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Micromorphological evidence of liquefaction, injection and sediment deposition during basal sliding of glaciers

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ABSTRACT

The sliding of an ice mass over its bed represents one of the main mechanisms for the forward motion of glaciers and ice sheets, facilitated by the periodic introduction of meltwater along the ice-bed interface or regelation of the overriding ice. In the geological record, however, physical evidence of this process having occurred beneath former ice masses is apparently limited. This paper presents the results of a detailed micromorphological study of thinly stratified subglacial tills exposed at two sites: (i) Galmis in Switzerland and (ii) Plumpe Farm, near Gretna in SW Scotland. The stratification within these tills comprises alternating layers of massive to weakly foliated diamicton and variably deformed (folded, faulted) laminated silt and clay. Microtextural and microstructural evidence is interpreted in terms of repeated phases of basal sliding as the ice overrode a soft-sediment bed. Elevated meltwater contents/pressures encountered immediately prior to, and during basal sliding promoted localised liquefaction within the bed. Decoupling of the ice mass from its bed enabled the injection of the liquefied diamicton along the ice-bed interface and/or into the laminated sediments immediately adjacent to this boundary. The laminated silts and clays record the settling out of fines (clay, silt) from meltwater trapped along the ice-bed interface after an individual phase of basal sliding has ceased. Injection of till into the locally water saturated silts and clays resulted in partial liquefaction and incomplete mixing of these fine-grained sediments with the diamicton. Density contrasts between the two liquefied sediments led to the development of a complex 'vinaigrette-like' texture comprising rounded to irregular till pebbles within a matrix of variably homogenised silty clay. Recoupling of the ice with its bed led to localised folding and thrusting within the laminated silts and clays, hydrofracturing and injection of a network of sand-filled veins, and the imposition of a variably developed clast microfabric in the diamicton layers. Analysis of the clast microfabrics indicates that the intensity of these fabrics is highly variable reflecting the variation in the intensity of deformation imposed by the overriding ice.

1. Introduction

The sliding of a glacier and/or ice sheet over its bed represents one of the principal mechanisms for the forward motion of both former and contemporary ice masses (Benn and Evans, 2010 and references therein). The basal sliding process is facilitated by either the introduction of meltwater along the ice-bed interface and/or the liberation of meltwater in response to regelation of the ice immediately adjacent to this boundary. The temporally variable nature of these conditions is thought to result in a stick-slip style of motion with phases of basal sliding leading to the repeated decoupling of the ice from its bed (Fischer and Clarke, 1997; Fischer et al., 1999; Winberry et al., 2009). This style of motion may occur over both hard (bedrock) and soft (sediment) beds. However, physical evidence in the geological record of this style of glacier motion having occurred over soft-sedimentary beds is apparently limited. Consequently, very little detail is known of the processes occurring during the sliding of ice over a soft bed.

Micromorphology is increasingly being used by glaciologists and Quaternary geologists as a primary tool for the analysis of subglacial sediments as the technique can provide far greater detail of the depositional and deformation histories recorded by these sediments than can be obtained from macro-scale studies alone (see Menzies and Maltman, 1992; van der Meer, 1993; Menzies et al., 1997; Khatwa and Tulaczyk, 2001; van der Meer et al., 2003; Hiemstra et al., 2005; Roberts and Hart, 2005; Baroni and

