Micromorphology and microstructural analysis of polyphase deformation of tills, West Runton

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1. Introduction

Glacially deformed sediments have been studied intensely since the 1970's (van der Meer and Menzies, 2011), and with this, the use of micromorphology as a component technique (Menzies and Maltman, 1992; van der Meer, 1993; Menzies, 2000; Phillips and Auton, 2000; van der Wateren, 2000; Carr, 2001; Khatwa and Tulaczyk, 2001; van der Meer *et al*., 2003; Larsen *et al*., 2004; Menzies *et al*., 2006; Hiemstra, 2007; van der Meer and Menzies, 2011). Initially micromorphology was applied to differentiate between types of tills (van der Meer, 1987). However, it was realised that this was not possible and the majority of studies have since focused on subglacial conditions and its affect on glacier or ice sheet behaviour (van der Meer *et al*., 2003, Menzies *et al*., 2006). Until now micromorphology has generally consisted of creating an inventory of what microstructures exist and trying to comprehend where they occur and in what sub-environments of the glacial system they form (McCaroll and Rijsdijk, 2003; van der Meer and Menzies, 2011). This descriptive technique is dated and although it is not assumed that all microstructures are known, the next stage of scientific development is towards interpretation and quantification (van der Meer and Menzies, 2011; Phillips *et al*., 2011). The recent introduction of a new microstructural mapping method has aided this method by determining a chronology of events that have lead to the development of the microstructures seen in thin section (Phillips *et al*., 2011).

Traditionally microstructures have been categorised into four groups; ductile, brittle, polyphase and porewater induced (Menzies, 2000) (see Figure 2.4). However, this is approach is possibly too simplistic. For example, different grain sizes often occur side-by-side, which means that even under the same moisture conditions, there are different responses to stress and thus varying structure development (van der Meer and Menzies, 2011). Ductile deformation is induced when porewater pressure is high and

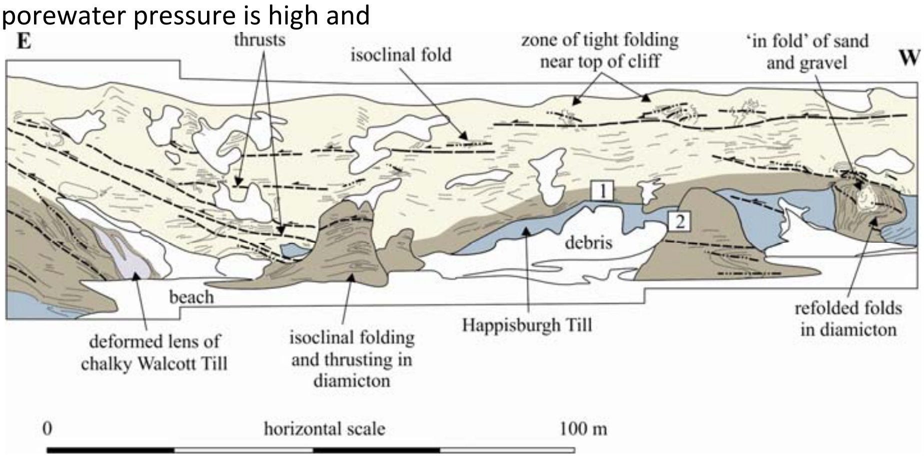

Figure 9.1. Location of samples WR09 1/4E (box 1) WR09 3/2 and WR09 3/3 (box 2), adapted from figure 5 in Phillips *et al*. (2008)

