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The evolution of periglacial patterned ground in East Anglia, UK

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Abstract

During the Late Pleistocene, East Anglia experienced multiple cycles of periglacial activity. This research investigates whether chalkland patterned ground infilled with coversand developed during one or more glacial cycles or only during the last period of intensive periglacial activity to affect lowland Britain. Single grain luminescence ages from polygons and stripes at six sites in East Anglia suggest that the patterns experienced multiple phases of activity during the last 90-10 ka but do not date back to earlier glacial cycles. This activity is attributed to four main phases: (1) ~55-60 ka, (2) ~31-35 ka, (3) ~20-22 ka and (4) ~11-12 ka. Most sites show some activity around the Greenland Stadial 2a and the Younger Dryas Stadial, but polygons show a longer, more temporally and spatially varied record than stripes. Interpreted phases of activity mostly coincide with stadials within the last glacial-interglacial cycle, possibly at the end of climatic cold phases.

Keywords: polygon, stripes, OSL, chalkland, coversand

Introduction

The utility of relict periglacial landforms in understanding palaeoenvironments has often been hampered by age uncertainties and the potential for near-surface features to be a palimpsest formed by multiple phases of activity (e.g. Paris basin, Thiry *et al.* 2013). Despite the complex glaciological history, the East Anglia region of the UK (Figure 1) contains abundant near-surface relict periglacial landforms and aeolian coversands (Figures 2 and 3; e.g. West 1963, 2007, 2009; Rose *et al.* 1985; Rothera, 2000; Scheib and Lee 2010). Rose *et al.* (1985) hypothesised that they formed during stadials in the Devensian (equivalent to the continental Weichselian; Marine Isotope Stage (MIS) 5d-MIS 2), particularly the final phase of periglacial activity to affect lowland Britain, during the Younger Dryas Stadial (equivalent to the Greenland Stadial 2 (GS1); ~12.9-11.55 ka, cf. Lowe *et al.* 2008). West and Williams (2012), in contrast, attributed initiation of patterned ground to earlier glacial periods. Murton and Kolstrup (2003) also

suggested that some Pleistocene cryogenic wedge structures in NW Europe are poly-cyclic.

This study aims to test if chalkland patterned ground infilled with coversand developed during one or more cycles of periglacial activity. Single-grain Optically Stimulated Luminescence (OSL) dating and detailed statistical analysis of the resultant OSL replicate data are used to establish the timing of sand deposition and/or reworking in order to determine the number of cycles of activity, their relative intensity and palaeoenvironmental significance in North Western Europe.

The Geological and Climatic Setting of Central East Anglia

East Anglia possesses a generally low-lying relief with the strata of the Upper Cretaceous limestones (Chalk Group; British Geological Survey, 2010; Figure 3a) forming a distinctive escarpment that extends from the



Figure 1: The East Anglian region with sites and places mentioned in the text.

eastern margins of the Wash in northwest Norfolk, south-westwards through Norfolk and Suffolk and into Cambridgeshire. East Anglia has been glaciated on a number of occasions. During the Anglian Glaciation (MIS 12) the landscape of East Anglia was extensively modified by ice with widespread lowering of the Chalk escarpment (Clayton, 2000) and excavation of the Wash (e.g. Fish and Whiteman, 2001; Gibbard *et al.* 2012). At this time chalk-rich tills were deposited across much of central East Anglia (e.g. Perrin *et al.* 1979; Rose, 2009; Lee *et al.* 2011; Scheib *et al.* 2011). Following deglaciation, drainage in central and western East Anglia was re-established but fed largely into the glacially-eroded Wash Basin (e.g. Boreham *et al.* 2010). In the Late Middle Pleistocene (the latter part of MIS 6) there is evidence that glacier ice entered the Wash Basin once more, over-running a periglacial landscape (Gibbard *et al.* 1992; 2009; 2012). In the Late Pleistocene, during the Dimlington Stadial (equivalent to GS2; ~22.9-14.7 ka cf. Lowe *et al.* 2008), ice from the North Sea banked up against the higher Chalk hills of north-western most Norfolk (England and Lee, 1991; Pawley, 2006; Moorlock *et al.* 2008). Aeolian coversand deposition has been extensive within East Anglia, with preserved coversand concentrated in the Breckland area (e.g. Perrin *et al.* 1974; Chorley *et al.* 1966; Catt, 1977; Bateman, 1995; Scheib and Lee, 2010, Figure 3a). The most recent period of Devensian coversand

deposition known in East Anglia occurred during the Younger Dryas Stadial and is represented in the coversands of west Norfolk (Hoare *et al.* 2002).

Climatically, East Anglia is the region of Britain most influenced by the continental air masses of Western and Central Europe and as a result, East Anglia is presently one of the driest (606 mm a^{-1}) parts of the UK, with a high number of days experiencing frost (46 days a^{-1} ; Met Office 2006). During Middle and Late Pleistocene glacial periods, when global ice volume was high and the shallow Southern North Sea Basin non-marine, the continentality of the East Anglian climate was greater (Huijzer and Vandenberghe, 1998). During the Devensian Stage, East Anglia experienced extreme polar conditions periodically interrupted by more temperate periods of climatic warming (e.g. West *et al.* 1974; Phillips and Sparks, 1976). During the Dimlington Stadial (GS2) and Loch Lomond Stadial (GS 1; equivalent to the Younger Dryas) coldest monthly temperatures fell by $>28^\circ\text{C}$ and warmest month temperatures by around 9°C and 7°C respectively (Atkinson *et al.* 1987; Huijzer and Vandenberghe 1998).

