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A comparison of micro-CT and thin section analysis of Lateglacial glaciolacustrine varves from Glen Roy, Scotland

Jacob M. Bendle [a, b], Adrian P. Palmer [a, b, *], Simon J. Carr [c]

[a] Centre for Micromorphology, Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK
[b] Centre for Quaternary Research, Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK
[c] Centre for Micromorphology, School of Geography, Queen Mary University of London, Mile End Road, London E1 4NS, UK

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ABSTRACT

Despite the prevalence of thin section analysis in studies of Quaternary sediments, there are limitations associated with the production of thin sections (sediment modification) and the inherently 2D view that a thin section affords. Non-destructive and rapid scanning technologies such as X-ray computed microtomography (μCT) enable material samples to be visualised and analysed in 3D. In a Quaternary context, however, such techniques are in their infancy. This paper assesses the optimum approach to μCT analysis of Quaternary sediments, applying the method on Lateglacial glaciolacustrine varves from Glen Roy, Scotland. Scan datasets are examined at each stage of the thin section process and comparisons are made between 2D μCT images and thin sections for the recognition of 2D sediment features, with further appraisal of 3D models to identify 3D sediment structures. Comparable sediment features are observed in 2D μCT images and thin sections, however, the μCT imaging resolution determines the precision of microfacies descriptions. Additional 3D structures are distinguished from volumetric models that are otherwise impossible to identify in thin section slides. These 3D structures can locally alter sediment properties (e.g. layer thickness) as seen in 2D thin sections and/or digital images, although such variation cannot be detected with these media. It has been demonstrated that clear benefits exist in understanding the 3D structure of Quaternary sediments, both prior to thin-sectioning to avoid complicating (e.g. deformation) structures, and after thin-sectioning to establish the complex 3D context of 2D datasets. It is recommended that μCT and thin section techniques are applied in parallel in future studies, which will profit from the integration of 'true' 3D data. It is also advised that samples are scanned soon after field sampling, due to the significant modification of *in situ* sediment structures that can occur during thin section processing.

1. Introduction

Thin section micromorphology is increasingly being used as a primary tool for the investigation of unconsolidated sediments from almost all depositional environments (van der Meer and Menzies, 2011 and references therein). The main advantage of thin section micromorphology is that samples obtained from sediment exposures or sediment cores can be observed *in situ*, as an aid to understanding the processes of sediment formation (e.g. deposition, deformation). Micromorphology also provides an important source of process information where sediment structures or facies are not readily observed with the naked eye.

These advantages attract scientists from an array of disciplines; however, the technique has become most popular among Quaternary geologists, especially those investigating glacial (e.g. Menzies and Maltman, 1992; van der Meer, 1993, 1997; Phillips and Auton, 2000; Carr and Rose, 2003; van der Meer et al., 2003; Heimstra et al., 2005; Larsen et al., 2006; Menzies et al., 2006; Hart, 2007; Phillips et al., 2007, 2011; Lee and Phillips, 2008) and lacustrine environments. For palaeolimnologists, micromorphological techniques have developed in line with recognition that lacustrine sediments may store environmental information on an annual and even sub-annual basis, in the form of discrete laminations and sub-laminations (e.g. Kemp, 1996; Dean et al., 1999; Brauer, 2004). Macroscopic techniques can often identify clastic or biogenic

* Corresponding author. Centre for Micromorphology, Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK.
E-mail address: a.palmer@rhul.ac.uk (A.P. Palmer).

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lamination structures of millimetre to centimetre-scale thickness but are unable to resolve the finer (seasonal) microstructures contained within, necessitating the use of thin sections to confirm the true nature of laminations and whether or not they preserve an annual (varve) structure (e.g. Brauer et al., 1999; Brauer and Casanova, 2001; Lücke and Brauer, 2004; Schlolaut et al., 2012). Using micromorphology to deconstruct, classify and measure varve constituents at short, specific time intervals has enabled environmental reconstructions of unprecedented temporal resolution, and improved models of past climatic change (e.g. Brauer et al., 2008a, 2008b; Mangili et al., 2010; Lauterbach et al., 2011; MacLeod et al., 2011; Martin-Puertas et al., 2012). Applications of the technique to both glacial and lacustrine sediments have also benefited from technical improvements in the manufacture of thin sections (e.g. Lamoureux, 1994; Lotter and Lemke, 1999; Palmer et al., 2008a) for sediment types that have previously proven problematic, e.g. clay-rich glaciolacustrine varves.

