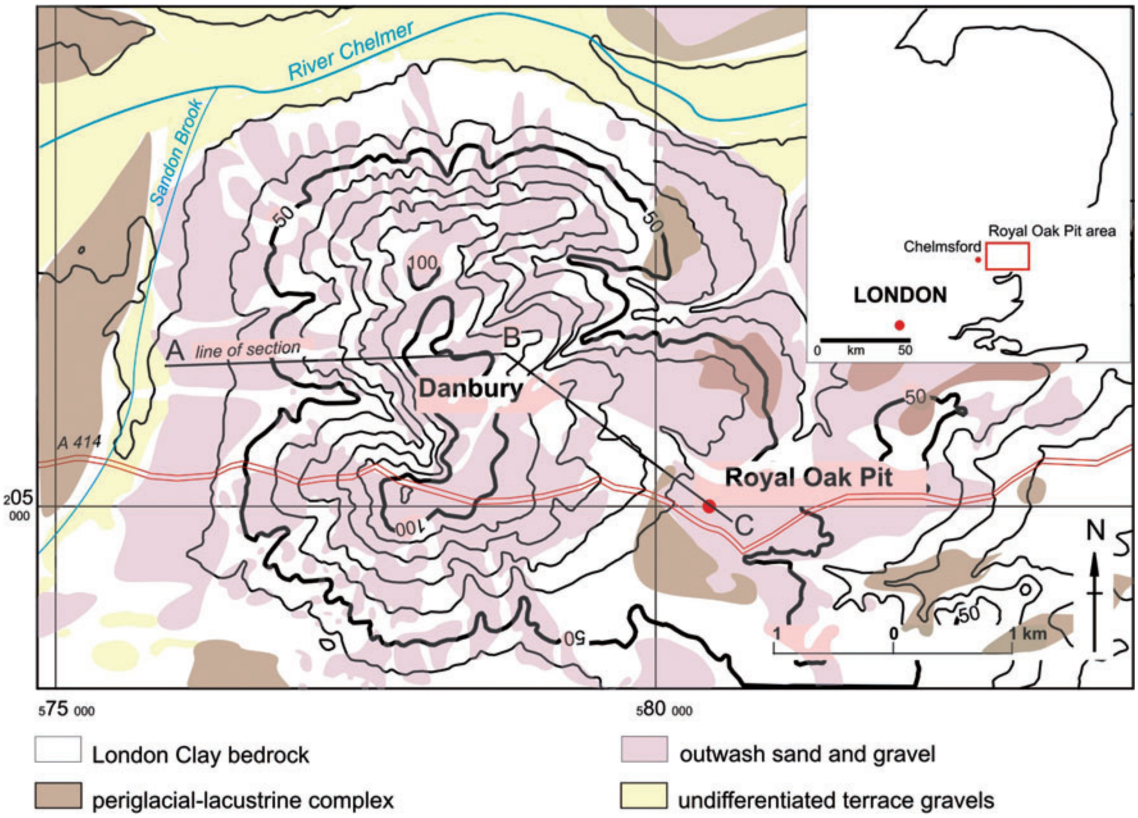
applied in various branches of archaeology, pedology, agricultural science and Quaternary geology (Fedoroff, 1986).

In Quaternary science, micromorphology helps to elucidate the origin and the evolution of a deposit (Bullock et al., 1985). It facilitates the differentiation of in situ soils and deposits from those which were transported, reworked or diagenetically alerted (Brewer, 1972; Kemp, 1985; Mucher, 1974; Mucher and Morozova, 1981). Moreover, the description of micro-features and their relationships from the Quaternary palaeosols allows not only the reconstruction of past environmental events and their chronology (Mucher and Morozova, 1981), but also construction of climatic curves similar to ones based on palynological investigations (Van Vliet-Lanoe, 1985). On the basis of the description of micromorphological features of sediments, various glacial deposits and geomorphic forms are differentiated (see research by Van der Meer (1980, 1996), Schluchter (1979), Evenson et al. (1977), Gaiglas (1971), Matveev (1976), Faustova (1973, 1980) and Shumilova (1974)). Micromorphology has also aided stratigraphical investigation and correlation of Quaternary deposits (Huddart, 1971; Kemp, 1998; Mucher and Morozova, 1981).

In this paper, we demonstrate that micromorphological analysis is a useful tool for the interpretation of climatic conditions during the evolution of the Elsterian (Anglian) Stage (480-420 ka BP) ice-marginal deposits of Danbury hill, Essex (Fig. 1a, b). Special attention is paid to the identification of freeze and thaw and soil forming processes associated with illuviation as well as presence of disturbance, compaction and displacement of the deposits as reflected by micromorphology. Micromorphological analysis of the deposits supplements field section investigations and addresses questions that are not possible to answer using macro-observation.



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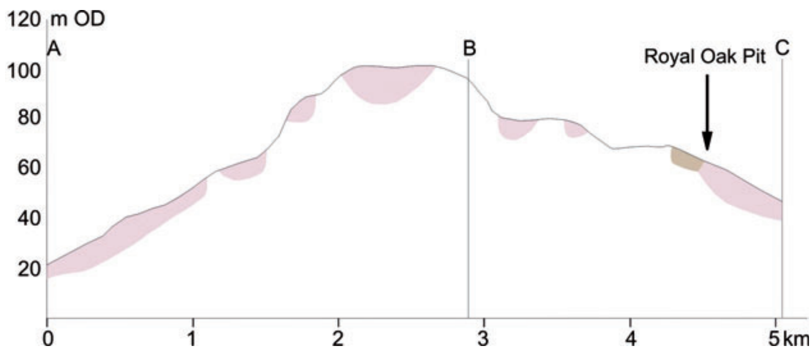


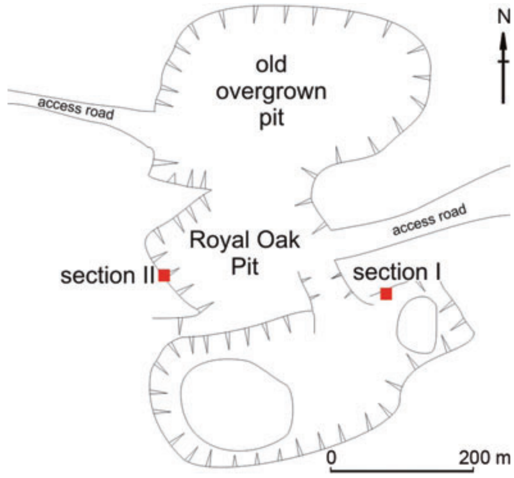
b.

Fig. 1. a. The topography and simplified geology map of Danbury hill and the Royal Oak Pit area with the line of the simplified geological cross-section A-B-C. Contour lines and river outlines after Ordnance Survey of Great Britain. Inset: location of the Royal Oak Pit area within East Anglia, Great Britain; b. Simplified geological cross-section along the line A-B-C (Fig. 1a) presenting relationship between the London Clay bedrock, outwash sand and gravel and periglacial-lacustrine complex on the Danbury hill and the Royal Oak Pit area.

Study site and methods

This study is centred on the periglacially disturbed deposits exposed in the Royal Oak Pit, a small disused quarry, on the eastern slope of Danbury hill, Essex (Fig. 1a, b). This part of East Anglia was glaciated only once during the Pleistocene, in the Elsterian (Anglian) Stage (480-420 ka BP), although multiple local re-advances within that stage may have occurred. Danbury hill is situated on south-eastern margin of the Anglian till sheet.

The stratigraphic sequence at the Royal Oak Pit (for plan of the quarry see Fig. 2a, for stratigraphic sequence see Fig. 2b and 3) comprises massive gravel (Gm), arranged in sheets (unit A, Fig. 2b and 3), overlain by fine sandy-silty-clay with



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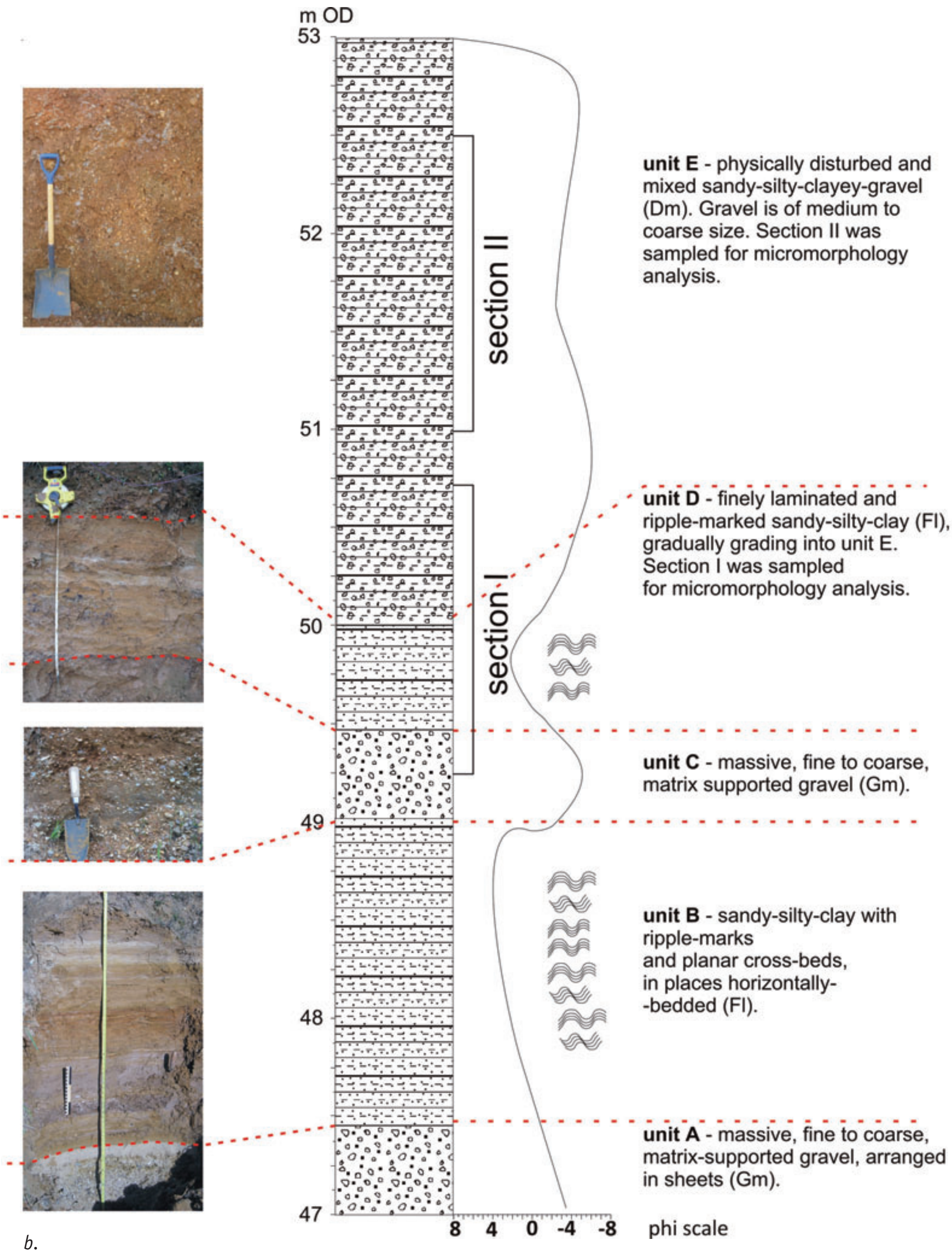

b.

Fig. 2. a. Schematic plan of the Royal Oak Pit with locations of sections sampled for micromorphological analysis; b. Composite section, representing sequence of deposits at the Royal Oak Pit and photos with examples of discrete, coded units A to E. Lithofacies code follows (Miall, 1977).

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ripple-marks and planar cross-beds (unit B, Fig. 2b and 3). This in turn is overlain by a 40 to 100 cm thick unit of massive gravel (Gm) (unit C, Fig. 2b and 3) capped with ca. 50 cm thick unit of finely laminated and ripple-marked sandy-silty-clay (Fl) (unit D, Fig. 2b and 3). Unit D gradually grades into periglacially disturbed sandy-silty-clayey-gravel (Dm) (unit E, Fig. 2b and 3). This sequence is situated on the eastern slope of Danbury hill, at an elevation of ca. 50 m OD. This is an atypical location for periglacially disturbed deposits of such a substantial thickness (up to 8 m), as usually deposits occurring on such an elevated locations and physically disturbed on numerous occasions would be removed down-hill by a solifluction.

