Sand intraclast development and the deformation of glacially-overridden permafrost, West Runton

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1. Introduction

Glacially-deformed sediments have often been observed to contain masses of sorted sediment in which delicate sedimentary structures remain preserved. These features, variously termed "lenses", "blocks", "intraclasts" range in surface area from a few mm^2 to many tens of m^2 and when extensive lead to the development of "glacial mélanges" (e.g. Menzies, 1990a,b; Hoffman and Piotrowski, 2001). Various hypotheses have been proposed to account for the inclusion of sorted-sediment masses within glacial tills. These include englacial meltwater deposition (Goodchild, 1875), basal freeze-on and transport within a debris-rich basal ice layer (e.g. Hoffman and Piotrowski, 2001) and entrainment and deformation within a subglacial deforming layer under both unfrozen (Rappol, 1987, Menzies 1990a) and partially frozen conditions (e.g. Menzies, 1990a; Waller *et al*., 2009; Waller *et al*., 2011). In spite of this previous research, their origin and significance remains the subject of debate, largely centering on the conditions required to explain the rheological contrasts inherent in glacial mélanges and the survival of cohesionless coarse-grained intraclasts within a deforming medium (e.g. Menzies 1990a,b).

A recently advocated hypothesis capable of resolving these issues stems from recent research into the nature and significance of glacier-permafrost interactions. Whilst it has been traditionally assumed that cold-based ice-masses are frozen to rigid and undeformable beds, recent research at contemporary glaciers has demonstrated the ability of basal processes to remain active at temperatures below the pressure melting point (Echelmeyer and Zhongxiang, 1987, Waller, 2001, Bennett *et al*., 2003). This has been corroborated by observations of glacitectonic structures within relict subglacial and submarginal sequences associated with high-latitude, Pleistocene ice sheets that have remained cryotic (below 0°C) both during and after deformation (e.g. Astakhov *et al*., 1996, Murton *et al*., 2004). These sequences commonly contain frozen intraclasts of sorted sediment that act as competent masses within highly-deformed glacitectonites. Such a rheological contrast is consistent with deformation at temperatures close to but slightly below the pressure melting point when porewater within coarser sediment freezes, producing an ice cement that increases their cohesion and shear strength (Andersland and Alnouri, 1970). In contrast, the yield stress of fine-grained sediments is reduced by the retention of substantial quantities of liquid water adsorbed onto the surfaces of the constituent particles with high interfacial pressures resulting in freezing point depression (Christofferson and Tulaczyk, 2003).

This chapter reports sedimentological and macroscopic structural observations of sand intraclasts within a highly-deformed glacitectonic mélange at West Runton (Waller *et al*., 2011). The observations are used to test the competing hypotheses for intraclast formation and to provide a new geological criterion to identify subglacial deformation of past Pleistocene permafrost in sediments that have long since thawed. This criterion has the potential to enhance our understanding of the extent, processes and distinctive products of glacier-permafrost interactions.

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

2. Site Location and Methodology

This study examined sand intraclasts within a complex mélange facies of Middle Pleistocene till exposed along coastal cliff sections c. 1.5 km long and 40 to 60 m high between West Runton (National Grid Reference (NGR): TG 181 432) and Sheringham (NGR: TG 165 433), North Norfolk, eastern England (Figure 5.1). This work (Waller *et al*., 2011) focused on two specific localities where a varied suite of intraclasts were particularly well-exposed and their relationships with the host till can be clearly established. The size and shape of the accessible intraclasts were recorded as well as the nature of the contact with the surrounding sediments. The orientation of folds, faults and lineations, as well as any bedding/foliations present both within the intraclasts and the surrounding diamicton were measured using a compass-clinometer and plotted on equal-area lower hemisphere stereographic projections. Three intraclasts were excavated to allow examination of their three-dimensional morphology. Bulk samples were air-dried and the sand fraction (63µm-2mm) dry- and wet-sieved at

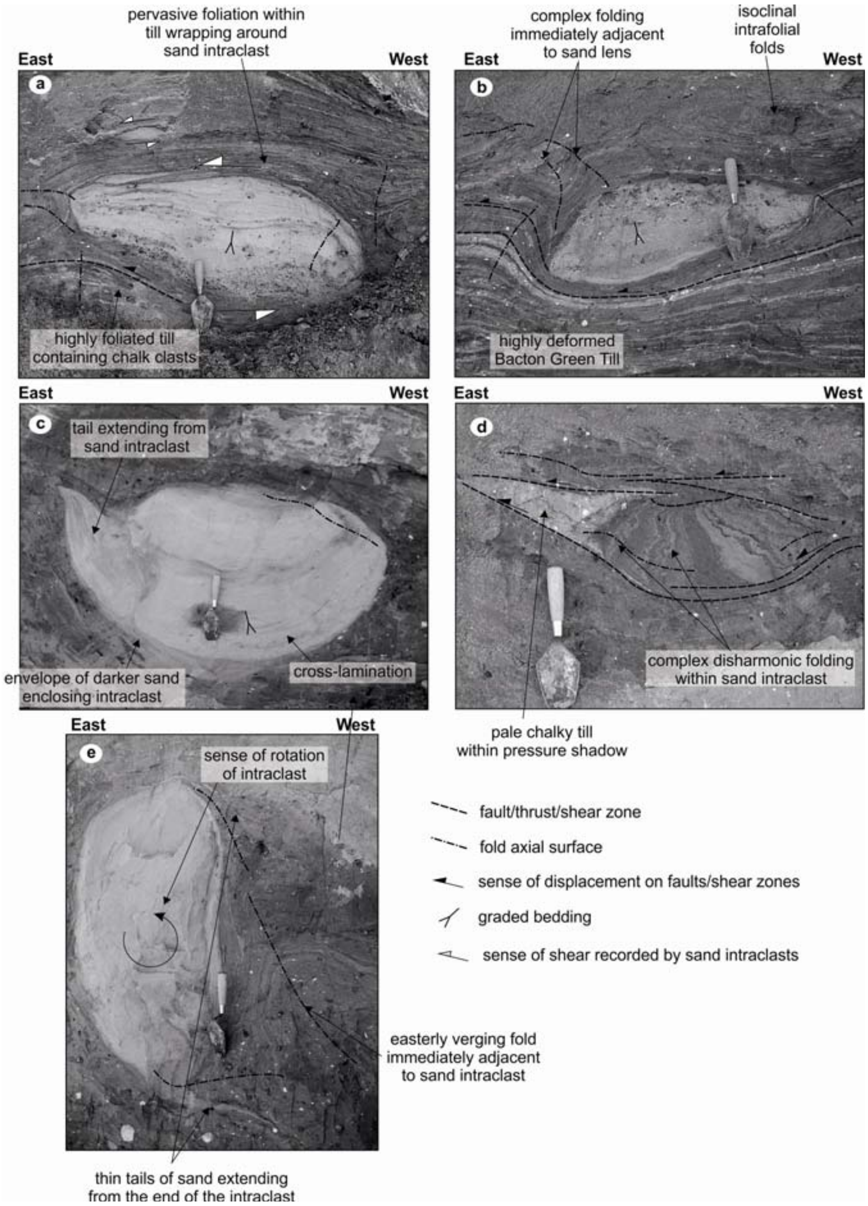

Figure 10.1. Morphology, orientation and key characteristics of isolated intraclasts exposed at site 2 (a-b) and site 1 (c-e) (from Waller *et al*., 2011)

