Glacitectonic rafting of chalk bedrock: Overstrand

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1. Introduction

A glacitectonic raft is defined as *"…a fragment of substratum with preserved original lithological character, detached from its primary bed and transported due to glacial activity, occurring within or immediately adjacent to corresponding glaciogenic deposits…"* (Ruszczynska-Szenajch, 1987; Evans, 2007). The distinguishing factor of a raft compared to an erratic is that the latter refers to a single consolidated clast transported in a matrix, whereas a raft is generally observed as a fault-bound wedge of relatively unlithified sediment. In contrast to sediment slabs involved in moraine ridge formation (Krüger, 1996), rafts are more capable of maintaining their lithological structure and can be transported comparatively large distances rather than being limited to local thrusting under direct stress from advancing ice.

Section Location: Park adjacent to the beach slipway at Overstrand (TG 254 405). Walk down the slipway and head east for 500m climbing over several breakwaters. Access at low-tide only.

1.1 Variety and controls on rafting

Glacitectonic rafts are recorded across a diverse range of glaciated terranes, including the Interior Plains of North Dakota where rafts of shale and sandstone bedrock are thrust into younger sediments (Bluemle and Clayton, 1983); across extensive tracts of the prairie regions of Alberta and Saskatchewan (Moran *et al.,* 1980); and within glacitectonites and associated subglacial tills in northeast Scotland (Peacock and Merritt, 1997; Phillips and Merritt, 2008). The material they are composed of is similarly varied; rafts can be composed of glaciogenic material, non-glacigenic deposits, or local bedrock. They have been described as units of glaciofluvial material thrust into predominantly clay till across central Poland (Ruszczynska-Szenajch, 1987), and as lithified bedrock units introduced into till in southwest Ireland (Hiemstra *et al.,* 2007) and north Norfolk (Hart, 1990; Phillips *et al.,* 2008; Burke *et al.,* 2009).

Despite the proliferation of rafted sections, a lack of standard terminology combined with disagreement in the literature over classification schemes has left the phenomenon relatively poorly understood. Controversy continues over the processes governing the detachment and transport phases, and several competing theories have become established. Under the framework described by Banham (1988), which applied the terminology of thin-skinned tectonics to glacitectonics, attempts were made to reclassify rafts in a complimentary scheme (cf. Ruszczynska-Szenajch, 1987). However, these early models are still limited by failing to combine both glaciological and geological factors into their interpretations. Fundamentally, there is disagreement over whether rafted blocks are frozen on to the base of the glacier (Banham, 1975; Aber, 1988) or whether initial detachment is controlled by high porewater pressure. This might occur at the décollement surface (Moran *et al.,* 1980; Phillips and Merritt, 2008), at the base of the deforming layer (Kjær *et al.,* 2006), or as a result of hydrofracturing under loading (Boulton and Caban, 1995; Rijsdijk *et al.,* 1999). It is also not clear whether detachment must take place at an actively advancing ice-margin, with transport occurring as the detached block is inducted subglacially, or whether any stage of raft development can occur independent of having a proglacial or subglacial location.

1.2 Proglacial and subglacial rafting

There are distinct morphological differences between rafts which have formed (detached and initiated transport) proglacially and subglacially. In proglacial environments, rafts can become emplaced in an imbricate thrust-stack (Ruszczynska-Szenajch, 1987; Burke *et al.,* 2009) which develops entirely in front of an actively advancing ice sheet. This is characterised by high angle reverse faulting or thrusting with a dip angle opposite to the ice direction, a multiple sequence of stacked rafts and potentially over-folded sediments at the basal décollement surface which also indicates the prevailing sense-of-shear. Such an environment may be fluidised, but unless the presence of permafrost traps porewater within an advancing zone of high pressure (Bluemle and Clayton, 1984), it is unlikely to become saturated. Therefore, in proglacial environments, it is the mechanical action of advancing ice which is likely to be the predominant control upon bedrock detachment, with planes of weakness being defined by paths of preferential fluid flow, the limits of permafrost, or a pre-existing geological plane of weakness (such as a change in lithology, structural feature, or bedrock ramp). In subglacial environments, décollement planes are inclined at comparatively less steep angles or may occur parallel to the bedrock surface. A traditional subglacial deforming layer may become established, with the greatest amounts of deformation occurring at the top of the sediment pile. Although this leads to homogeneity on the macro-scale, micro-structural interpretation of clast-fabrics are able to provide sense-of-shear data. Furthermore, there is potential for saturation of the sediment pile which reduces the effective pressure of the ice, increasing the likelihood of gravity gliding to contribute to transport of material in the deforming zone (Schultz-Ela, 2001).

2. Background

The Quaternary coastal exposures of north Norfolk feature an extensive distribution of chalk rafts emplaced several metres above their original stratigraphic position and associated with various elements of faulting and folding in surrounding glacial sediments (Banham, 1975; Hart, 1987; Burke *et al*., 2009). They have been widely recognised as glacitectonic rafts, in the context of wider regional-scale glacitectonic deformation (Banham, 1975; Hart, 1987). The rafts are located along an east-west transect that exhibits a glacitectonic overprint that is superimposed upon the glacigenic sequence. Deformation includes ice-marginal and proglacial deformation at Overstrand and proglacial to subglacial deformation at East and West Runton and Sheringham. Detailed palaeontological examination of the chalk that forms the rafts show that they are of local derivation with their primary accretion associated with North Sea ice moving southwards parallel to the strike of the chalk bedrock (Peake and Hancock, 1978; Burke *et al*., 2009). Because of their local provenance, we are able to study the different stages of development of raft features, relative to the ice-margin.