The deposits at this site were investigated using field-section logging, ground-penetrating radar, clast lithology, loss-on-ignition and clay mineral analysis, together with thin-section analysis (Leszczynska, 2011). The micromorphology descriptions of the thin-sections are presented in this paper.

The three topmost units of the deposits from the Royal Oak Pit (C, D and E, Fig. 2b and 3) were sampled for micromorphology analysis using five metal monoliths tins (two 50 cm long and three 30 cm long). The sections from which the monoliths were taken, had been previously cleaned, logged, described and photographed (Fig. 3). The monoliths were sub-sampled in the Physical Geography Laboratories, Department of Geography, University of Cambridge. The sub-samples were processed and impregnated in the Earthslides Laboratory, by Julie Boreham (JB). Four 137 mm × 65 mm 'mammoth' slides, and seven 75 mm × 50 mm slides were prepared for analysis by JB.

The thin-sections were described by Karolina Leszczynska (KL) using circular polarised and dark field illumination, under the cross-polarised optical microscope in the Charles McBurney Laboratory for Geoarchaeology, Department of Archaeology, University of Cambridge. All the percentage relations were estimated visually by comparison to standard charts from Bullock et al. (1985) and Stoops (2003).

Methodology of the description

The first attempts to devise a systematic approach to thin-section description date back to 1964, when Brewer published his textbook of micromorphology. The scheme proposed by Brewer was later supplemented by Barrat (1969) and Bal (1973). All three authors concentrated their work on a methodological approach to the description of organic matter in deposits. Other accounts of micromorphological terminology were published inter alia by Brewer and Pawluk (1975) and later by Brewer and Sleeman (1988). In 1969 during the Third International Working Meeting on Soil Micromorphology, the Working Group on Soil Micromorphology was launched. Its purpose was to compile a comprehensive textbook for micro-morphological analysis of soil. As a result, the 'Handbook for Thin-section Description' was published (Bullock et al., 1985).

Although micromorphological terminology has been evolving since 1960, there have been few attempts to establish a systematic approach for thin-sections description, which could serve as a guideline to students, inexperienced researchers and those who are new to the field. Widely accepted terminology,

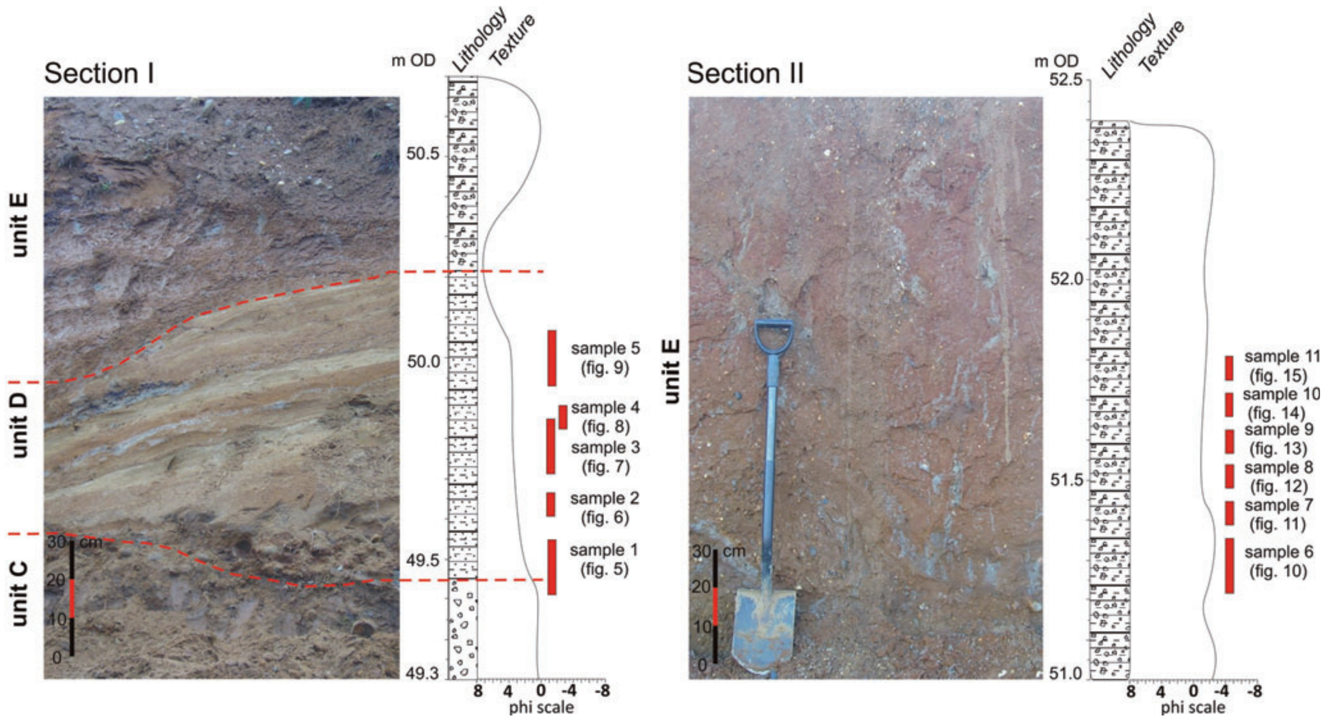

Fig. 3. Geological logs and photography of sections from the Royal Oak Pit sampled for micromorphological analysis with locations of discrete samples and references to relevant figures. For locations of sections see Fig. 2 and for images of samples see Figs 5-15.

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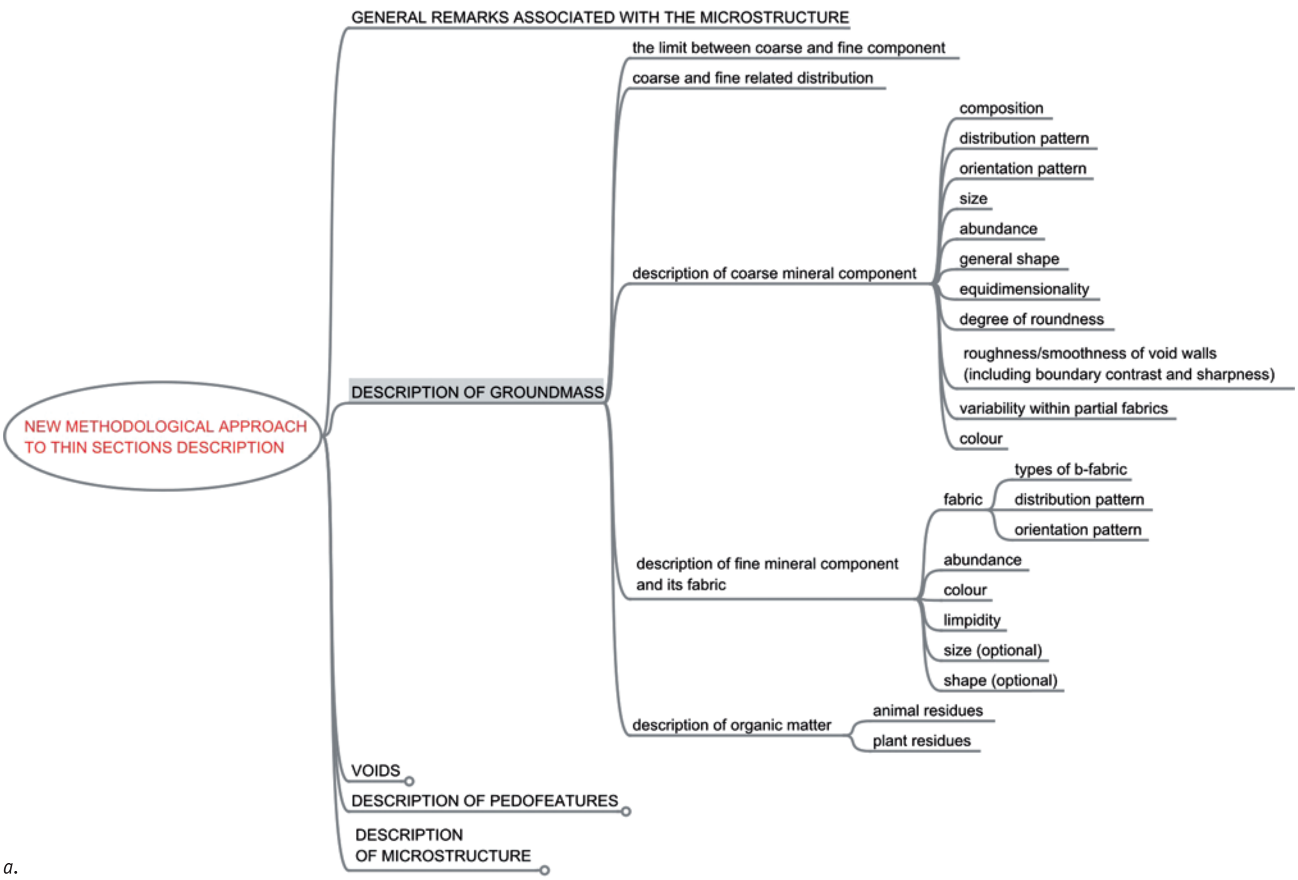
published inter alia in Bullock et al. (1985) and Stoops (2003) serve as a basis for the novel systematic approach for thin-section description. A step-by-step diagram is presented, which leads the user through all the stages necessary for a complete description of any thin-section, including samples from Quaternary sediments. This approach may be applied regardless of the purpose of the analysis or the features of the deposit. The thin-section description diagram is arranged in the form of a branching, unfolding outline (Fig. 4a-d). For the purpose of graphic presentation, the open-source software 'MindMap' has been used. The diagram presented in Fig. 4a-d is a mind-map which may be supplemented with definitions of specific terms, new categories and more detailed divisions of presented categories. It is a fully interactive tool which may be further developed by its users.

The novel systematic approach divides the process of micromorphological description into five main stages. Each stage is represented by a discrete branch of the diagram. The five major stages of description are represented by the five component features of every thin-section analysis. These are: (1) general remarks associated with the microstructure, (2) description of groundmass (coarse and fine component description, including coarse to fine component related distribution (C/F distribution)), (3) description of voids,



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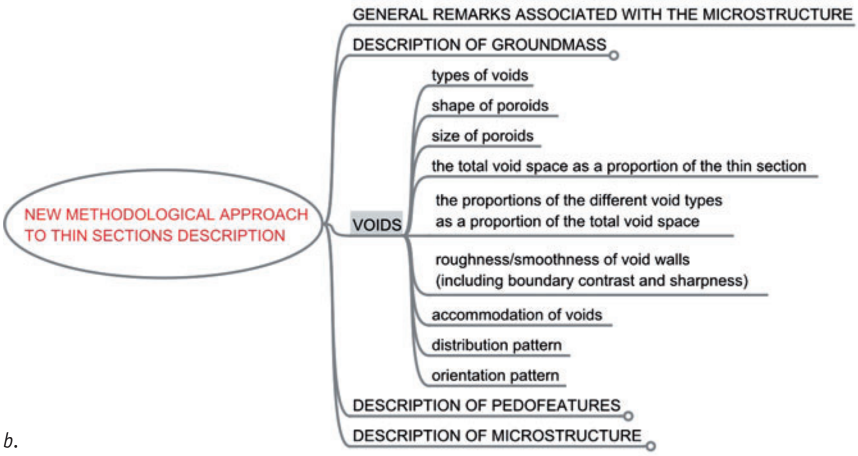

b.

Fig. 4. An unfolding diagram presenting the New Methodological Approach to Thin-Sections Descriptions. Note that 'General remarks associated with the microstructure' does not unfold. Discrete branches of diagram are presented on following images: a. Description of groundmass; b. Description of voids; c. Description of pedofeatures; d. Description of micro-structure.

Fig. 4c.

(4) description of pedofeatures (classification, presence and general description, specific description) and (5) description of microstructure. Each branch of the diagram, beside the general remarks associated with the microstructure, unfolds step-by-step to lead to a complete description of each category.

The novel systematic approach for thin-section description is an open scheme, which may evolve together with the terminology. Elements may be added and modified as the knowledge of the subject advances. This systematic approach, especially its graphic presentation (branching diagram – Fig. 4a-d), ensures that all elements and details of the micromorphology are included in the final description. All thin-sections described according to the proposed scheme are easy to compare with each other. The new scheme does not impose a fixed way of presenting the results. Thin-section descriptions that follow the diagram may be presented as text, in the form of a table or in any other convenient way.