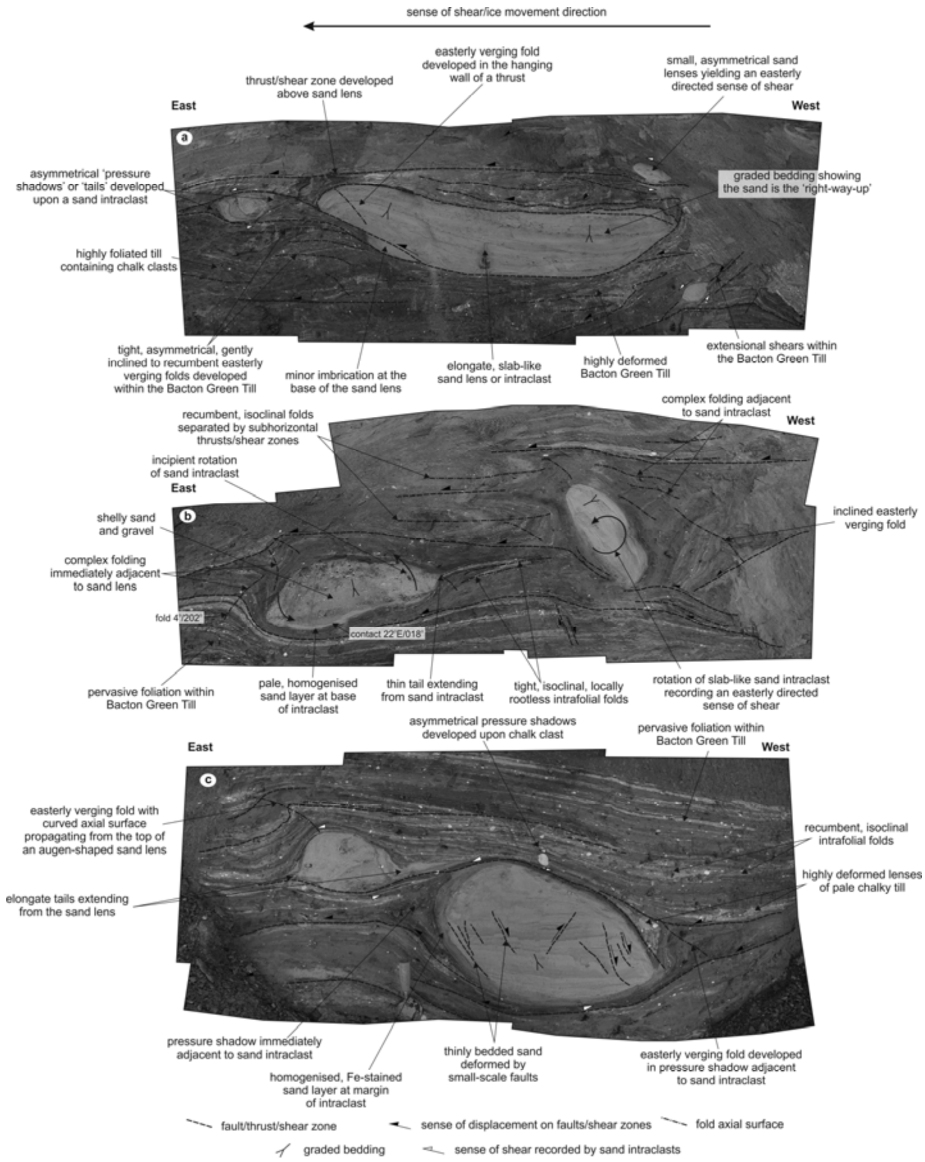

Figure 10.2. 'Strings or chains' of intraclasts at site 2 illustrating their interrelationships and association with foliation within the surrounding till (from Waller *et al*., 2011)

