Processes associated with the transport and emplacement of glacitectonic rafts as inferred from micromorphology: a detailed microstructural investigation of a bedrock-sediment raft at West Runton, north Norfolk, UK

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Abstract

The results of a detailed macro- and microstructural study of the deformation structures associated with the emplacement of a bedrock-sediment raft into the polydeformed Mid-Pleistocene glacial sequence at West Runton, north Norfolk, are presented. A four stage conceptual model for raft transport and emplacement is proposed, with deformation being partitioned into the relatively weaker Happisburgh Till; the latter forming the host to the raft. ***Stage 1*** is the main transport phase and was dominated by easterly (down-ice) directed ductile shearing. During ***Stage 2*** a narrow ductile shear zone propagated upward through the base of the raft leading to the detachment of an elongate block of chalk. Attenuated lenses of diamicton in this shear zone possess an S-C-like, S1 clast fabric which records an easterly directed sense of shear. As deformation progressed, ***Stage 3***, the detached block impinged on the 'high strain' zone wrapping the base of the raft influencing the style of deformation partitioning, leading to localised antithetic, up-ice directed shear and the imposition of a composite, westerly directed S2-S3 shear fabric. ***Stage 4*** represents the final stages of raft emplacement when the detachment zone at the base of the raft began to 'lock-up'. Micromorphological evidence, in particular the preservation of thin shelled bioclasts in the diamicton, indicates that shear strains associated with raft emplacement were relatively low. The kinematics of deformation are consistent with easterly directed subglacial shearing, with rafting occurring in response to glacitectonism associated with the advance of a major ice sheet from the west.

1. Introduction

Glacitectonic rafts, 'floes' or 'megablocks' are defined as dislocated slabs of bedrock and/or unconsolidated sedimentary strata that preserve their original lithological character, but have been transported from their original position by glacial action (Stalker, 1976; Christiansen and Whitaker, 1976; Ruszczynska-Szenajch, 1987; Aber, 1985, 1988; Broster and Seaman, 1991; Benn and Evans, 1998; Evans, 2007; Aber and Ber, 2007; Burke et al., 2009). These rafts are typically very thin (up to a few tens of metres) in comparison to their aerial extent (up to several 100 km^2), and may have been transported for just a few tens of metres up to several hundred kilometres (Bluemle and Clayton, 1984). They can occur as single, horizontal slab-like features, or form several stacked fault-bound bodies located within conspicuous ice-pushed moraines of various types (Banham, 1975; Aber, 1988; Kruger, 1996; Benn and Evans, 1998). Although internally the rafts can appear relatively undeformed, in some examples they are cut by shear zones, faults and breccia/cataclastic zones, or even folded. In the geological record glacitectonic rafts have been described from a diverse range of glaciated terrane, including: the Interior Plains of North Dakota where rafts of shale and sandstone bedrock are thrust into younger sediments (Bluemle and Clayton, 1984); sandstone blocks occurring across extensive tracts of the prairie regions of Alberta and Saskatchewan (Moran et al., 1980); rafts of penecontemporaneous glaciofluvial deposits thrust into a predominantly clay-rich diamicton in central Poland (Ruszczynska-Szenajch, 1988); limestone and shale rafts within till in southwest Ireland (Hiemstra et al., 2007); thrust-staked blocks of chalk within a highly glacitectonised sequence in north Norfolk (Peake and Hancock, 1961; Banham, 1975; Hart and Boulton 1991; Phillips et al., 2008; Burke et al., 2009 and Denmark (Jakobsen et al., 1996); and unconsolidated marine sediments within a glacitectonised sequence in Banffshire, Scotland (Peacock and Merritt, 1997; Phillips and Merritt, 2008).

Early models (Banham, 1975; Aber, 1988) of rafting suggested that they were detached and transported due to them being frozen to the base of cold-based ice sheets and glaciers with deposition occurring as a result of melt-out from decaying stagnant ice. These transported blocks were then deposited as a result of melting out during the stagnation and decay of the ice. More recent studies of ice-rafted sediments and bedrock, have suggested that failure, leading to detachment, is associated with elevated pore-water pressures that may occur along water-rich décollement surfaces within the subglacially deforming layer (Moran et al., 1980; Aber, 1985; Broster and Seaman, 1991; Benn and Evans, 1998; Phillips and Merritt, 2008), at the base of the deforming layer (Kjær et al., 2006), or as a consequence of subglacial hydrofracturing by forceful upward dewatering (Boulton and Caban, 1995; Rijsdijk et al., 1999). Alternative rafting models, however, consider that rafts are generated as a result of thrusting associated with proglacial deformation, occurring within an imbricate thrust stack (thrust moraine) formed in front of the advancing glacier or ice sheet (Banham, 1975; Christiansen and Whitaker, 1976; Moran et al., 1980; Bluemle and Clayton, 1984; Ruszczynska-Szenajch, 1987; Burke et al., 2009). It is not clear from any of these published models whether the detachment of rafts must occur at an active ice margin, with subsequent transport occurring as the detached block is overridden and entrained subglacially, or whether all the stages of the rafting process can occur entirely within a subglacial setting. Furthermore, the processes occurring during the detachment, transport and emplacement of the rafts remain poorly understood.

Micromorphological analysis of deformed glacial sediments is increasingly being used as a principal tool to unravelling the often complex deformation histories recorded by glacigenic sequences (van der Meer, 1993; Phillips and Auton, 2000; van der Wateren et al., 2000; Menzies, 2000; Phillips et al., 2007; Lee and Phillips, 2008; Denis et al., 2010); investigating the role played by pressurised pore-water/melt water during these deformation events (Hiemstra and van der Meer, 1997; Phillips and Merritt, 2008; van der Meer et al., 2009; Denis et al., 2010); and therefore as an aid to our understanding of the processes occurring beneath glaciers (Menzies and Maltman, 1992; van der Meer, 1997; Menzies et al., 1997; Khatwa and Tulaczyk, 2001; van der Meer et al., 2003; Roberts and Hart, 2005; Hiemstra et al., 2005; Baroni and Fasano, 2006; Larsen et al., 2006, 2007; Hart, 2007). The terminology used in many of these studies follows that proposed by van der Meer (1987, 1993) and Menzies (2000). The recent development of a quantitative microstructural mapping method (Phillips et al., 2011) for the detailed analysis of glacial deposits, alongside these traditional methods, has the potential to further contribute to our understanding the processes occurring during the deformation of glacial sediments. During this process the relationships between successive generations of clast microfabrics and other microstructures (e.g. plasmic fabrics, turbate structures, folds, faults, shears…etc) are determined. This allows a detailed relative chronology of fabric development to be established, applying the terminology and approach typically used by structural geologists and metamorphic petrologists to unravel the often complex, polyphase deformation histories recorded by glacigenic sediments. Consequently, the application of macrostructural field techniques, combined with detailed micromorphological and microstructural analysis could provide valuable insights into the mechanisms involved during the detachment, transport and emplacement of ice-rafted sediment and bedrock slabs.

This paper presents the results of a detailed macro- and microstructural study of the glacitectonic features associated with an elongate raft exposed at West Runton on the north Norfolk coast, eastern England (Figure 1). Unlike many rafts described in the literature, the raft examined from West Runton is a composite body composed of both lithified chalk bedrock overlain by unconsolidated pre-glacial sediments (sands and gravels). The study has focused upon the deformation occurring within the detachment at the base of the raft. This allows a detailed relative chronology of foliation development (in response to ductile shearing) within this major décollement to be established. The results of this detailed study are further used to shed light upon the processes occurring during the transport and accretion of glacitectonic rafts within a subglacial setting.

2. Geological setting of West Runton

The presence of large rafts of chalk bedrock is locally a distinctive feature of the polydeformed Middle Pleistocene glacial deposits (the 'Contorted Drift' of Banham 1975) of north Norfolk in eastern England (see Figure 1). These rafts were first recognized by Marshall (1787) and later described by a series of researchers including Reid (1882), Slater (1927), Peake and Hancock (1961), Banham (1975, 1988), Hart and Boulton (1991a), Burke et al. (2009), and more recently Vaughan-Hirsch et al. (2011). The West Runton site [National Grid Reference (NGR): TG 181 432] (Figure 1), which forms the focus of the present study, represents one of a number of locations (which also include Overstrand [NGR: TG 256 405] and East Runton [NGR: TG 197 428]; see Vaughan-Hirsch et al., 2011) along the north Norfolk coast where the underlying chalk bedrock has been elevated as a result of glacitectonism above the chalk bedrock surface, and emplaced into the overlying variably deformed glacial sequence.

At the study site a slab-like composite glacitectonic raft, comprising both lithified chalk bedrock and unconsolidated preglacial sediments, occurs towards the base of a polydeformed sequence of Early to early Middle Pleistocene deposits (Phillips et al., 2008; Burke et al., 2009). This sequence rests unconformably upon Upper Cretaceous chalk bedrock which dips gently (<1˚) eastwards (Moorlock et al., 2002). The overlying Early to early Middle Pleistocene preglacial sequence comprises the fluvial Cromer Forest-bed Formation and estuarine to shallow marine Wroxham Crag Formation (West, 1980; Briant et al., 1999; Allen and Keen, 2000; Rose et al., 2001; Pawley et al., 2004; Lee et al., 2006). The overlying glacial sequence comprises a series of diamictons, including the Happisburgh (HTM), Walcott (WTM) and Bacton Green till members (BTM), and outwash deposits (the Runton Sands and Gravels, Phillips et al., 2008). An additional diamicton unit present within the regional succession between the HTM and BTM is the Walcott till member (WTM). However, this unit is largely absent from the sequence, being preserved only as small stringers and inclusions throughout the lower part of the succession (Phillips et al., 2008). These sediments were deposited by the British Ice Sheet (Lee et al., 2002, 2004) during the Middle Pleistocene although the precise number and age of the glaciations concerned is a matter of debate (see Clark et al., 2004; Preece et al., 2009; Rose, 2009; Lee et al., 2011a for an overview). The glacitectonic deformation history recorded by these sediments has been described in detail by Phillips et al. (2008) and is only summarised here to provide a context for the present study on glacitectonic rafting.

Phillips et al. (2008) and Lee et al. (2011b), using the regional stratigraphy of Lee et al. (2004) and Hamblin et al. (2005), were able to unravel the complex, larger-scale glacitectonic history recorded by the sediments at West Runton, recognising that they had been affected by six major deformation events (D1 to D6; Table 1). The first and second deformation events (A1 and A2) in the West Runton area were associated with ice advancing from the north, and led to the deposition of the HTM and a second re-advance diamicton facies. Deformation event A3 was associated with an ice advance from the northwest into north Norfolk and led to the deposition of the WTM, with the BGTM and associated glacial outwash laid-down during a further southerly directed ice advance (A4). The preglacial and glacial deposits were then deformed and disrupted by a major ice advance from the west/south-west (A5). This event marked a major change in ice flow dynamics in northern East Anglia (see Figure 1) and has been recognised elsewhere (Banham, 1966; Ehlers et al., 1987; Lee et al., 2004; Pawley et al., 2004; Hart, 2007; Lee and Phillips, 2008), and is characterised by a shift from small- to large-scale and more pervasive glaciotectonism (Lee et al., 2011b). Phillips et al. (2008) interpreted this event in terms of a progressive proglacial to subglacial deformation model. Subglacial A5 deformation that reworked the BGTM was highly variable in both its style and intensity, ranging from heterogeneous folding and thrusting, through to more ductile shearing associated with the formation of a subglacial shear zone (also see Lee and Phillips, 2008). The thickness and complexity of this shear zone increased up-ice, where it is characterised by the formation of a thick (20 to 30 m) glacitectonic mélange composed predominantly of remobilised BGTM and containing rafts or thrust slices of the chalk bedrock and pre-existing glacial and preglacial sediments. Slab-like to lenticular sand intraclasts contained within this mélange have been interpreted by Waller et al. (2011) as providing evidence that the easterly advancing ice overrode and deformed an area of “warm" permafrost developed in front of this ice sheet. A5 is superseded by a final deformation event, A6, associated with a final ice advance from the north that formed the Cromer Ridge push moraine complex.