Detailed micromorphology results

In Fig. 5-15 thin-sections prepared for this study are presented. They illustrate 'Hidden Ice Worlds' of sediments from the Royal Oak Pit, Danbury hill, Essex. Images of samples 1 and 2 (Fig. 5 and 6) are representative of the middle part of the sequence, unit C and D (for location of samples see Fig. 2a and 3, for stratigraphy see Fig. 2b). Samples 3-5 (Fig. 7-9) come from unit D and E and represent the transition between well-organised basal deposits of unit D, and the very disturbed and physically mixed top of the sequence, unit E. Samples 6-11 (Fig. 10-15) come from the disturbed upper deposits of unit E.

Detailed results of description of all thin-sections are presented in tables. They are preceded with general introductory description and illustrated with photographs. On photographs of thin sections approximate boundaries of units are indicated by black dashed line. Accurate delineation of each boundary is difficult as in many places they are gradual and discernible only under the magnification. At the end of the section 'Detailed micromorphology results' in Fig. 16 examples of micrographs of typical features described from the samples are presented. In order to provide with clear examples, micrographs are taken from samples in which these particular characteristics are best developed.

In all samples, if not stated otherwise, distribution and orientation of all features is random, clay is of undifferentiated b-fabric and speckled and dotted aspect and walls of all voids and peds are non-accommodating.

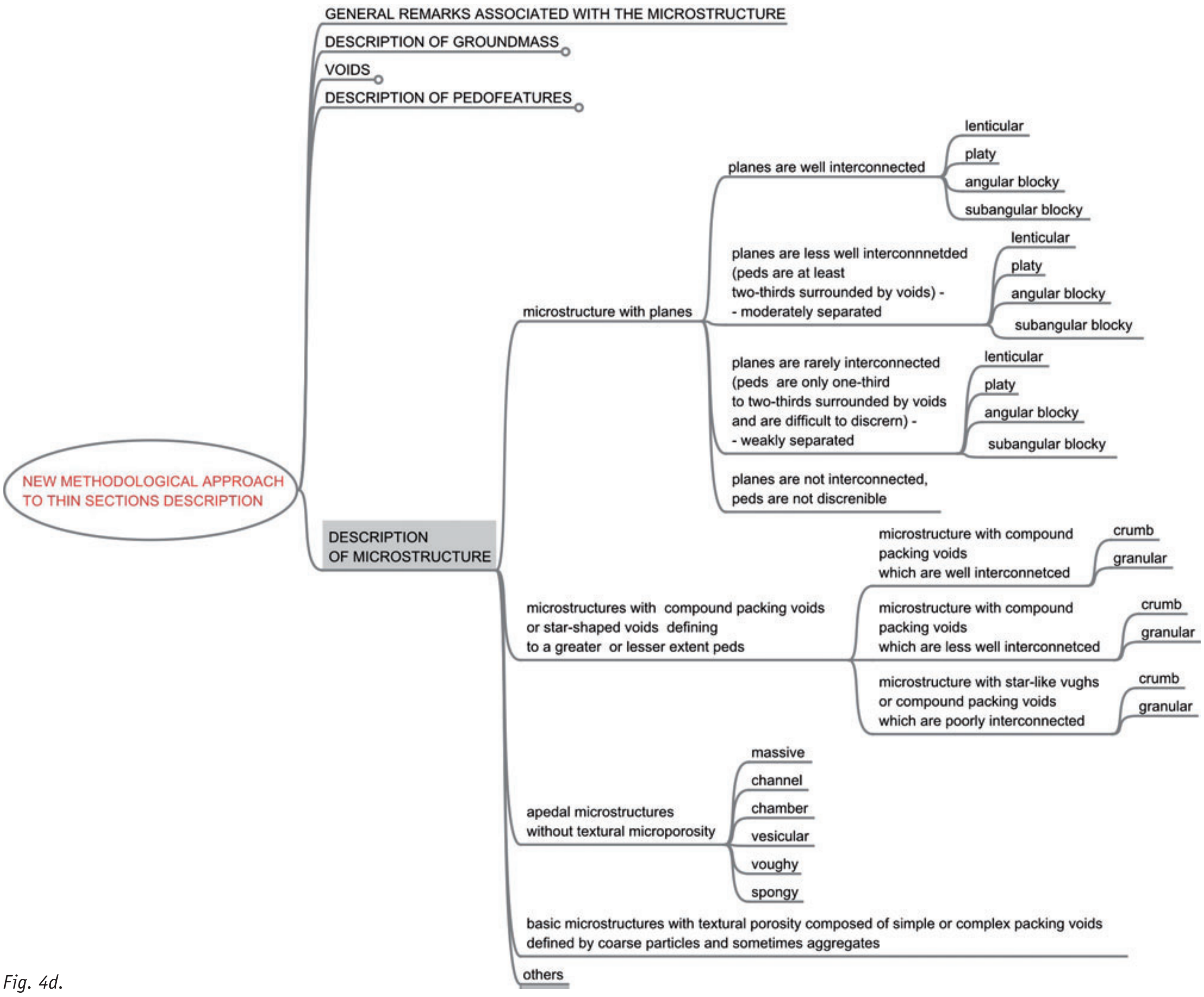

Fig. 4d.

Sample 1 (Fig. 5), taken from the transition between unit C and D (see Fig. 2b and 3), represents change between compacted and micro-laminated unit of fine clay, silt and sand seen at the bottom of the sample (unit 1/A, Fig. 5) and less dense, disorganised aggregates of sub-angular coarse sand embedded within a silty-clay matrix at the top of the image (unit 1/C, Fig. 5). Within the cluster of aggregates of unit 1/C, as if in suspension, floats a 'galaxy' structure (unit 1/B, Fig. 5) of internally laminated clayey-silty fine sand. Lower boundary of unit 1/C is sharp, erosional, however some mixing of material from unit 1/A occurs. Several generations of channels and chambers can be seen in each unit. Particularly well developed are chambers, of which an example is presented in Fig. 16a. For detailed description of the sample see Table 1.

Sample 2 (Fig. 6) also consists of three various units (2/A, 2/B and 2/C). This thin-section represents a unit of blocky, sub-angular, clustered aggregates of sand suspended in a space of compound packing voids. Variable density of the components divides the image into a few units, which represent the original character of the deposit. In this sample for the first time good examples of striated sand grains occur (see Fig. 16e). Micrographs from this sample depicted in Fig. 16j and l represent chitonic to convex gefuric and enaulic C/F related distribution. Detailed description of all units from this sample is presented in a Table 2.

The disturbed the nature of the deposit increases with distance up the stratigraphic sequence, what is depicted in **sample 3** (Fig. 7, Table 3). It represents very complicated pattern of 4 interdigitating units (3/A, 3/B, 3/C and 3/D). Strongly developed separation of the peds highlights the division of the deposit into four units. Characteristic feature of this sample is presence of iron oxide nodules, depicted in micrograph in Fig. 16g. A typical porphyric C/F related distribution (Fig. 16h) is observed in the upper part of this sample. Exemplary micrograph of clay coatings on the walls of channels from this sample is presented in Fig. 16b.

Image of **sample 4** (Fig. 8, Table 4) represents three alternating units (4/A, 4/B and 4/C) representing densely and loosely packed aggregated sand within a silty and clayey matrix. Characteristic feature of this sample is presence of decomposed and relocated limpid, micro-laminated clay coatings in matrix, very well depicted also in sample 6 and presented on micrograph in

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Table 1. Description of units – sample 1.

Unit	Groundmass	Voids	Pedofeatures
1/A	**C/F distribution**: enaulic (open); **C/F limit**: clay/silt; **coarse component**: 10% of the t.t.s.a., silt and fine sand, shape blocky, sub-rounded to sub-angular, low variability within partial fabric associated with shape, elongated grains are parallel, with medium angle of parallelism, strongly expressed, parallel to the base of the unit; **fine component**: 60% of the t.t.s.a., dusty quasi- and hypo-coatings on walls of channels (up to 50 µm thick); **microstructure**: sub-angular blocky	15-20% of the t.t.s.a.; channels, chambers, vesicles and vughs; **channels**: up to 1-2 mm wide and few centimetres long, arranged along straight and zig-zag planes, walls rough, partially accommodating, orientation of channels is parallel to each other and to the top of the unit, parallelism strongly expressed, dusty quasi- and hypo- clay coatings on walls, some are filled with dusty clay; **chambers**: up to a size of 400 µm; **vesicles and vughs**: up to 400 µm, the amount of vughs increases towards the top of the unit, while their size decreases, parallel to the boundary of the unit, surrounded by iron oxides	Pedality moderately developed; impregnative and fabric pedofeatures; peds very weakly separated; blocky, sub-angular to angular; size is very variable: from 5 mm for 5 mm up to 2 cm for 3 cm
1/B	**C/F distribution**: chitonic changing into porphyric; **C/F limit**: clay/silt; **coarse component**: 60% of the t.t.s.a., silt and fine to coarse sand, the rest of characteristic as above; **fine component**: 10% of the t.t.s.a., clay particles are clustered, they create dusty quasi- and hypo-coatings on walls of channels/peds (up to 50 µm thick); **microstructure**: moderately separated granular	40% of the t.t.s.a.; **compound packing voids**, channels; compound packing voids: up to a size of 250 µm; **channels**: up to 50 µm wide and few centimetres long, dusty quasi- and hypo-coatings present on walls, channels continue beyond the limit of the unit and are interconnected with channels from other units	Pedality weakly developed; impregnative and textural pedofeatures; peds very weakly separated; blocky, sub-angular to angular; orientation of elongated peds is parallel to the bottom of the unit; size: width 200-300 µm, length 200-300 µm; on surface of peds hypo-coatings of dusty clay (up to 50 µm thick)
1/C	**C/F distribution**: enaulic (open); **C/F limit**: clay/silt; **coarse component**: 10% of the t.t.s.a., silt and fine sand, the rest of characteristic as above; **fine component**: 60% of the t.t.s.a., creates quasi- and hypo-coatings on walls of channels/ peds, clay coatings up to 50 µm thick; **microstructure**: fine monic	5% of the t.t.s.a.; channels, vesicles and vughs; **channels**: up to 50 µm wide and few centimetres long, walls of channels rough, orientation is parallel, they are interconnected, there are quasi- and hypo-coatings on walls; **vesicles and vughs**: up to 400 µm, the amount of vughs increases towards the top of the unit, while their size decreases, parallel to the boundary of the unit, surrounded by iron oxides	Pedality strongly developed; impregnative and fabric pedofeatures; strongly separated; blocky, sub-angular to angular; orientation of elongated peds is unimodal, horizontal, strongly expressed; size: up to 2 cm in width and length; quasi- and hypo-coatings on walls of peds, coatings up to 50 µm thick

Fig. 16h. Remains of an unidentified mollusc shell on the mid-right border of the image are present. C/F related distribution represents typical monic changing into chitonic type (Fig. 16k).

Sample 5 (Fig. 9, Table 5) is very variable and pedality within the whole sample is very well developed. Both units (5/A and 5/B) are separated by channels and chambers. Deposits in the lower part of the sample are less densely packed than those in the upper part. Very typical concave gefuric C/F related distribution is described from unit 5/A (Fig. 16i).

Very well developed pedality as well as red staining, associated with presence of iron oxides, becomes an ubiquitous feature of all samples overlying **sample 6** (Fig. 10, Table 6). In some cases iron oxides create concentric rings around voids as depicted on micrograph in Fig. 16c. Another interesting feature of sample 6 is presence of cloudy aspect of clay within voids (Fig. 16d), mentioned before in sample 3.

Despite high degree of pedality only one unit is differentiated in **sample 7** (Fig. 11, Table 7). Some pebbles (grains >2 mm) of flint cut through by the thin-section are present (highlighted in Fig. 11). They differ from ubiquitous quartz grains in mainly because of the colour and in micro-scale because of the internal structure of discrete grains – they are not crystalline. They are recognised as flint pebbles.

Moving towards the top of the periglacially disturbed sequence, the deposit becomes increasingly pebbly, as depicted in sample, 8 (Fig. 12, Table 8). The central feature of this sample is a flint pebble. Fine to coarse gravel is suspended within a silty, clayey, sandy matrix, and usually the long axes of clasts are oriented parallel to macrostructures such as ice wedge casts or involutions. There are two units within this sample.