East Anglian Chalkland Patterned Ground

Chalkland patterned ground in East Anglia, mostly in the form of polygons and stripes, occur across an

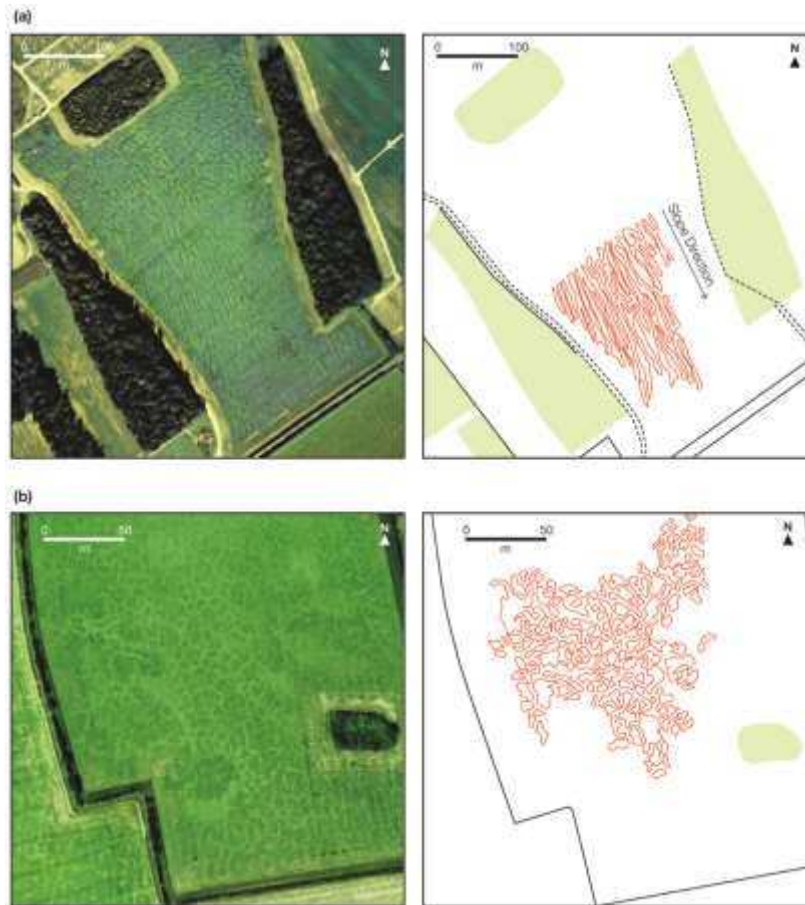


Figure 2: Examples of periglacial patterned ground from East Anglia, UK. (a) Periglacial stripes on a slope near Brettenham, Suffolk. Note farm building bottom right corner for scale. The mean stripe length is around 10 m. (b) Periglacial polygons near Titchwell, Norfolk.

observed patterned ground reflect vegetation differences caused by the underlying chalky centres and sand-filled marginal troughs of the patterns (Williams, 1964, 1968; Watt *et al.* 1966; Evans, 1975; Ballantyne and Harris, 1994, pp. 96–97; Figure 3). The troughs are commonly 2–3 m wide and penetrate up to 1.8 m into brecciated chalk (Williams, 1968). Trough bases as well as the tops of the chalky centres are irregular. Polygons grade into stripes at slope angles between about 1° and 6° (Figure 2a). Polygon diameters (measured between partition centres) are commonly 10.5 m, and stripe spacings are about 7.5 m (Williams, 1964). Post-depositional concentration of sub-surface water within the features has caused solution of the underlying brecciated chalk, creating both irregularities and/or rounded bases to the features (Figure 5).

Chalk bedrock occurs within 2.5 m of the surface of all of the patterns (Nicholson, 1976), the upper part of which is brecciated. Above this, two stratigraphic horizons, chalky diamicton and coversand can be distinguished within the patterns. The matrix-supported chalky diamicton overlies the brecciated chalk and is *c.* 0.5–2 m thick. It comprises of subrounded chalk pebbles and chalk powder mixed

with varying concentrations of non-carbonate sand and rock fragments. The sand is fine grained, well-rounded to subangular with some coarser grains showing frosted surfaces. Rock fragments are mostly flint, which tend to be angular, fresh-looking (i.e. locally derived from underlying chalk) and, where elongate, are vertical to steeply dipping. Above the chalky diamicton, a unit of fine to medium sand (0.1 – 0.3 mm) generally occurs, thickest in stripe and polygon troughs, and in pockets and pipes descending from them. This sand is thought to be coversand deposited primarily by aeolian processes as indicated by the texture, surface frosting of grains, and by the polished (sand-blasted) flints (Williams 1964). Coversand formation primarily took place when landscapes had limited or broken vegetation cover and a plentiful supply of unconsolidated sediment (e.g. Bateman 1998).