2.1 Applications for the north Norfolk chalk rafts

The bedrock rafts of Overstrand and north Norfolk offer a two-fold contribution. Firstly they are an accessible opportunity to study the forms and processes of chalk bedrock rafting, where the glaciological environment is broadly understood (Hart, 1990; Phillips *et al.,* 2008; Hamblin *et al.,* 2005). Secondly, by comparing the structural aspects of rafts at various locations along the coast, we are able to demonstrate a subglacial to proglacial

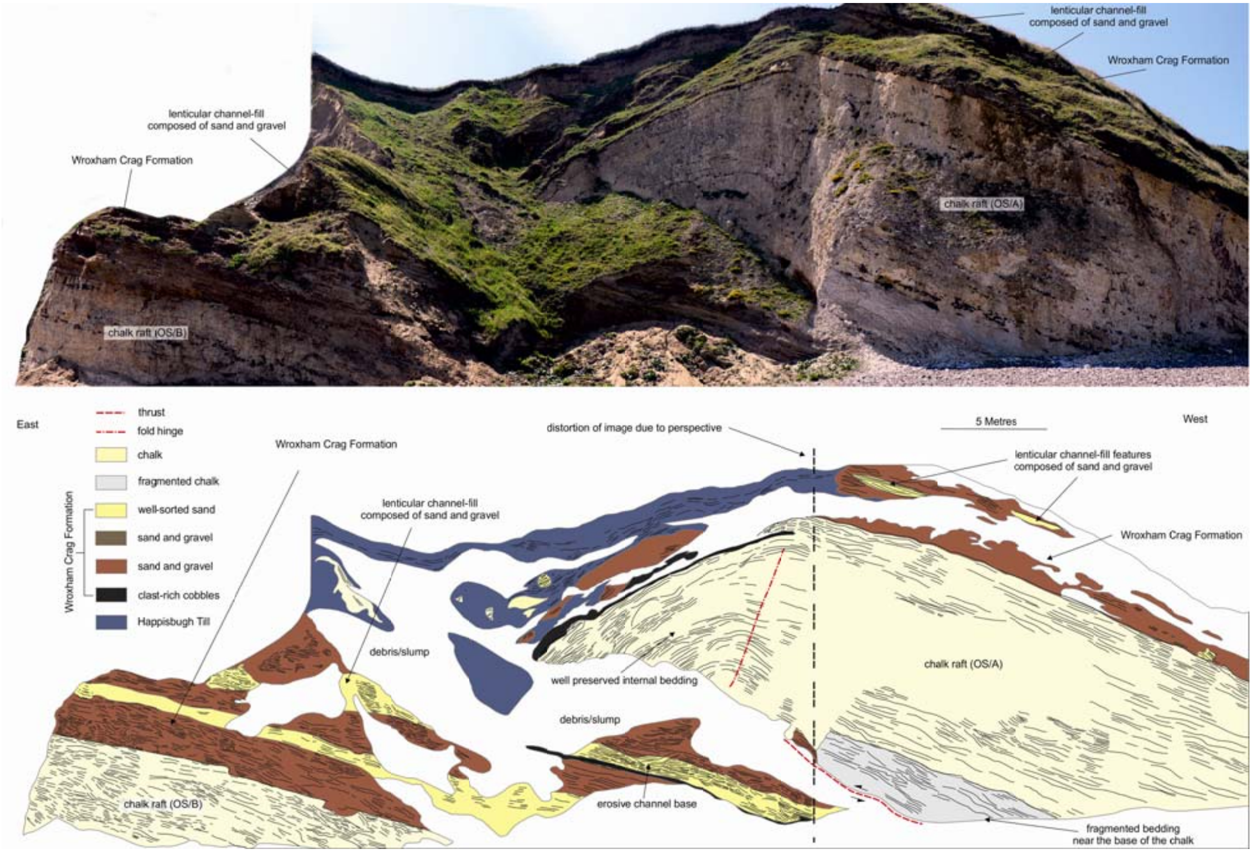

Figure 12.1. Glacitectonic rafts OS-A and OS-B at Overstrand

sequence, and therefore refine the existing regional ice sheet models. The glaciological succession sequence was explored by Burke *et al.,* (2009), in which the rafting at Overstrand was identified as a proglacial or ice-marginal feature compared with the emplacements at East and West Runton which are suggested to have developed, or been subsequently modified, subglacially.

2.2 Overstrand location

Overstrand (National Grid Reference TG 206 405) is a well-known British Quaternary site, having being known for its famous chalk rafts in several previous studies (Banham, 1975; Hart, 1990; Burke *et al*., 2009), and for the dramatic appearance and large-scale of its main features. Access to the section is by foot from Clifton Way, Overstrand village, and a descent down an access slipway to beach level at low tide. The main sections are located approximately 200 m east of a mound of rock armour that protects the toe of an engineered zone of landslip.

3. Description of structural geology

In this section we present data, working from the macro-scale to the micro-scale on the structures of the chalk rafts. Burke *et al.,* (2009) recognised three main thrust-bound chalk rafts at the site, labelled OS-A, -B and -C and this classification is also employed here.

3.1 Cretaceous bedrock

The underlying bedrock is a relatively soft, calcareous limestone (chalk) of Cretaceous age. It is highly porous and permeable. These properties make it susceptible to frost action, the effects of permafrost penetration, and weathering (Murton *et al.,* 2001). The bedrock surface in this region forms a broad plateau which dips at a shallow angle towards the east. Previous research studying the foraminifera present in the *in-situ* bedrock (Burke *et al.,* 2009) determined that the outcropping chalk originates from the Upper Campanian-Maastrichtian (Upper Cretaceous) boundary.

3.2 Chalk Raft OS-A

Chalk raft OS-A is the most easterly feature, and outcrops to between 5 and 7 m above beach height (Figure 12.1). It comprises a chalk unit C-1 (4 m high at its eastern extent) which is conformably overlain by >5 m of bedded sands and gravels identified as belonging to the Wroxham Crag Formation, a