A notable feature of **sample 9** (Fig. 13, Table 9) is the alternating presence and absence of iron oxides and red

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staining associated with them. Peds enriched in iron oxides appear to be dense and compacted, while peds depleted in iron occur usually along channels. There is only one unit identified within this sample.

Sample 10 (Fig. 14, Table 10) represents material dominated by voids. This is due to the original state of the sediment when sampled from the field, with further contraction of the silty clayey peds caused by air-drying of the sample before impregnation. This slide illustrates that towards the top of the sequence the deposit is more and more disturbed and physically mixed. It is apparent that red staining occurs some distance from the channels.

The topmost **sample 11** (Fig. 15, Table 11) represents a unit of the deposit with no internal organisation. Along with clay, silt and sand-size grains flint pebbles are present. The character of this thin-section is constituted by very well interconnected channels and chambers and vughs.

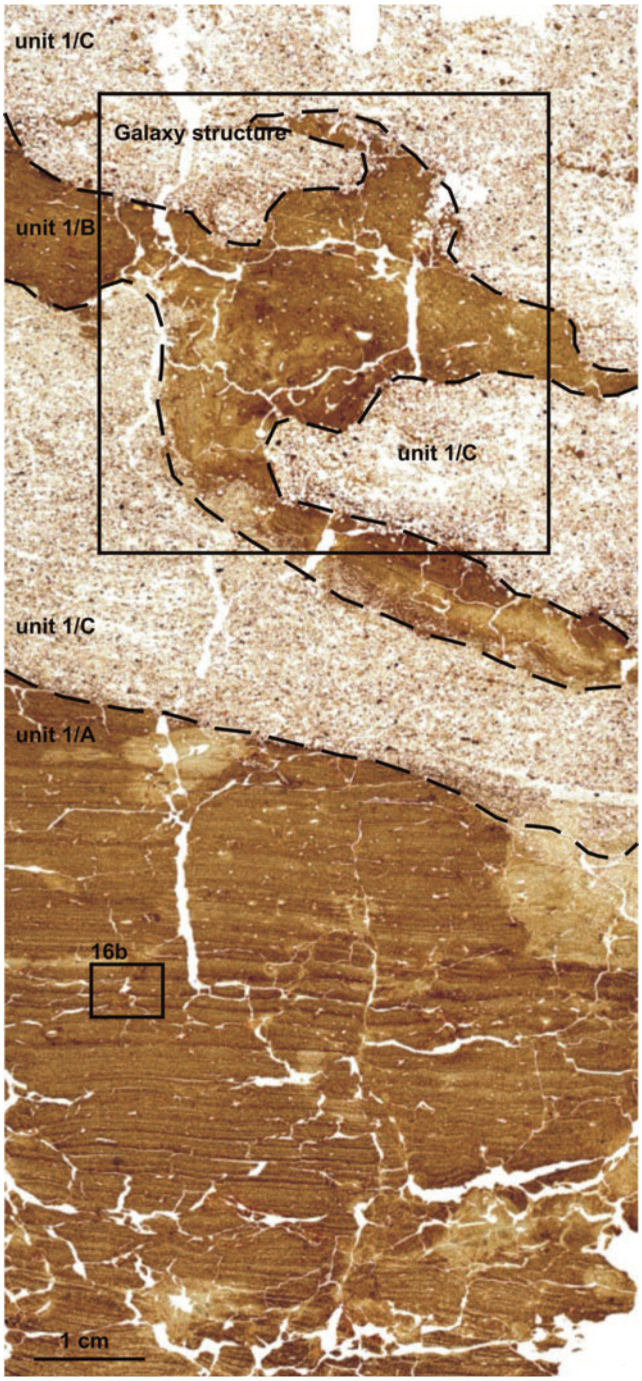

Fig. 5. High resolution scan of sample 1. Box in the upper part of the photograph highlights galaxy structure described in the text. Small box in the lower part of the photograph indicates the location of the micrograph depicted in Fig. 16b. Black dashed line indicates the boundary between discrete units.

Synthesis of results

In samples from the bottom of the sequence (samples 1-4) the fine to coarse component limit was placed between the clay and silt (or coarser) fraction. Moving towards the top of the sequence where coarser fractions prevail, the limit was placed between silt and sand-size fraction.

The C/F distribution varied markedly throughout the whole sequence. The dominant types are: porphyric (sensu Stoops 2003)

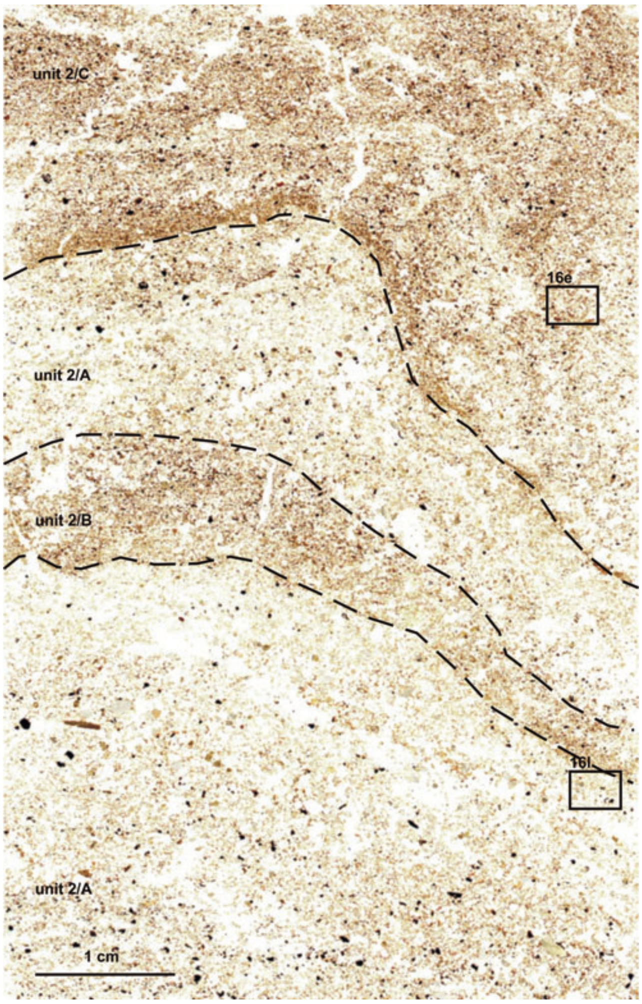

Fig. 6. High resolution scan of sample 2. Black boxes indicate location of micrographs depicted in Fig. 16e and l. Black dashed line indicates the boundary between discrete units.

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Table 2. Description of units – sample 2.

Unit	Groundmass	Voids	Pedofeatures
2/A	**C/F distribution**: chitonic to gefuric (convex); **C/F limit**: clay/silt; **coarse component**: 40% of the t.t.s.a., silt and medium to coarse sand, shape blocky, sub-rounded to sub-angular, medium variability within partial fabric associated with size and shape, only in places elongated grains are parallel to each other, with broad angle of parallelism, **occasionally grains are striated**; **fine component**: 10% of the t.t.s.a., clustered distribution (around edges of coarse components or aggregates), creates partial, dusty and impure clay quasi- and hypo-coatings around grains and aggregates (10-50 µm thick); **microstructure**: basic with textural porosity of simple and complex packing voids	5% of the t.t.s.a.; **simple and compound packing voids**, **vesicles** and **vughs**: few of the voids are up to 400 µm but majority are of size of up to 1 mm, orientation of elongated voids is parallel, with small angle of parallelism, weakly expressed	Pedality very weakly developed; impregnative and depletion pedofeatures; very weakly separated; size difficult to measure due to low degree of separation of discrete peds; dusty and impure quasi- and hypo-coatings on edges of aggregates (10-50 µm thick)
2/B	**C/F distribution**: chitonic and gefuric (convex) changing into enaulic (fine); **C/F limit**: clay/silt; **coarse component**: 40% of the t.t.s.a., silt and fine and medium sand, shape blocky, sub-angular, low variability within partial fabric associated with size, **occasionally grains are striated**; **fine component**: 30% of the t.t.s.a.; **microstructure**: voughy, in places apedal	30% of the t.t.s.a.; **simple and compound packing voids**: size of up to 500 µm	No pedality developed
2/C	**C/F distribution**: enaulic (fine); **C/F limit**: clay/silt; **coarse component**: 50% of the t.t.s.a., silt and well sorted medium sand, shape tabular, sub-rounded to rounded, low variability within partial fabric associated with shape; **fine component**: 30% of the t.t.s.a.; **microstructure**: lenticular, granular	15 to 20% of the t.t.s.a.; **simple and compound packing voids**: size of up to 500 µm	Pedality moderately to weakly developed; matrix and textural pedofeatures; peds weakly separated; shape lenticular; orientation – linear, parallel to the lower boundary of the unit; size – 2-3 cm in length, 1-1.5 cm in width

(samples 1, 3, 4, 8, 10 and 11; Figs 5, 7, 8, 12 and 15 respectively; for example see micrograph in Fig. 16j), chitonic (sensu Stoops 2003) (samples 2, 3, 4, 6; Figs 6, 7, 8 and 10 respectively; for example see micrograph in Fig. 16l), enaulic (sensu Stoops 2003) (sample 1, 5 and 9; 5, 9 and 13 respectively; for example see micrograph in Fig. 16l). Additionally gefuric (samples 3 and 7; Figs 7 and 11 respectively; for example see micrograph in Fig. 16i) and monic (sample 4; Fig. 8; for example see micrograph in Fig. 16k) distributions are described, however they occur only occassionally. The porphyric distribution is characterised by larger clusters occurring within the dense fine matrix. On the contrary, chitonic distribution is defined by larger aggregates being covered by smaller clusters. Distinctively, the enaulic distribution is described within all samples where small clusters of particles occur within void spaces between bigger aggregates. Gefuric distribution is defined as coarse component mineral grains being bridged by braces of clusters of fine mineral component, while monic distribution is described in case when only one fabric unit is present (Stoops 2003, p. 42-44).

Similarly, porosity of the deposit, estimated visually by comparison with standard chart from Bullock et al. (1985) and Stoops (2003), varied markedly, from 5 to 30% at the base of the sequence (sample 1, Fig. 5) to >50% at the top of the sequence (sample 11, Fig. 15). Channels (for example see micrograph in Fig. 16a) – lengthy voids in a straight, zig-zag or slightly undulating shape (Stoops 2003, p.65), chambers (for example see micrograph in Fig. 16b) – equidimensional voids with rounded with smooth walls, usually connected by channels (Stoops 2003, p.65), simple packing voids (for example see micrograph in Fig. 16e) – between discrete grains (Stoops 2003, p. 64), complex packing voids (for example see micrograph in Fig. 16k and l) – between aggregated components (Stoops 2003, p. 64), vughs (for example see micrograph in Fig. 16 g) – roughly equidimensional, irregular voids interconnected with each other (Stoops 2003, p. 65) and vesicles (for example see micrograph in Fig. 16g) – rounded voids within not disturbed matrix occur within this sequence. Channels, associated with vughs and chambers, occur in all samples, with the exception of 2 (Fig. 6) and 5 (Fig. 9). They are the dominant type of void in the topmost part of the sequence (sample 10 and 11, Figs 14 and 15 respectively). At the base of the sequence, channels can be seen cutting across stratigraphic laminations, and towards the top of the sequence they cut across entire units. The walls of the channels are non-accommodating – they do not match each other, due to alternations of the voids surface, which

Table 3. Description of units – sample 3.