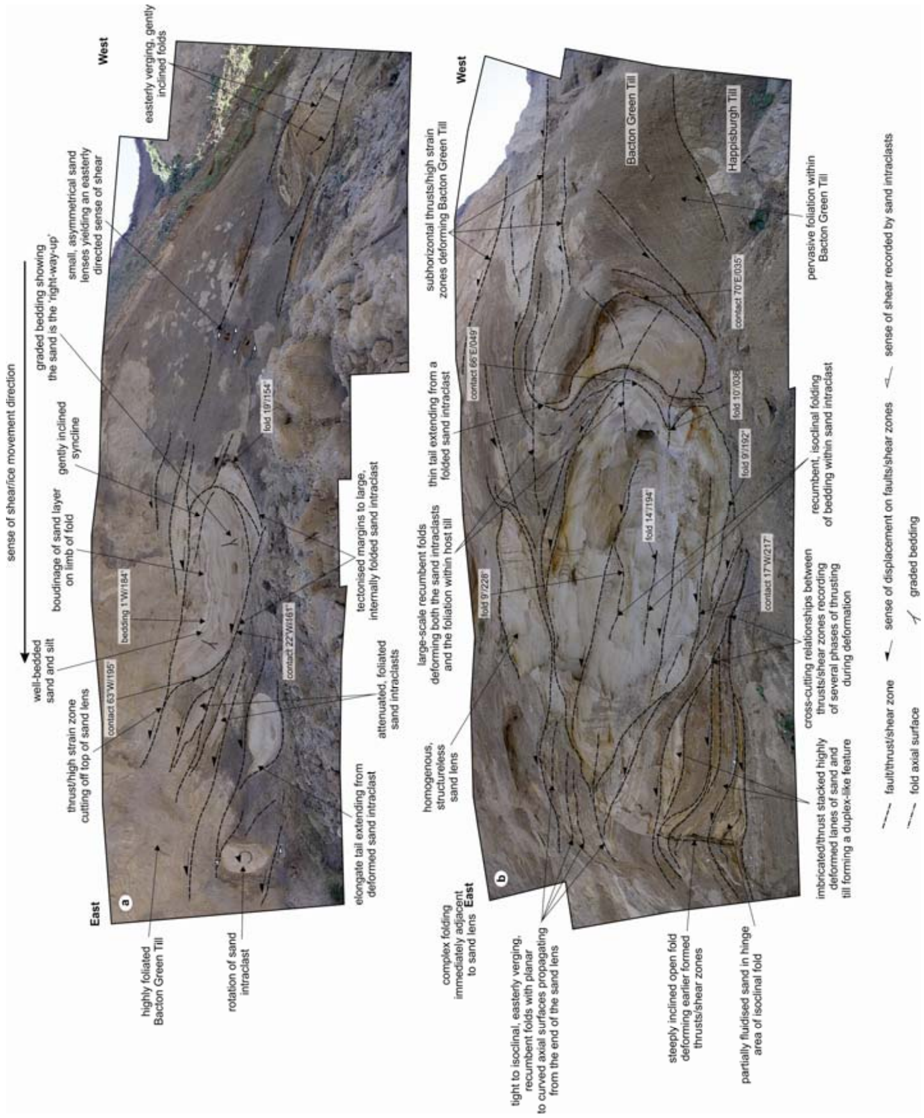

Figure 10.3. Complex interactions between intraclasts at site 1 (a) and site 2 (b) (from Waller *et al*., 2011)

individual phi intervals to record dry weight (Gale and Hoare, 1991). The particle size distribution of the <63 µm was calculated using the Sedigraph Method (Coakley and Syvitski, 1991), with the bulk particle size composition of samples expressed as percentages of sand, silt and clay. Heavy mineral analysis was undertaken on 23 separate sand intraclasts to constrain the stratigraphic provenance of the intraclasts, via comparison with a regional heavy mineral data-set that encompasses the preglacial and glacial deposits of the region (Lee, 2003, 2009; Lee *et al*., 2004, 2006). Studies reveal that bulk comparison of the abundances of garnet and zircon relative to epidote, pyroxene and amphibole is sufficient to be able to discriminate between many of the preglacial and glacial deposits (Lee, 2003). Separation of heavy minerals was undertaken using standard techniques (Gale and Hoare, 1991), with 400-500 non-opaque grains counted per sample using a standard petrological microscope. Counts were performed on a narrow size range (fine sand - 63-125 µm) to produce uniform observational conditions, and to reduce potential hydraulic effects on heavy mineral sorting.

3. Key Characteristics

3.1 Stratigraphical context and spatial distribution

The sand intraclasts occur within a mélange facies that includes remobilised elements of the Bacton Green Till Member (BGTM), the Happisburgh Till Member (HTM), preglacial sands and gravels belonging to the Wroxham Crag (WGF) and chalk. Highly attenuated and drawn-out stringers of an additional till (the silt-rich chalky Walcott Till) occur throughout the basal part of the mélange. The stratigraphic position of the mélange clearly post-dates the primary deposition of all of these materials. It is highly disrupted in appearance and locally contains numerous variably-deformed lenses or intraclasts of poorly-consolidated sand within a highly-deformed sandy till matrix that form the focus of this section (Figures 10.1, 10.2 and 10.3). It is also laterally-extensive having been recognised by Lee and Phillips (2008) at Bacton Green some 15 km to the SE of West Runton, indicating that the processes leading to its formation occurred over a relatively wide area beneath the advancing ice sheet.

Spatially, the density of sand intraclasts within the mélange is highly variable, ranging from one or two isolated blocks (Figure 10.1), to 'strings' or 'chains' of several lenses or pods that occur at approximately the same structural level (Figure 10.2), through to areas in which variably-deformed intraclasts form up to 60 to 70% of this complex deposit (Figure 10.4).

3.2 Intraclast size and morphology

The size of the intraclasts varies from a few tens of centimetres to >10 m in length. They display a variety of morphologies ranging from elongate slab-like bodies with variably rounded to tapered terminations (Figure 10.2a), to more rounded 'eye' or 'augen' shaped pods (Figures 10.1c, 10.2c) with variably developed 'tails' that extend into the foliation within the adjacent till, through to more highly-deformed examples in which the sand intraclasts are folded and thrusted leading to localised imbrication and stacking of several fault-bound lenses or slices of sand (Figure 10.3). The contacts between the intraclasts and the surrounding till are typically sharp and distinct (Figures 10.2b, 10.2c, 10.3). However, some intraclasts are enclosed within an outer envelope (a few centimetres thick) of dark, massive to finely laminated/banded, sand and silt (Figures 10.1c, 10.7e) indicative of some degree of intermixing. In a limited number of cases, there is evidence of a greater degree of disturbance associated with folding (Figure 10.5c) or liquefaction of intercalated layers of sand and till (Figure 10.5d).

The three-dimensional morphology of the intraclasts was revealed by removal of the sand from two small augen-shaped intraclasts (depicted in Figure 10.2c). Both were pod-like in shape with a smooth outer surface. They were approximately elliptical in section (Figures 10.8b, 10.8d) with long-axes orientated parallel to the ice movement direction (W to E). Asymmetrical tails of homogenised sand developed on the intraclasts yield an easterly directed sense of shear (Figure 10.6). The leading edges of the intraclasts are arcuate in form and gently curved backwards in an up ice direction (Figure 8b). In sections orthogonal to the ice movement direction, the intraclasts thin or taper laterally, forming single or double wing-like terminations (Figures 10.8c, 10.8e).