Pattern genesis

The brecciated chalk bedrock that forms a layer at least 0.5–1.0 m thick beneath the patterns (Williams, 1987) is thought to have developed by ice segregation associated with freezing and micro-cracking of moist

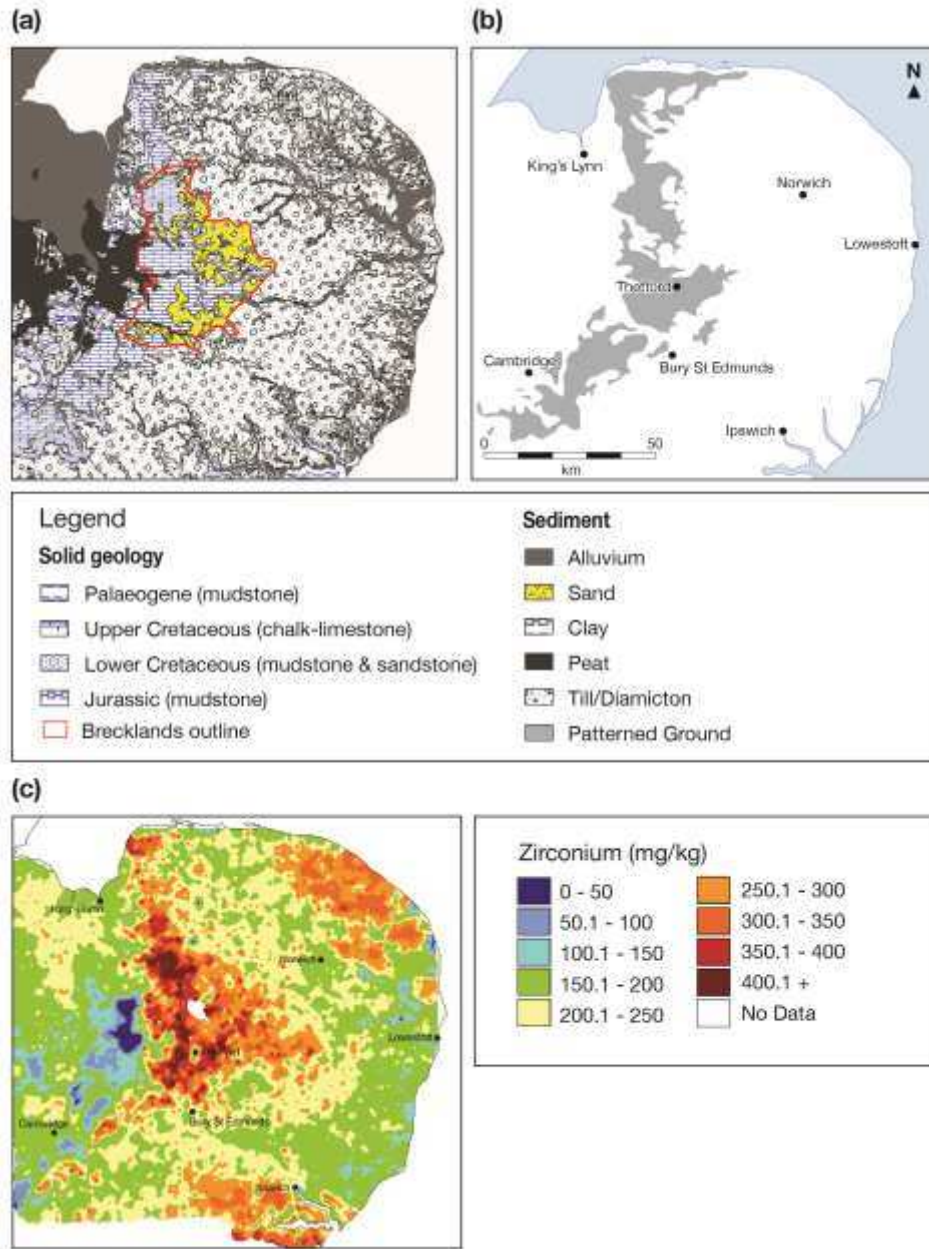


Figure 3 (a) Present-day geology of East Anglia (solid and drift) with the Breckland area in which coversand most commonly found indicated (red-line) (b) Distribution of patterned ground in East Anglia as mapped by Nicholson (1969) (c) Soil concentrations of zirconium (Zr) which is a robust proxies for an aeolian-derived (e.g. coversand or loessic) soil component. Zr data from British Geological Survey © NERC.

frost-susceptible chalk (Murton and Ballantyne, submitted; Murton *et al.* 2006). As segregated ice tends to be most abundant in frost-susceptible sediments and bedrocks in the transition zone between the active layer and the long-term permafrost, the presence of the brecciated layer suggests the presence of past permafrost. The chalk diamicton layer, which is thickest at stripe and polygon centres, has clearly formed by mixing of predominantly chalky material (chalk bedrock, chalky till or solifluction debris) with overlying sand, probably

in large part by cryoturbation because involutions are abundant in the chalk diamicton and always present beneath stripes and polygons (Williams 1968). Three types of involutions (Type 1-3 as per Murton *et al.* 2003) underlie the East Anglian patterns, with two generations of involutions sometimes apparent. Within stripes, involutions show downslope distortion. Beneath some stripes, unweathered flint clasts and abundant chalk fragments are most concentrated in a vertical zone in the middle and lower part of the pattern centre (Watt *et al.* 1966).