Unit	Groundmass	Voids	Pedofeatures
3/A	**C/F distribution**: chitonic (single spaced) changing into enaulic (fine), in places porphyric; **C/F limit**: clay/ fine sand; **coarse component**: 40% of the t.t.s.a., fine to medium sand, shape blocky, sub-angular to angular, medium variability within partial fabric associated with size and shape; **fine component**: 5-15% of the t.t.s.a., clay with considerable admixture of silt, distribution clustered close to the edges of aggregates, clay creates dusty and impure quasi- and hypo-coatings (20-40 µm thick), some decomposed clay coatings are present in matrix; **microstructure**: granular to spongy	55-45% of the t.t.s.a.; **compound packing voids**, **vughs** and **channels**; compound packing voids, vesicles and vughs: size of up to 2 mm; channels: width of up to 3 mm length up to 2 cm, along straight lines, orientation parallel and perpendicular to each other; all voids are filled with dusty clay	Pedality weakly developed; textural peds; peds not separated by voids; blocky shape; size very variable – difficult to measure due to weak separation of peds
3/B	**C/F distribution**: gefuric (concave); **C/F limit**: clay/ very fine sand; **coarse component**: 40% of the t.t.s.a, very fine to fine sand, shape blocky, sub-angular to angular, medium variability within partial fabric associated with size and shape, orientation of discrete, elongated grains is unimodal, parallel, with medium angle and moderately expressed parallelism; **fine component**: 55% of the t.t.s.a., distribution clustered; **within clay matrix iron oxide as concentric nodules is present**; **microstructure**: spongy (not well developed)	5% of the t.t.s.a.; **vesicles** and **vughs**: size up to 250 µm	No pedality developed in this unit; whole unit creates one ped, and it is divided from other units by channels and chambers
3/C	**C/F distribution**: gefuric (concave); **C/F limit**: clay/ very fine sand; **coarse component**: 40% of the t.t.s.a., very fine to medium, sand, shape blocky, sub-rounded to sub-angular, medium variability within partial fabric associated with size and shape, orientation is unimodal, parallel, with medium angle and moderately expressed; **fine component**: 55% of the t.t.s.a., distribution clustered in bands or fan-like with radial orientation, creates quasi- and hypocoatings on walls of vughs (10-20 µm thick) and cloudy aspect in the light of voids; **microstructure**: granular	40% of the t.t.s.a.; **vesicles** and **vughs**: size of coarse sand grains, cloudy aspect and quasi- and hypo-coatings coatings present (10-20 µm thick)	Pedality weakly developed; textural peds; peds weakly separated; size – very variable
3/D	**C/F distribution**: porphyric; **C/F limit**: clay/silt; **coarse component**: 20% of the t.t.s.a., silt and fine sand, shape blocky, sub-angular to angular, low variability within partial fabric associated with shape; **fine component**: 40% of the t.t.s.a., only in places distribution is radial, creates quasi- and hypocoatings on walls of channels (10-30 µm thick); **microstructure**: spongy (not well developed)	40% of the t.t.s.a.; vughs, channels, chambers; **channels and chambers**: aligned along curved planes, width up to 500 µm, length up to few centimetres, with dusty and impure quasi- and hypo-coatings (10-30 µm thick), orientation parallel and perpendicular, with medium angle and moderately expressed parallelism, chambers are of size of up to 1 mm; **vesicles** and **vughs**: size of up to 1 mm	Pedality weakly developed; textural peds; shape platy; peds not separated by voids; size of up to 1 cm in width and 2.5-3 cm in length

occurred after the origin of these features. Simple and complex packing voids prevail in samples 3, 4, 5, 7 and 8 (Figs 7, 8, 9, 11 and 12 respectively). As a general rule, it is observed that in places where packing voids prevail there are not channels and chambers present. Alternatively, where channels and chambers are the major type of void, the packing voids are not present. In most of the samples (apart from sample 7, Fig. 11) the walls of voids are covered with clay coatings (for example of clay coatings on walls of channels see micrograph in Fig. 16a). The clay coatings are most often not laminated, hence dusty and impure (Fig. 16a). However, the clay coatings on the walls of channels in samples 4 and 6 are micro-laminated, well organised and display diffuse extinction lines (Fig. 16a). In samples 2 and 6 (Figs 6 and 10 respectively), impure and dusty clay coatings are associated with walls of aggregates. In sample 9 (Fig. 13), some dusty and impure clay coatings occur on the surface of peds. Within the two topmost samples, 10 and 11 (Figs 14 and 15 respectively), some well organised, micro-laminated clay clusters occur within the matrix (for example see micrograph in Fig. 16h). These are probably clay coatings

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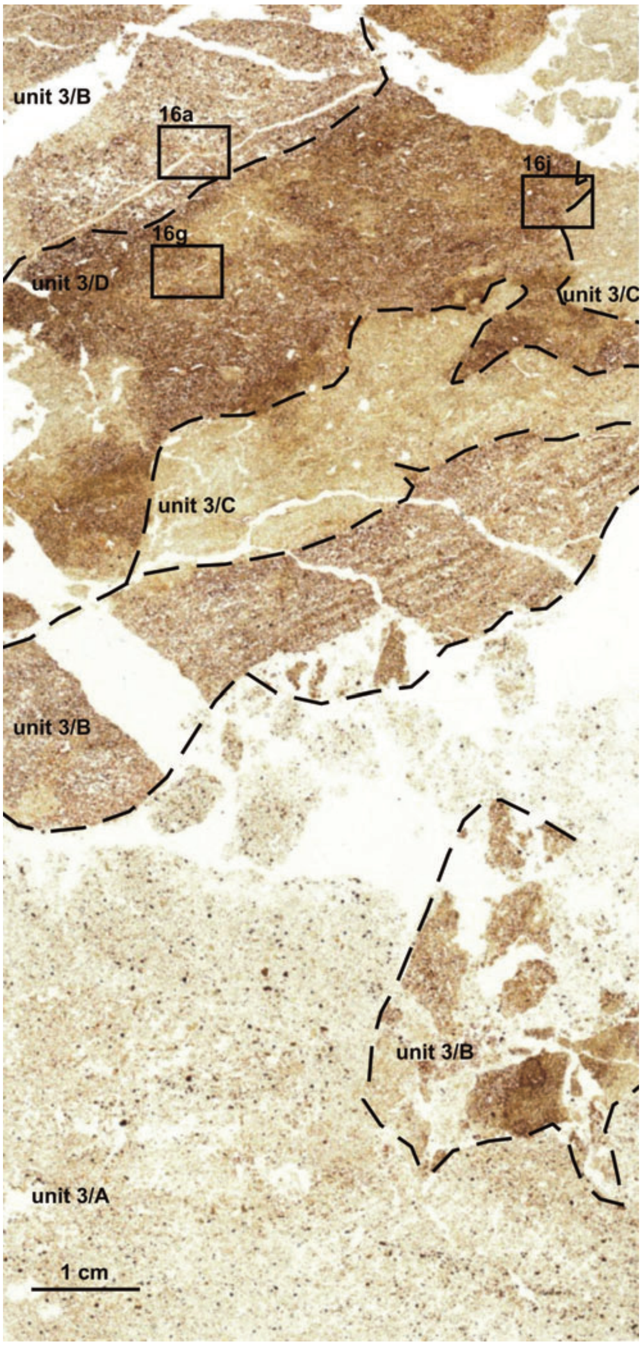

Fig. 7. High resolution scan of sample 3. Black boxes indicate location of micrographs depicted in Fig. 16a, g and j. Black dashed line indicates the boundary between discrete units.

which were formed on walls of voids and subsequently displaced into the matrix. Within samples 8-11 (Figs 12-15), there is a cloudy aspect to the clay within voids (for example see micrograph in Fig. 16d).

The degree of pedality increases towards the top of the sequence. All peds in the samples are blocky. In the topmost samples, the size of the peds becomes more variable.

There are some unique characteristics associated with particular samples. Within thin-section 3 (Fig. 7) there are depletion peds associated with iron-oxide nodules surrounded by rings of fine material enriched with iron-oxide (for example see micrograph in Fig. 16g). Moving toward the top of the sequence within samples 6, 8 and 11 (Figs 10, 12 and 15 respectively), alternations of iron-depleted and iron-enriched deposits may be observed. Iron-oxide is depleted usually from the component surrounding voids, especially channels.

Interpretation and discussion

Before any conclusion about the evolution of the periglacially disturbed sequence of the deposit is drawn, all micromorphological features have to be interpreted.

The finely laminated base of the sequence, depicted in sample 1 (Fig. 5), is either evidence for deposition from suspension in a low energy, lacustrine environment (Brewer, 1964) or the depletion of coarse particles in the deposit. Alternations in colour of the laminae are associated with cyclic (possibly seasonal) changes of the depositional environment. The unit above is composed of aggregates of sub-angular, coarse sand, embedded in a silty-clay matrix. Here, a fine component fills the gaps between the skeletal grains and aggregates. Fine

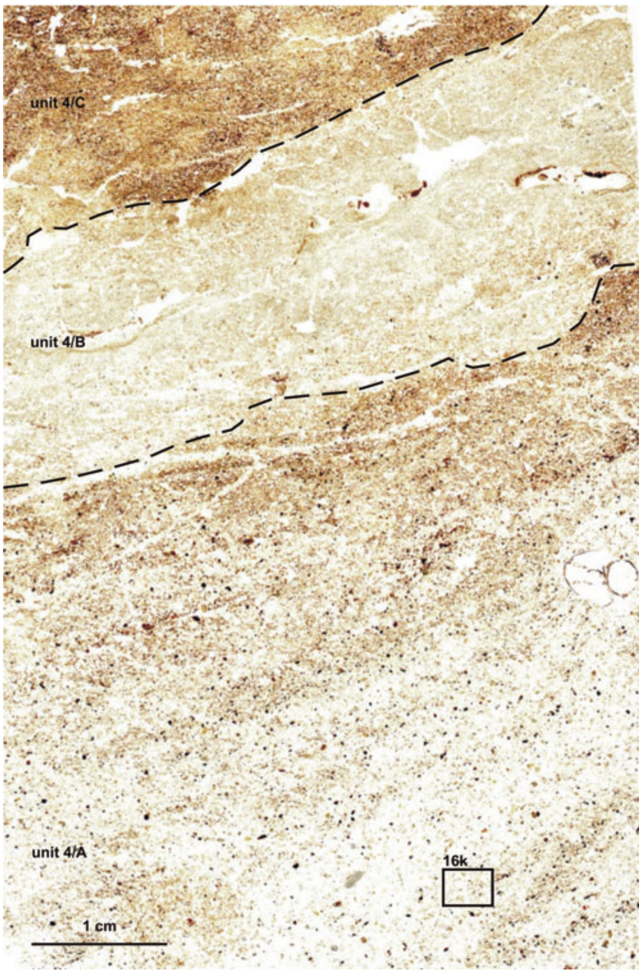

Fig. 8. High resolution scan of sample 4. Black boxes indicate location of micrographs depicted in Fig. 16k. Black dashed line indicates the boundary between discrete units.

Table 4. Description of units – sample 4.

Unit	Groundmass	Voids	Pedofeatures
4/A	**C/F distribution**: chitonic; **C/F limit**: clay/silt; **coarse component**: 40-50% of the t.t.s.a., silt and medium to coarse sand, shape blocky, sub-angular to angular, high variability within partial fabric associated with size and shape; **fine component**: 40-50% of the t.t.s.a; microstructure: basic with textural porosity – crumb microstructure	5% of the t.t.s.a.; simple and compound packing voids and vughs; **simple and compound packing voids**: size of up to 250 µm; **vughs**: size of up to 250-300 µm	Pedality weakly developed; textural and fabric pedofeatures; peds weakly separated; lenticular shape; distribution linear, parallel to the top of the unit; orientation is unimodal and strongly expressed
4/B	**C/F distribution**: chitonic, changing in places into monic (coarse); **C/F limit**: clay/fine sand; **coarse component**: 20% of the t.t.s.a., fine sand, shape blocky, sub-angular to angular, medium variability associated with shape, orientation of elongated grains is linear, perpendicular, parallel to the base of the unit, with small angle and strongly expressed parallelism; **fine component**: 5-10% of the t.t.s.a.; **microstructure**: granular to spongy	20% of the t.t.s.a.; compound packing voids, vughs and channels; **compound packing voids**: size of up to 250-500 µm; **vughs**: size of up to 250-300 µm; **channels**: width up to 1 mm, length up to 5 mm, aligned along curved planes, orientation is parallel and perpendicular to each other, with small angle and strongly expressed parallelism	Pedality moderately developed; textural and fabric pedofeatures; peds moderately separated; lenticular shape; size: width up to 5 mm, length up to 2 cm; distribution linear; orientation parallel, strongly expressed
4/C	**C/F distribution**: porphyric (single and double spaced); C/F limit: silt/fine sand; **coarse component**: 40% of the t.t.s.a., fine to medium sand, shape platy, only occasionally blocky, sub-angular, medium variability within partial fabric associated with size; **fine component**: 50-70% of the t.t.s.a., distribution is clustered in dusty quasi- and hypo-coatings on walls of channels/peds (10-50 µm thick); **microstructure**: vughy	5-10% of the t.t.s.a.; channels, chambers and vughs; **channels and chambers**: width up to 1 mm, length up to 5 mm, along curved and zig-zag planes, parallel and perpendicular to each other and base and top of the unit, with small angle and strongly expressed parallelism, dusty quasi- and hypo-coatings, chambers are of size of up to 5 mm; **vughs**: size of up to 1 mm	Pedality moderately developed; textural pedofeatures; peds moderately separated; elongated, lenticular shape; size: width up to 5 mm, length up to 1 cm; distribution linear; orientation parallel, strongly expressed

Table 5. Description of units – sample 5.