3.3 Deformation Structures

The till matrix to the mélange possesses a locally intense domainal foliation (also see Hart and Roberts, 1994; Roberts and Hart, 2005; Phillips *et al*., 2008; Waller *et al*., 2011) which is itself deformed by several phases of small- to meso-scale, E–SE-verging folds (Figures 10.1a, 10.1b, 10.2b, 10.2c and 10.6). These folds are locally disharmonic with earlier developed foliation becoming progressively disrupted and diffuse towards the fold hinge, consistent with the mélange locally containing a high porewater content during deformation. S-C and ECC (S-C = Schistosity-Cisaillement; EEC = Extensional Crenulation Cleavage, (Passchier and Trouw, 1996)) fabric geometries, asymmetrical folds and off- sets on faults, thrusts and ductile shears typically record an E-SE-directed sense of shear. The alignment of the intraclasts is generally accordant with the plane of the foliation within the surrounding till (Figures 10.1a, 10.1b, 10.2a, 10.2c). However, examples do occur where the intraclasts appear to have been variably rotated (sense of

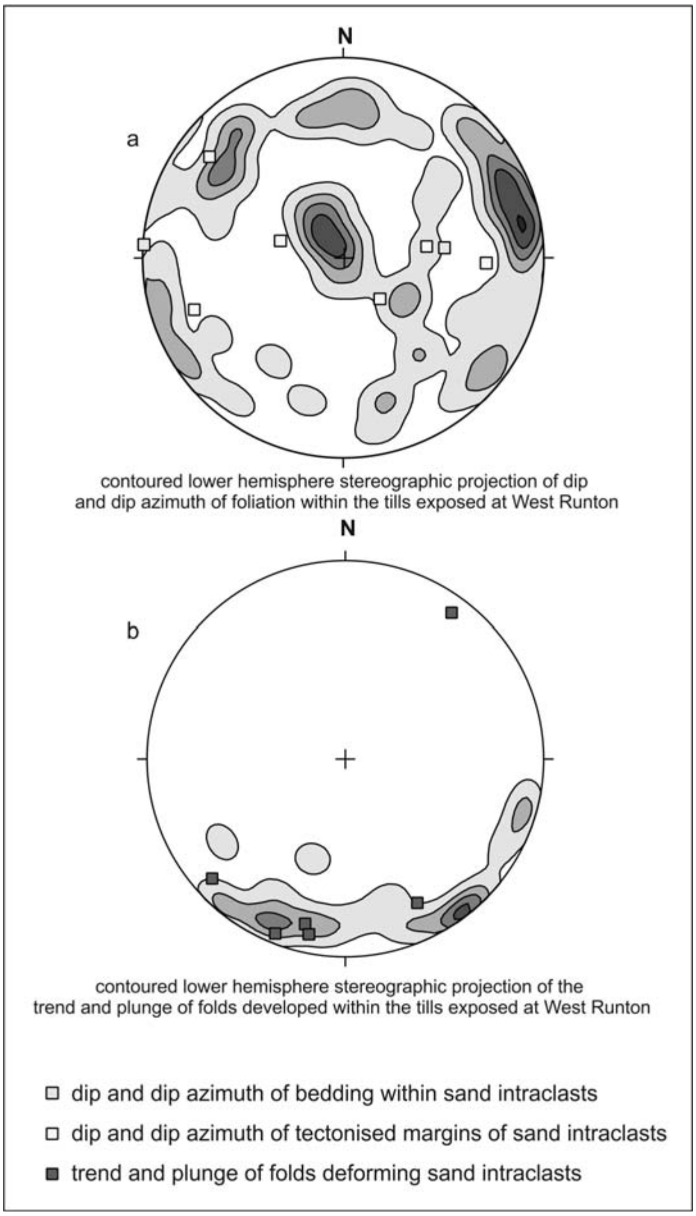

Figure 10.4. Contoured lower hemisphere stereographic projection of dip and dip azimuth of foliation within the tills exposed at West Runton; (b) contoured lower hemisphere stereographic projection of the trend and plunge of folds developed within the tills exposed at West Runton (from Waller *et al*., 2011)

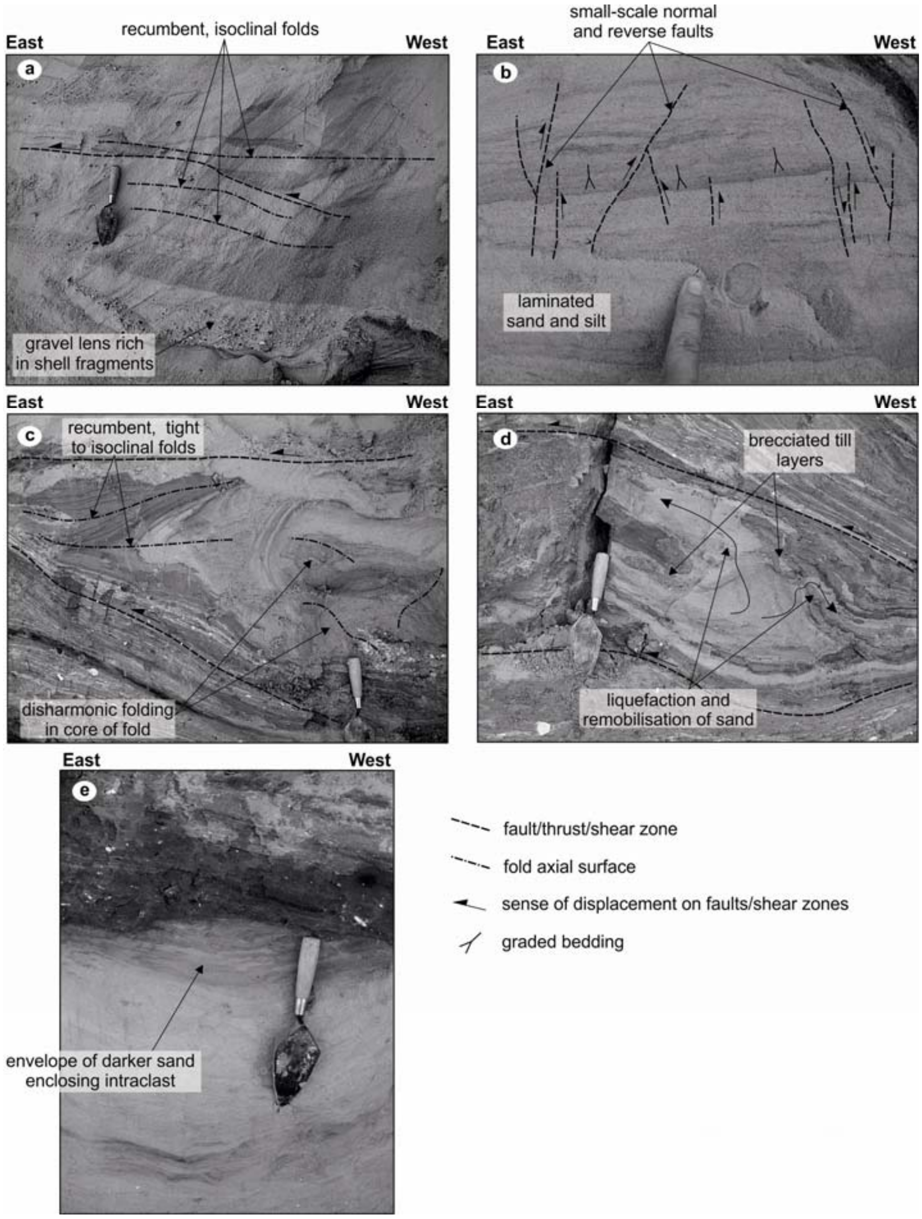

Figure 10.5. Detailed images illustrating small-scale folding within the intraclast infills (a, b) and the nature of interactions around their boundaries (c, d, e) (from Waller *et al*., 2011)