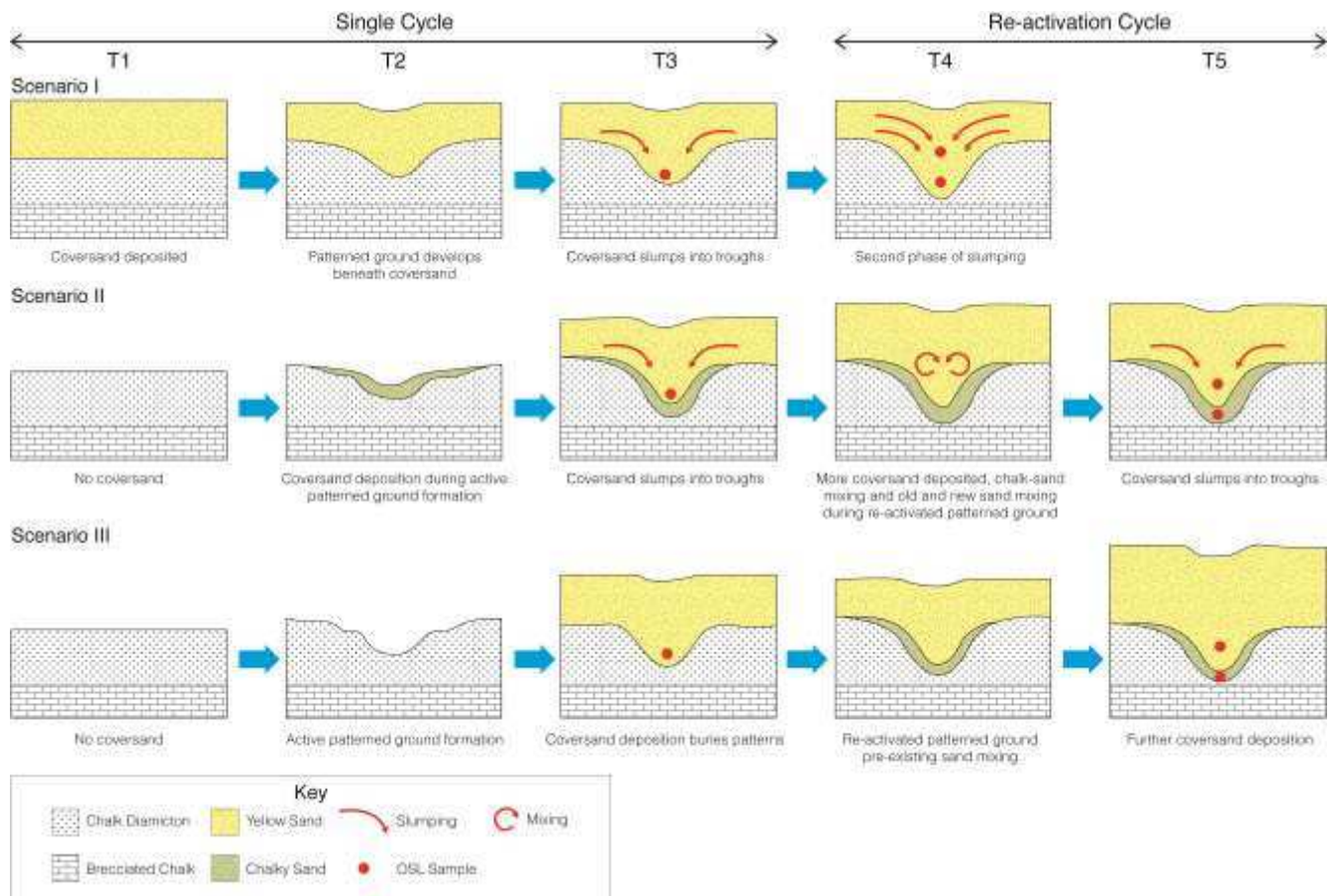


Figure 4 Conceptual model for the relationship of polygon and coversand for a single periglacial cycle (T1-T3) and for subsequent periglacial re-activation cycles (T4-T5). Scenario I is based on Williams (1964), Scenario II is based on Watt *et al.* (1966) and Nicholson (1976) and Scenario III based on current authors' observations. For clarity details of all processes occurring within the formation of pattern ground (e.g. jacking and polishing of flints, involutions, small-scale thermal contraction cracking) are not shown.