Unit	Groundmass	Voids	Pedofeatures
5/A	**C/F distribution**: enaulic (single to double spaced); **C/F limit**: silt/very fine sand; **coarse component**: 40% of the t.t.s.a., very fine to medium sand, shape is blocky, sub-angular to sub-rounded, high variability within partial fabric is associated with size and shape, distribution is clustered, orientation unimodal, parallel to each other and to the bottom of the unit, strongly expressed; **fine component**: 15% of the t.t.s.a., distribution clustered; **microstructure**: vughy to granular	50% of the t.t.s.a.; **compound packing voids and vughs**: size of up to 750 µm up to 1 mm	Pedality weakly developed; textural pedofeatures, variable size
5/B	**C/F distribution**: enaulic (open); **C/F limit**: silt/very fine sand; **coarse component**: **less than 3%**, very fine sand, shape tabular to lenticular, sub-rounded, very low variability within partial fabric, orientation unimodal, parallel, strongly expressed; **fine component**: 70% of the t.t.s.a., clay, silt and dissolved, decomposed organic matter, distribution clustered; **microstructure**: vughy to granular	5% of the t.t.s.a.; **vughs**: size of up to 250-500 µm	Pedality very weakly developed; textural peds; variable size

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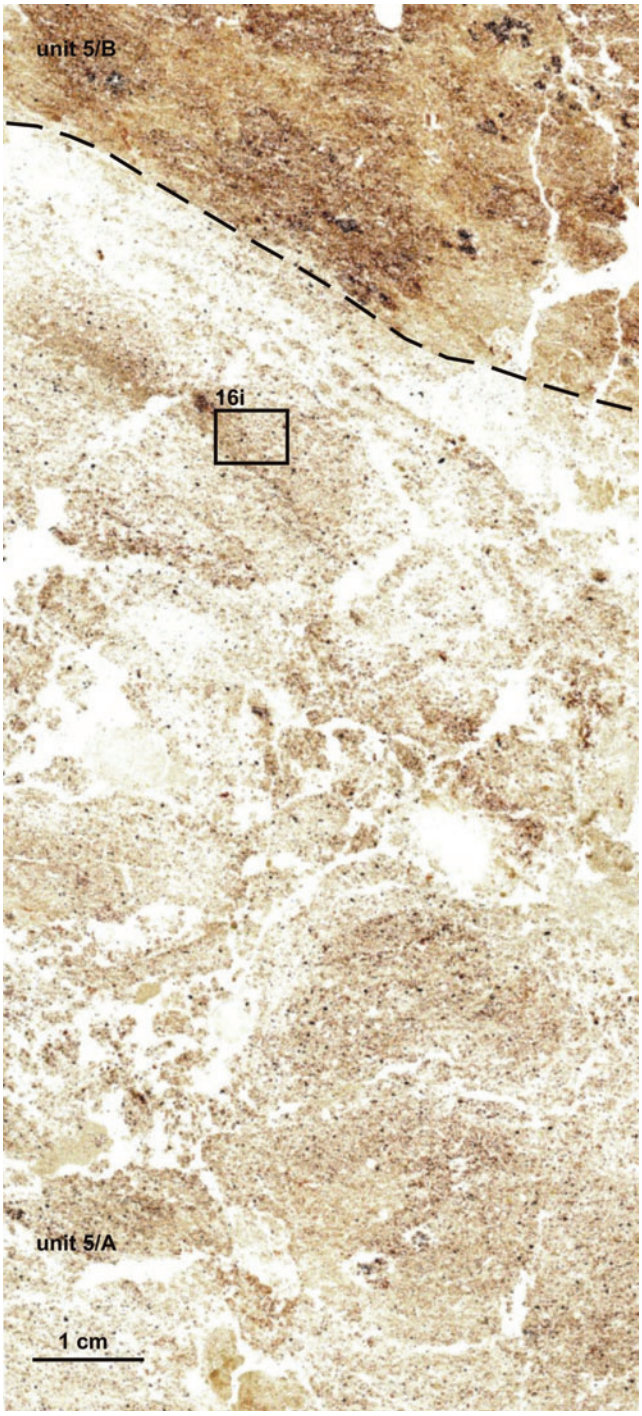

Fig. 9. High resolution scan of sample 5. Black boxes indicate location of micrographs depicted in Fig. 16i. Black dashed line indicates the boundary between discrete units.

particles (clay, and in some cases silt – see description of discrete samples in tables) come from either disturbed lower unit (unit 1) or the reworked clayey soils (Bertran, 1993). Towards the top of the sequence the coarse versus fine related distribution becomes more loose and unorganised. This deposit is associated with a higher energy environment, with less pronounced sorting, more rapid deposition and more distinct reworking of the deposit (Brewer, 1964).

The voids present in the deposit including channels, chambers, compound and simple packing voids vughs and vesicles, may be of various origins.

Channels and chambers which occur in the deposits from the Royal Oak Pit are interpreted after Brewer (1964) as the product of shrinking and swelling during wetting and drying cycles (Brewer 1964). If the walls of channels are non-accommodating, as is the case in the deposits from the site, they are interpreted as the product of shrinking and swelling during freezing and thawing of the deposit. (Van Vliet-Lanoe 1985). Channels that cut across laminations and sediment units are of post-depositional origin. Chambers usually evolve in places where two channels cross-cut and air bubble collapse (Brewer, 1964).

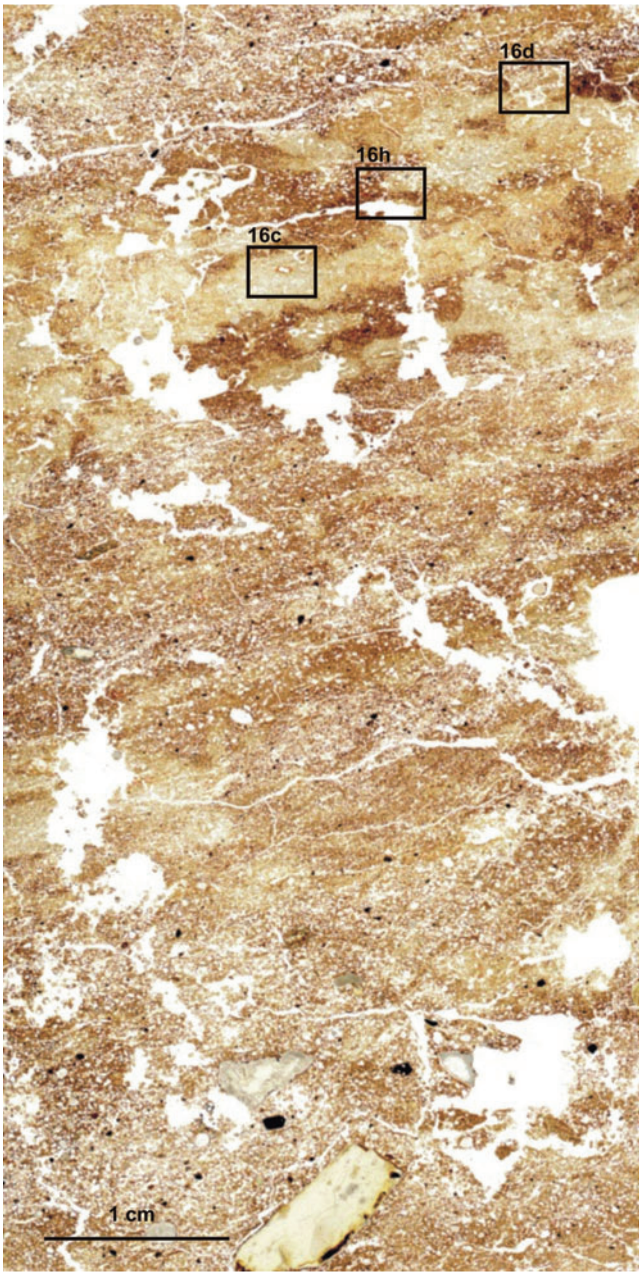

Fig. 10. High resolution scan of sample 6. Black boxes indicate location of micrographs depicted in Fig. 16c, d and h.

Table 6. Description of units – sample 6.

Unit	Groundmass	Voids	Pedofeatures
6/A	**C/F distribution**: chitonic; **C/F limit**: silt/ fine sand; **coarse component**: 20-30% of the t.t.s.a., fine to coarse sand, shape blocky, sub-rounded to sub-angular, high variability within partial fabric associated with size and shape, orientation bimodal, moderately expressed with medium angle; **fine component**: 50% of the t.t.s.a., distribution is clustered within bands, concentric lines around coarser clasts, clay creates dusty and impure as well as striated and limpid quasi- and hypo-coatings on walls of channels and chambers (10-50 µm thick); **microstructure**: very well developed vughy	Abundance very variable within thin section, from 0 to 30% of the t.t.s.a.; channels, chambers, vesicles and vughs; **channels**: width up to 25 µm, length up to few centimetres, aligned along zig-zag planes, walls are partially accommodating, dusty as well as striated and limpid quasi- and hypo- clay coatings on walls (10-50 µm thick); **chambers**: 1-1.5 mm, dusty and impure and disintegrated clay coatings, aggregates present within chambers, longer axes of these aggregates aligned with line of chambers; **vesicles** and **vughs**: size of up to 1-1.5 mm	No pedality developed

Vughs are voids inherent to welding of aggregates, microstructure disruptions or dissolution of components (Stoops, 2003). Any of these causes is plausible in the case of deposits from the Royal Oak Pit, however in the case of vughs with iron-oxide ‘rings’ around them (e.g. sample 3, Fig. 7) the latter explanation is most probable (Brewer, 1964; Van Vliet-Lanoe, 1985). Similarly, simple and complex packing voids are the products of physical disturbances and aggregation of deposit components. These two types of voids are very common in many types of deposits.

On the contrary, vesicles are interpreted as air and moisture migration remnants. Van Vliet-Lanoe et al. (1984) stress that vesicles are characteristic for frost-susceptible sediments and associated with conditions of super-saturation (Bertran, 1993; Van Vliet-Lanoë et al., 1984). The role of frost and the stress of proglacial conditions in evolution of vesicles is also highlighted by Fitzpartick (1956), Chandler (1972) and Bunting (1977) (Brewer, 1964).

The condition of preservation of all described voids is a stable character of the deposits achieved by compaction (Van Vliet-Lanoe et al., 1984).

The environmental interpretation of voids is intimately associated with the degree of pedality of the deposit. Strongly developed pedality (samples 6-11. Figs. 10-15) is evidence for poor consolidation, intense reworking or physical mixing of the deposit. Coexistence of strongly developed pedality with channels and chambers on non-accommodating walls and vesicles would indicate physical mixing of the deposit associated with action of frost and moisture as the most probable explanation (Brewer 1964). A downward decrease of pedality as well as presence of preserved voids is associated with pressure consolidation and hence stable character of the deposits and decreasing influence of freezing and thawing on the character of the deposit (Van Vliet-Lanoe, 1985).