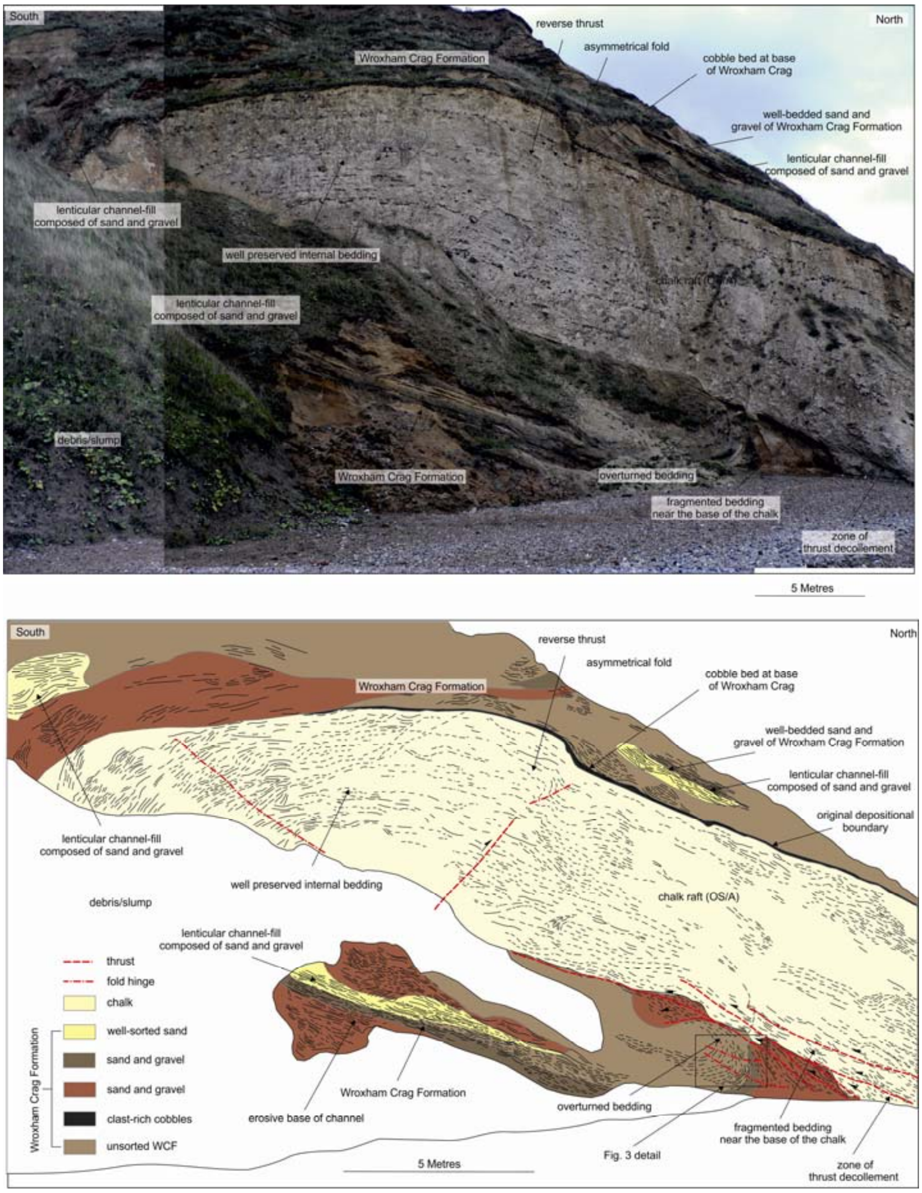

Figure 12.2. Structural detail of the western raft OS/B

pre-glacial shallow marine deposit (WCF-1). The contact between C-1 and WCF-1 is oriented at 20˚dip-105˚ strike, which is parallel to the internal bedding of nodular flint horizons present within OS-A. There is no evidence for a thrust surface at the boundary between C-1 and WCF-1, or for any deformation associated with it, suggesting an original contact which predates glacitectonism. The lower contact of C-1 occurs below beach height and is not exposed, therefore the deformation structures associated with the transport and emplacement of OS-A are located beneath beach height and not measured.

3.3 Chalk Raft OS-B

OS-B is the largest raft, and features a more complicated structure than OS-A (Figure 12.2). It comprises a chalk unit (C-2) which maintains a uniform thickness of 10m, and an overlying Wroxham Crag unit (WCF-2) of >5m thickness. It outcrops for a length of 50 m, at a moderate dip (25˚-35˚) towards the northwest. The dip is also defined by internal bedding of laterally extensive flint horizons, which remain parallel to the upper and lower chalk surfaces. The eastern end of the raft rises 15m above beach height, with a large part of the raft being gently bent to form an open anticlinal fold which verges to the north. All internal bedding and flint horizons remain parallel to the limbs of the fold and their respective units. The anticline overlies and is truncated by the basal thrust. The non-folded (southern tip of raft) and folded sections of OS-B are separated by a steeply-dipping (75˚ towards the south) reverse-fault which has created an offset of >1 m throughout C-2 and WCF-2. This high-angle reverse fault is interpreted as a back-thrust feature. Micromorphological data demonstrates a homogeneity to the majority of the chalk body, with the exception of the lowermost 5-10 cm of the unit which appears increasingly brecciated and deformed with proximity to the basal contact (described in section 4).

Similarly to OS-A, the chalk at OS-B features a sharp, conformable contact with the base of WCF-2. WCF-2 is overlain by extensive deposits of clay till (the Happisburgh Till), which itself is overlain by limited exposures of a second till, the Bacton Green Till (Burke *et al.,* 2009). The majority of deformation appears to be contained within the Happisburgh Till.

The most structurally detailed evidence at Overstrand is contained in the section of WCF-2 beneath raft OS-B, and the contact between the two. The lowermost surface of OS-B is defined as a northerly-dipping thrust zone of <1 m thick, composed of a set of moderate angle (30˚-40˚) reverse faults occurring in the underlying WCF-2. The scale of offset across each individual fault is on the 1-2 cm scale. The series of faults extends laterally for over 2 m of exposure in the basal shear zone of OS-B. These are referred to as the primary faults within WCF-2.