Despite its advantages for sediment analysis, thin section micromorphology comes with (typically under-reported) limitations that are relevant to all sediment types. First, thin section preparation is both labour- and time-intensive, with 10–14 weeks required for thin section production, whilst the procedure itself can be regarded as destructive. The resin used to impregnate and lithify the sample prevents subsequent subsampling of the sediment block for other lithological investigations (e.g. extraction of heavy minerals, particle-size analysis) or for the extraction of palaeoenvironmental and/or chronological samples (e.g. microfossils or dateable material). While certain subsampling approaches may retain sufficient sediment to allow a variety of multi-proxy analyses (e.g. Nakagawa, 2007), such methods typically make use of material from adjacent core segments, instead of material taken directly from the thin-sectioned sample. Second, the plane of thin-sectioning is rarely selected with prior knowledge of the internal sample structure or constituents, the potential outcome of an arbitrary selection process being a misrepresentative thin section. Moreover, the time-consuming nature of thin section manufacture usually limits the creation of multiple thin sections to assess for representativeness. Third, thin sections are limited to 2D representation of 3D features that are complex, variable and spatially interconnected (e.g. Lea and Palmer, 2014), the possible outcome being misclassification or misidentification of features. The detailed structure of laminated sediments is now more commonly reported, and given the significance attributed to micromorphological evidence in these published studies, it is important to test alternative techniques for their potential to address the limitations of thin section studies, whilst providing information of comparable quality.

One such technique is X-ray computed microtomography (μCT), a high-resolution variant on the medical CT scanner (Houndsfield, 1973). μCT is based on the principle of X-ray attenuation by matter (Duliu, 1999; Mees et al., 2003; Carlson, 2006; Davis et al., 2010), the level of which closely corresponds to the density and composition (effective atomic number) of the scanned material(s) (Orsi et al., 1994; Denison et al., 1997; Orsi and Anderson, 1999; Ketcham and Carlson, 2001; Van Geet et al., 2001; Schreuers et al., 2003; Carlson, 2006). During scanning and reconstruction, a stack of z slices is generated through tomographic back-projection based on a large number of X-ray radiograms. This enables the creation of a true 3D volumetric model (volume rendering) whereby voxels (volumetric pixels) are co-registered within and between slices. Volume renderings offer a means to visualise and measure spatial variations in internal sample structure and composition. In the geosciences, this has enabled users to collect new evidence in a non-destructive way to support traditional thin section analysis and to overcome some of its limitations (see Ketcham and Carlson, 2001; Carlson, 2006; Baker et al., 2012; Cnudde and Boone, 2013 for reviews). μCT has been used extensively, although not exclusively, for pore characterisation (e.g. Sleutel et al., 2008; Bouckaert et al., 2009; Polacci et al., 2010; Sok et al., 2010; Rozenbaum, 2011; Dewanckele et al., 2012), grain analysis (e.g. Benedix et al., 2008; Gualda et al., 2010; Cnudde et al., 2011, 2012), structural (e.g. fracture) analysis (e.g. Zhu et al., 2007; Zabler et al., 2008; Ketcham et al., 2010), and for morphological analysis (and digital archiving) of rare or delicate specimens (e.g. Dierick et al., 2007; Parfitt et al., 2010; Gai et al., 2011). In Quaternary sedimentology, however, μCT has received scant attention until very recently. Developing upon the preliminary work of Kilfeather and van der Meer (2008), Tarplee et al. (2011) applied the technique to glacigenic sediments, providing new insights on kinematic indicators within pro- and subglacial sediments. Tarplee et al. (2011) emphasise the requirement for further applications of the technique on unconsolidated Quaternary sediments, to examine the possibilities of μCT for research into other sediment types.

Glaciolacustrine laminated sediments and, more specifically, glaciolacustrine varves, are well suited to test the potential of μCT scanning for microscale analyses of unconsolidated sediments for three reasons: 1) the macroscale sedimentology of such sediments are commonly composed of distinct lamination couplets of silt or sand, with sharp contacts to laminations of clay; 2) thin section micromorphology is well-established in the study of laminated lacustrine sediments, which can be composed of many fine-scale (sub-mm) individual laminations. As such, descriptive protocols have been developed to differentiate lamination microfacies (e.g. Ringberg and Erlström, 1999; Palmer, 2005; Palmer et al., 2012) that can also be applied to μCT analysis; 3) compared to many other types of sedimentary deposit, distal glaciolacustrine varves accumulate under comparatively stable conditions, and are more likely to be unaffected by syn- or post-depositional deformation structures. Consequently, glaciolacustrine varves present a clear primary structure and a relatively unambiguous reference point with which to apply μCT analysis. This paper therefore aims to compare visible microstructures within two samples of laminated lacustrine sediment through a combination of thin section and μCT analysis. To achieve this, the study will:

- Establish the nature of μCT output from scanning glaciolacustrine laminated sediments at the macroscale;
- Offer 2-dimensional (2D) comparisons between thin section and μCT slices for the recognition of microstructures and discrimination of sediment microfacies;
- Investigate the potential of 3-dimensional (3D) μCT volumes for the recognition of sediment structures and compare this to thin sections;
- Investigate the evidence for changes to sediment properties and structures resulting from thin section preparation.

2. Methods

2.1. Sample selection

Glaciolacustrine sediments from the Glen Turret Fan (GTF), Upper Glen Roy, Scotland (Fig. 1; 56°59′N, 04°43′W) were chosen for this investigation because they comprise clear, regular clastic lamination structures that have previously been classified using thin section micromorphology (Palmer, 2005; Palmer et al., 2010, 2012). The GTF sequence forms an integral component of the composite Lochaber Master Varve Chronology (LMVC), one of the few annually-resolved records of glacier and climate variability