Whilst pattern genesis in East Anglia clearly involved sediment movement within an active layer above permafrost, their precise origin and relation to permafrost conditions remain uncertain. Thermal contraction cracking is discounted as a cause of stripe initiation because this process is not known to produce stripe patterns (Williams, 1968). Limestone solution is discounted because the striking geometrical regularity of the patterns is at odds with irregular and often pipe-like features attributed to solution beneath periglacial deposits in the English chalklands (Murton and Ballantyne, submitted). Sorted patterns, at least in a fully developed form, can be ruled out because the chalkland patterns lack a regular alternation of clasts and fine sediment at the surface. Nicholson (1976) suggested that sediment circulated within active chalkland patterns, moving downward and inward from beneath the margins and upward in the centres, with fresh material introduced into the circulation by active-layer deepening. Murton *et al.* (2003) noted that similar chalkland patterns on Thanet in Kent have several features in common with

earth hummocks in subarctic western Canada: both are developed on highly frost-susceptible sediments, have dome-shaped surfaces, become elongate on sloping ground and contain poorly-defined involutions. These authors attributed the large size of the Thanet patterns to active-layer deepening, which is thought to have allowed soil circulation in a deep active layer about 2 m thick and determined pattern size.

Three scenarios may explain the relationship between coversand and polygons (Figure 4). Williams (1964) thought the coversand was originally deposited *before* the patterns started to form beneath it, with flint clasts on pattern centres slumping into surrounding troughs. Burial of the exposed pre-existing chalky substrate is inferred where flint faces projecting above it are polished (Williams 1964; scenario I in Figure 4). Both Watt *et al.* (1966) and Nicholson (1976) suggested that coversand was deposited *during* the development of the structures (with slumping later) as some coversand is mixed with the underlying chalky material and flints are found at slightly greater depths within sand-filled troughs than

in sand above pattern centres (Scenario II in Figure 4). Finally, it cannot be ruled out that patterns were initiated prior to coversand deposition with subsequent raised polygon and stripe centres being buried at some later time beneath aeolian sand (Scenario III in Figure 4). Based on the scenarios laid out in Figure 4 and assuming multiple phases of periglacial activity, scenario I cannot account for the mixed layer observed (e.g. Figure 5) and Scenario III cannot account for the concentration of flints within the sand (e.g. Figure 5). Scenario II, with co-occurrence of coversand deposition with polygon development, would allow for wind polishing of flints sticking out of the initial phase. The mixed layer of sandy chalk diamicton could have formed by mixing of sandy involutions with chalky material (as inferred in Thanet by Murton *et al.* 2003), perhaps supplemented by sand infilling small-scale thermal contraction/desiccation cracks to form sand veins and small sand wedges which were subsequently homogenised by cryoturbation. As ice-rich chalky breccia within the active layer was thrust upward, coversand as it was being deposited would have been forced downward filling troughs. Jacking of large clasts within the active layer may have allowed flints originating from the chalk breccia to move into the sand which would also explain their vertical alignment and concentration within troughs (Williams, 1968; Nicholson, 1976). Where coversand attained a thickness greater than the active layer, polygon development either was precluded or became moribund within the permafrost.

Application of luminescence dating to periglacial deposits

As reviewed by Bateman (2008), luminescence dating has been successfully applied to a range of periglacial deposits (e.g., Bateman 1995; Murton *et al.* 2003; Bateman and Murton 2007; Bertran *et al.* 2011). It is particularly applicable to periglacial features where the sand-fill is of aeolian derivation which would have had plenty of exposure to sunlight during saltation thereby resetting (bleaching) the OSL signal prior to burial. Where multiple phases of sand-wedge development (either epigenetic or syngenetic) have been identified from stratigraphy, then OSL ages have been shown to reflect these different phases of development (Buylaert *et al.* 2009). The development of optical rather than thermal stimulation, use of quartz rather than feldspar and the ability to measure individual grains has overcome many of the shortcomings raised by Kolstrup (2007a).

Coversand deposition probably occurred during polygon/stripe development (section 1.2.2), such that luminescence samples should provide ages of

coversand deposition and/or pattern activity. Potentially, each sand-filled trough of polygons/stripes may have undergone multiple cycles of freeze-thaw, cryoturbation and/or small scale thermal contraction cracking, with the result that the ages within a given trough/stripe which developed epigenetically may not show a trend in ages either laterally or vertically. Initial polygon activity would have incorporated pre-existing surficial aeolian sand units, with OSL ages reflecting burial age of the aeolian deposit. Subsequent activity may have caused already incorporated sand grains to move laterally and vertically, perhaps within sediment circulation cells (e.g. Mackay, 1980; Hallet and Prestrud, 1986; Hallet and Waddington, 1992; Peterson and Krantz, 2003), during which time exhumation and further exposure to sunlight could have taken place. In such cases OSL would provide ages reflecting the time when the periglacial feature was active, with the youngest age giving the best indication of when it became relict.

Study Sites

Initially, regions of interest were identified based on earlier work (e.g. Watt 1955; West 1961; Williams 1964). An important resource was mapping by Nicholson (1969, 1976) of all patterned ground visible on Royal Air Force imagery from 1945 (Fig 3b). The latter, in conjunction with further aerial photographs held at the Landscape Unit, Department of Geography, University of Cambridge; English Heritage National Monuments record as well as imagery from Google Earth and Getmapping was used to identify potential sampling sites (Figure 3b). Historical data showed substantial variation in the appearance of the patterns from year to year due to differences in vegetation growth and agricultural practices (e.g. modern deep ploughing to 0.4-0.6m). The latter also having implications for post-depositional sediment disturbance. Sites were selected where they exhibited well-preserved and verifiable former periglacial features away from field boundaries and pipe line routes. At several localities, polygons and stripes were delineated by high-resolution mapping (Figure 2). This, combined with auger surveying, were used to compile a base map for determining field excavation sites. Ground penetrating radar, unfortunately, failed to delineate subsurface patterns due to flints and high-angle reflectors (see supplementary text for details). Six sites were selected within three areas, in north-west Norfolk [TF 7637], around Thetford [TL 8783] and from south-west of Cambridge (Figure 1). Three sites contained polygons sites and three contained stripes. All sites were outside the limits of the Dimlington Stadial Ice advance.