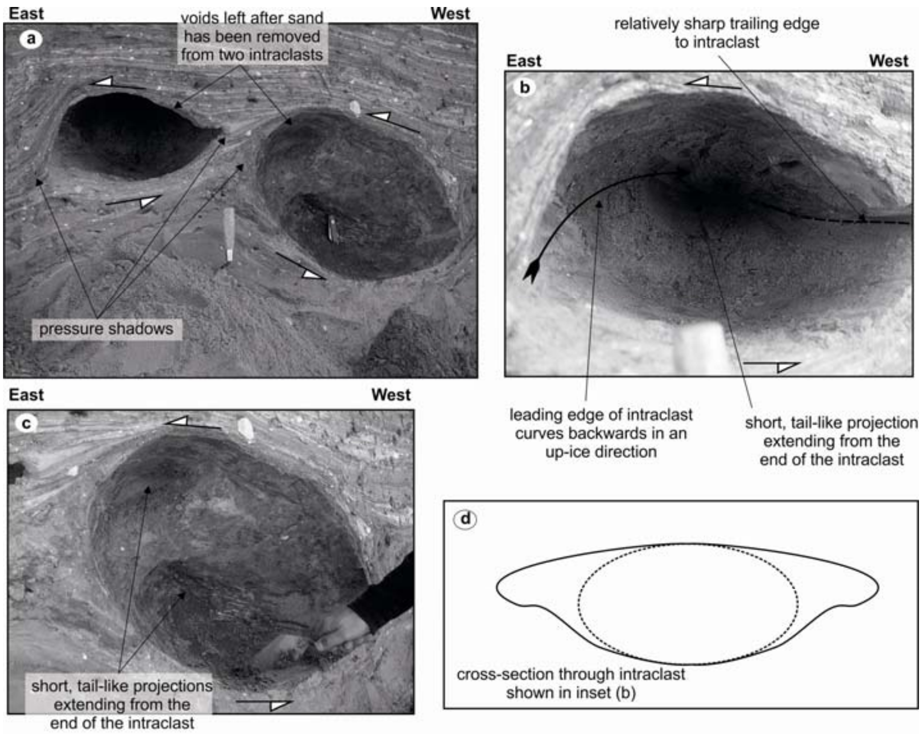

Figure 10.6. Three-dimensional morphology of two augen-shaped intraclasts excavated at site 2 (see Figure 5c) (from Waller *et al*., 2011)

rotation typically towards the E or SE), becoming locally steeply inclined or even overturned (Figures 10.1e, 10.2b). The orientation of the glacitectonic fabric within the till matrix to the mélange is highly variable (Figure 10.4a). This fabric clearly wraps around the sand intraclasts (Figures 10.1, 10.2), indicating that they represented relatively rigid bodies during deformation and foliation development.

There is a marked contrast in the apparent intensity of deformation recorded by the sand intraclasts and the surrounding BGTM. The dominant structure within the till is a pervasive, domainal to compositionally-banded foliation that is deformed by several generations of E–SE-verging asymmetrical, tight to isoclinal, inclined to recumbent folds (Figures 10.1a, 10.1b, 10.2, 10.3b). These folds are locally cut by, or developed in the hanging-walls of gently W-dipping, E–SE-directed thrusts and/or narrow ductile shear zones (Figure 10.3b). The folds range in scale from a few tens of centimetres up to several metres, with the larger structures also locally deforming both the margins and bedding within the sand intraclasts (Figure 10.3b). Data collected from the folds developed within, and at the margins of the intraclasts indicate that they are coaxial to the folds within the till (Figure 10.4).

In contrast to the host till, many of the intraclasts exhibit very little evidence of internal deformation and locally contain well-preserved primary sedimentary structures including bedding, graded bedding, parallel lamination, cross-bedding, ripple-drift lamination and climbing ripples (Figures 10.1c, 10.2). In the least deformed examples, bedding has been rotated or offset by small-scale normal faults (Figure 10.5b). In others, observed tectonism is more intense and bedding is deformed by recumbent and isoclinal folds (Figures 10.7a, 10.7c) locally dissected by low-angle E-directed thrusts (Figure 10.5a). The axial surfaces of the folds are parallel to the foliation developed within the host till. Furthermore, similar recumbent folds have been recognised within the till (Figures 10.2b, 10.2c), with these intrafolial structures representing the very earliest structures developed within this glacitectonic mélange. This indicates that whilst deformation within the intraclasts is limited, they have recorded all of the phases of deformation imposed upon the more highly-strained till.

The geometry of small-scale folds developed within the till immediately adjacent to the sand intraclasts (Figures 10.2a, 10.2b, 10.2e, 10.3b, 10.4c) is consistent with their formation during either the passive rotation of the intraclasts, or folding of the foliation as it is wrapped around the intraclast. A number of the folds appear to have nucleated upon the upper surfaces of the augen to pod-like sand intraclasts (Figures 10.1b, 10.2c). These shear folds possess a distinctive curved axial surface which arcs away from the intraclast and records a E–SE-directed sense of shear, comparable to that recorded by the geometry of the host sand lens (Figure 10.2c). The tightness and amplitude of the fold decreases away from the intraclast in a down-ice direction. This relationship indicates that the folds nucleated upon, or near, to the margin of the intraclast and propagated towards the E–SE in a down ice direction. These relationships again indicate that these sand bodies, rather than being weak as their unconsolidated nature would suggest, acted as a relatively rigid bodies during deformation. The latter was partitioned into the weaker till with the presence of the sand intraclasts leading to localised mechanical instabilities within the actively deforming mélange matrix and the initiation and propagation of shear-related folds.

A number of the larger intraclasts represent the dissected hinges of large-scale folds that have been cut through by sub-horizontal to gently W-dipping thrusts or ductile shear zones (Figures 10.3, 10.9). Kinematic indicators developed within the immediate hanging wall and/or footwall of the thrusts and shears record a sense of displacement towards the E-SE. Thinner sand beds on the limbs of the folds show evidence of attenuation (thinning) or, in some cases, boudinage. The structurally more complex intraclasts are composed of several stacked (imbricated) lenses of well-bedded sand, separated by low-angle to bedding-parallel thrusts (Figures 10.4, 10.5). Both the thrusts and bedding are locally deformed by the meso-scale, E–SE-verging folds (Figure 10.3b). These cross-cutting structural relationships indicate that the intraclasts and mélange matrix have undergone at least two phases of thrusting separated by a period of folding. However, the E–SE-directed sense of movement recorded by all of these various phases of thrusting and folding occurred during the same overall deformation event (D3 of Phillips *et al*., 2008).