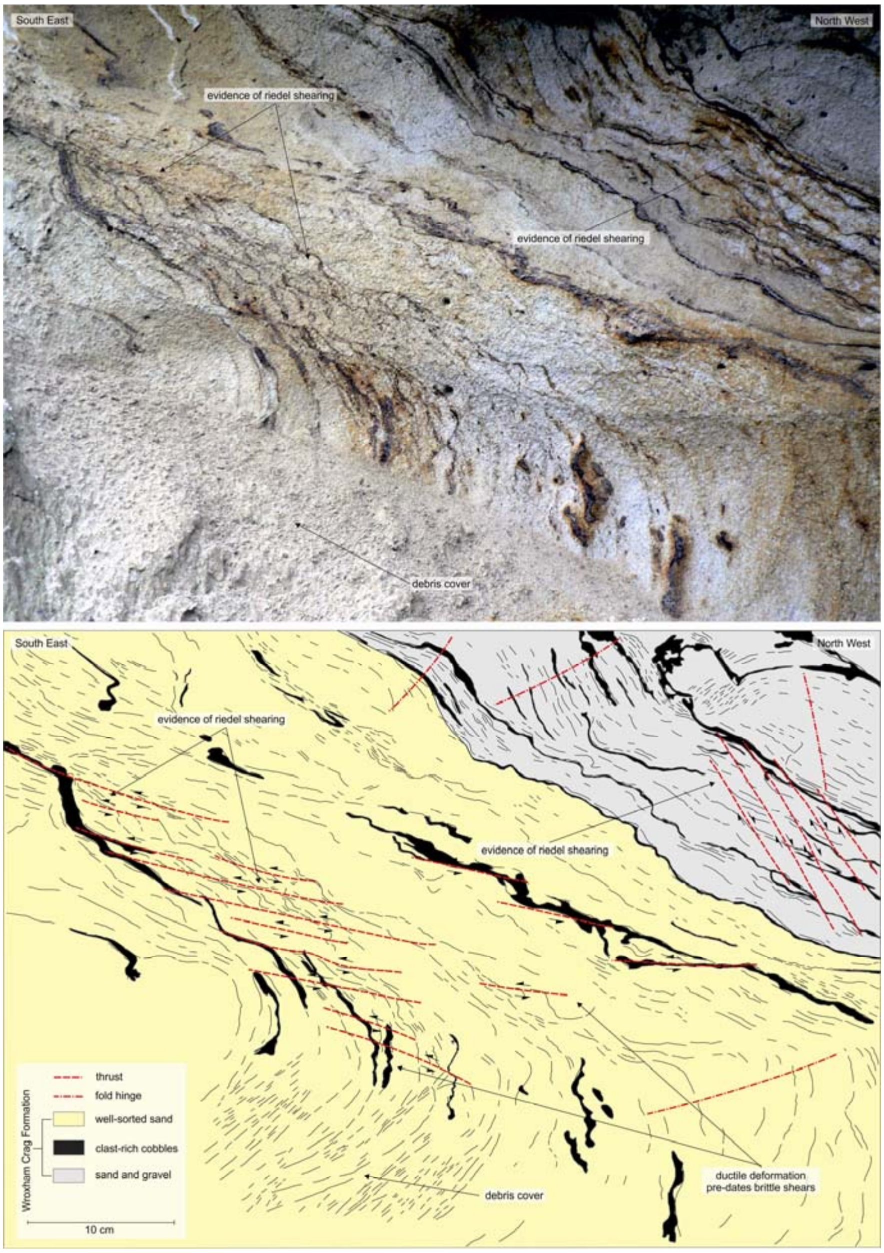

Figure 12.3. Context of the Riedel shears beneath OS-B

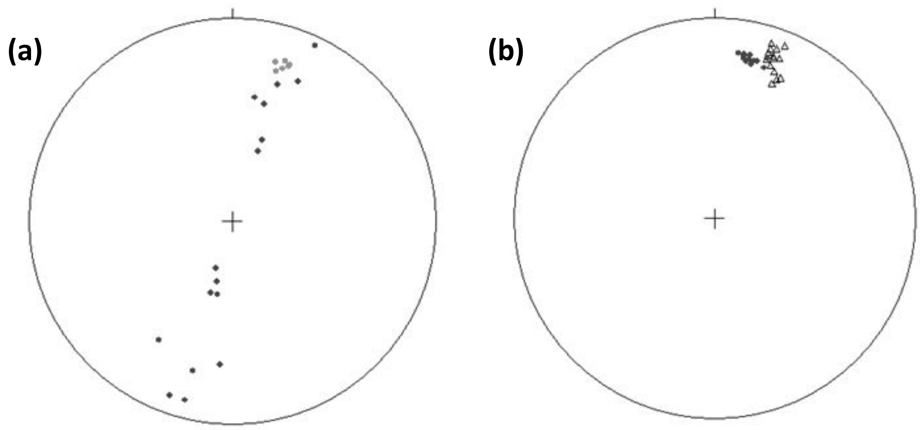

Figure 12.4. (a) Stereonet showing the orientation of bedding planes within the Wroxham Crag (preglacial deposits) units WCF-1 (lying parallel to the basal thrust surface of OS-B) in light grey. Also the orientation of the over-folding (dark grey) within the WCF-1 which has occurred due to movement along the basal thrust OS-B. The trend of both datasets lies along an 18°-198° bearing which indicates a linear development of deformation and a lack of rotation or torsion of rafts throughout the emplacement and final deformation stages at OS-A and OS-B. (b) Stereonet showing the orientation of the contact surface between chalk C-1 and marine sediment WCF-1 within raft OS-A (black triangles); also between the chalk C-2 and WCF-2 within raft OS-B (dots). These indicate that both rafts are emplaced along similar orientations of thrust surface, with a slightly more Easterly component to the emplacement to the initial emplacement of OS-A

These faults are truncated by a second set of faults; a complex series of southerly-dipping shear planes parallel to each other, that have developed in an identical tectonic direction (010˚ to 015˚ dip direction). These second structures truncate and thus are relatively younger than the primary faults. However their orientation suggests an association with emplacement. The sense-of-shear described by the combined series of faults is sinistral, indicating that the OS-B was transported along this zone of deformation towards the south. Due to the late development of these faults and their angle of occurrence, they are described as antithetic Riedel shears (cf. Dresen, 1991; Figure 12.3).

3.4 Chalk rafts OS-C

OS-C remains unstudied due to an inaccessible location on the cliff, but is structurally highest of the three chalk rafts. It is also thrust-bound and although frequently poorly exposed, Burke *et al.* (2009) describe how its associated thrust truncates the two present tills of HTM and BTM.