3. Methodology

Prior to sampling, the glacitectonic raft exposed at West Runton was logged, photographed and described in detail (see Figures 2a and b), with particular emphasis being placed on recording the dip and strike of the main lithological contacts and related glacitectonic structures (see Figure 2c), as well as the geometry, orientation and inter-relationships between the various macroscale deformation structures associated with the emplacement of this raft. A total of five intact block samples were taken using 10 cm cubed, aluminium Kubiena tins. These samples (sample numbers WRA-315, WRA-316, WRA-317, WRA-318, WRB-319; see Figure 2d) were collected vertically through the highly deformed HTM which structurally underlies the raft, with samples WRA-317, WRA-318 and WRB-319 also containing the tectonised contact between the chalk at the base of the raft and the underlying diamicton. The tins were either cut or pushed into the face in order to limit sample disturbance. The position of the sample relative to the base of the raft, its orientation relative to magnetic north, depth and way-up were marked on the outside of the tin during collection. The samples were collected at different locations from below the raft (see Figure 2d) to provide detailed information on the progressive changes in the style and intensity of deformation towards this glacitectonic contact. A sequence of photographs were then taken of the Kubiena tins embedded in the face to provide a visual record of the location of the individual samples and their context with respect to the raft. Each sample was then removed from the face, sealed in two plastic bags, and stored in a cold store to prevent the material from drying out prior to sample preparation.

Sample preparation (total time c. 4 months) was carried out at the Centre for Micromorphology at Royal Holloway University of London. Preparation of the samples involved the initial air drying followed by acetone replacement to remove all of the pore-water. The sample was then placed in a vacuum chamber and the acetone progressively replaced by a resin and allowed to cure (Carr and Lee, 1998). Large format orientated thin sections were taken from each of the prepared samples. The thin sections were examined using a standard Zeiss petrological microscope and Zeiss projector, the latter allowing detailed study of the range of microstructures at very low magnification. The terminology used to describe the various microtextures developed within these sediments in general follows that proposed by van der Meer (1987, 1993) and Menzies (2000). High resolution scans of the thin sections were also analysed using a commercial graphics package (CorelDraw) following the methodology described by Phillips et al. (2011) and the resultant microstructural maps are shown in Figures 4 to 8. Long axis orientation data obtained from very fine sand to small pebble sized clasts included within the diamicton were plotted on a series of rose diagrams generated using the computer plotting package GEOrient.

4. Macrostructural description of West Runton raft site

When compared to the other rafts exposed along the north Norfolk coast, for example at Overstrand and East Runton (see Figure 1) (Burke et al., 2009; Vaughan-Hirsch et al., 2011), the glacitectonic raft at West Runton [NGR: TG 174 433] is a relatively small-to-medium scale body. The basal contact between the West Runton raft and the underlying HTM is well-exposed (see Figure 2) allowing the deformation associated with its transport and emplacement to be examined in detail. The raft is an elongate (traced laterally for c. 20 m) composite body comprising a discrete basal unit of altered chalk bedrock (70 cm to 1 m thick) overlain by unconsolidated preglacial sands and gravels of the Wroxham Crag Formation (WCF) (3 to 4 m thick). This lithological boundary (Figure 2a and b) preserves the original, gently undulating unconformity between the chalk and the much younger shelly, shallow marine sediments. The WCF can be divided into two units; a lower (c .1 m thick) variably hematised sequence of sands and pebbly gravels; conformably overlain by an upper pale orange-brown unit (>2 m thick) of thinly bedded to cross-bedded sands. The basal gravels of the WCF immediately above the unconformity are essentially undeformed, leading Burke et al. (2009) to suggest that the unconsolidated WCF was frozen to the underlying chalk bedrock during rafting.

Unlike the well-bedded chalk bedrock which dominates the rafts exposed at Overstrand and East Runton (Burke et al., 2009; Vaughan-Hirsch et al., 2011), the chalk forming the basal part of the raft at West Runton is highly altered. Occasional pebble to cobble (10 to 15 cm across) sized flints occur within an apparently massive matrix of soft, putty-like chalk, but these do not form distinctive horizons as occurs within *in situ* chalk bedrock. A locally well-developed, closely spaced fracture cleavage and/or fissility (Figure 2a), and centimetre-scale banding (Figure 2e) are present within the chalk. In detail, the chalk is composed of well-rounded, elliptical, coarse sand to pebble sized fragments (up to 8 mm in diameter) within a fine-grained, micritic carbonate matrix. Work by Murton has demonstrated that this pebble-like texture, which occurs within near-surface elements of the chalk bedrock in southern Britain, is a direct result of periglacial alteration (Murton, 1996; also see Younger, 1989). The pebbly chalk occurs throughout the bedrock component of the raft at West Runton with this alteration having occurred prior to glacitectonism, potentially supporting the interpretation that it had been frozen during rafting (cf. Burke et al., 2009).

The raft at West Runton occurs within a highly glacitectonised sequence comprising the HTM (c. 2 to 10 m thick) overlain by the mélange facies of the BGTM (up to 25 m thick) which Phillips et al. (2008) interpreted as having undergone pervasive subglacial deformation associated with ice advancing from the west (A5 of Lee et al., 2011b). The raft occurs at, or immediately below, the contact between the dark grey, massive to locally stratified, clay-rich HTM and the structurally overlying highly foliated, sandy diamicton which characterises the BGTM. This polydeformed sequence also contains variably deformed rafts of WCF and slab-like to lenticular sand intraclasts, with the asymmetrical shape of these included sand bodies recording a consistent sense of shear towards the east (Phillips et al., 2008; Waller et al., 2011). The stratification within both the HTM and BGTM is deformed by a series of tight to isoclinal, east to southeast-verging, locally disharmonic folds and westerly dipping thrusts and ductile shear zones.

The base of the raft is well-exposed in the cliff face c. 2 m above the beach. The upper contact between the WCF, which forms the upper part of the raft, and the structurally overlying BGTM (located at a height of 10 to 12 m within the cliff) however is poorly exposed, and was not examined during this study. The chalk at the base of the raft rests directly upon a 20 to 30 cm thick zone of variably stratified to locally fissile HTM (Figure 2a, b and d). The stratification occurs parallel to the base of the raft and is defined by thin stringers and laterally persistent layers (individual layers can be traced laterally for 2 to 3 m) of relatively chalk-rich, pale to moderate grey diamicton. Individual layers range from a few millimetres up to 3 to 4 cm thick and can be locally seen wrapping around small (up to 10 cm across, but typically ≤ 2 cm in diameter) chalk pebbles included within the diamicton. The chalk-rich stringers were observed forming elongate 'tails' of disaggregated chalk centred around a chalk pebble; similar in appearance to porphyroclast systems developed in mylonitic rocks (see Passchier and Trouw, 1996).

The orientation of the stratification within the HTM is variable due to it wrapping around the margins of the raft (see Figure 2a). However, in general, it dips at approximately 25˚ towards the east (Figure 2c) and becomes more intense towards the base of the raft, indicating that it is related to deformation occurring along this glacitectonised contact. This glacitectonic layering/foliation is also developed in the chalk exposed towards the ends of the raft (see Figure 2e). In detail, the contact between the HTM and raft is typically sharp and undulatory (Figure 2a and b) dipping at a range of angles from 25˚E/185˚, 11˚E/162˚, 28˚E/185˚ through to 10˚W/010˚ (Figure 2c). Locally, however, the chalk bedrock appears to grade, over a 2 to 3 cm, into the adjacent chalk-rich diamicton. The HTM immediately adjacent to this gradational contact contains well-rounded clasts or pebbles of chalk locally occurring within or wrapped by thin layers and stringers of pale diamicton rich in disaggregated chalk. Asymmetrical pressure shadows and chalk-rich tails are variably developed on the chalk clasts with these kinematic indicators recording an overall easterly directed sense of shear (Figure 2e).

In the central part of the section, the chalk within the raft is divided into two by a number of thin (2 to 3 cm thick) lenses (up to 1.5 m in length) of highly deformed HTM (Figure 2). The diamicton within these lenses possess a fine-scale, wispy looking compositional layering which occurs oblique to their margins and is seen to wrap around small, included chalk pebbles. The highly deformed lenses of HTM are interpreted as delineating a narrow gently dipping (10˚E/350˚ to 20˚W/010˚; Figure 2c) ductile shear zone cutting the base of the raft. The lower chalk block (WR/A on Figure 2) occurring beneath this shear zone is approximately 1 m thick and at least 4 m long, and appears to have been detached from the main body of the raft (labelled WR/B on Figure 2) during its emplacement. The eastern end of the detached block is obscured by a thick layer of debris, but at its western end it thins rapidly and is truncated against the tectonised based of the main part of the raft (Figure 2d). The HTM immediately adjacent to the western termination of the block contains an elongate, angular fragment of chalk (c. 20 to 30 cm long) aligned parallel to the lower margin of WRA.

Deformation associated with the narrow shear zone cutting the base of the raft and within the underlying HTM has formed the focus of the detailed micromorphological and microstructural study (see below). The highly deformed zone immediately beneath the raft at West Runton is interpreted as representing the basal décollement responsible for the transport and emplacement of this detached block into the highly deformed sequence at West Runton. The easterly directed shear sense recorded by kinematic indicators within this 'high strain' zone are consistent with the overall easterly directed D3 subglacial deformation event proposed by Phillips et al. (2008). Consequently, it is concluded that the westerly dipping (10˚W/010˚) décollement surface at the base of the raft resulted in its emplacement (out-of-sequence) into the polydeformed HTM and BGTM during this subglacial deformation event.

5. Micromorphological and microstructural analysis of the thin sections

A total of five samples (WRA-315, WRA-316, WRA-317, WRA-318, WRB-319) were taken from the HTM and a c. 20 to 30 cm wide zone of deformation which forms the basal detachment of the raft (Figure 2d). The thin sections provide a vertical section through this 'high strain' zone allowing the progressive changes in the style and intensity of deformation towards the base of the raft to be examined in detail. Samples WRA-316 and WRA-315 were taken at from within the HTM approximately 60 cm and 15 cm, respectively, below the contact with the chalk. Sample WRA-316 occurs well below the 'high strain' zone and allows the 'background' deformation within the HTM to be assessed. The remaining samples (WRA-317, WRA-318 and WRB-319) were taken across the glacitectonic boundary between the chalk and HTM (Figure 2d). For ease of description the petrography of the chalk bedrock, micromorphology of the HTM and the range of microfabrics developed within the 'high strain' zone at the base of the raft will be described separately.

5.1. Petrology of the chalk bedrock

The chalk bedrock forming the basal part of the raft at West Runton occurs in samples WRA-317, WRA-318 and WRB-319 (Figures 3, 4, 5 and 6). In all three thin sections, the chalk has been highly altered, consisting of well-rounded, elliptical (elongate) to spherical (equant) coarse sand, granule, to pebble sized clasts (up to 8 mm in diameter) set within a very fine-grained, massive, micritic carbonate matrix (Figure 3). A range of broken and complete microfossils, including foraminifera, are preserved within the relatively harder (based upon field evidence) chalk clasts (Figure 3). Burke et al. (2009) concluded that foraminifera within the chalk raft belonged to the Upper Campanian (Cretaceous) *B. mucronata* Zone, consistent with the raft possibly having been derived from the local chalk bedrock at West Runton.

In outcrop, the contact between the chalk and the structurally underlying HTM appears sharp (see Figure 2a, b and d). However within the thin section, this contact is more gradational in nature with the chalk appearing to grade into the adjacent chalk-rich diamicton over 2 to 3 mm (see Figure 5). In this narrow transitional zone the matrix of the chalk becomes progressively darker and more silty or clayey, indicative of localised mixing of the chalk with the matrix of the host diamicton. Importantly, there is no obvious change in the shape and/or grain size of the chalk 'pebbles' within this transitional zone.

5.2. Micromorphology of the Happisburgh Till Member

The diamicton which characterises the HTM occurs within all five of the thin sections were it comprises a massive to weakly to moderately stratified, fine-grained, silty sandy clay (see Figures 4 to 8) containing well-rounded, elliptical (elongate) to spherical (equant) coarse sand, granule, to pebble sized clasts (up to 8 mm in diameter) of chalk and occasional angular to subangular chert fragments, as well as rare fragments of strained polycrystalline vein quartz or quartzite. The stratification is most clearly developed in samples WRA-315 and WRA-317 (i.e. within 20 to 25 cm of the base of the chalk raft) and dips at approximately 15˚ to 20˚ towards the east (in this plane of section), coplanar with the base of the structurally overlying raft. The individual layers vary from c. 2 mm up to 20 mm thick (see Figures 5 and 6) and increase in thickness towards the base of the raft. Thinner layers of both chalk- and clay-rich diamicton are laterally discontinuous and are 'pinched out' to form thin, elongate, lenticular ribbons or stringers. The margins of the individual layers vary from sharp to gradational, and range from planar to locally irregular in form where the stratification wraps around chalk pebbles included within the diamicton (see Figure 6). The stratification is most clearly developed immediately below the base of the raft becoming more diffuse further away from this contact (compare Figures 5 and 6). The relationships between the stratification within the diamicton and the contact with the structurally overlying raft are consistent with its formation being as a result of the incorporation of chalk-rich material into the HTM during the rafting process (see section 6.3).