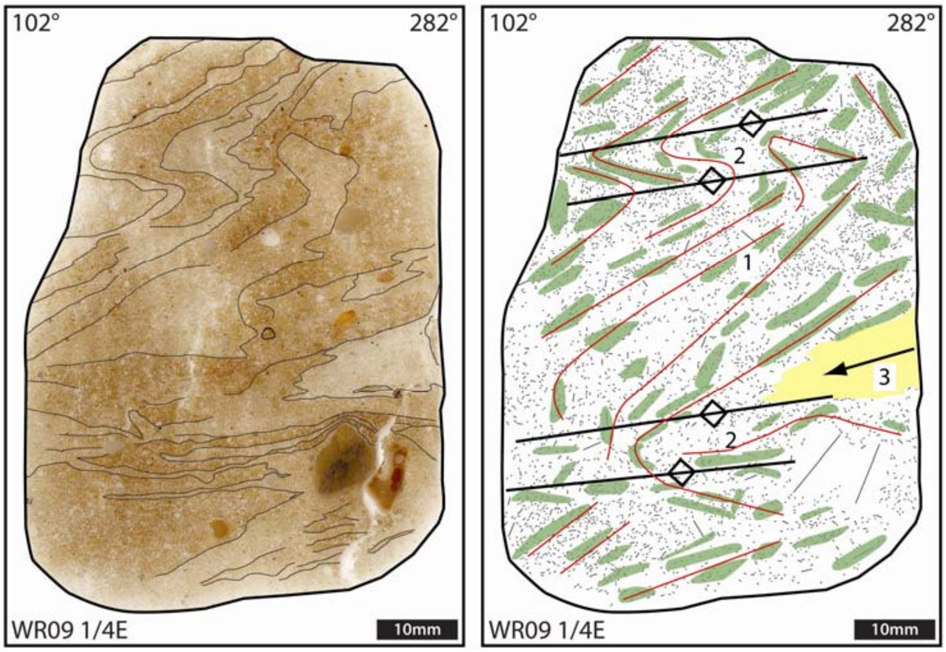

Figure 9.2. Microstructural map of sample WR09 1/4E

there is a low effective stress; whilst brittle deformation occurs when porewater decreases and effective stress increases or freezing occurs (Evans *et al*., 2006; Menzies *et al*., 2006). These variations affect the stress and strain levels in the material which allows for sediments to be repeatedly mobilised and reworked (Menzies *et al*., 2006). However, the microstructures observed cannot be categorised into one of four groups as the processes which lead to the formation of an individual microstructure could have undergone varying conditions to reach that point. Therefore it is important to realise that the term *polyphase deformation* encompasses all types of deformation including ductile, brittle and porewater induced structures, independently or combined (Phillips and Auton, 2000; Phillips *et al*., 2002; van der Meer *et al*., 2003; Phillips *et al.,* 2007; Kilfeather and van der Meer., 2008). As a result of this, polyphase deformation can relate to both temporally separated phases of deformation and/or to the simultaneous different deformation styles caused by compositional differences. Because of this, polyphase deformation is often used where there is evidence of deformation and as a result has become a generic term that differs in meaning between different members of the scientific community. It is important when discussing polyphase deformation (at all scales) to define the context in which it is being used.

West Runton has a complex deformation history because of the sediment record indicates a change from subglacial to ice-marginal to a proglacial environment (Phillips *et al*., 2008). The use of micromorphology will add to our understanding of polyphase deformation as it individually dissects the microstructures, that when pieced together give us a detailed model of polyphase deformation at West Runton. Below are three examples of common features recorded at West Runton and what can be extracted from the samples when using interpretive and quantitative methods. Figure 9.1 indicates the approximate locations of the samples using Phillips *et al*. (2008) detailed structural interpretation of the relevant part of the coastline.

*Location of sections**:** sections are located between West Runton (TG 181 341) and Sheringham (TG 165 433) and are best examined on an east to west traverse. Car parking is available at West Runton beach car park which also has a café and lavatories.*

2. Sample WR09 1/4E

Sample WR09 1/4E (orientation 102°-282°) was collected from a coastal exposure of the Bacton Green Till at West Runton (TG 176 850 BNG 43284). The sample was taken vertically in a Kubiena tin from a fold hinge within the Bacton Green Till. The fold has been highlighted by chalk stringers and grey Walcott Till which has been incorporated into the till. The sample was taken from the lower inverted limb of a tight fold with a horizontal axial plane.

The sample (Figure 9.2) is composed of a matrix supported till that has rare sub-rounded flint and chalk clasts. The two main components of the matrix are a lighter chalky till (Walcott Till) and a darker fine silt till (Bacton Green Till). The older Walcott Till has been incorporated into the younger Bacton Green Till as it overrode it. The contrast between the two tills highlights how the sediment has deformed. There are two large (>20 mm) sub-vertical fissures in the bottom right and the centre of the sample which were both formed during the manufacturing process. In addition there are occasional pebble type III rounded intraclasts in the Bacton Green Till (example highlighted in black circle).

It is most likely the tills would have been sub-horizontally layered (primary bedding) during an early phase of deformation as the older till would have been pulled up into the younger till above. This would account for the alternating tills which are still preserved and highlight the shape of the fold (secondary bedding). The proximal area around the fold shows a mélange of till in a generally horizontal direction, in line with ice movement. At a macro-scale, the hinge is a moderately smooth curve. However, at a micro-scale the fold hinge is irregular and feathery. The feathery appearance of the hinge was not caused by brittle deformation as there is no evidence of shearing; it was induced by increased water content at soft-sediment deformation in the latter stages of formation. There is a fine sand inclusion with no fabric or matrix direction (yellow polygon) in the inner limb of the fold hinge which has been incorporated from one of the larger sand intraclasts at an early stage which has then been deformed under high pressure with a high water content. The microfabric does not have a single dominant direction; it (green polygons) has a discontinuous spaced foliation that follows the hinge of the fold, as outlined by the red lines.