3.5 Structural alignment

The overall alignment of structures at Overstrand (Figure 12.4) indicates a strong correlation between all structural data, aligned along a NNE-SSW bearing of 18°–198°. The data demonstrates how the final stages of raft emplacement and associated deformation at Overstrand all occurred in the same direction, suggesting that the full spectrum of deformation was a result of the same overall stress regime. It would appear that no rotation or torsion has occurred throughout raft emplacement. Furthermore, the angles of inclination of contact surfaces and bedding planes are similar across the section; the exception being the representation of the folding within WCF-2 in the basal deformation zone of OS-B.

4. Micro-scale deformation within C-2

Previous work at Overstrand recognises that the internal structure of C-2 remains comparably undeformed, even within centimetres of the main basal décollement (Burke *et al.,* 2009). Micromorphological evidence broadly supports this hypothesis, whilst demonstrating how the shear zone is constructed of a complex series of micro-thrusts, modifying the structure of chalk at the boundary and developing a brecciated band of material at the décollement surface.

The lithology of chalk at the basal contact of C-2, represented by thin section OS/A/1 (Figure 12.5), is subdivided into several domains. The chalk in this vicinity is fragmented into a breccia with a fining trend towards the lowest section of the sample (nearest the décollement surface). The subdivision is based upon grain size and angularity, orientation and percentage void space. The contacts between domains are defined by thrust planes, which all assume a northerly dip (30˚-70˚) and record a sense-of-shear towards the south.

Domain 1 is highly brecciated, with a relatively high percentage void space between chalk fragments. The average clast size is 1 mm, and space between clasts is commonly filled by a very fine chalk-based matrix. Clasts are angular and non-spherical. There is evidence for multiple rotational structures indicating a sinistral sense-of-shear towards the south. Altogether Domain 1 is suggested to represent a highly mobile deforming horizon which

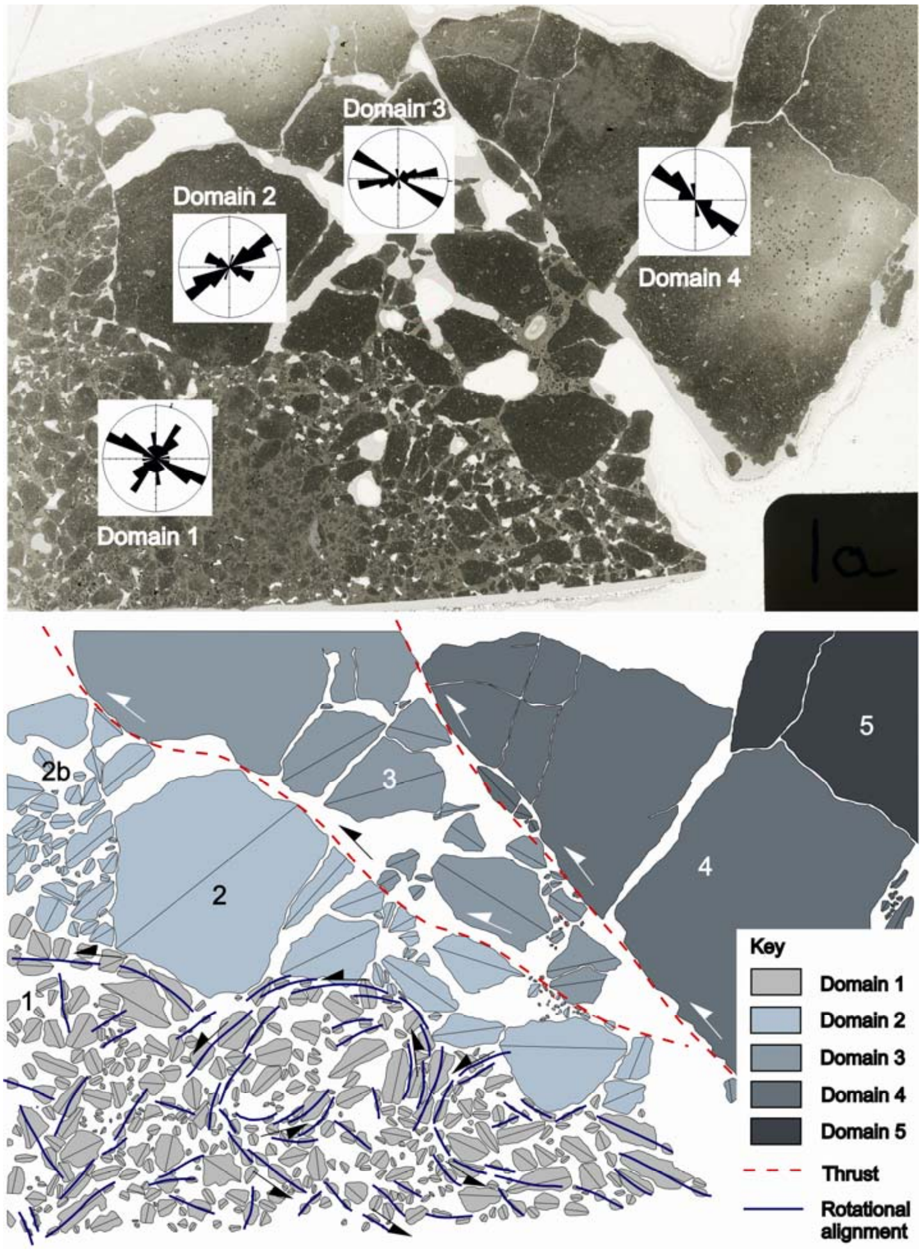

Figure 12.5. Scan and schematic cartoon of thin section OS/A/1

has undergone extensive fracturing, brecciation and then rotation of fragments into recognisable aligned structures. There is no dominant grain orientation or fabric resulting from the rotational alignments. The mobile nature of individual grains combined with the disaggregation of chalk which has created the matrix, suggests either that the majority of lateral movement has occurred a saturated zone, or that the chalk has been crushed very effectively. We suggest the former; that as the rotational structures are thrust-bound, they reflect a distinct phase of ductile deformation relating to high porewater pressure. However, this may be disputed, as there is a lack of water-escape structures or laminated grain alignments. Thrust 1 (T1) is a low angle (20˚-25˚) reverse fault, dipping north. It appears to be truncated at the basal décollement by later faults, which occur at more steeply inclined angles. T1 represents the earliest phase of deformation recorded in thin-section OS/A/1, and movement along it is associated with the rotational structures directly underlying it. In several instances, the thrust truncates the uppermost limb of rotational structures in Domain 1, evidence that it not only caused deformation but also defined the boundary of the domain. It is suggested that the change in deformation style from ductile (Domain 1) to brittle (T1 and thereafter) records the dewatering of the sediment pile and, therefore, a change in glaciological conditions acting on the control between transport (Domain 1) and emplacement (T1 and thereafter) of OS-B on the macro-scale.