The stratification in the HTM is also defined by a variation in the modal proportions of included coarse silt to sand grade quartzose grains (skeleton), as well as the proportion of clay and silt grade material and micritic to very finely microcrystalline carbonate in the matrix; reflected in the overall colour of the layers (pale grey = chalk-rich, very dark grey = clay-rich). The clay-rich layers lack any included chalk fragments and possess a low quartzose component. The more quartzose layers are characterised by a higher modal proportion of comprising angular, subangular to occasionally subrounded, low to rarely moderate sphericity included skeleton grains set within a fine silty to clay-rich matrix. The quartzose clasts are mainly composed of monocrystalline quartz as well as minor to accessory plagioclase, polycrystalline quartz, white mica, chloritic and/or glauconitic material, amphibole, epidote and opaque minerals. Broken and complete bioclasts, including foraminifera, echinoderm spines, thin-walled shell fragments, calcispheres and calcareous algae are locally well-preserved within the more chalk-rich laminae (e.g. samples WRA-317, WRA-318 and WRA-319). Lithologically the pale-grey, very chalk-rich layers in the diamicton are very similar to the chalk forming the base of the raft and contain a high proportion of bioclasts, including complete foraminifera. In sample WRA-317 the number and thickness of chalk-rich layers within the diamicton increases immediately adjacent to the contact with the raft.

5.3. Microfabrics and microscale deformation structures within the 'high strain' zone

Detailed mapping of the microfabrics present within the thin sections from beneath the raft at West Runton has revealed that there is a systematic change in their style, intensity and orientation towards its base (see Figures 4 to 8, and also Figure 9). For ease of description the range of microfabrics developed in each of the thin sections from across this 'high strain' zone will be described separately. The terminology used to describe the morphology of the clast microfabrics follows that proposed by Phillips et al. (2011). Successive generations of these fabrics are distinguished by the nomenclature normally used in structural geological studies with being the S1 earliest fabric to Sn latest foliation developed within the sediment (cf. Phillips and Auton, 2000; Phillips et al., 2007; Phillips et al., 2011). However, it is not intended that this nomenclature, i.e. S1, S2, S3.... etc, necessarily implies that each fabric represents a separate deformation event. No obvious plasmic fabrics have been identified in any of the thin sections examined during this study due to the high carbonate content in the matrix of the HTM.

5.3.1. Sample WRA-316: structurally lowest sample within the Happisburgh Till Member

Sample WRA-316 is the structurally lowest sample, collected from entirely within the HTM c. 60 cm below the base of the raft (see Figures 2d and 8). Four main clast microfabrics have been recognised in thin section (Figures 4 and 9): ***(i)*** The earliest foliation (S1, green on Figures 3 and 8) is a disjunctive, spaced, gently (15 to 20˚, in this plane of section) westerly dipping (up-ice) clast microfabric defined by short discontinuous domains and is relatively uniformly developed throughout the thin section; ***(ii)*** The second foliation (S2, purple on Figures 4 and 9) can be classified as a disjunctive, spaced microfabric which dips at approximately 30˚ to 40˚ towards the east (in this plane of section). The apparent intensity of this second fabric appears to vary across the thin section. S2 is defined by short discontinuous microfabric domains that clearly crosscut and, therefore, postdate the earlier S1 foliation; the latter being preserved within the S2 microlithons (see Figure 4); ***(iii)*** The third foliation, S3 (brown on Figures 4 and 9), is very weakly developed and dips at c. 58˚ towards the east; and ***(iv)*** The final fabric (S4, blue on Figures 4 and 9) is a highly heterogeneous disjunctive foliation which dips at approximately 45˚ to 55˚ towards the west and is most apparent along the eastern side of the thin section where it crosscuts both S1 and S2 (Figure 4). The relationship between S3 and S4 is uncertain as they are developed in different parts of the sample.

The variation in the intensity of the clast microfabrics across WRA-316 is shown by the rose diagrams constructed for clast long axis data from Areas A and B on Figure 4. In detail the rose diagrams clearly show that in Area A, S2 and S1 are both well-developed with the later S3 and S4 foliations being relatively poorly represented. This confirms the visual impression that S1 and S2 are the main foliations developed within the HTM beneath the raft at West Runton. In contrast, in Area B the S2 is the most pervasively developed foliation with S1 being much weaker. Furthermore, the steeply west-dipping S4 fabric is also relatively well-developed in this area. These data clearly show that clast microfabric development within the HTM is heterogeneous and varies over the scale of a few tens of millimetres, reflecting the microscale partitioning of deformation within this diamicton.

5.3.2. Sample WRA-315

Sample WRA-315 was collected from the lower part of the 'high strain' zone; approximately 15 cm below the base of the raft. It is clear from the detailed microstructural map, clast orientation data and the interrelationships between the foliations present within of this thin section (Figure 5), that the same four clast microfabrics (S1, S2, S3 and S4) occur in both samples WRA-316 and WRA-315 (compare Figures 4 and 5). However, the relative intensity of these fabrics is clearly different. Sample WRA-315 can be divided into two parts. In the lower, western part of the thin section, the diamicton exhibits a similar pattern of fabric development and relative intensity to sample WRA-316. It is likely, therefore, that the fabric geometries present in sample WRA-316 and the lower part of WRA-315 potentially represent the 'background' pattern of foliation development within the HTM. In WRA-316 all four clast microfabrics crosscut the stratification present within the HTM (see Figure 4), indicating that foliation development post-dated this compositional layering.

In contrast to sample WRA-316 and the lower part of WRA-315, the upper part of WRA-315 is characterised by a pervasively developed, relatively continuous planar disjunctive S2 foliation (Figures 5 and 9). In this part of the thin section the earlier formed S1 fabric has largely been overprinted, and is now only locally preserved within the S2 microlithons. S2 occurs parallel to the stratification within the diamicton, the latter having apparently been reduced to thin, discontinuous stringers of relatively chalk-rich material (see Figure 5). S2 clearly crosscuts and, therefore, postdates S1 indicating that the intensification of the second fabric within the lower part of the 'high strain' zone occurred at a later stage in the deformation history. S4 is absent within the upper part of sample WRA-315. S3 in the upper part of this sample is a sigmoidal in shape, occurring between the narrow zones or bands of relatively more intense S2. The result is a composite S-C-like fabric which records a westerly (dextral, top to right) sense of shear (Figures 5 and 9).

5.3.3. Sample WRA-317

Sample WRA-317 was collected from across the chalk-HTM boundary at the base of the detached chalk block (WRA) immediately below the main body of the raft (see Figure 2e). In this thin section the contact between the chalk and diamicton dips at c. 15˚ towards the east, parallel to the stratification and S2 clast microfabric in the structurally underlying HTM (Figures 6 and 9). S2 takes the form of a spaced, disjunctive planar foliation defined by relatively short microfabric domains. The microstructural map for thin section WRA-317 clearly shows that deformation within the HTM immediately adjacent to the chalk contact is characterised by the development of a composite, S-C-like fabric defined by S2 and S3 recording a westerly (up-ice) directed shear sense (Figure 6). A comparison between samples WRA-315 and WRA-317 shows that the apparent intensity of this composite foliation has increased upwards through the 'high strain' zone (see Figures 5, 6 and 9), consistent with an overall increase in dextral ductile shearing towards the base of the raft. The increased spacing of S2 in sample WRA-317 is, however, accompanied by an apparent decrease in the relatively intensity of the fabric (see Figure 9). Detailed analysis of the microfabrics in three different areas of the thin section (Areas A, B and C on Figure 5) has shown that the relative intensities of S2 and S3 vary across the sample. Immediately adjacent to the chalk raft (Area A, Figure 6) S2 occurs parallel to the chalk-till boundary and S3 is only relatively weakly developed. In Area B, structurally lower in the sample (Figure 6), S3 is the dominant fabric and dips at c. 40˚ to 45˚ towards the east (i.e. down-ice). Area C is from the lower part thin section where S2 is once again the dominant fabric present within the diamicton. This type of analysis demonstrates that clast microfabric development in the 'high strain' zone beneath the chalk raft is highly heterogeneous, potentially recording a shifting pattern of deformation partitioning within the HTM during ductile shearing.

The S1 fabric is only weakly developed and S4 is absent. S3 can locally be seen wrapping around the included chalk and chert fragments present within the HTM, indicating that these granule to pebble sized clasts acted as rigid bodies during deformation. Weakly developed pressure shadows have also been noted developed adjacent to some of these chalk clasts. However, no obvious broken chalk pebbles and/or evidence of these clasts being 'ground down' (cataclasis/grain reduction) to form elongate tails (c.f. porphyroclast systems in mylonitic rocks, Passchier and Trouw, 1996) has been observed within this, or any other of the thin sections from West Runton. As noted above (section 5.1), the chalk within the raft is altered, possessing a distinctive pebbly texture. The morphology of these relict chalk 'pebbles' is comparable to the size and shape of the chalk clasts in the HTM. These observations are inconsistent with the chalk clasts included within the diamicton having undergone significant grain size reduction, rounding and/or cataclasis during ductile shearing.

5.3.4. Sample WRA-318

Sample WRA-318 was taken across the boundary of an elongate fragment of chalk contained within HTM, approximately 10 cm from the western end of chalk block WRA (Figure 2d). The chalk fragment (c. 30 cm in length), partially included in thin section WRA-318, appears to have been detached from the main part of the raft during deformation. In marked contrast to samples WRA-315 and WRA-317, which possess a well-developed S2 and, to a lesser extent, S3 fabrics defining a composite S-C-like fabric, clast microfabrics within WRA-318 are more weakly developed. The pattern and relatively intensities of S1, S2, S3 and S4 in the HTM in this sample (Figure 7) are compatible are to those of sample WRA-316 (compare Figures 4 and 7, also see Figure 9); the latter recording deformation outside the 'high strain' zone. S2 and S4 are the dominant fabrics in sample WRA-318 with the steeply, westerly dipping S4 occurring at a high-angle (c. 70˚ to 80˚) to the contact with between chalk block and host diamicton (see Figure 7). Detailed analysis of the microfabrics in two different areas of the thin section (Areas A and B on Figure 7) demonstrates that the relative clast microfabric intensity within the diamicton is highly variable. In Area A, in the upper part of the HTM, S3 is relatively well-developed and occurs parallel to the boundary between the chalk and diamicton. The lower Area B is 5 to 10 mm away from this contact and shows a more complex pattern of fabric development with S2 and S4 being the dominant fabrics (Figure 7).

The chalk in this sample once again possesses a pebbly texture with the morphology of the relict chalk 'pebbles' being comparable to the size and shape of the chalk clasts in the host diamicton (see Figure 7). The relict chalk 'pebbles' exhibit a preferred shape-alignment parallel (in this plane of section) to both S1 and, to a lesser extent, S4 within the HTM (Figure 7). This evidence clearly shows that the dominant clast microfabrics, in this case S1 and S4, were locally being imposed upon the chalk within the raft.

5.3.5. Sample WRB-319

Sample WRB-319 was taken across the narrow (c. 3 to 4 cm across) ductile shear zone that separates the smaller chalk raft WRA from the structurally overlying main body of the raft WRB (Figure 2d). The microstructural map constructed for this thin section (Figure 8) clearly shows that deformation within the thin layer of HTM separating the two chalk bodies resulted in the development of a S-C-like fabric geometry primarily defined by the S1, and possibly S4 (Figures 8 and 9). However, the relationship of S4 to this composite foliation is uncertain, as this steeply inclined, westerly dipping fabric can be locally seen crosscutting S1 (see Figures 8 and 9). In marked contrast to samples WRA-315 and WRA-316, the composite S1 fabric in sample WRB-319 yields an easterly (down-ice) directed sense of shear. Importantly, the weakly to moderately developed S2 clast microfabric clearly crosscuts S1, indicating that imposition of this second fabric post-dated easterly directed ductile shear leading to the development of the S-C-like S1 foliation.