3. Samples WR09 3/2 and WR09 3/3

Samples WR09 3/2 and WR09 3/3 (TG178 820 BNG 43264) were collected from a section comprised of two units; a lower massive Happisburgh Till and an upper Bacton Green Till which had fine-medium sands that defines locally well-developed stratification within the till. The layering at the base of the Bacton Green Till, near the sharp contact to the underlying Happisburgh till, is sub-horizontal dipping 14° towards the east. This layering progressively steepens to a maximum dip of 75° at the top of the section.

WR09 3/2 (orientation 167°-347°) was taken in a Kubiena tin vertically over the contact between the two tills. There are rare sub-rounded large clasts of flint and chalk (<22 mm) and occasional smaller (<7 mm) sub-rounded clasts (Figure 9.3). The lower limit of the sharp boundary between the tills is defined by a strong orange and brown compacted silty clay boundary. Above this point, there is irregular layering between the alternating layers of Bacton Green Till and fine-medium sands which trends at the same orientation of the boundary. Below the boundary there is a more diffuse layering at the same orientation as above. There is also more broken layers of finer clays within the more clast (<2 mm) rich layer of the Happisburgh Till. As the ice sheet overrode the effect of it on the material below decreased with depth. This could account for the deformed layers and the more broken appearance of the Happisburgh Till. There are small vughs (<5 mm) randomly across the thin section which were formed during sample processing.

Three microfabrics directions are recognised in sample WR09 3/2, the dominant fabric direction is illustrated by the blue polygons (Figure 9.3) dipping moderately to the south (1), the second fabric is younger (2) and cuts across the blue fabric domain dipping more steeply to the south (green polygons) both form a semi-discontinuous foliation with c.50% zonal foliations. The final stage of deformation occurred with the reactivation of the blue fabric (3) along the boundary as the stress regime changed (intensity decreased) and slip occurred along the boundary. The third fabric direction is much less pervasive (yellow polygons) and dipping to the north, these discontinuous irregular foliations have a co-planar relationship with the dominant fabrics. It is clear that the microfabric is more strongly developed in the Bacton Green Till indicating that deformation was partitioned into the sandier till as higher water content in the upper part dilated the sediment.

Sample WR09 3/3 (orientation 167°-347°) was taken vertically in a Kubiena tin c.20 cm further up the section, over layers of sand inter-bedded with the Bacton Green Till. The direction of these layers are dipping steeper and more uniformly to the south (20°) than those in WR09 3/2. There are occasional flint and chalk clasts (4-10 m), all the clasts are orientated in the