3.4 Intraclast composition

The intraclasts are composed of massive to well-bedded, pale grey to yellow-brown unconsolidated sand and silty sand with, in some cases, inter-beds of silt, gravel and shelly gravel. Particle-size analysis confirms the sand dominated nature of the intraclasts and the limited content of clay and silt (mean composition = 97.0% sand (range 76.9 - 100%), 2.8% silt (0-18.9%) and 0.2% clay (0-4.2%)). Comparative figures for the BGTM indicate a poorly-sorted grain size distribution with a greater fine-grained component (mean composition = 47.9% sand (39.9 - 53.2%), 22.3% silt (0 - 18.9%) and 28.4% clay (14.5 - 37.1%)). The Mundesley Sands (MM) (mean composition = 91.8% sand (84.1 - 98.1%), 3.7% silt (0.4 - 11.1%) and 4.5% clay (2.2 - 9.1%)) and the Runton Sands and Gravels (RSG) (mean composition = 94.2% sand (92.1 - 95.6%), 3.4% silt (1.3 - 4.7%) and 2.1% clay (1.2 - 3.4%)) are texturally similar to the intraclasts displaying a predominance of sand size material, although in both cases they contain a slightly higher clay and silt content.

Locally the sand within the intraclasts possesses a weakly to moderately developed hematitic cement. The sands and gravels of the WCF (West, 1980; Rose *et al*., 2001), which structurally underlie the BGTM, possesses a locally well-developed hematite cement indicating that the cemented sand clasts were probably derived from these preglacial sediments. However, cemented sand intraclasts form only a minor component within the mélange.

In terms of their lithology, the sand intraclasts exhibit a distinctive heavy mineral composition with between 22-55% zircon and garnet, and 35-59% amphibole, epidote and pyroxene which is distinctively different from the regions tills including the host till. Instead, the composition overlaps with the WCF (preglacial marine deposits that underlie the glacial sequence in the region), and a penecontemporaneous outwash deposit (RSG). The data implies that the RSG are at least in-part sourced from the erosion of the WCF, and that CF was being eroded and entrained both as intraclasts within the till, and as glacial outwash (RSG).

4. Origin of the intraclasts

Two hypotheses previously advocated to explain the presence of intraclasts within tills can be rejected at the outset. The hypothesis that they represent channel fills formed englacially (e.g. Goodchild, 1875) or subglacially (Clayton *et al*., 1989) following ice stagnation can in the case of the BGTM be rejected. This hypothesis predicts that the original sedimentary architecture of the channel fills will be preserved unless the sequence was deformed by a subsequent ice readvance. However, no channel-like morphologies have been observed within the intraclasts at West Runton. In addition, the presence of intact but over-steepened (occasionally sub-vertical) bedding (e.g. Figures 10.1e, 10.2b) is inconsistent with this hypothesis.

An alternative hypothesis involving the entrainment of intraclasts by basal adfreezing and their subsequent deformation as part of a basal ice layer is also unlikely in this case. This hypothesis predicts that following entrainment into and transport within a basal ice layer, the intraclasts are deposited through melt-out from stagnant ice and will therefore occur within a melt-out till. However, the BGTM does not display characteristics considered diagnostic of melt-out tills such as very strongly-orientated clast fabrics (e.g. Lawson, 1979). In addition, the mélange facies of the BGTM is 20-30 m thick at West Runton. In order for this to be generated through melt-out, this would require the ablation of a stratified basal ice layer of 65-100 m thick (assuming a mean debris content of the ice of 30% by volume; Knight *et al*., 2000); far exceeding the reported thickness of such layers at the base of modern day glaciers (Knight, 1997).

4.1 Entrainment into a subglacial deforming layer

Most previous studies have agreed that the deformation imposed on the BGTM was subglacial in origin (Banham, 1975, 1988; Hart, 1987; Hart *et al*., 1990; Hart and Boulton, 1991a, b; Hart and Roberts, 1994; Lee and Phillips, 2008; Phillips *et al*., 2008) and this is considered the most likely process of entrainment. The entrainment of sand intraclasts into an actively deforming layer may have occurred in response to either: *(i)* subglacial erosion of preglacial sediments associated with an increase in subglacial shear stresses and a thickening of the deforming layer during ice advance (Menzies *et al*., 1990a); *(ii)* subglacial folding and subsequent attenuation at the base of a deforming layer (décollement surface) (Hart and Boulton, 1991b); or *(iii)* proglacial folding and thrusting of pre-existing sediments followed by continued displacement along the thrusts leading to the upward transport of detached blocks of sand into an actively deforming subglacial shear zone (Phillips *et al*., 2008). The first two models preferentially incorporate detached sediment blocks into the base of the subglacial deforming layer and therefore should lead to an observed increase in the density and/or concentration of sediment intraclasts towards the base of this zone. However, although the density of intraclasts within the BGTM varies laterally, they occur at all structural/stratigraphic levels within this complex deposit and therefore the third model is considered most likely.

This involves large-scale thrusting of the glacial and preglacial sediments in response to both proglacial and ice-marginal deformation (Phillips *et al*., 2008). This led to the dissection, stacking and repetition of thrust-bound slices of the penecontemporaneous glacial outwash sediments with different parts of the older glacial to preglacial sequences to form a series of ice-marginal thrust-moraines (Figure 10.7 Phillips *et al*., 2008). Reactivation of these thrusts, coupled with the propagation of a new-generation of thrusts and ductile shears during subglacial deformation would have tectonically transported slices of folded and faulted pre-existing sediment and bedrock into a higher structural position within the deforming bed. This process would have kept the mélange fed with bedded sand, which became progressively deformed to produce the distribution of intraclasts observed throughout the mélange. Furthermore, the source materials for the intraclasts were already folded and dismembered, and ready for incorporation into the deforming bed of the ice sheet.