Detailed analysis of the microfabrics in three different areas of the thin section (Areas A, B and C on Figure 8) has shown that the relative intensities of S1 and S2 vary across the sample, with S1 occurring parallel to the boundary between the chalk and HTM. In areas A and B, S1 is clearly the dominant fabric (see Figure 8). Data for Area C was recorded from the elongate, relict chalk pebbles present in the raft of chalk bedrock. As in sample WRA-318, the clast microfabrics present within the adjacent HTM are also recognised within the raft indicating that ductile shearing, which led to the imposition of S1 and S2 in the diamicton, also affected the chalk.

6. Interpretation of the macro- and microstructures developed within the detachment zone at the base of the West Runton raft

Detailed analysis of the macro- and microstructures developed within the Happisburgh Till Member associated with the emplacement of the chalk raft at West Runton has revealed that:

- The stratification within the HTM is most pervasively developed immediately below the base of the raft becoming more diffuse away from this contact. This relationship is consistent with the layering having formed as a result of chalk-rich material being derived from the base of the raft and incorporated into the HTM during rafting.

- Four main clast microfabrics (S1, S2, S3 and S4) can be recognised within the HTM (sample WRA-316) representing the 'background' deformation within this diamicton. The highly heterogeneous nature of these fabrics, even over the scale of a few tens of millimetres, reflects the microscale partitioning of deformation within the HTM.

- Detailed microstructural mapping and clast orientation data obtained from the remaining thin sections (WRA-315, WRA-317, WRA-318 and WRB-319) clearly demonstrates that the same four clast microfabrics can be identified throughout the 'high strain' zone which forms the basal detachment of the raft (see Figure 9). However, the relative intensity of these fabrics varies in different parts of this zone of enhanced ductile deformation.

- The onset of deformation within the 'high strain' zone is characterised by the imposition of a well-developed S2 fabric aligned parallel to the stratification in the HTM (WRA-315; Figures 6 and 9). This grades rapidly upwards into a composite S-C-like shear foliation defined by S2 and S3, the latter recording a westerly (up-ice) sense of shear (WRA-315 and WRA-317; Figures 5, 6 and 9).

- Sample WRA-318 apparently records a switch back to the 'background' fabric development within the HTM and lacks the more intense S2 and S-C-like fabrics which characterise the 'high strain' zone at the base of the raft.

- The structurally higher sample, WRB-319, shows that deformation within the narrow ductile shear zone separating the chalk block WRA from the structurally overlying main raft (WRB) was dominated by easterly (down-ice) directed shear that led to the imposition of a composite S-C-like S1 fabric. The crosscutting S2 fabric clearly post-dates S1 and therefore the related ductile shearing.

- The chalk in samples WRA-318 and WRB-319 is altered possessing a distinctive pebbly texture, with the morphology of the relict chalk 'pebbles' being comparable to the size and shape chalk clasts present in the adjacent HTM. The preferred shape-alignment of the relict chalk 'pebbles' clearly shows that microfabric development also affected the margins of the raft.

It is clear from both the macroscale (field observations) and microscale (thin sections) structural evidence that the relative intensity of deformation recorded by the HTM increase towards the base of the raft and that shearing was focused along its margins. The most obvious evidence of this in the field is the progressive increase in the intensity of a glacitectonic layering or stratification within the diamicton towards the base of the raft (Figure 2). This layering defines a 20 to 30 cm thick 'high strain' zone in which a range of kinematic indicators (including the wrapping of the foliation around rounded chalk pebbles, highly attenuated chalk-rich stringers forming elongate 'tails' on these clasts, asymmetrical pressure shadows) all record an overall easterly directed sense of shear (Figure 2e). The 'high strain' zone forms the basal décollement which accommodated the bulk of the transport/displacement during rafting. The shear sense recoded by the 'high strain' zone is consistent with the easterly directed subglacial A5 deformation event of Phillips et al. (2008) and Lee et al. (2011b). Emplacement of the raft is therefore thought to have accompanied A5, during which the unconsolidated WCF remained attached to the underlying chalk bedrock, preserving their original stratigraphic relationship. The lack of evidence for disruption along this lithological boundary supports the idea proposed by Burke et al. (2009) that the rafts were probably frozen during transport, with the West Runton raft acting as a relatively rigid block which underwent very little internal deformation. However, immediately adjacent to the base of the raft, the chalk does show some evidence of glacitectonic modification. In the central part of the section, the chalk is cut by a narrow, gently westerly dipping ductile shear zone delineated by thin lenses of foliated HTM (Figure 2d). This shear zone resulted in the detachment of a large block (labelled WRA on Figure 2) or slice of chalk from the base of the raft. Furthermore, close to the contact with the underlying HTM the chalk possess a moderately well-developed foliation which is coplanar to the stratification present in the diamicton (Figure 2e).

6.1 Ductile shearing along the margin of the chalk raft and the evolution of the basal shear zone

The results of the macro- and microstructural can be used to erect a detailed conceptual model of the deformation associated with the transport and emplacement of the West Runton raft.

Microstructural data obtained across the 'high strain' zone at the base of the raft shows that the relative intensity of deformation varied across this basal décollement (see Figure 9). However, comparison of the structurally lowest sample (WRA-316, Figure 4), taken from outside the 'high strain' zone, with those located within this detachment demonstrates that they all record the same deformation sequence which led to the imposition of the four clast microfabrics (Figure 9). The variation in the relative intensity of these foliations is interpreted as recording the microscale partitioning of deformation within the 'high strain' zone. Importantly, the majority of the microfabrics (S1, S3 and S4) crosscut the stratification in the HTM (see Figure 9) indicating that foliation development post-dated the formation of this layering (see section 5.3.3). Consequently, clast microfabric development is thought to record the later stages of the deformation history, equating to the end stages of raft transport and emplacement.

The lower boundary of the 'high strain' zone is marked by the appearance of the pervasive, relatively continuous S2 fabric (sample WRA-315, Figures 5 and 9) which defines a series of relatively narrow, easterly dipping bands or shears. These shears occur parallel to both the stratification in the HTM and the contact with the overlying chalk (Figure 9). The spacing of the shears increases upwards from sample WRA-315 (Figure 5) into the structurally higher WRA-317 (Figure 6), where S3 in the intervening lithons defines a sigmoidal S-C-like foliation. Consequently, the spacing and apparent intensity of this composite fabric increase towards the base of the raft (Figure 9). However, the geometry of the composite S2-S3 foliation records a westerly (up-ice) sense of shear (Figure 9), opposite to that derived from the macroscale structures present elsewhere within the 'high strain' zone (see Figure 2).

In contrast to samples WRA-315 and WRA-317, the pattern and relatively intensity of fabric development in thin section WRA-318 is more compatible with those of the HTM (sample WRA-316) outside the 'high strain' zone (Figure 9). This sample occurs adjacent to a large chalk clast contained within the HTM (see Figure 2d) and lacks any of the features (e.g. S-C-like shear fabrics) indicative of shearing associated with the glacitectonic emplacement of the raft (see Figure 9). Consequently, although sample WRA-318 is located well within the detachment at the base of the raft, it is thought to represent a 'pressure shadow' or 'low strain' area within this zone.

Thin section WRB-319 occurs across the narrow ductile shear zone cutting the basal part of the chalk raft (see Figure 2d). It shows that deformation of the HTM within this detachment was characterised by the development of a sigmoidal S-C-like S1 shear fabric (Figures 8 and 9). In marked contrast to samples WRA-315 and WRA-316, S1 in thin section WRA-319 records an easterly (down-ice) directed sense of shear consistent with the macroscopic field evidence (see above). This S1 shear fabric is crosscut by S2 (see Figure 8), with this second fabric therefore postdating the earlier (S1 in age) easterly directed ductile shear. This relationship also suggests that westerly directed shear leading to the imposition of the composite (S2-S3) shear fabric in samples WRA-315 and WRA-316 occurred at a later stage in the rafting process (i.e. post S1 easterly directed shear).

It is clear from the above that any model of the deformation associate with raft emplacement at West Runton needs to take into account the observed opposing sense of shear recorded by the clast microfabrics in the HTM. The relative chronology of clast microfabric development indicates that the antithetic, up-ice (westerly) shearing post-dated the initial down-ice (easterly) shear deformation. A four stage model is proposed to explain the microfabric development associated with 'high strain' zone at the base of the West Runton raft.

Stage 1 – was dominated by easterly directed (down-ice) ductile shearing (Figure 10a). This stage is thought to equate to the main transport phase of the raft and its emplacement into the structurally lower part of the deforming bed of the ice sheet. Ductile deformation was focused along the margins of the raft and largely partitioned into the adjacent HTM, resulting in the formation of a 20 to 30 cm thick 'high strain' zone (Figure 10a). Although the raft is internally relatively undeformed, shearing of its margins led to the imposition of a glacitectonic banding in the chalk (Figure 2e) and the detachment of small fragments of chalk as well as elongate stringers of bedrock which were progressively incorporated into the diamicton (see section 6.3). Deformation within the 'high strain' zone at this stage was characterised by the progressive development of the glacitectonic stratification within the HTM with this layering wrapping around the irregularities in the base of the raft (Figure 2).

Stage 2 – is characterised by the propagation of a gently westerly dipping ductile shear zone cutting through the chalk at the base of raft and the initial separation of the block WRA from the main body of the raft (WRB) (Figure 10b). Thin lenses of the HTM were progressively sheared into the opening developing between WRA and WRB, with easterly directed shear leading to the imposition of the S-C-like S1 fabric. S1 foliation development also occurred within the chalk immediately adjacent to this propagating shear zone (see Figure 7). Elsewhere beneath the raft, S1 in the HTM developed as a spaced, gently westerly dipping (up-ice), disjunctive foliation (Figure 9). The base of the raft at West Runton is irregular (see Figure 10b) possibly leading to 'drag' at the base of the raft, 'slowing' the rate of emplacement. Consequently, the detachment of these irregularities, such as the one represented by chalk block WRA, would have progressively led to the 'flattening' of this contact facilitating raft transport, effectively 'streamlining' the raft during its emplacement.

Stage 3 – the continuing detachment of block WRA from the main body of the raft began to effect the style deformation within the underlying 'high strain' zone as it wrapped around its base (Figure 10c). As the fracture separating the two blocks progressively widened the relative motion of the block WRA, with respect to the main raft, would have been downwards into the HTM. This would have resulted in the deflection of the underlying, actively deforming HTM, forcing it downwards as it tried to accommodate both the expansion of the gap forming between WRA and WRB, but also the continuing easterly directed shearing imposed by the overriding ice sheet. The result was the localised antithetic (up-ice), westerly directed shear within HTM immediately adjacent to the base of the 'subsiding' block (Figure 10c) and the imposition of the composite S2-S3 shear fabric present in samples WRA-315 and WRA-317 (Figures 5, 6 and 9).

Stage 4 – represents the final stage of deformation associated with the emplacement of the West Runton raft. Deformation within the HTM and 'high strain' zone at the base of this raft is thought to have begun to 'lock-up', leading to the imposition of the heterogeneously developed S4 fabric which crosscuts all of the earlier shear fabrics (S1, S2 and S3) (Figure 10d).

6.2. Evidence for low shear strains and elevated porewater contents within the basal shear zone responsible for raft emplacement

Although the traditional view is that tectonically laminated and homogenized tills are a product of intense strains (Boulton, 1987; Hart et al., 1990; van der Wateren, 1995; Hart, 1995), more recent detailed field, micromorphological and laboratory studies have demonstrated that the strains encountered by subglacially deformed sediments are much lower than expected (Iverson et al., 1996; Benn and Evans, 1996; Piotrowski and Tulaczyk, 1999; van der Wateren et al., 2000; Khatwa and Tulaczyk, 2001; Thomason and Iverson, 2006, 2009; Evans et al., 2006). The absence of deformation structures within an apparently homogeneous subglacial diamicton, like parts of the HTM at West Runton, should not be used on its own as an indicator of intense deformation. Unless a progression from undeformed, through intensely deformed and into homogenised sediments can be demonstrated, the homogenisation of a diamicton due to intense deformation and/or high shear strains cannot be proven. It is known that the composition and porewater content of the sediment represent important factors controlling the apparent intensity of deformation imposed on subglacial deposits by the over-riding by ice (Evans et al., 2006 and references therein). Elevated porewater pressures can lead to the dilation and partial liquefaction of subglacially deforming sediments resulting in the lowering of their cohesive strength, weakening the sediment, and ultimately leading to their homogenisation even at low strains (Piotrowski et al., 2001, 2004; Lee and Phillips, 2008; Phillips et al., 2008).