Domain 2 is a moderately brecciated zone, featuring several distinctly larger clasts between 2-3mm, which have not fractured as in Domain 1 and appear less angular. Domain 2 possesses a more strongly defined unimodal orientation of grains, at an inclination of 35˚-40˚which is generally parallel with the dip of bounding thrusts T1 and T2; again evidence that it is the thrusts that bound the structures present within the domains. Domain 2 features significant void space which has remained unfilled by fine material, indicating no disaggregation of chalk has occurred above T1. This is evidence for a change from saturated to relatively dry conditions. Domain 2b, although similar in most respects to Domain 2, is characterised by a smaller clast size and greater diversity in grain orientations; however it is still fault-bound by T1 and T2 thrusts. T2 is a moderate angle (45˚) northerly-dipping reverse fault, which truncates T1 and forms the boundary between domains 2 and 3. It is associated with a c. 3 mm offset of the hanging wall towards the south, denoted by the separation of several clasts at this boundary.

Domain 3 is moderately brecciated and is characterised by a larger clast size, less angular clasts that the other domains, and a fabric which is defined by the bounding thrusts. Void space is significant and with the pore spaces between the clasts remaining open and unfilled by fine chalk. T3 is a high angle (60˚-65˚) reverse thrust, postdating T2 and T1, making it the youngest and most steeply inclined fault surface observed. Domain 4 is a significantly more lithified zone of chalk with only the appearance of an extensional fracture distinguishing it from the comparatively undeformed Domain 5. These domains seem to demonstrate a region of relatively low internal deformation, indicating that the thrust zone extends only a short distance (cm-scale) into the base of C-2. Most of the deformation observed at the basal contact of raft OS-B occurs within the folded and faulted WCF unit underlying the raft.

5. Glacitectonic interpretation

5.1 Orientation of glacitectonism

Structural evidence at Overstrand, including the northerly-dipping thrusts, angle of dip of the rafts OS-A, -B and –C, the sense of shear identified on the macro- (Riedel shears) and micro- (thin section OS/A/1) scales and the sense of vergence of the asymmetrical overfold developed within WCF-1, indicates that deformation is associated with a glacial advance from the north (cf. Burke *et al*., 2008). This is analogous to nearby deformational evidence at Sidestrand (Lee, 2009) which is also contained within the Happisburgh Till. All the observed rafts and deformation align along a linear deformation trend from north to south, with little or no rotation of rafted bodies as they were transported or emplaced. Data suggests that OS-A and OS-B share identical directional characteristics, suggesting they were emplaced as part of the same glacial advance and the similarities between the bodies in terms of orientation, structure and emplacement imply that they underwent the same physical processes in their detachment and transport phases.

The rafts observed at Overstrand are much thicker than those of more subglacial sections in northern East Anglia, and because the extent of deformation here is relatively low compared to West and East Runton, the complex relationships between host sediments and rafts are maintained.

5.2 A process-based approach to glacitectonic rafting

The three fundamental conditions of raft transport require; (1), the forward motion of ice, either thrusting the detached block from behind (in a proglacial/ice-marginal environment) or overriding the detached block and transmitting energy through a mobile deforming and slipping bed, occurring over a basal detachment in a subglacial environment; (2), the ability for a rafted block to maintain its integrity throughout the duration of transport and not to lose energy through deformation; and (3), the ability for a rafted block to maintain a basal detachment surface along which transport can occur. These conditions are referred to previously in part (Ruszczynska-Szenajch, 1987), but not in the context of a single model maintaining discrete stages of detachment, transport and emplacement.

The first condition is applied to the rafted body and suggests that if the application of stress transmitted by advancing ice is terminated (glacial retreat, stagnation or potentially the uncoupling of the glacier motion to the substrate due to increased slip for example), the transport phase of rafting ends and the transported block effectively becomes 'emplaced'. Without the energy to drive rafting, develop thrust planes and deform substrate, none of these structures may continue to develop.

The second condition refers to the fact that in order to remain a discrete raft, the block must maintain a higher cohesive shear strength than the surrounding deforming medium which it is transported in. If the energy applied by a glacier to its bed was distributed perfectly evenly, the outcome would be a homogenised sequence devoid of structural features. This very rarely occurs, because of physical discontinuities within the bed which either concentrate, or dissipate applied energy, causing structural features to develop. This production of structural features is recognised widely in the literature, in both *in situ* studies (Banham, 1988; Evans, 1989) and numerical models which predict where deformation occurs relative to loading (Andersen *et al.,* 2005*)*. Simply, a raft must maintain its discrete form otherwise it will be deformed in an increasingly identical manner to its surrounding sediments and be amalgamated within them, no longer recognisable as a raft.

The third condition is what distinguishes a raft from a clast or erratic; the latter two are (relatively small) freely-rotating particles effectively acting in suspension. They are only able to deform sediments in very close proximity to them, because they are transported with them and so they are not identified with any energy differential. In contrast, rafts are always associated with transport occurring along a basal detachment, or thrust. Because of this, they are able to move at an independent rate compared to surrounding sediments, deforming them as long as they maintain the first and second conditions.

All three conditions are required during both detachment and transport phases. Each condition is independent from the others; the first relies on glaciology, the second and third a combination of geological and glaciological factors. The interrelationships between glaciology and geology exist through temperature, pressure and porewater pressure profiles, which represent complex, dynamic contributing factors.

5.3 Mechanism of the detachment phase

The detachment phase of a raft is suggested to comprise of two phases; 'pre-detachment', where glaciological conditions modify the bedrock and create a situation where it is possible for rafts to detach along specified thrust boundaries, and 'mechanical-detachment', at which point the forces applied by the glacier act on the raft as an independent body.