4.2 Preservation of the intraclasts

Arguably the most fundamental yet contentious question regarding the inclusion of sediment intraclasts within subglacially-deformed tills, is how they survive as competent and coherent blocks within what is commonly considered a pervasively deforming medium. At West Runton, the intraclasts are locally very common, forming up to 60 to 70% of the mélange. They have remained as intact, rigid bodies that not only acted to

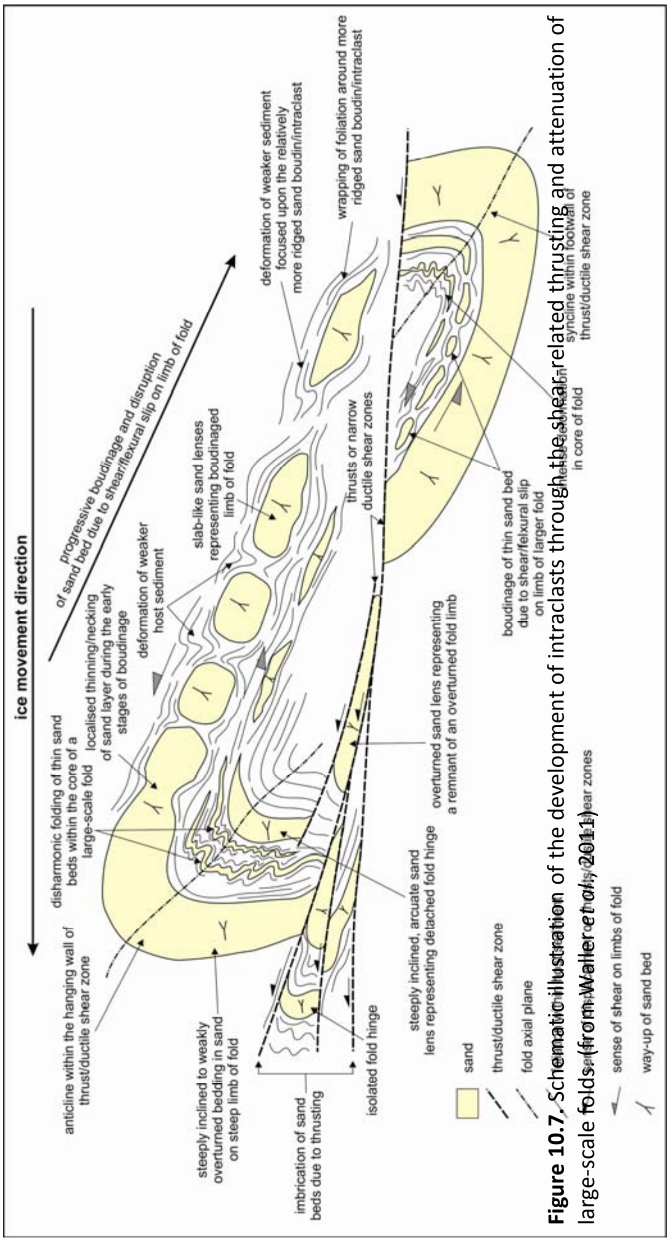

Figure 10.7. Schematic illustration of the development of intraclasts through the shear-related thrusting and attenuation of large-scale folds (from Waller *et al.*, 2011)

partition deformation into the weaker mélange matrix, but also formed localised mechanical instabilities within the till, leading to shear-related folding immediately adjacent to these bodies (Figures 1b, 2c). They also record the same suite of deformation structures (folds and faults), albeit less pervasively developed, and polyphase deformation history as the surrounding till. However, they are largely composed of unconsolidated sand which can be easily excavated by hand.

Phillips *et al*. (2008) and Lee and Phillips (2008) argued that the BGTM possessed a high porewater content (or pressure) at the time of formation, leading to the observed enhanced ductile deformation within the matrix of the mélange. This conclusion is supported by the disharmonic nature of folding and evidence of liquefaction and water-escape within the BGTM (see Phillips *et al*., 2008). However, comparable high porewater contents would have also existed within the intraclasts, leading to the preferential liquefaction and remobilisation of the unconsolidated sand and its rapid assimilation into the surrounding till. The clear distinction between the heavy-mineral signatures of the intraclasts and the host till indicates that this style of sediment mixing did not occur within the BGTM. Additionally, the sharp contacts displayed between the intraclasts and the host till would have been lost/blurred during this deformation-induced mixing process. This leads us to reject the hypothesis that the intraclasts were associated with subglacial sediment deformation during unfrozen conditions.

Cementation would increase the cohesion of sand, enabling the intraclasts to behave as rigid blocks during deformation, and therefore increasing their preservation potential. Although the sand in a few intraclasts has a weakly to moderately developed haematitic cement, the majority lack any visible form of cementation. Alternatively, an ice cement may have been present during deformation as inferred by Menzies (1990a, 1990b), who sought to explain the rheological heterogeneity of a similar mélange in Canada in terms of a marked difference in the temperature and state of the porewater between the sand rafts and host sediment. Key evidence for this difference was the presence of brecciated aureoles of till surrounding the intraclasts thought to be caused by cryosuction and desiccation. However, no such aureoles were observed around the intraclasts at West Runton. In addition, any initial temperature difference between the two components of an actively-deforming mélange is likely to have been short-lived due to the small size and limited heat capacity of many of the intraclasts. Therefore, whilst this hypothesis is considered unlikely, we agree that the sand intraclasts were probably cemented by ice.

4.3 Formation and deformation of ice cemented intraclasts

Although the ice cement in the intraclasts at West Runton has long since melted, it is likely that the intraclasts were firmly cemented by pore ice at the time of deformation, based on analogy with pore-ice-cemented sand intraclasts within frozen glacitectonite in the Canadian Arctic. Because ice cements in granular soils under most natural earth-surface conditions exist close to the bulk melting temperature of ice, they are vulnerable to pressure melting. The application of a hydrostatic confining pressure to a frozen granular soil causes: *(i)* pressure melting at contacts between mineral grains; *(ii)* migration of water towards regions of lower stress; and *(iii)* recrystallisation (regelation) in these lower stress regions (Williams and Smith, 1989; Andersland and Ladanyi, 2004). Localised melting of the ice cement at points of high stress between adjacent sand grains would have allowed limited granular rotation, enabling the intraclast to respond to any imposed deformation (e.g. folding). The very small volumes of liberated meltwater will migrate towards lower stress areas, represented by the adjacent open intergranular pore spaces, where it refreezes and maintains the pore ice cement. But, had the pressure increased sufficiently to melt most or all of the pore ice, then the strength of the sand would drop dramatically (cf. Chamberlain *et al*., 1972) with the unfrozen intraclasts undergoing enhanced ductile deformation and/or liquefaction and incorporation into the host till. Instead, we infer that limited amounts of pressure melting occurred within the frozen sand intraclasts and that this tended to increase their shear strength.