It has been demonstrated that the proposed 'high strain' zone forming the décollement at the base of the raft at West Runton represents a zone of enhanced ductile deformation which accommodated the bulk of the displacement associated with the emplacement of this rafted block (see section 6.1). Although it is tempting to suggest that this deformation was the result of high shear strains imposed during rafting, micromorphological evidence clearly contradicts this theory. The matrix of the chalk-rich layers within the stratified diamicton contain complete, as well as broken bioclasts such as foraminifera, echinoderm spines, thin-walled shell fragments, calcispheres and calcareous algae (Figure 3). The preservation of complete tests of, for example the foraminifera, argues against the HTM having encountered very high shear strains, as these would have resulted in the fragmentation and destruction of this bioclastic material. Consequently, it is concluded that glaciotectonic transport and emplacement of the rafted block at West Runton was achieved under conditions of relatively low shear strain. This may have been achieved due to elevated inter-granular porewater pressures driving increased sediment dilatancy and resulting in lower transmission of effective stresses into the plastic groundmass (Lee, 2009).

Lee and Phillips (2008) and Phillips et al. (2008) argued that subglacial deformation responsible for the formation of the mélange facies of the BGTM at West Runton, and further east along the coast at Bacton Green (see Figure 1), occurred within a thick subglacial shear zone (also see Waller et al., 2011). These authors concluded that this shear zone accommodated most of the movement of the overriding ice sheet, with deformation being partitioned into an anastomosing network of relatively 'high strain' zones which progressively shifted through the deforming bed (c.f. Piotrowski and Kraus, 1997; Hoffman and Piotrowski, 2001; van der Meer et al., 2003; Piotrowski et al., 2004; Evans et al., 2006; Lee, 2009). Partitioning of deformation within the BGTM, and the upper part of the structurally underlying HTM, was thought to have been controlled by the variation in porewater content and/or pressure. This conclusion is supported by the disharmonic nature of folding and evidence of liquefaction and water-escape within the BGTM and HTM (see Phillips et al., 2008). The zone of enhanced ductile deformation at the base of the West Runton raft would have made an ideal fluid pathway aiding the migration of porewater through the deforming bed, weakening the HTM within this zone, and thereby facilitating the emplacement of the raft. During dewatering, the shear zone would begin to 'lock' and earlier ductile deformation, characterised by the imposition of S1 to S3, superseded by the imposition of the heterogeneous S4 foliation. Waller et al. (2011) considered that the easterly advancing ice which resulted in much of the deformation at West Runton was overriding 'warm' permafrost. The liquid water in the overridden permafrost was concentrated into the HTM and BGTM as a result of pre-melting within these the clayey sediments at temperatures below the bulk freezing point (Dash et al., 2006), with pore ice being most abundant in unconsolidated sand and gravels of the WCF and sand intraclasts. The raft at West Runton is thought to have remained frozen during glacitectonism, protecting the unconsolidated WCF from being stripped off the top of the chalk bedrock during transport and emplacement. This composite raft would have acted as a relatively rigid body during subglacial deformation with the bulk of the ductile shear accompanying its emplacement being partitioned into the relatively weaker, water-rich/partly frozen HTM.

6.3. Melting of a pore ice cement leading to deformation, disaggregation and incorporation of the chalk into the Happisburgh Till Member

The chalk-rich layers and stringers which partially define the stratification within the HTM exposed immediately below the raft at West Runton indicate that chalk from the base of this raft was being incorporated into the underlying diamicton; a conclusion supported by the increase in number and thickness of these chalky bands towards the base of the raft (see sections 4 and 5). As described above, the chalk bedrock within the raft was periglacially altered and shows evidence of having been deformed during rafting (see Figures 2a and e). In detail, this altered chalk comprises well-rounded sand to pebble sized fragments set within a fine-grained, micritic carbonate matrix. Importantly, the morphology (size and shape) of the chalk pebbles included within the HTM closely resembles that of the relict chalk fragments within the altered bedrock. Although it is tempting to compare the morphology of the stringers and tails developed upon the chalk pebbles in the HTM with porphyroclast systems present in mylonitic rocks (Passchier and Trouw, 1996), the shear strains recorded by the diamicton (see section 6.2) would have been far too low to have resulted in the intense cataclasis, dynamic recrystallisation and grain reduction typical of the creation of such structures in bedrock ductile shear zones. Consequently, it is concluded that the chalk pebbles within the diamicton may have simply been derived by the 'passive' disaggregation of the altered bedrock in response to elevated porewater contents/pressures under relatively low strain conditions.

The raft at West Runton acted as a relatively rigid body which largely remained frozen during glacitectonism. However, shearing at the margin (during Stage 1 of the deformation model, see section 6.1) may have resulted in deformation induced (strain heating) partial melting of the pore ice cement in the chalk. The direct introduction of this meltwater into the micritic matrix of the altered bedrock would have turned it into the soft, pliable 'putty chalk' seen in the present day outcrop (see section 4), effectively weakening the bedrock immediately adjacent to the chalk-HTM contact. This is supported by the micromorphological evidence which shows that the dominant clast microfabric present in the diamicton has also been imposed upon the chalk (see Figures 7, 8 and 9). Continued melting of the pore ice cement, softening of the matrix of the bedrock, coupled with the related increase in liquid porewater content in the chalk would have led to its disaggregation and its incorporation into the adjacent HTM. Consequently, the breakdown and incorporation of the chalk bedrock into the diamicton is simply a result the strain induced partial melting of the permafrost along the margins of the raft, rather than an indicating high shear strains during deformation. Furthermore, melting of the pore ice cement will liberate more liquid water into the 'high strain' zone at the base of the raft, this will not only facilitate the mixing of the disaggregated chalk into the diamicton, but also help maintain the high porewater content within this décollement, aiding raft emplacement.

7. Conclusions and Discussion

A number of conclusions can be made regarding the deformation associated with the emplacement of the composite bedrock-sediment raft exposed at West Runton, north Norfolk, eastern England:

- Deformation associated with the transport and emplacement of the raft was focused along its margins with the bulk of the displacement being partitioned into the relatively weaker HTM. The kinematics of this deformation are consistent with the overall easterly directed subglacial (D3) event identified by Phillips et al. (2008), with rafting occurring in response to glacitectonism associated with ice advancing from the west.

- A detailed macro- and microstructural study has allowed a four stage conceptual deformation model of raft emplacement to be established: ***Stage 1*** – corresponding to the main transport phase of the raft, dominated by easterly directed (down-ice) ductile shearing; ***Stage 2*** – continued easterly directed shear resulted in the propagation of a narrow ductile shear zone upward through the base of the raft leading to the eventual detachment of an elongate block of chalk from the main body of the raft; ***Stage 3*** – the detached chalk block impinged on the deformation occurring within the 'high strain' zone at the base of the raft leading to localised antithetic, westerly (up-ice) directed shear; and ***Stage 4*** – the locking up of the basal 'high strain' zone during the final stages of raft emplacement.

- The irregular nature of the base of the raft at West Runton probably resulted in 'drag' during rafting. The detachment and removal of these irregularities would have progressively led to the 'flattening' of this basal contact facilitating raft transport and effectively 'streamlining' the raft during its emplacement.

- The preservation of complete bioclasts within the detachment zone provides evidence that glaciotectonic transport and emplacement of the rafted block at West Runton was achieved under relatively low shear strains. Elevated porewater contents and/or pressures within the HTM would have lowered its cohesive strength facilitating ductile shearing and displacement of the overriding raft.

- The West Runton raft remained frozen during glacitectonism protecting the unconsolidated WCF from being stripped off from the underlying chalk during rafting. Shearing related melting of the pore ice cement within the chalk at the base of the raft, however, led to the localised softening and disaggregation of this already periglacially altered bedrock and its incorporation into the HTM. Meltwater liberated during this processes would have migrated into the adjacent 'high strain' zone helping to maintain the elevated porewater contents within this basal décollement.

- The results of the present study clearly demonstrate the power of a multidisciplinary approach, involving micromorphology and macro- and microstructural analysis, to unravelling complex, polyphase deformation histories and thereby aid our detailed understanding of glacitectonic processes.

Although the transport and emplacement phases of rafting at West Runton can be directly related to the pervasive subglacial deformation event associated with an easterly directed ice advance, evidence of the initial detachment of this composite bedrock-sediment raft is no longer preserved. It is possible that the initial detachment of the raft occurred in response to subglacial thrusting. This would require the shear generated by the overriding ice sheet to be transmitted through the highly ductile BGTM and HTM, which formed the thick (20 to 30 m) deforming bed beneath the advancing ice sheet (Phillips et al., 2008), into the underlying preglacial sediments and bedrock. The high porewater contents/pressures within this subglacial shear zone, however, would have resulted in preferential partitioning of shear into the much weaker diamictons (c.f. Lee and Phillips 2008; Phillips et al., 2008; also see Waller et al., 2011). As a result very little, if any, deformation would have penetrated into the underlying WCF and chalk bedrock. Phillips et al. (2008) demonstrated that the ice marginal deformation at West Runton was dominated by large-scale folding and thrusting, resulting in the stacking of fault-bound slices of the pre-existing sedimentary sequence in front of the advancing ice sheet (see figs. 3, 4 and 10 in Phillips et al., 2008). Consequently, the initial detachment phase of the raft at West Runton is more likely to have occurred in response to ice-marginal, or even submarginal, thrusting. The detached block was then overridden and incorporated into the subglacial shear zone. The pervasive nature of this subglacial deformation would have led to the overprinting of any structures formed during the initial detachment phase of the rafting process. This has implications for other glacitectonic rafts, in that although transport and emplacement can occur within the subglacial environment, their initial detachment requires glacier induced deformation to have penetrated into these pre-existing sediments and/or bedrock. So although, in theory, raft detachment may be achieved beneath the overriding ice, it is more likely that this process occurs at the margins of ice sheets or glaciers.

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12. Figures

Figure 1. Map showing **(a)** the location of West Runton study area, north Norfolk, eastern England, **(b)** the location of West Runton relative to nearby Quaternary sites, **(c)** the model for ice re-advance as suggested in

Phillips *et al*. (2008) and **(d)** the location of the raft study site within Domain 2 of the Phillips *et al.* (2008) deformation interpretation.

Figure 2.(a) and **(b)** Detailed diagram and photo-mosaic showing the stratigraphy and principal deformation structures associated with the composite raft exposed at West Runton [TG 174 433]; **(c)** Lower hemisphere stereographic projection of orientation data obtained for the main lithological contacts (plotted as poles to planes); **(d)** Photograph showing the base of the raft and the location of the samples (WRA-315; WRA-316; WRA-317; WRA-318; WRA-319) taken for micromorphological and microstructural analysis of the small-scale structures developed within the décollement zone at the base of this body; **(e)** Photograph of the western part of the exposed raft showing the presence of a well-developed glacitectonic banding or foliation in the chalk and deformed fragment of chalk within the structurally underlying Happisburgh Till Member recording an easterly (down-ice) sense of shear.

Figure 3. Photomicrographs of Foraminifera within a micritic carbonate matrix, demonstrating complete or partially preserved tests; examples from thin section WRA-317 **(a)** and **(b)**, WRA-318 **(c)** and **(d)**, and WRB-319 **(e)** and **(f)**.

Figure 4. High resolution scan and microstructural map of the polydeformed diamicton within sample WRA-316, characterising the deformation within the Happisburgh Till Member outside the 'high strain' zone which forms the décollement beneath the raft exposed at West Runton. Four main clast microfabrics have been identified within the diamicton defined by the preferred shape alignment of included sand to small pebble sized clasts (see text for details).

Figure 5. High resolution scan and microstructural map of sample WRA-315 taken across the lower boundary of the 'high strain' zone developed within the Happisburgh Till Member beneath the chalk raft. The lower part of the thin section possesses the same pattern and intensity of clast microfabric development as sample WRA-316. The upper part of thin section WRA-315 occurs within the 'high strain' zone where deformation is characterised by the development of a pervasive S2 fabric defining narrow bands of shears separating relatively lower strain areas where the S4 foliation defines a sigmoidal, S-C like foliation which yields a westerly (up-ice) sense of shear (see text for details).

Figure 6. High resolution scan and microstructural map of sample WRA-317 taken across the boundary between the chalk at the base of the raft and the structurally underlying Happisburgh Till Member. The lower part of the thin section possesses the same pattern and intensity of clast microfabric development as sample WRA-316. The upper part of thin section WRA-315 occurs within the 'high strain' zone where deformation is characterised by the development of a pervasive S2 fabric defining narrow bands of shears separating relatively lower strain areas where the S4 foliation defines a sigmoidal, S-C like foliation which yields a westerly (up-ice) sense of shear (see text for details).