Barnham Spinney [52° 22' 20" N 0° 45' 56" E]

At the Barnham Spinney site, located 1.5 km south-west of the village of Euston in Suffolk, aerial photography revealed well developed polygons. A hand-dug test pit, located initially by test augering, was dug into one sand-filled feature within the polygon (Figure 5; Figure S1). Beneath a compact dark yellowish brown sandy (10YR 4/4) ploughed soil, up to 0.4 m thick, were three sand units that filled an irregular trough-like feature penetrating involuted chalky diamicton. A yellow sand unit comprised of fine yellowish brown (10YR 5/6) homogeneous sand, devoid of organic material and contained occasional flint clasts. An orange brown unit comprised of fine orange medium sand (7.5YR 5/4) with frequent flint clasts. Finally, a chalky sand unit which was comprised of yellowish brown in colour (10YR 6/6) with frequent degraded chalk clasts and flints. Pockets of orange sand penetrated the underlying chalky sand and chalk diamicton, their contacts typically diffuse showing wispy and flame-like tongues protruding down-profile. The irregular base of the trough feature also had numerous pipes into the underlying brecciated chalk and Chalk. This was taken to indicate that some post-depositional solution within the feature has taken place. Ten sediment samples were collected for OSL dating.

Brettenham Heath (East) [52° 26' 29" N 0° 50' 41" E]

The Brettenham Heath (East) site, located 2.5 km north-west of the village of Bridgham in Suffolk, was chosen due to the prominent polygonal pattern discernible from aerial photography. A mechanically excavated trial pit exposed two sand-filled troughs (about 1.5 m deep) in a single polygon (Figure 6; Figure S2). The troughs were beneath a vegetation covering of *Calluna* spp., and the dome of chalky diamicton between them, whose top was at a depth of about 0.7 m, was beneath grass. Beneath the vegetation was a dark brown (7.5 YR 3/2) sandy silt relict plough soil that contained frequent flint clasts and roots. Underneath the soil, a trough structure comprised sand units that varied from structureless yellowish brown sands (10YR 4/6) with a minor silt component to darker orange sands (10YR 5/4). The contacts between them were highly irregular and marked by chalky inclusions, flame-like and wispy boundaries. A prominent pipe feature in the trough was infilled with very pale brown (10YR 7/4) medium sand and fine reddish brown (7.5YR 4/6) sand laminae. The chalk diamicton surface was pitted with a number of sand-filled solution hollows which, based on augering, extended in excess of 1.5 m below the trial pit base. One such pipe contained a 25 cm thick homogenous, stone-free structureless dark yellowish

brown (10YR 3/6) clay. The chalk diamicton comprised fine silty comminuted chalk with inclusions of very pale brown (10YR 7/4) sand and numerous sub-angular flint clasts. It possessed a platy structure characteristic of former ice lenses (Figure S3). Between the two troughs, the contact between the sand and the underlying chalk diamicton was densely pitted with root casts. Ten samples were collected for OSL dating including one (Shfd08010) collected by auger from the clayey sand above the clay at the base of a pipe feature.

East Farm Barnham [52° 22' 29" N 0° 45' 24" E]

The East Farm Barnham site located 1 km south-east of the village of Barnham in Suffolk was selected as it showed elongated polygons in aerial photographs (Figure 7; Figure S4). The trial pit exposed a sand-filled trough with an irregular base and bounded by chalk diamicton and light yellowish brown (10YR 6/4) sand. There was a marked degree of colour change between the units of sand observed ranging from reddish yellow (7.5 YR 6/6) to darker orange brown (7.5YR 4/6) sand. Some units were folded into vertically-aligned structures with sharp to diffuse contacts and banding orientated parallel to the structure margins. All sand units contained large flint clasts, many of which were fractured. A weak trend of flint banding was identified towards the base of the plough soil, a common feature within the region. Nine sediment samples were collected at East Farm for OSL dating.

Rectory House Farm [52° 03' 55" N 0° 8' 44" E]

At Rectory House Farm, 2 km southwest of Ickleton in Cambridgeshire, a trial pit was dug across a stripe. This revealed a sand-filled trough within the underlying Chalk bedrock, which was relatively wide at ~ 5 m (Figure 8). This was infilled with three main units of sand; a basal chalky sand overlain, a homogenous slightly silty fine orange sand, and just beneath the plough soil pockets of fine dark yellowish brown sand. Three samples were collected from the respective sand units.