OS-A and –B are comprised of two very different units: in both instances a lower calcite (C-1 and C-2) and upper shelly marine sand of Wroxham Crag (WCF-1 and WCF-2). As described, there is no evidence for deformation along the contacts between chalk and WCF; instead, there is evidence for preservation of shells even at the contact surface. In order to meet the second condition, OS-A and –B are suggested to have been altered by freezing to a depth specified by overburden pressure. As pressure increases with depth, a depth is reached where freezing no longer occurs; this provides the basal surface of a pre-detachment phase raft. In the case of Overstrand, this surface lies parallel to the bedding planes of the chalk unit at a depth in the region of 7-8 m, which is likely to have been a contributing factor in allowing mechanical-detachment to occur. Under these conditions, mechanical-detachment is likely to have occurred either proglacially or at the ice-margin.

It has been suggested that elevated porewater pressures might aid, or even be required for, detachment to occur (Burke *et al.,* 2009). While the presence of a lubricating surface theoretically aids the development of a décollement surface by reducing effective pressure on the substrate, there is little evidence for hydrological factors to contribute to the detachment mechanism at Overstrand. Instead, the structures associated with the presence of porewater are likely to have developed in the emplacement phase. There is more conclusive evidence regarding the frozen nature of the sediment pile; for this reason, although it is acknowledged that the subglacial environment is commonly saturated, we cannot determine elevated porewater pressures as a contributory factor for rafting to occur, but it remains a possibility.

5.4 Mechanism of the transport phase

Rafts OS-A and –B show little evidence for internal deformation. On the micro-scale, it is clear that deformation rapidly diminishes within 1-2 cm of the main thrust boundaries and thin-section samples from 1 m above the basal thrust of OS-B exhibit no visible deformation structures inside the chalk whatsoever. The back-thrust and folding developed within OS-B may be explained by forces acting on the raft block during the final stages of emplacement rather than processes acting on the raft body during normal transport conditions. Therefore the rafts are suggested to have only been transported a relatively short distances and are likely to have not been displaced far southwards from their source. Burke *et al.* (2009) substantiated this claim by provided palaeontological evidence that the chalk of OS-B is sourced from nearby and from the north (offshore); a source direction which corresponds with the inferred ice-direction. The rafts largely maintained their integrity throughout their transport phases, indicating they remained frozen throughout.

5.5 Development of emplacement structure

The emplacement of a glacitectonic bedrock raft occurs when the conditions of transport are no longer present. The Overstrand chalk rafts are thrust over preglacial (Wroxham Crag Formation) sediments, and are associated with thrusts cutting through overlying glacial sediments (Happisburgh Till). This allows for the transport and emplacement phases of raft development to occur in a proglacial to ice-marginal environment (Moran *et al.,* 1980; Bluemle and Clayton, 1983; Ruszczynska-Szenajch, 1987). It is suggested that the emplacement phase at Overstrand was initiated by a cessation of the advancing ice leading to stagnation of the ice-margin, thus not meeting the glaciological conditions required for rafting to occur.

As suggested in earlier work (Burke *et al.,* 2009), the development of chalk rafting at Overstrand may be considered as an imbricate thrust-stack, where OS-A was emplaced initially, at a relatively shallow dip angle. OS-B was then emplaced at a steeper angle above. There is evidence for extensive deformation in the upper 2 metres of WCF-1 (the upper surface of OS-A) which is associated with the basal thrust of OS-B. WCF-1 was preserved via the transport and emplacement of OS-A, only to be deformed in a ductile manner (through extensive folding) by the onset of the basal thrust of OS-B, during a later event. It is suggested that by this point, OS-A was at least part unfrozen, and was thus able to deform in a ductile manner.