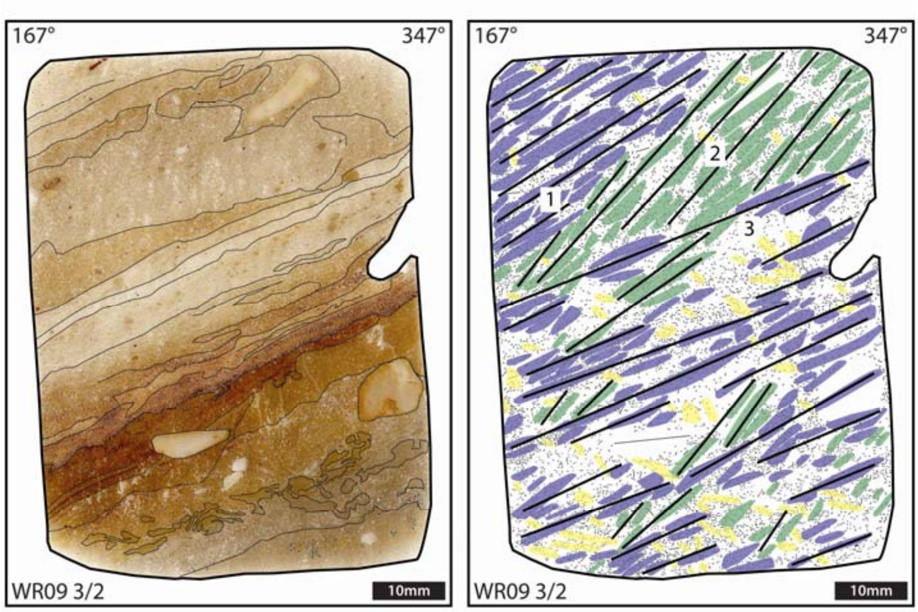

Figure 9.2. Microstructural map of sample WR09 3/2

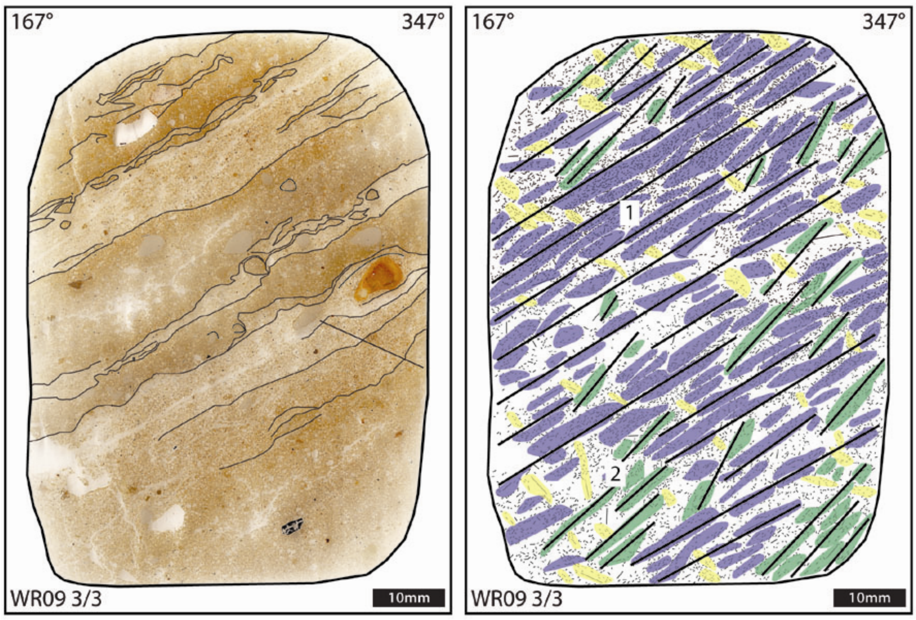

Figure 9.3. Microstructural map of sample WR09 3/3

direction of the bedding (Figure 9.4). There are large irregular vughs randomly across the sample which was formed during processing. To the right of the thin section there is a solitary shear (black straight line) which crosses the alternating sand and till layers perpendicularly. The alternation between the silty till and the fine-medium sand is irregular across the thin section.

There are also three microfabric direction recognised in WR09 3/3 as seen in WR09 3/2; the dominant microfabric (blue polygons) is dipping moderately to the south and have a more continuous foliation than in WR09 3/2. The second fabric is the younger, more steeply dipping green polygons, this fabric still cuts through the older blue fabric domain but not as pervasively as in WR09 3/2. In both fabrics the zonal foliations has increased to c.60%. The third fabric dips to the north and is discontinuously distributed across the thin section, highlighted by the yellow polygons.

Initially the Happisburgh Till would have been deposited and overridden by the later deposition of the Bacton Green Till. As the ice sheet overrode these sediments it further deformed them into part of a large scale recumbent fold, suggested because of the unusual and increasing steepness of the section. Being that the only potential evidence of brittle deformation was a small shear in WR09 3/3, glacial tectonism can be ruled out; instead the single shear is evidence of dewatering. In both WR09 3/2 and WR09 3/3 the shallower dip of the blue domain indicates that this microfabric was the earliest to form (1) and as the sediment folded the bedding was pushed upwards its dip increased. The direction of the fabric in the green microfabric occurred in the later stages of the folds formation, as the sand was injected into the till and it folded and reoriented to dip more steeply towards the south (2). The yellow fabric domain was not part of this deformation event.

4. Conclusions

All three samples show evidence of polyphase deformation. In WR09 1/4E there is only evidence of ductile deformation, the material has been deformed in phases and so has undergone temporal polyphase deformation. WR09 3/2 has undergone the same processes as WR09 1/4E but displays them differently as the scale of the fold has increased. In addition, it has also undergone spatial polyphase deformation as the clayey Happisburgh Till has subtle variations when compared to the silty Bacton Green Till. WR09 3/3 is predominantly ductile deformation, but has evidence of brittle deformation in the latter phases of deformation; meaning that WR09 3/3 has undergone ductile and brittle temporal polyphase deformation.

The thin sections discussed here are a small example of the potential when studying polyphase deformation at a micro-scale. It is important to remember that the use of the term polyphase deformation alone is not detailed enough to describe variations in tills, even with three samples deposited and deformed in similar conditions there are variations in the deformation processes which can be interpreted more fully when stipulating whether spatial and/or temporal polyphase deformation has occurred.