Figure 7. High resolution scan and microstructural map of sample WRA-318. The thin section possesses the same pattern and intensity of clast microfabric development present within the HTM outside this zone consistent with the formation of a pressure shadow adjacent to a detached block of chalk contained within the 'high strain' zone at the base of the raft (see text for details).

Figure 8. High resolution scan and microstructural map of sample WRA-319 taken across a narrow ductile shear zone separating the main body of the raft (WR/B) from a large block of chalk (WRA) detached during emplacement. The thin section is characterised by the development of a pervasive S1 fabric defining a sigmoidal, S-C like foliation which records an easterly (down-ice) sense of shear (see text for details).

Figure 9. Interpretation diagram derived from the combined microstructural maps of thin sections WRA-316, WRA-315, WRA-317, WRA-318 and WRA-319 showing the variation in pattern and relative intensity of clast

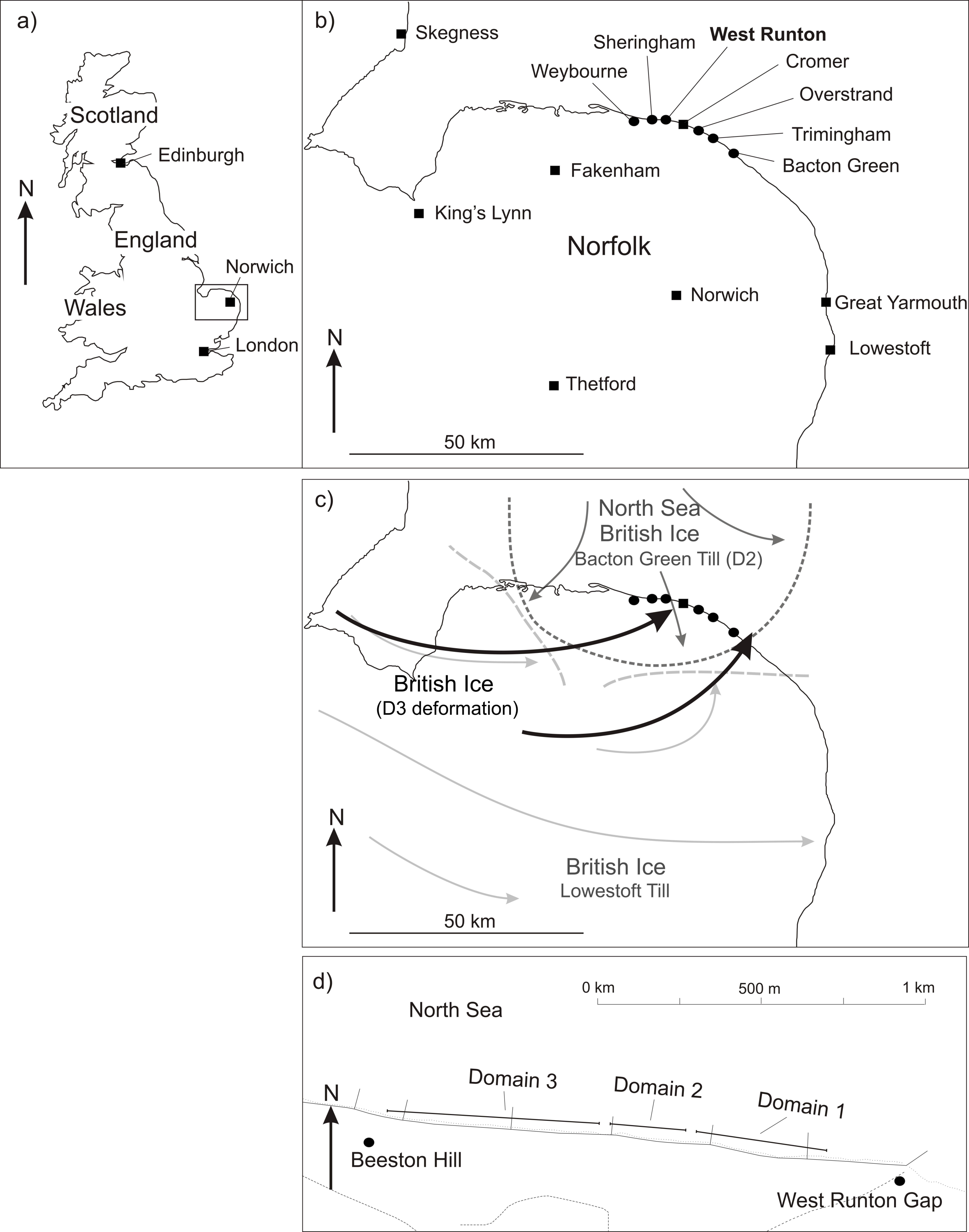
microfabric development within the 'high strain' zone which accommodated the bulk of the displacement associated with the emplacement of the raft at West Runton (see text for details).

Figure 10. Diagram showing the four stage conceptual deformation model resulting in the clast microfabric development observed within the 'high strain' zone developed at the base of the composite raft at West Runton, with **(a)** ductile shearing partitioning through HTM underlying the undulating base of the raft; **(b)** the propagation of a shear zone cutting through the base of the raft associated with an S-C-like fabric development described by the S1 fabric; **(c)** the separation of WR/A from WR/B and continuing development of 'high strain' zones at the contact of WR/A, associated with the S2-S3 composite fabric development; and **(d)** the locking-up of the 'high strain' zone, leading to the heterogeneously developed S4 fabric.

13. Tables

Table 1. A tectonostratigraphic scheme proposed for the glacial succession of northeast Norfolk, showing the primary tectonic events (from Lee *et al.* 2011b).

	ICE ADVANCE	GLACITECTONIC SIGNATURE	STRUCTURAL EVIDENCE
A6	Re-advance from N	Large-scale glacitectonism associated with ice-marginal thrust-stacking; Cromer Ridge and smaller ice-contact features.	Listric thrust faults, thrust duplex structures, inverted stratigraphy, large- and small-scale open folding.
A5	Ice advance from W	Large-scale glacitectonism associated with subglacial deforming bed processes (<30m); generation of Bacton Green Till melange; development of terminal moraine – extensional basin complexes; and accretion of 'western facies' Weybourne Town Till.	Sheath folding, thrusts, crenulation cleavage, hanging-wall anticlines, over-turned folding, small-scale soft-sediment deformation.
A4	Re-advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of Bacton Green Till (subglacial and subaqueous).	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, decollement surfaces, small-scale soft-sediment deformation.
A3	Ice advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of Walcott Till.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, decollement surfaces.
A2	Re-advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of Corton Till.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, soft-sediment deformation.
A1	Ice advance from N	Local-scale glacitectonism associated with subglacial deforming processes (<8m); accretion of Happisburgh Till.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, decollement surfaces.