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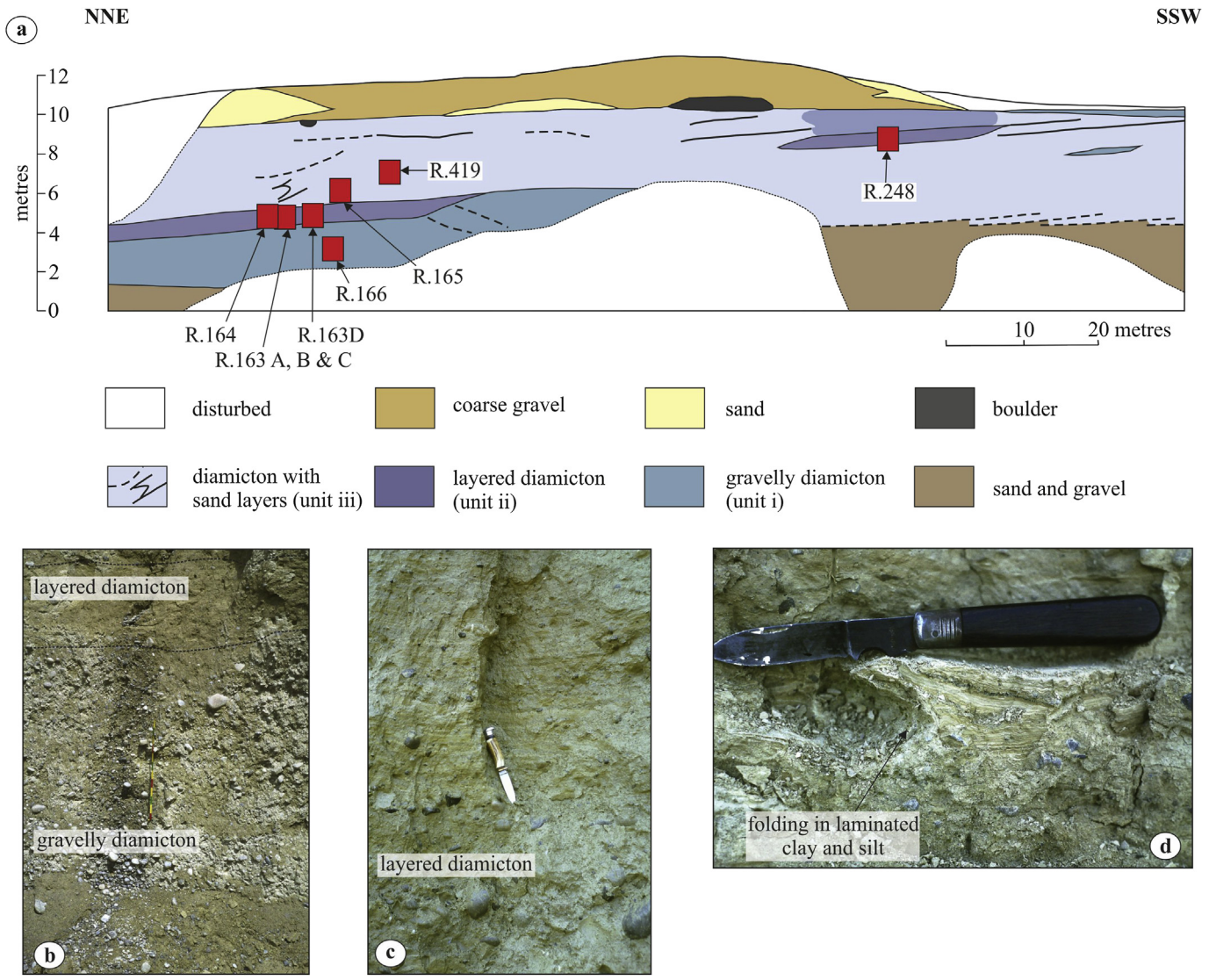

Fig. 1. (a) Diagram showing the distribution of the main sedimentary units exposed in the gravel pit, Galmis, Switzerland (after van der Meer, 1979, 1982). The location of the samples R.163A to D, R.164, R.165, R.166, R.248 and R.419 are also shown; (b) Photograph of the lower part of the till sequence comprising massive to weakly bedded diamicton overlain by thinly stratified diamicton. The boundary between the two units is sharp; (c) Photograph showing the layering which characterises the stratified diamicton; and (d) Small-scale asymmetrical fold deforming a laminated silt and clay layer within the thinly stratified diamicton.

Fasano, 2006; Evans et al., 2006; Larsen et al., 2006, 2007; Phillips and Lee, 2011; Neudorf et al., 2013). In particular, this approach has been used to unravel the often complex deformation histories recorded by glacigenic sequences (van der Meer, 1993; Menzies, 2000; Phillips and Auton, 2000; van der Wateren et al., 2000; Phillips et al., 2007; Lee and Phillips, 2008; Denis et al., 2010; Narloch et al., 2012, 2013; Vaughan-Hirsch et al., 2013) as well as investigate the role played by pressurised meltwater during these deformation events (Hiemstra and van der Meer, 1997; Phillips and Merritt, 2008; van der Meer et al., 2009; Denis et al., 2010; Phillips et al., 2013; Narloch et al., 2012, 2013). Subglacial diamictons are typically polydeformed deposits, the so-called "tectomict" of Menzies et al. (2006), having encountered several phases of deformation during either a single progressive event associated with a single phase of ice advance, or several multiple deformation events related to separate phases/pulses of ice advance. The recent development of a quantitative microstructural mapping method (Phillips et al., 2010) has the potential to increase our understanding of the processes occurring during subglacial deformation by highlighting the relationships between the various microstructures developed within the sediment thereby allowing a detailed relative chronology of deformation events to be established.

This paper presents the results of a detailed microstructural and sedimentological study of thinly stratified subglacial tills exposed at Galmis, Switzerland and Plumpe Farm, near Gretna in SW Scotland. The complex relationships displayed between the variably deformed, finely laminated silts and clays, and diamicton layers which comprise these stratified tills are interpreted in terms of a basal sliding model. The micromorphology of these sediments yields valuable insights into the processes occurring during basal sliding which include soft-sediment deformation, till liquefaction and injection, as well as the penecontemporaneous deposition of fines due to ponding of meltwater between individual "sliding events". Quantitative data (E1 and E2 eigenvalues) obtained for clast microfabrics present within the diamicton layers are used to investigate the variation in the intensity and partitioning of deformation imposed by the overriding ice as it recouples with the bed. The potential triggers leading to liquefaction of the diamicton