Courtyard House Farm [52° 56' 16" N 0° 33' 43" E]

At Courtyard Farm, 1.5 km east of Ringstead in North West Norfolk a trial pit was located across a stripe. The trial pit expose a trough shaped feature in the underlying chalky diamicton with a sand-filled pipe feature which augering showed extended at least 1.2 m below the bottom of the exposure (Figure 9). Two main sand units were observed with a diffuse boundary between them. The first was a slightly silty fine yellow sand, which graded into a slightly clayey

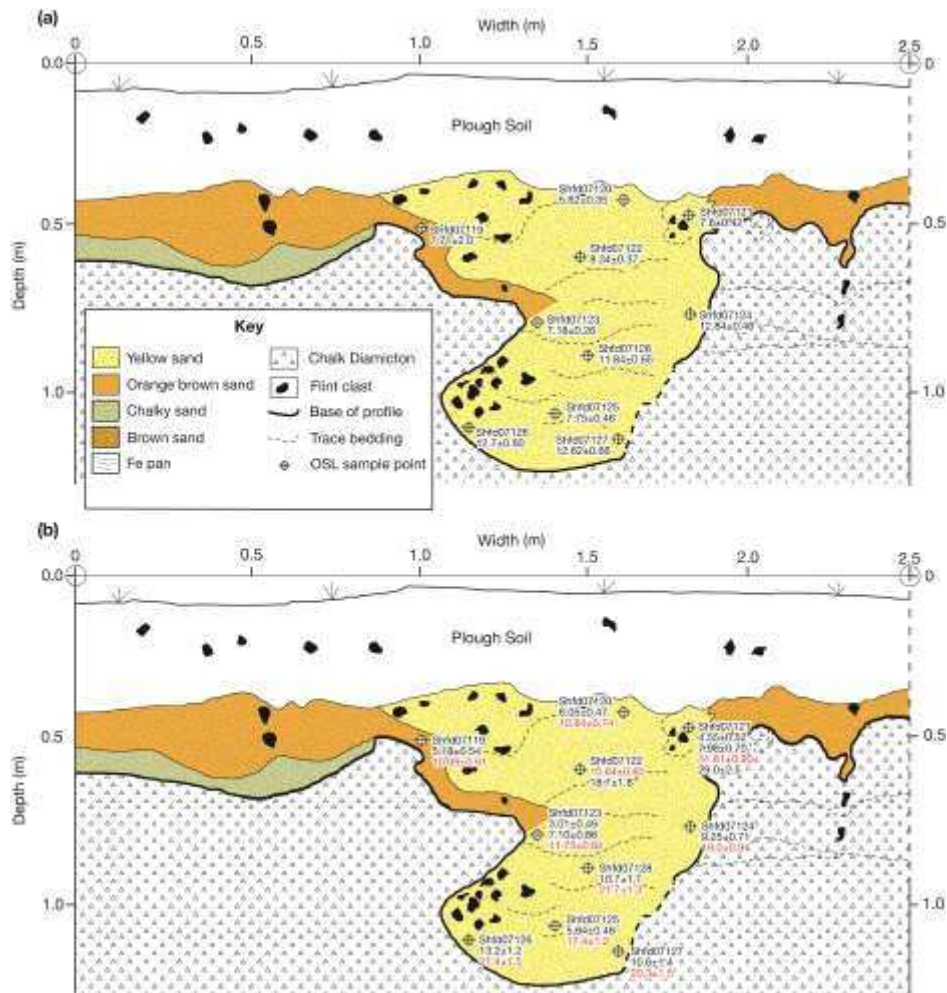


Figure 5: Section and samples from the polygon excavated through at Barnham Spinney. (a) single aliquot OSL ages; (b) OSL component ages calculated from single grain data as extracted using finite mixture modelling. The age component representing largest proportion of data is highlighted in red. Components representing <10% of OSL data within a sample are not shown. Note the chalk diamicton grades downward into brecciated chalk.

medium orange brown sand with frequent large flint clasts. The second was a slightly silty fine reddish orange sand. Three sediment samples were collected from the two units for OSL dating.

2.6 Manor Farm [52° 06' 25" N 0° 1' 38" E]

At Manor Farm, 2 km north-east of the village of Meldreth (near Fowlmere) in Cambridgeshire, a small test pit was dug into a stripe located from an auger transect. Only a limited excavation was possible at this locality so the extent and nature of the stripe were not examined. The test pit revealed 30 cm of silty sand (10YR 5/2) greyish brown in colour with frequent inclusions of fractured flint clasts and rootlets.

Beneath this were 20 cm of homogenous silty fine (10YR 3/4) yellowish brown sand with occasional flint clasts. This sand was sampled for OSL dating.