Micro-laminated clay coatings are only typical for the top of the sequence. They are associated with water travelling through the voids and fissures in the sediment and depositing clay leached from the levels above. This is evidence for illuviation processes, which occur during environmentally stable periods as a part of soil forming processes. Dusty and

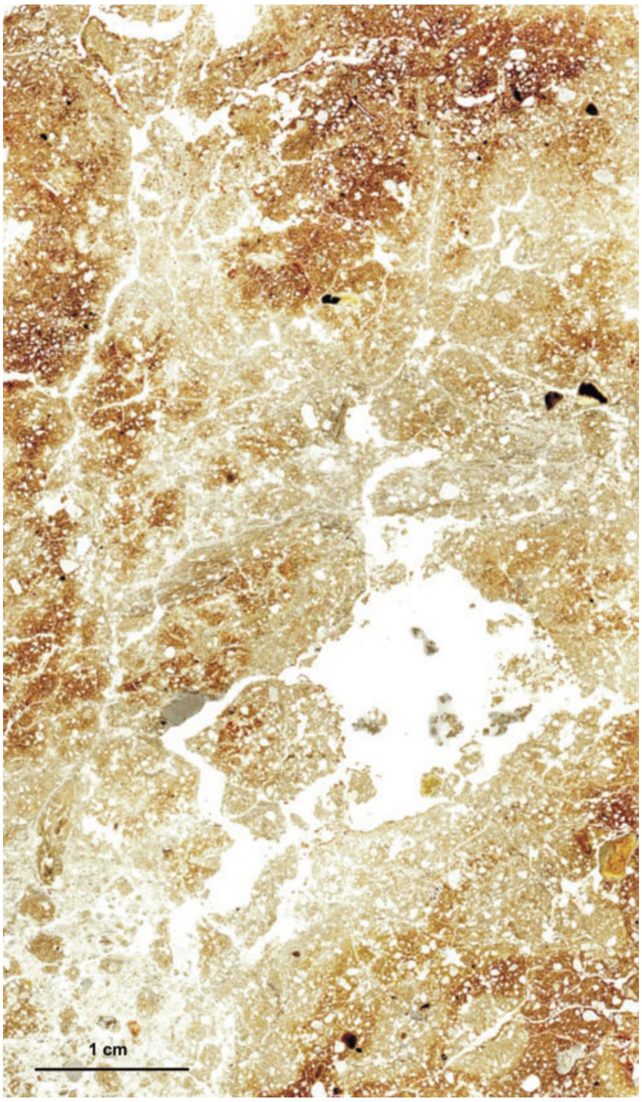

Fig. 11. High resolution scan of sample 7.

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Table 7. Description of units – sample 7.

Unit	Groundmass	Voids	Pedofeatures
7/A	**C/F distribution**: gefuric (concave); **C/F limit**: silt/very fine sand; **coarse component**: 60% of the t.t.s.a., very fine to very coarse, shape blocky, sub-rounded to sub-angular, medium variability within partial fabric is associated with size, distribution clustered, orientation parallel, unimodal, moderately expressed with medium angle, however, variable in various parts of the thin section; **fine component**: 30-40% of the t.t.s.a., in places stained red cross-striations present (orientation bimodal, with small angle of parallelism, strongly expressed); **microstructure**: vughy	Abundance very variable within thin section, from 0 to 50% of the t.t.s.a.; compound packing voids, vesicles and vughs, channels and chambers; **compound packing voids**, **vesicles** and **vughs**: size of up to 1.5-2 mm; channels and chambers: width from 50 µm up to 1 mm, length up to few centimetres, walls only in places partially accommodating	No pedality developed

Table 8. Description of units – sample 8.

Unit	Groundmass	Voids	Pedofeatures
8/A	**C/F distribution**: porphyric (single to double spaced); **C/F limit**: silt/very fine sand; **coarse component**: 20-25% of the t.t.s.a., very fine to medium sand, shape is blocky, sub-angular, high variability within partial fabric associated with size and shape, orientation is bimodal, with medium angle, moderately expressed.; **fine component**: 70% of the t.t.s.a., distribution is clustered, linear, and orientation is bimodal, parallel and perpendicular to each other, moderately expressed (cross-striated), colour yellow to orange and grey; **microstructure**: massive with textural peds, not separated by voids is described; textural peds are associated with orientation of partial fabric	5% of the t.t.s.a.; **vesicles** and **vughs**: distribution clustered, size of up to 1-1.5 mm, cloudy aspect of clay in voids	No pedality developed
8/B	**C/F distribution**: porphyric (close); **C/F limit**: silt/very fine sand; **coarse component**: 30% of the t.t.s.a., very fine to very coarse sand, shape blocky, sub-rounded, medium variability within partial fabric associated with shape and size, distribution of very fine sand – clustered; **fine component**: 30-40% of the t.t.s.a., distribution clustered linear, orientation parallel in various directions – bow-like, crescent-like, create dusty quasi- and hypo-coatings on walls of channels and cloudy aspect (20-40 µm thick); **microstructure**: vughy	Abundance very variable within thin section, from 5 to 50% of the t.t.s.a.; channels, chambers and vughs; **channels and chambers**: aligned along zig-zag lines, width up to 5 mm, length up to few cm, size of chambers of up to 3 mm, walls covered with dusty quasi- and hypo-coatings (20-40 µm thick); **vesicles** and **vughs**: distribution clustered, size of up to 1-1.5 mm; cloudy aspect of clay in all voids	Pedality moderately developed; textural, fabric pedofeatures; peds weakly separated; shape blocky or elongated and platy; size: width up to 5 mm, length up to 2 cm

impure clay coatings as well as cloudy aspect of clay, which replace well-organised structures towards the base of the sequence, are due to remobilisation and disruption of originally well-organised structures some time after the deposition, during phases of subsequent freezing and thawing (Brewer, 1964; Bullock et al., 1985; Stoops, 2003).

Clay-sized (and only occasionally silt-sized) particles present in spaces between coarse component and aggregates (as in the porphyric, gefuric and enaulic C/F distribution) and covering them with coatings (as in the chitonic C/F distribution) are the product of fine particles travelling through the sequence with water after the thawing of the ground ice. The movement of grains and aggregates is necessary for fine particles to be able to cover them (as in the chitonic C/F distribution). Following this, fine particle coatings on the sand-sized component is evidence for mass movement of the deposit (Harris and Ellis, 1980). Interpretation of the available evidence provides details of the processes of evolution and tentative chronology of the periglacially disturbed sequence at the Royal Oak Pit. The material associated with the base of the sequence strongly suggests deposition in a low-energy lacustrine environment. Clay and silt deposited in this unit probably came locally from the London Clay bedrock. The lack of coarser particles suggests either a distal position from the site with respect to the ice sheet, or a lack of coarser material in a source area. The deposition of lacustrine sediments was followed by the implacement of coarser material, including sand and pebbles. This may be evidence for a more proximal environment of deposition, with respect to the ice sheet or a new source of coarser material. Characteristics such as presence of voids

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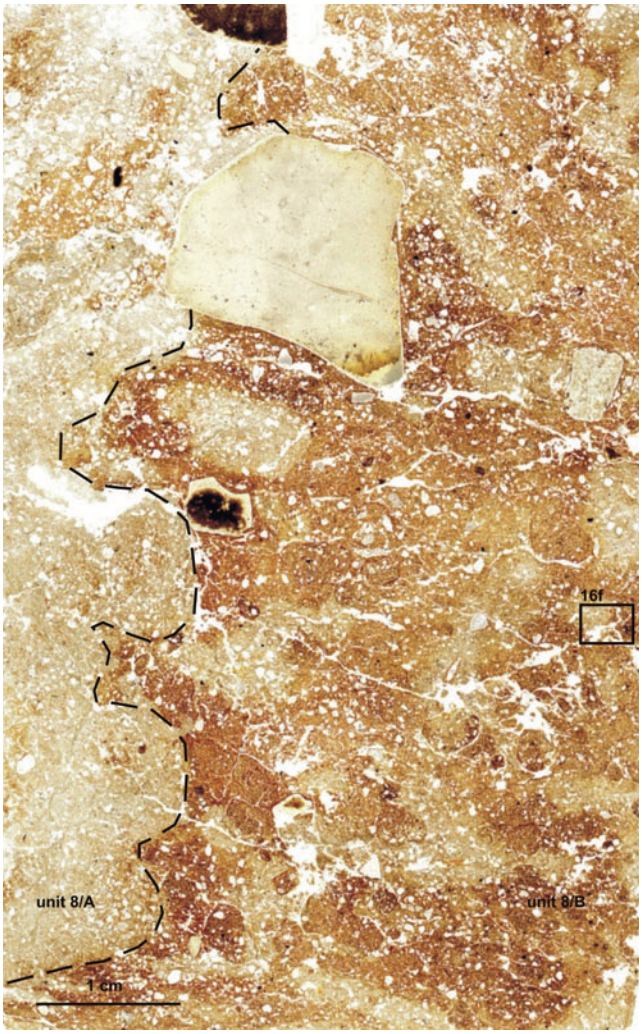

Fig. 12. High resolution scan of sample 8. Black boxes indicate location of micrographs depicted in Fig. 16f. Black dashed line indicates the boundary between discrete units.

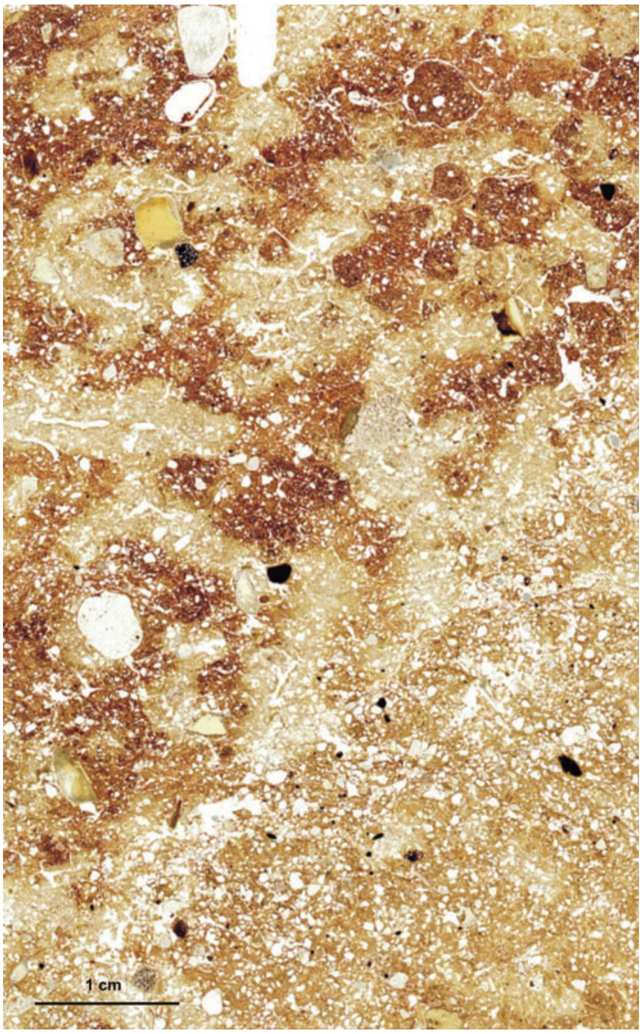

Fig. 13. High resolution scan of sample 9.

associated with shrinkage (channels), presence of voids characteristic for super-saturated, thawed and frozen deposits (vesicles), presence of voids characteristic for reworked sediments (vughs) and presence of fine particles coatings on coarse component grains and aggregates, allow interpreting the deposits as freeze, thawed and displaced. The presence of few generations of these features (e.g. channels) indicates that physical reworking associated with periglacial conditions took place on multiple occasions. It is also clear that some soil forming processes associated with illuviation took place. The presence of clay coatings (well organised, striated clay coatings, both in situ and displaced) on walls of channels and peds throughout the whole sequence, not only in the topmost part, suggests that the soil forming processes, characteristic for

Table 9. Description of units – sample 9.

Unit	Groundmass	Voids	Pedofeatures
9/A	**C/F distribution**: enaulic (open); **C/F limit**: silt/very fine sand; **coarse component**: 40-45% of the t.t.s.a., very fine to very coarse sand, shape is tabular, only occasionally blocky and sub-rounded, high variability within partial fabric associated with size and shape; **fine component**: 50-60% of the t.t.s.a., clay creates limpid, quasi- and hypo-coatings (10-30 µm thick); **microstructure**: sub-angular blocky	5% of the t.t.s.a.; vesicles, channels and chambers; **vesicles**: size of up to 1 mm; **channels and chambers**: width up to 20 µm, length up to few centimetres, aligned along curved planes, walls partially accommodating, limpid, quasi- and hypo- clay coatings on walls are present (10-30 µm thick), chambers are of size of up to 1 mm	Pedality strongly developed; impregnative pedofeatures; peds highly separated; shape blocky, in places spherical; distribution and orientation random; size: very variable; variability within partial fabric – very high, associated with size and shape of peds

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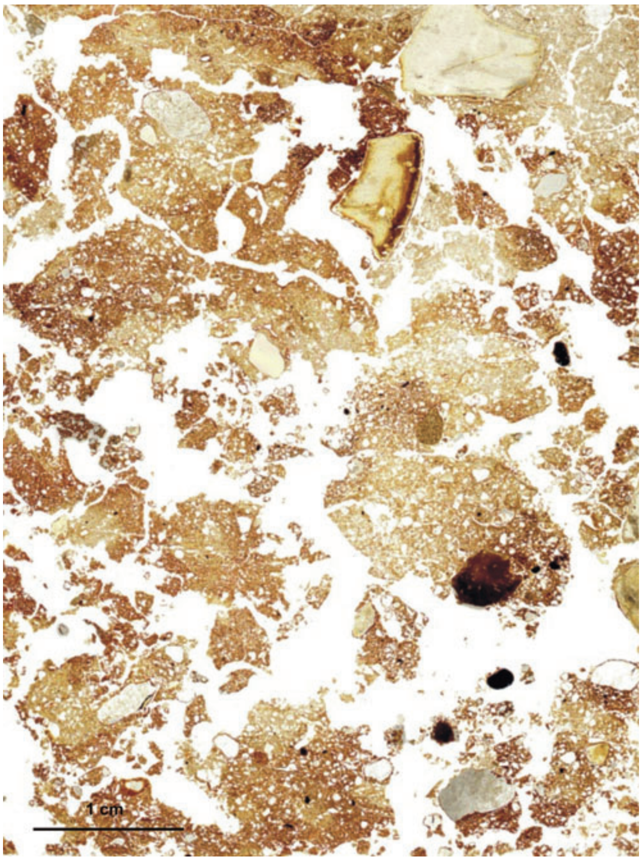

Fig. 14. High resolution scan of sample 10.