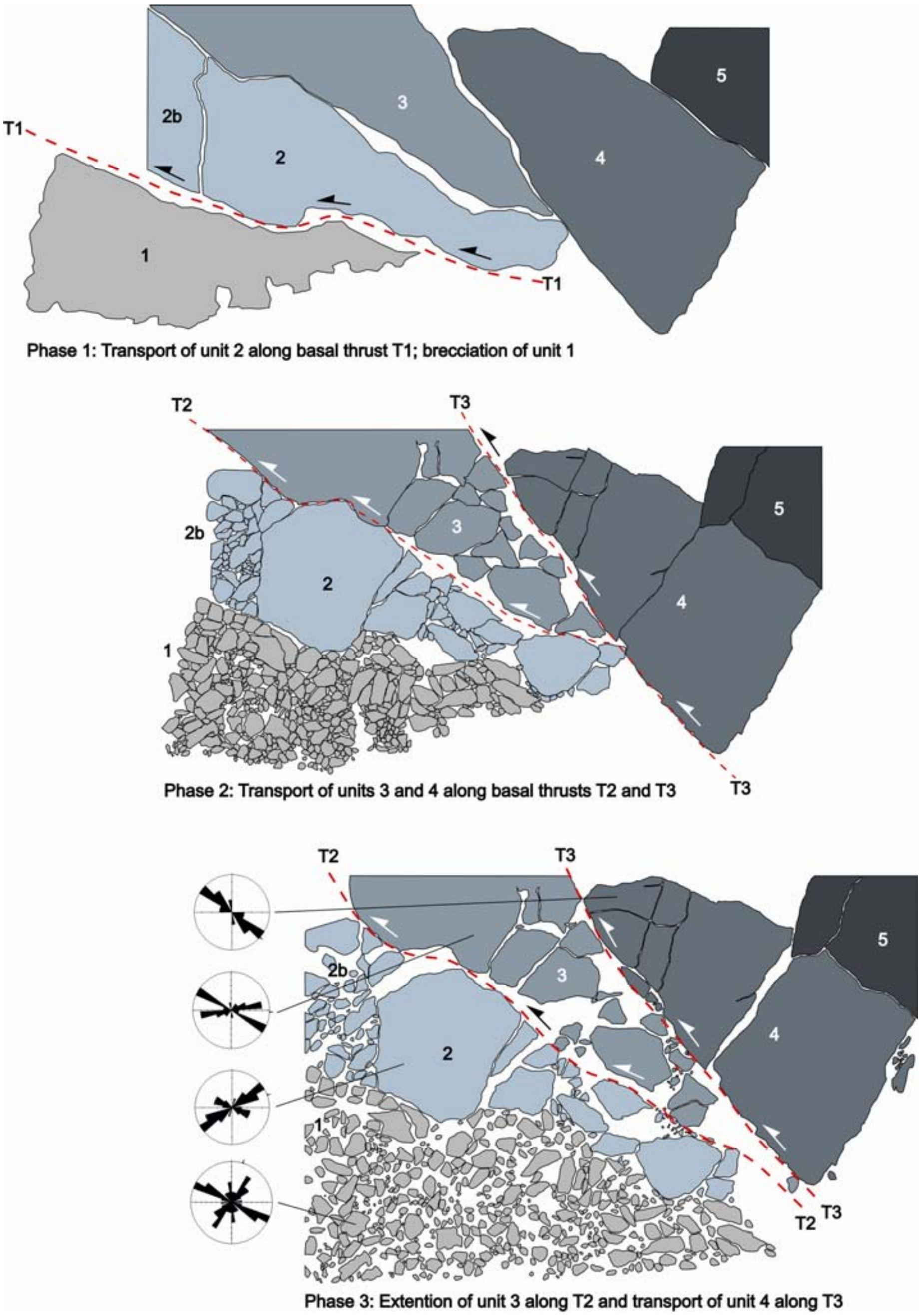

Figure 12.6. Three phase evolution model for thin section OS/A/1

A detailed story emerges from the sequence of Riedel shears present within the WCF-1 and deformation revealed by micromorphology within the lowermost section of C-2. There appears to have been multiple stages of the final emplacement of the raft; whether this reflects a particularly oscillatory phase, or simply that the late stages of emplacement are the best preserved, is uncertain.

If the rafts adhere to the frozen model, they are required to undergo de-watering during unfreezing. If unfreezing is suggested to at least partially occur rapidly after or even during emplacement, it is possible for the rafts to undergo a brief phase of saturation which would enable both the macro-scale folding structures observed in WCF-1 to develop, and for the rotational grain alignments and clay fines in unit 1 of thin section OS/A/1 to be produced. As water is removed from the sediments, they are liable to lock-up again as demonstrated in the late-emplacement phase thrusting (T2 and T3) within OS/A/1 (phases 2 and 3 of Figure 12.6) Like the macro-scale structural evidence of the imbricate thrust stack, thin-section analysis demonstrates that thrust angles become steeper during later events. More elevated angles of thrusting appear to develop, as later units are deflected upwards by previous structures and deposits creating an ever-increasing obstacle at the décollement surface.

The final stages of emplacement are also identified by the series of Riedel shears cutting through earlier ductile deformation within WCF-1. The shears are parallel features, dipping at low angle northwards, and at a relatively high frequency (>3 shear planes per cm for around 1 m of exposure). They are related to the basal shear zone of OS-B, and correspond to the final stages of emplacement. They post-date the folding associated with earlier phases of raft transport into thrust-stack feature, and so are evidence for a two-phase deformation event. The initial ductile deformation characterised by folding and requiring a saturated sediment pile is replaced by a more brittle deformation style, indicating a period where dewatering of the deforming sediments has occurred. This pattern of deformation relates well to that observed on the micro-scale and does suggest that after the thawing of the rafted units, a period of water saturation occurred which was then replaced by a final, 'dry', phase of deformation.

5.6 OS-A and –B as 'proto-rafts'

In isolation, the Overstrand rafts appear as well-defined bedrock slabs contributing towards the development of an ice-marginal imbricate-stack landform. However, in a wider context, the processes and structures identified here are clearly relevant to the rafting of identical sediments observed at West and East Runton and Sheringham, identified as more subglacially-deformed environments. These sites are regarded as various stages of raft development along an ice-marginal to subglacial continuum, and provide evidence for different phases of rafting accordingly. OS-A and –B are less extensively transported or deformed as their Runton and Sheringham counterparts, yet exhibit a dramatically high dip-angle 'end-emplacement' phase because of their ice-marginal location. Therefore we can identify the structures at Overstrand as 'proto-rafts', terminated in their development by the cessation of actively advancing ice. It is suggested that as the offshore ice-margin moved south towards the rising chalk bedrock of the North Norfolk coast, bedrock rafts detached in a similar manner over the entire region. As the rafts were over-run by the glacier, the early high-angle ice-marginal thrusts were modified to become more like what is observed at West and East Runton; low angled thrusts accommodating more extensive transport distances, more extensive deformation, and less preservation of the early detachment structures. The value of Overstrand as a section is that it appears to provide evidence for a marginal landform developing at the furthest glacial extent.

6. Conclusions

The glacitectonic rafting assemblage at Overstrand comprises two main thrust-bound slabs of chalk bedrock, emplaced in an imbricate thrust stack (cf. Burke *et al.,* 2009) with an associated chalk raft emplaced higher in the sequence, which is also suggested to represent an upper section of the thrust stack.

- The low intensity of deformation at Overstrand compared with comparable sites further to the north-west suggests that the structures observed are locally-derived. They represent the transport and emplacement phases of rafting well, and are comparable to rafting features at West and East Runton and Sheringham, which are suggested to be similar features but those which have been modified by subglacial conditions.
- Detachment of OS-A and OS-B is likely to have occurred near to the ice-margin or proglacially, and are suggested to have developed under the onset of permafrost conditions. The role of freezing in generating conditions conducive to rafting is considered crucial. The role of elevated porewater pressure is less certain, especially during detachment.
- The depth of detachment for rafted blocks in the region appears to be relatively consistent and in the region of 5-7 metres depth. This is suggested to be defined by the base of permafrost development, and accentuated by occurring along bedding planes of the chalk bedrock unit, within which detachment occurs.
- Transport of OS-A and –B occurred within the basal deforming bed or active layer, indicated by being located adjacent to HTM or BTM. The rafted units were therefore likely not frozen to the base of the glacier itself.
- Final emplacement is associated with a carapace of HTM, so the exposure is likely to have been overrun by a late advance of the ice sheet. A relatively brief phase of melt-water induced saturation of deforming sediments is suggested by a shift in deformation styles from brittle to ductile. This reflects the likely fluctuating ice-marginal conditions under which the structures of Overstrand were created and modified.

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