a)
Scotland
Edinburgh
N
England
Norwich
Wales
London
b)
Skegness
Sheringham
West Runton
Weybourne
Cromer
Overstrand
Trimingham
Bacton Green
Fakenham
King's Lynn
Norfolk
Norwich
Great Yarmouth
N
Lowestoft
Thetford
50 km
c)
North Sea
British Ice
Bacton Green Till (D2)
British Ice
(D3 deformation)
N
British Ice
Lowestoft Till
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d)
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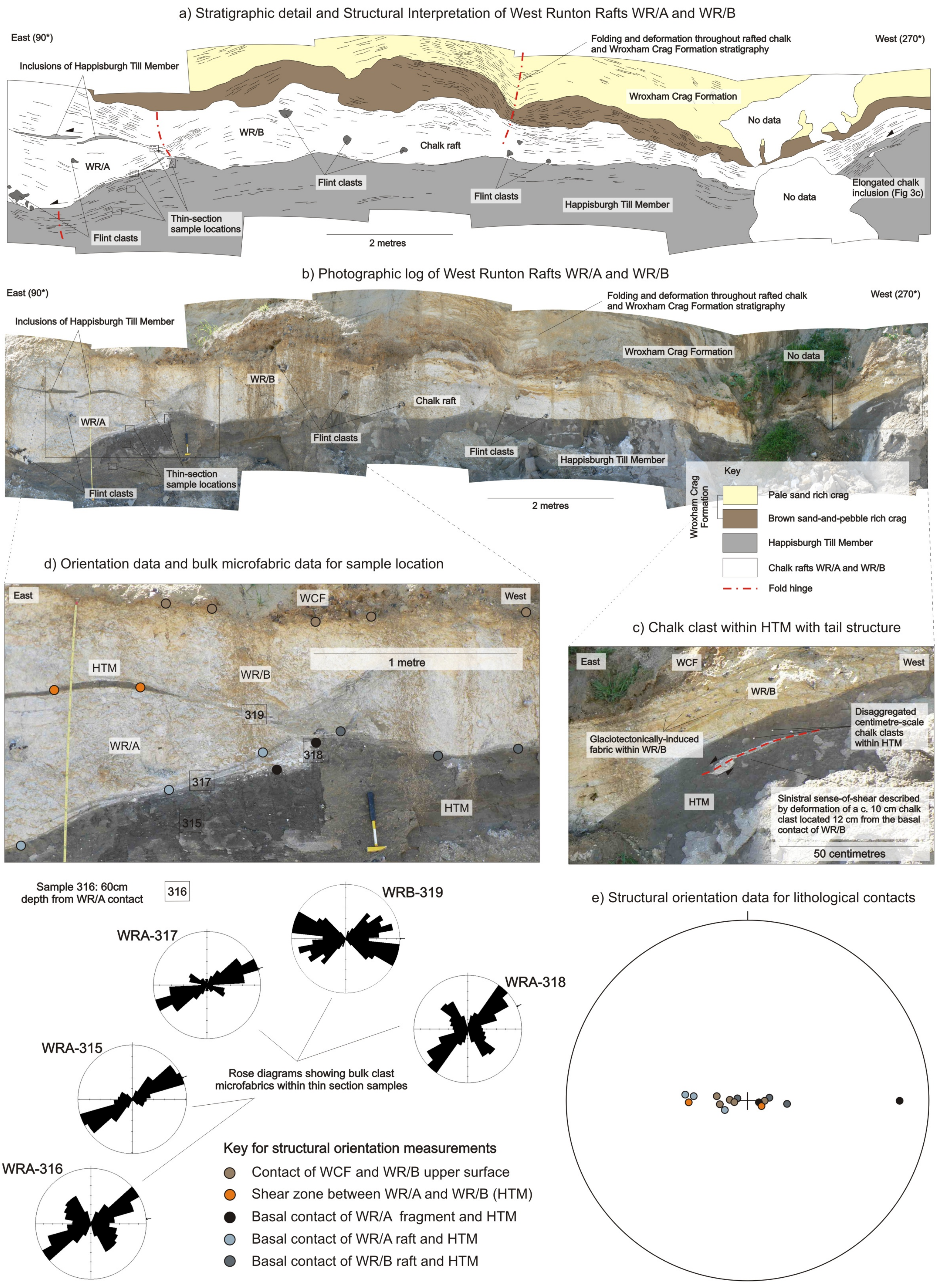
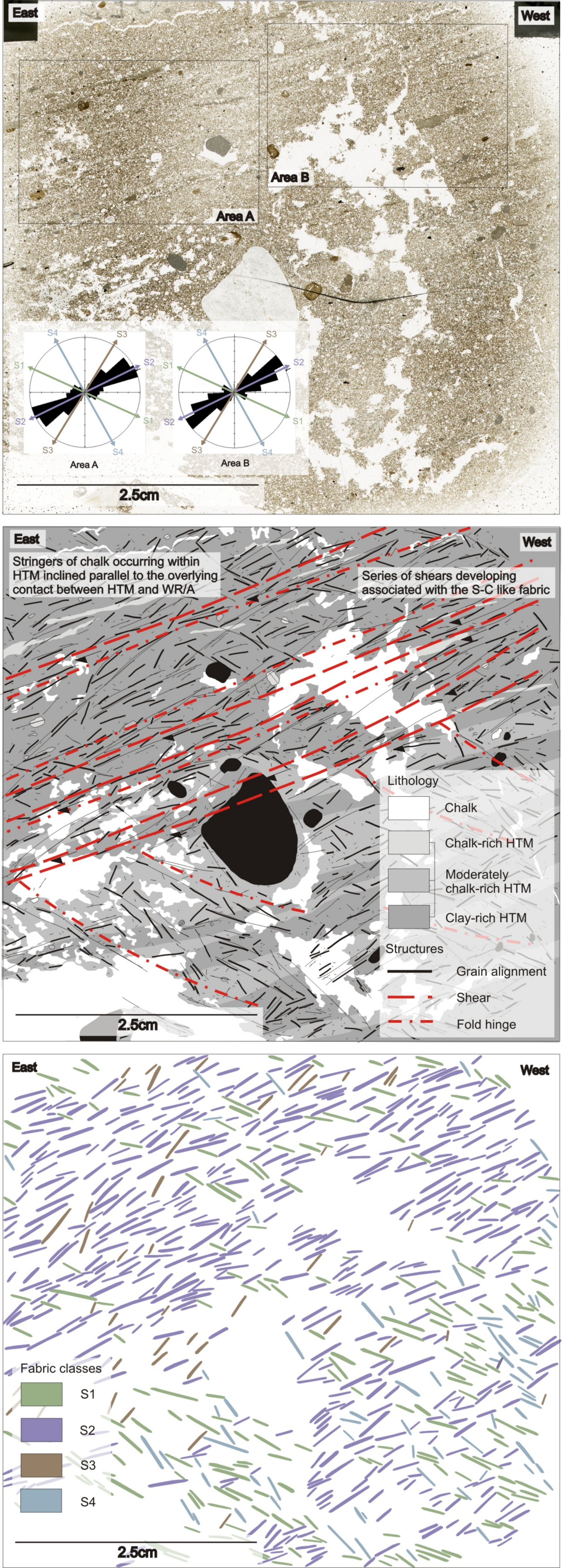
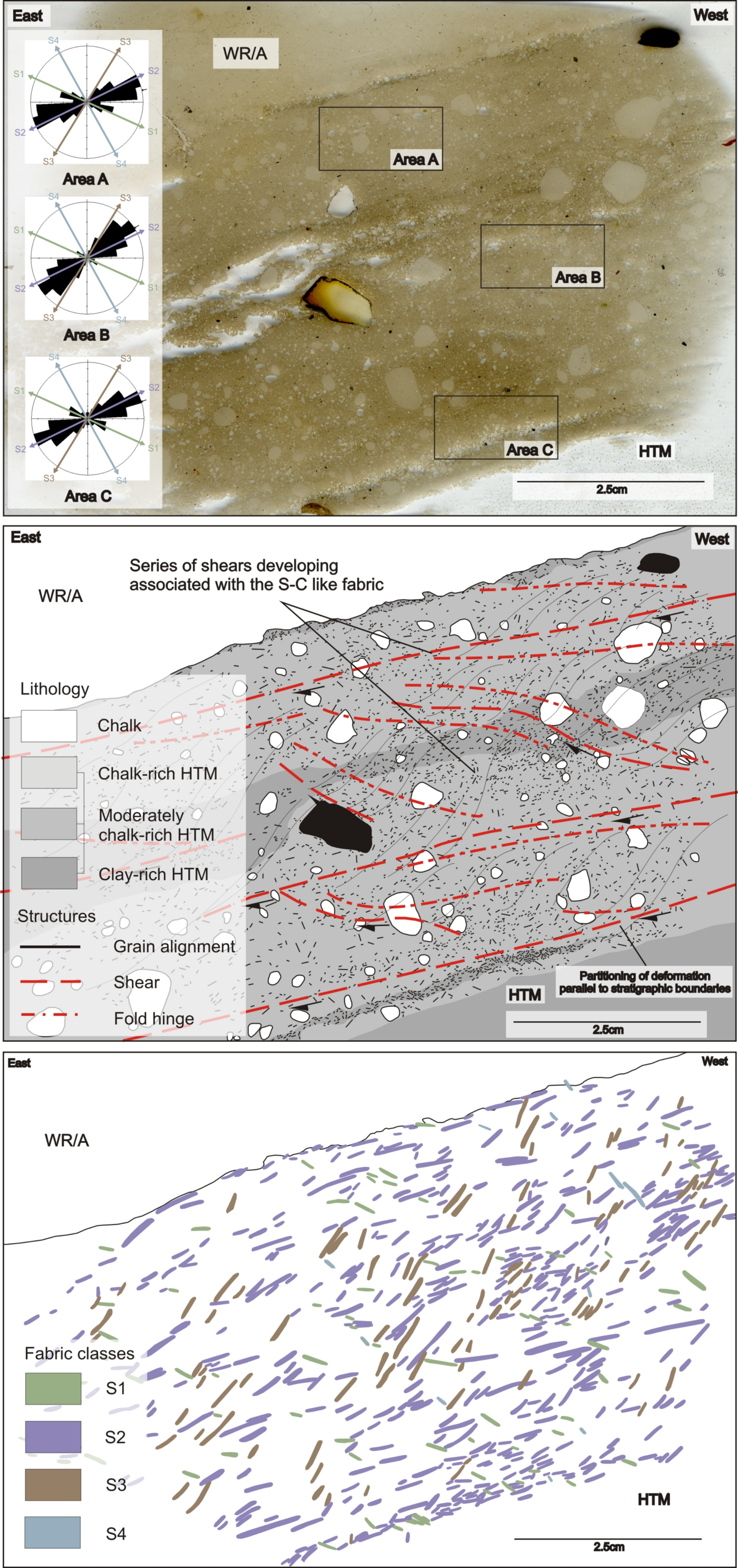
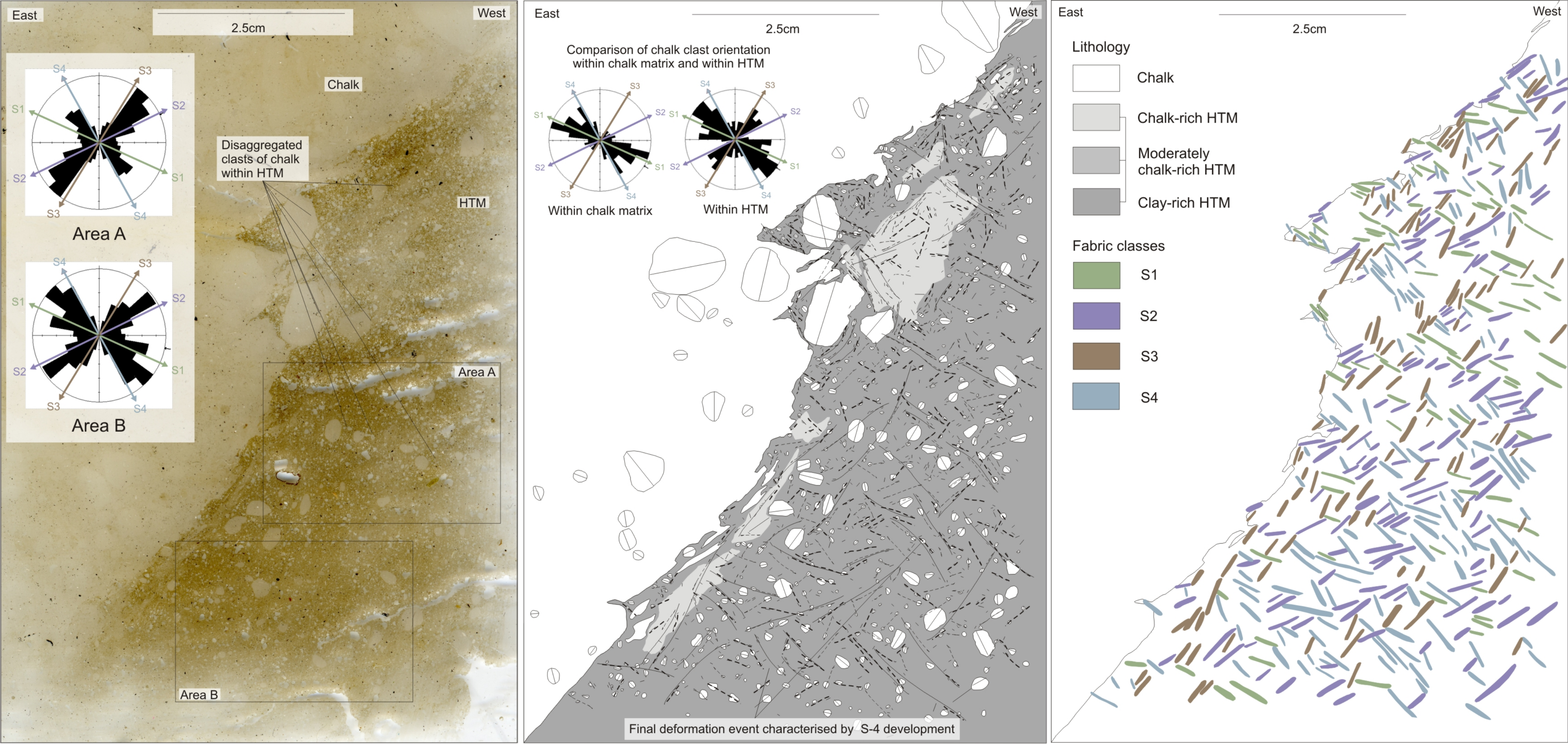
1 km
North Sea
Domain 3
Domain 2
Domain 1
N
Beeston Hill
West Runton Gap