The highest shear strengths in frozen granular materials develop when the following conditions are met: *(i)* pore ice completely fills the available pore space, maximizing both the cohesive effect from ice and the frictional effect from sand grain-to-grain contacts, and impeding dilatancy of the sand during deformation; *(ii)* temperature is as low as possible, minimizing the amount of liquid water along ice crystal and sand grain boundaries and thus maximizing the adhesive effects of ice bonding with sand (see Fish and Zaretsky 1997); *(iii)* normal stress is of a moderate value, but does not exceed a critical limit where the energy needed for dilatation equals the shear strength of individual particles (~100 kPa for the coarse granular debris; Nickling and Bennett, 1984), beyond which dilatancy is partly replaced by particle fracture and crushing and, as a result, shear strength decreases or remains relatively constant; and *(iv)* strain rates are high, restricting volume change and accommodation cracking (Goughnour and Andersland, 1968). Meeting one or more of these conditions during subglacial deformation of the BGTM would have increased the shear strength of the sand intraclasts relative to the host till, leading to a marked rheological contrast between these two components and promoting deformation partitioning into the matrix of the mélange. This rheological contrast is most likely to have developed in warm permafrost.

4.4 Subglacial deformation of warm permafrost

The survival of relatively undeformed frozen intraclasts within an actively deforming till, and the associated rheological heterogeneity, can be explained by deformation at temperatures below, but close to, the pressure melting point of permafrost. The presence and quantity of liquid water, and therefore the mechanical properties of frozen ground at these relatively warm temperatures, are strongly grain-size dependent (Williams and Smith, 1989). In sand, the maximum temperature at which most of the water within it is frozen is about – 0.5°C (Williams and Smith, 1989, p. 257). Where such 'warm' permafrost develops in sediments of varied particle size, the permafrost is partially frozen and comprises a mixture of sediment, ice and liquid water. The liquid water will be most abundant in clayey sediments, in response to pre-melting at temperatures below the bulk freezing point (Dash *et al*., 2006), and the ice will be most abundant in sand and gravels. Consequently, if such a sequence was overridden by ice, enhanced ductile deformation would occur preferentially within the partially-frozen, fine-grained till matrix. In contrast, the frozen intraclasts would have possessed a greater shear strength than the wet, plastic-frozen till, allowing them to act as more competent (rigid) blocks within the actively deforming mélange. As a result the majority of the shear imposed by the overriding ice sheet would have been partitioned within the matrix of the mélange (Phillips *et al*., 2008; Lee and Phillips, 2008).

This hypothesis circumvents the requirement for a significant thermal contrast between the constituent elements of the mélange and is considered the most likely explanation for the development and preservation of the intraclasts. Accordingly the mélange facies of the BGTM at West Runton would have comprised 'hard-frozen' sandy bodies (intraclasts) dispersed within a 'plastic-frozen' silt-clay (till). Hard-frozen ground (Tsytovich, 1975) is firmly cemented by pore ice and its deformation is characterised by brittle failure and low compressibility. This is consistent with the faulting and low-angle thrusting within the sand intraclasts, and the three-dimensional form of these bodies indicating that they largely resisted compression and attenuation into tectonic laminations developed within the adjacent host till. Plastic-frozen ground contains substantial amounts of liquid water and its deformation is characterized by creep and ductile behaviour, and relatively high compressibility.

The hypothesis is also consistent with the evidence for extensive preglacial permafrost in the region. In the coastal sections at Weybourne, the preglacial deposits and chalk bedrock are deformed by convolute folds and ice-wedge pseudomorphs, with flints within the chalk and, in some areas, pebbles within the overlying preglacial gravels exhibiting a pronounced vertical alignment indicative of frost heave. Furthermore, numerous occurrences of ice-wedge pseudomorphs and relict sand wedges have been reported from the preglacial deposits of northern East Anglia (e.g. West, 1980; Whiteman, 2002) formed during multiple periglacial events (Lee *et al*., 2003). Large-scale rafts of chalk are a distinctive feature of the glacitectonism in the North Norfolk area that have also been related to the existence of permafrost (Phillips *et al*., 2008; Burke *et al*., 2009).

5. Conclusions

- Coarse-grained intraclasts are common within the Bacton Green till mélange observed at West Runton, occurring as individual blocks, ‘strings' or 'chains’ comprising up to 60-70% of the exposed area of the deposit. They measure between a few tens of centimetres to >10 m in length and are typically characterised by sharp contacts with the surrounding till and well preserved sedimentary structures. They are composed of unconsolidated sands with little clay and silt that are both texturally and mineralogically distinct from the surrounding till.
- The wrapping of glacitectonic foliation around the intraclasts and the development of folds relating to mechanical instabilities indicates that the intraclasts acted as rigid bodies during deformation, with strain being largely partitioned into the surrounding tills. In contrast, the intraclasts exhibit little evidence of internal deformation and locally contain well-preserved primary sedimentary structures.
- The existence of unconsolidated sand intraclasts within highly-strained tills is difficult to explain in terms of existing hypotheses that include meltwater deposition within stagnant ice, entrainment into a basal ice layer and subglacial deformation during unfrozen conditions.
- The evolution of intraclasts is best explained by the proglacial and sub-marginal deformation of warm permafrost. Initially, proglacial folding, thrusting and stacking of the permafrozen preglacial sediments and penecontemporaneously-deposited proglacial sediments resulted in the development of a stacked sequence. Subsequent over-ridding and subglacial deformation of the sequence led to the progressive disruption, shearing and boudinage of the constituent beds and the development of the intraclasts.
- The preservation of the intraclasts is likely to have been promoted by the development of a pore-ice cement. In this respect, the observed rheological contrast between the rigid sand intraclasts and more highly-deformed tills is consistent with deformation at temperatures close to but slightly below the pressure melting point (warm or plastic-frozen permafrost). Under these conditions, the intraclasts are likely to have been cemented by pore ice whilst the surrounding finer-grained tills would have contained significant amounts of liquid water. Given sufficient time, continued deformation and strain heating of the subglacial sediments would result in a breakdown in this rheological contrast and an assimilation of the intraclasts into the till matrix.
- The presence of unconsolidated intraclasts within highly-deformed tills provides geological evidence for the deformation of partially-frozen sediments that can potentially be used to identify the extent of glacier-permafrost interactions beneath former ice masses. Experimental work offers the potential to clarify the thermal conditions under which intraclasts are generated and preserved. If they are indicative of glacier-permafrost interactions, this provides a sedimentological criterion that can complement geomorphological inverse models previously used exclusively to reconstruct basal thermal regimes.