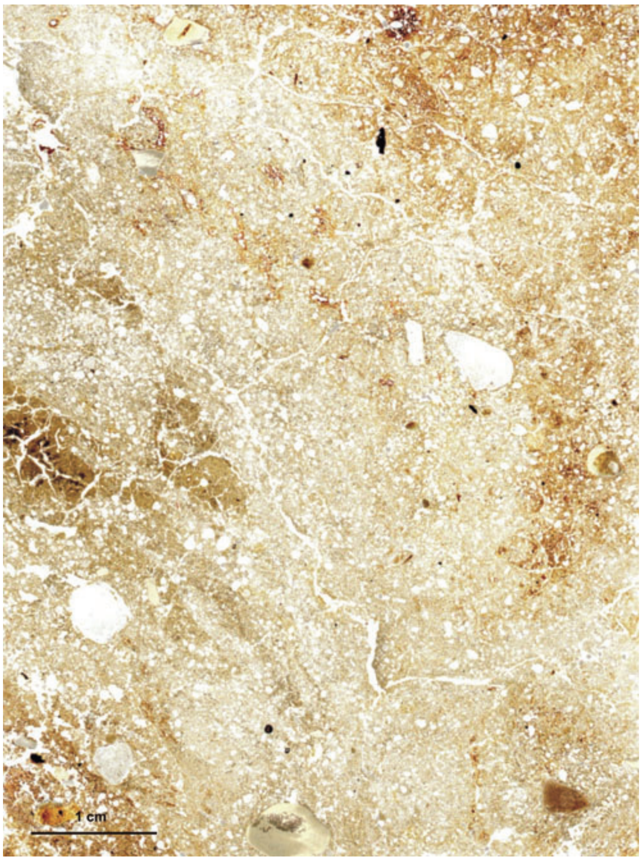

Fig. 15. High resolution scan of sample 11.

Table 10. Description of units – sample 10.

Unit	Groundmass	Voids	Pedofeatures
10/A	**C/F distribution**: porphyric (close); **C/F limit**: silt/ fine sand; **coarse component**: 20% of the t.t.s.a., fine to very coarse sand, shape blocky, angular, high variability within partial fabric associated with size and shape; in the upper part of the thin section coarse mineral component is composed mainly of fine to medium sand, shape blocky, sub-angular to sub-rounded; **fine component**: 30% of the t.t.s.a., in the upper part of the thin section clay fills horizontal channels, clay creates limpid quasi- and hypo-coatings (20-40 µm thick); **microstructure**: granular with well interconnected compound packing voids	50% of the t.t.s.a.; channels and chambers, vesicles and vughs and compound packing voids; **channels and chambers**: width up to 50 µm, length up to few centimetres, aligned along straight planes, orientation bimodal, parallel and perpendicular to each others, superposition of vertical channels on horizontal, in the upper part of the thin section limpid quasi and hypo- clay coatings present on walls of channels (20-40 µm thick), chambers are of size of up to 1 cm in diameter; **vesicles, vughs and compound packing voids**: size of up to few milimetres	Pedality strongly developed; textural, impregnateve pedofeatures; peds highly separateed; shape blocky; size very variable – in the upper part of the thin section peds are bigger

Table 11. Description of units – sample 11.

Unit	Groundmass	Voids	Pedofeatures
11/A	**C/F distribution**: porphyric (close); **C/F limit**: silt/very fine sand; **coarse component**: 25% of the t.t.s.a., very fine to coarse sand, shape tabular, sub-rounded, variability within partial fabric medium, associated with size, distribution clustered, orientation bimodal, parallel and perpendicular to each other; **fine component**: 60-70% of the t.t.s.a., distribution clustered, orientation bimodal, parallel, strongly expressed (cross-striated), creates dusty and impure, quasi- and hypo- clay coatings on walls of channels/peds (10-20 µm thick); **microstructure**: vughy.	10% of the t.t.s.a.; channels and chambers, vesicles and vughs; **channels and chambers**: width up to 20 µm, length up to few centimetres, aligned along straight and zig-zag planes, some dusty and impure quasi- and hypo- clay coatings present on walls (10-20 µm thick), chambers are of size of up to few millimetres in diameter; **vesicles** and **vughs**: size of up to 1 mm.	Moderately developed pedality; textural pedofeatures; peds moderately separated; shape: blocky, sub-angular; size: very variable.

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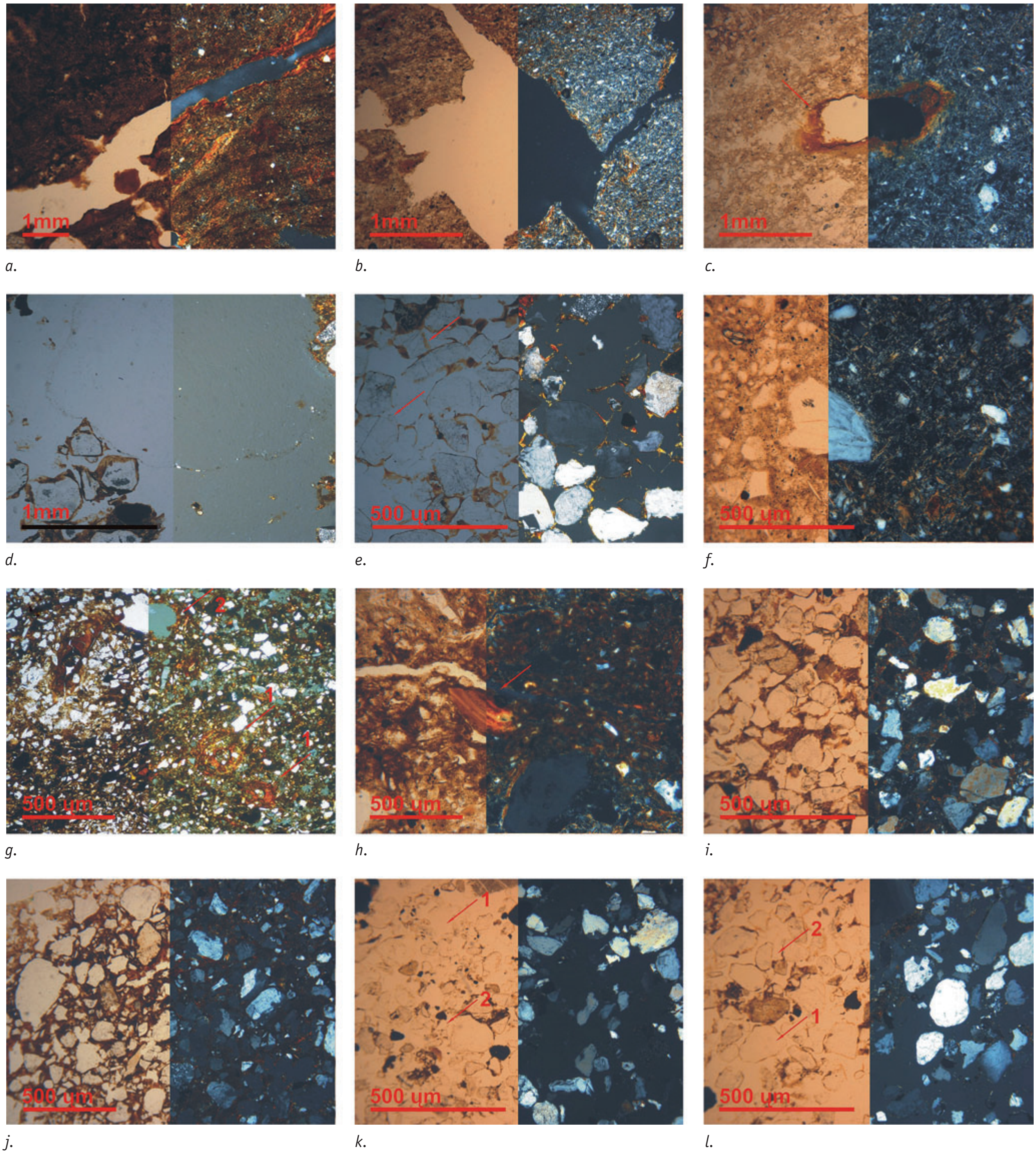

Fig. 16. Micrographs of examples of characteristic features in micromorphology of samples taken from the Royal Oak Pit deposits. Locations of discrete micrographs is indicated in figures of samples from which they come: a. channel with dusty, impure as well as limpic clay coating; walls of channel are rough and non-accommodating; on this micrograph monic (fine) C/F distribution is also depicted (sample 1); b. chamber with smooth walls and without clay coatings (sample 1); c. vesicle with red staining caused by accumulation of iron-oxides around (red arrow indicates accumulation of red stained iron-oxides) (sample 6); d. cloudy aspect of clay within void (sample 6); e. striated sand grains (red arrow indicates grain with well developed striation); on this micrograph simple packing voids are also well depicted (sample 2); f. cross-striated matrix; note that under plain light it displays cloudy aspect, while bi-modal orientation is visible only under cross-polarised light (sample 8); g. nodule-like concentrations of red stained iron-oxides (red arrows 1 indicate examples) and vugh (red arrow 2 indicates example) (sample 3); h. decomposed and relocated well organised, finely laminated clay coatings within matrix (red arrow indicates example) (sample 6); i. gefuric C/F distribution (sample 5); j. porphyric C/F distribution (sample 3); k. monic (arrow 1) changing into enaulic (arrow 2) C/F distribution (sample 4); l. chitonic (arrow 1) changing into enaulic (arrow 2) C/F distribution (sample 2).

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stable environmental conditions occurred on few occasions throughout the history of the evolution of this deposit.

It is worth considering the conundrum presented by the presence of such a pronounced thickness of periglacially disturbed deposits at a location on the slope of the Danbury hill. As it was presented above, the deposits from the Royal Oak Pit, have been preserved despite the fact that they were multiply reworked, occasionally super-saturated with water and displaced. It is hence plausible to conclude that such a thick sequence of periglacially disturbed deposits must have originally been deposited in an area with sufficient protection and accommodation space to have been preserved. It is proposed here that the periglacially disturbed deposits at the Royal Oak Pit site, currently located at the slope of the Danbury hill, must once have been laid-down in a valley or col, at a relatively low altitude compared to the surrounding hills. It is the action of intense periglacial activity over the last 400,000 years that has destroyed the surrounding hills of London Clay, and preserved the 'armoured' periglacial sediments in an elevated position in the landscape. Such 'inversion of relief' is common over Quaternary timescales in the soft clay and limestone bedrocks of Southern England.

Conclusion

Micromorphology has proved to be a useful tool in the description of Elsterian (Anglian) periglacially disturbed deposits. The sequence of evolutionary processes of the periglacially disturbed deposits at the Royal Oak Pit has been established, and a hypothesis of topographic inversion has been advanced to explain their incongruous location and elevation. Deposits from this location have been described as modified by freeze-thaw processes and displaced on multiple occasions. All the samples from the periglacially disturbed sequence were described according to the New Methodological Approach for Thin-Section Description. This proposed approach not only unifies micromorphological descriptions, but also serves as a guiding tool for those new to the field of micromorphology.

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