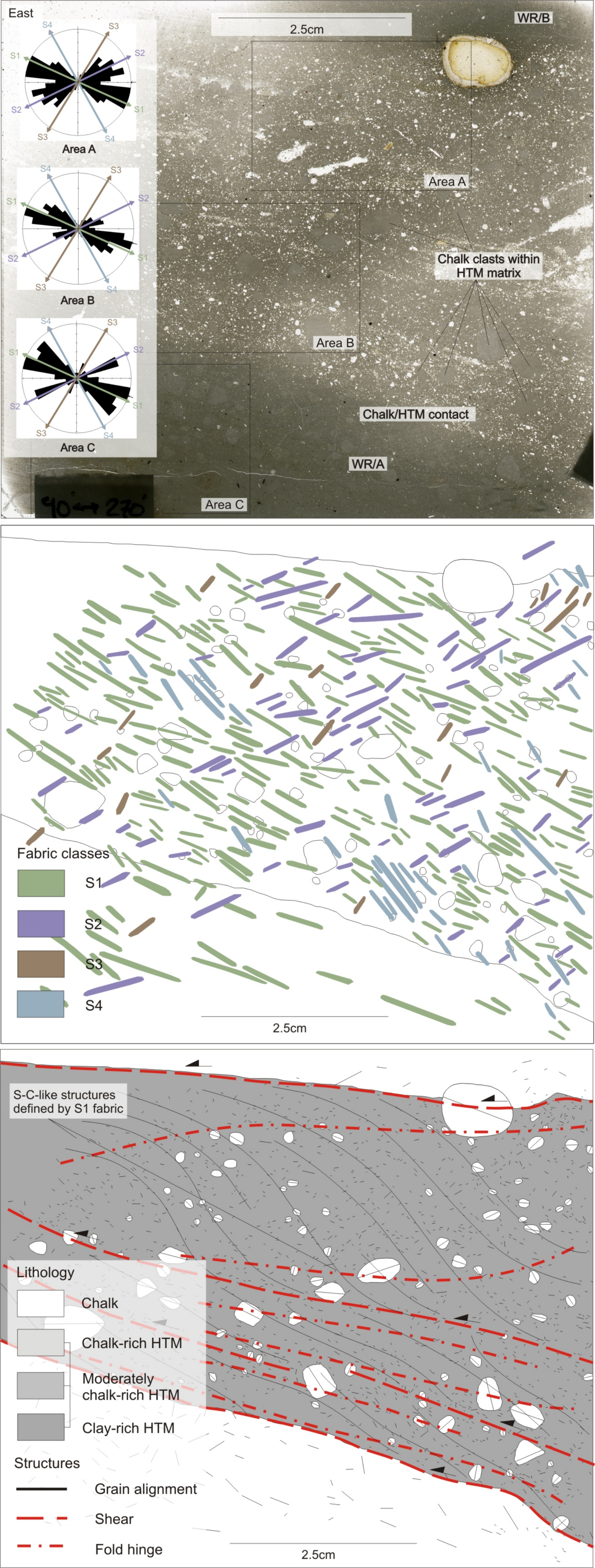


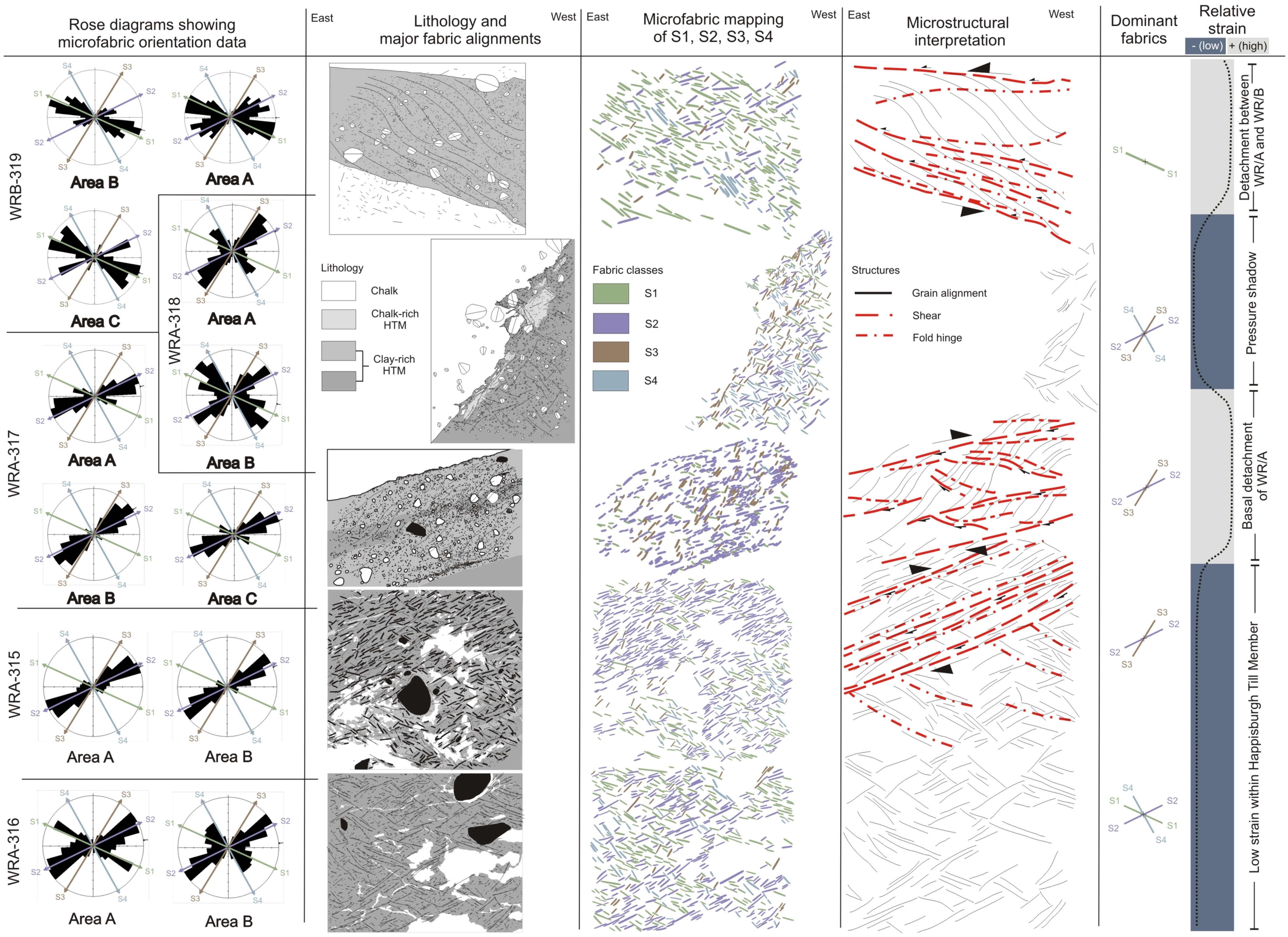
a) Stratigraphic detail and Structural Interpretation of West Runton Rafts WR/A and WR/B
East (90*)
West (270*)
Inclusions of Happisburgh Till Member
Folding and deformation throughout rafted chalk and Wroxham Crag Formation stratigraphy
Wroxham Crag Formation
No data
WR/B
Chalk raft
WR/A
Flint clasts
Flint clasts
Flint clasts
Happisburgh Till Member
No data
Elongated chalk inclusion (Fig 3c)
Thin-section sample locations
Flint clasts
2 metres
b) Photographic log of West Runton Rafts WR/A and WR/B
East (90*)
West (270*)
Folding and deformation throughout rafted chalk and Wroxham Crag Formation stratigraphy
Inclusions of Happisburgh Till Member
Wroxham Crag Formation
No data
WR/B
Chalk raft
WR/A
Flint clasts
Flint clasts
Happisburgh Till Member
Thin-section sample locations
Flint clasts
2 metres
Key
Wroxham Crag Formation
Pale sand rich crag
Brown sand-and-pebble rich crag
Happisburgh Till Member
Chalk rafts WR/A and WR/B
Fold hinge
d) Orientation data and bulk microfabric data for sample location
East
WCF
West
1 metre
HTM
WR/B
319
WR/A
318
317
315
HTM
c) Chalk clast within HTM with tail structure
East
WCF
West
WR/B
Disaggregated centimetre-scale chalk clasts within HTM
Glaciotectonically-induced fabric within WR/B
HTM
Sinistral sense-of-shear described by deformation of a c. 10 cm chalk clast located 12 cm from the basal contact of WR/B
50 centimetres
Sample 316: 60cm depth from WR/A contact
316
WRB-319
WRA-317
WRA-318
WRA-315
Rose diagrams showing bulk clast microfabrics within thin section samples
WRA-316
Key for structural orientation measurements
Contact of WCF and WR/B upper surface
Shear zone between WR/A and WR/B (HTM)
Basal contact of WR/A fragment and HTM
Basal contact of WR/A raft and HTM
Basal contact of WR/B raft and HTM
e) Structural orientation data for lithological contacts


East
West
Area A
Area B
S1
S2
S3
S4
Area A
Area B
2.5cm
East
West
Stringers of chalk occurring within HTM inclined parallel to the overlying contact between HTM and WR/A
Series of shears developing associated with the S-C like fabric
Lithology
Chalk
Chalk-rich HTM
Moderately chalk-rich HTM
Clay-rich HTM
Structures
Grain alignment
Shear
Fold hinge
2.5cm
East
West
Fabric classes
S1
S2
S3
S4
2.5cm

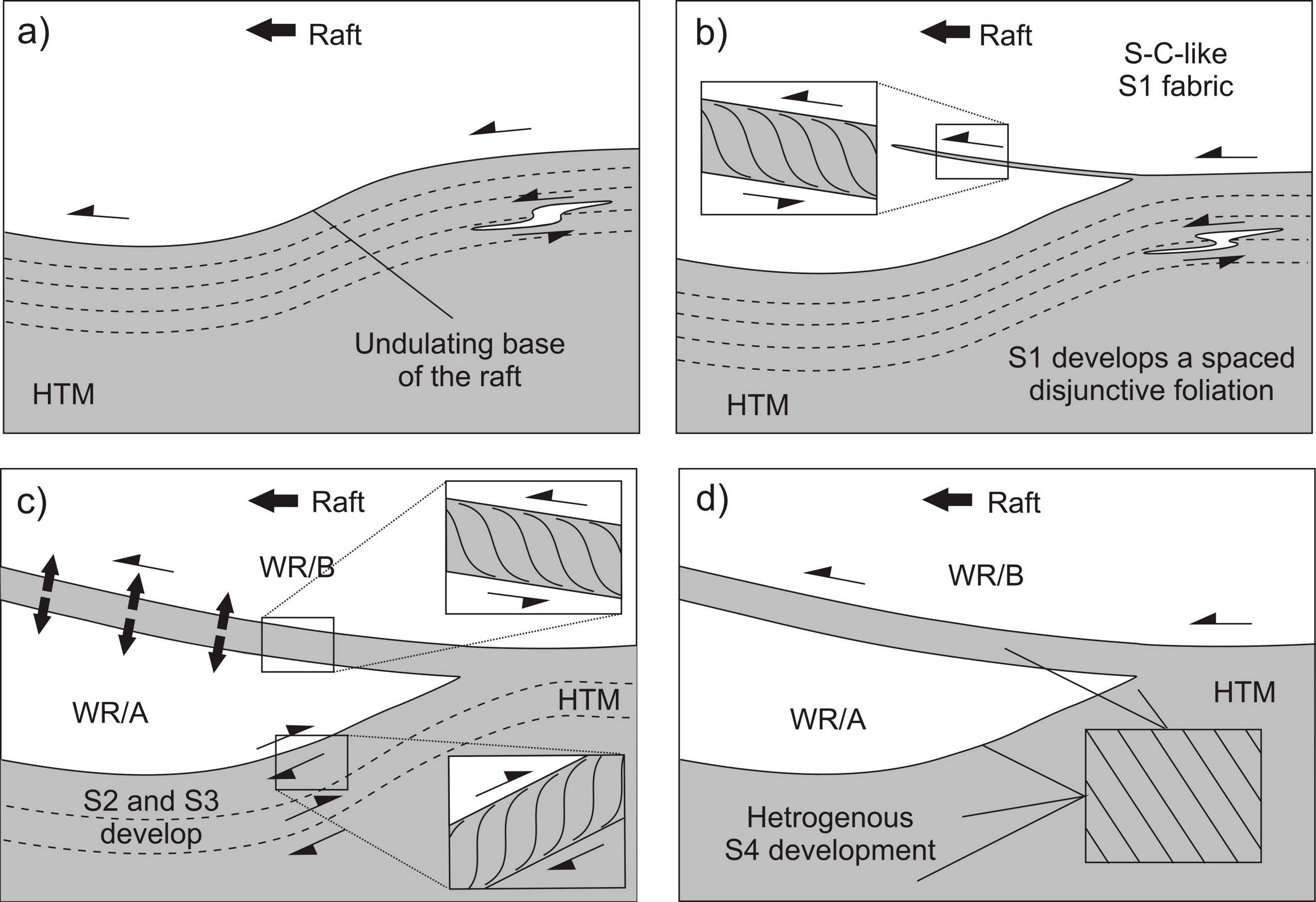

East
West
WR/A
Area A
Area B
Area C
HTM
2.5cm
East
West
Series of shears developing
associated with the S-C like fabric
WR/A
Lithology
Chalk
Chalk-rich HTM
Moderately
chalk-rich HTM
Clay-rich HTM
Structures
Grain alignment
Shear
Fold hinge
HTM
Partitioning of deformation
parallel to stratigraphic boundaries
2.5cm
East
West
WR/A
Fabric classes
S1
S2
S3
S4
HTM
2.5cm


East
West
2.5cm
Chalk
Disaggregated clasts of chalk within HTM
HTM
S1
S2
S3
S4
Area A
Area B
East
West
2.5cm
Comparison of chalk clast orientation within chalk matrix and within HTM
Within chalk matrix
Within HTM
Final deformation event characterised by S-4 development
East
West
2.5cm
Lithology
Chalk
Chalk-rich HTM
Moderately chalk-rich HTM
Clay-rich HTM
Fabric classes
S1
S2
S3
S4


East
Area A
Area B
Area C
2.5cm
WR/B
Area A
Chalk clasts within HTM matrix
Area B
Chalk/HTM contact
WR/A
Area C
Fabric classes
S1
S2
S3
S4
2.5cm
S-C-like structures defined by S1 fabric
Lithology
Chalk
Chalk-rich HTM
Moderately chalk-rich HTM
Clay-rich HTM
Structures
Grain alignment
Shear
Fold hinge
2.5cm



Rose diagrams showing microfabric orientation data
East
Lithology and major fabric alignments
West
East
Microfabric mapping of S1, S2, S3, S4
West
East
Microstructural interpretation
West
Dominant fabrics
Relative strain
- (low)
+ (high)
WRB-319
Area B
Area A
Area C
WRA-318
Area A
Area B
WRA-317
Area A
Area B
Area C
WRA-315
Area A
Area B
WRA-316
Area A
Area B
S1
S2
S3
S4
Lithology
Chalk
Chalk-rich HTM
Clay-rich HTM
Fabric classes
S1
S2
S3
S4
Structures
Grain alignment
Shear
Fold hinge
Detachment between WR/A and WR/B
Pressure shadow
Basal detachment of WR/A
Low strain within Happisburgh Till Member



a)
Raft
Undulating base
of the raft
HTM
b)
Raft
S-C-like
S1 fabric
S1 develops a spaced
disjunctive foliation
HTM
c)
Raft
WR/B
WR/A
HTM
S2 and S3
develop
d)
Raft
WR/B
WR/A
HTM
Hetrogenous
S4 development