Methods

Sampling

At each locality subsurface features were located using the constructed base map and verified with a series of test auger holes cored at 1 m intervals along 10 m transects. Once a sand-filled feature had been located, a trial pit at least 2 m x 1 m² was dug either mechanically (Brettenham East, East Farm Barnham)

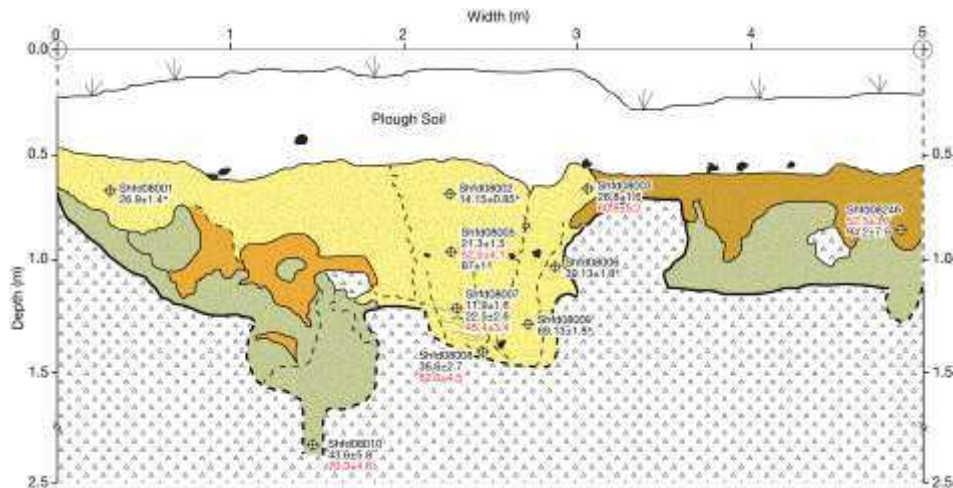


Figure 6: Section and samples from exposure through patterned ground at Brettenham Heath, with legend as Figure 5. Also shown are OSL component ages calculated from single grain data as extracted using finite mixture modelling. The age component representing largest proportion of data is highlighted in red. Components representing <10% of OSL data within a sample are not shown. Ages marked with an asterisk are based on single aliquot measurements as single grain data not available. Note the chalk diamicton grades downward into brecciated chalk.

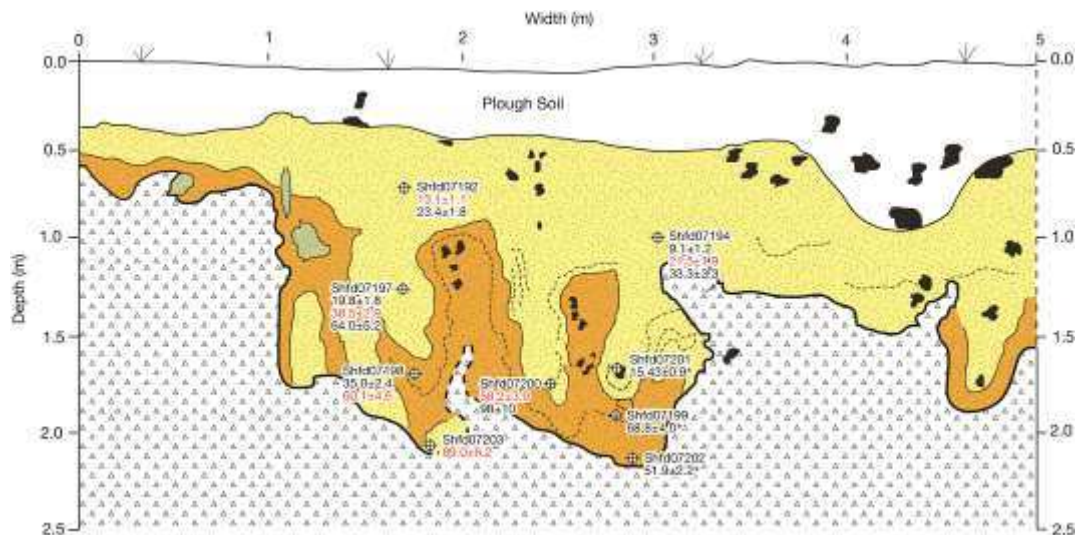


Figure 7: Section and samples from exposure through patterned ground at East Farm, Barnham with legend as Figure 5. Also shown are OSL component ages calculated from single grain data as extracted using finite mixture modelling. The age component representing largest proportion of data is highlighted in red. Components representing <10% of OSL data within a sample are not shown. Ages marked with an asterisk are based on single aliquot measurements as single grain data not available. Note the chalk diamicton grades downward into brecciated chalk.

or by hand through one or more relict sand-filled periglacial feature. Once a face had been cleaned the details of its soil and sediment stratigraphy were recorded along with details of soil colours, texture, structure, compactness, stoniness etc. OSL samples were collected from the sand-filled troughs in opaque 2 cm diameter PVC tubes. Areas of recent

bioturbation (e.g. rabbit holes) and sediment within 40 cm of the surface (the plough zone) were avoided. This generated a total of twenty nine samples from the three polygon sites and 7 samples from the three stripe sites.

OSL Measurement

As each sand-grain might have had a different cryoturbation history, sediment age may vary quite markedly over distances of centimetres or millimetres within features. Adjacent grains may relate to cracks of different age or grains which have had greater or less exhumation during cryoturbation. Whilst adoption of small diameter (2 cm) sampling tubes for this study mitigated the potential age variability incorporated within a single sample, other strategies were also employed. Typically when OSL measurements are made they are carried out on aliquots 9.6 mm in diameter which may contain around 2000 grains. Thus

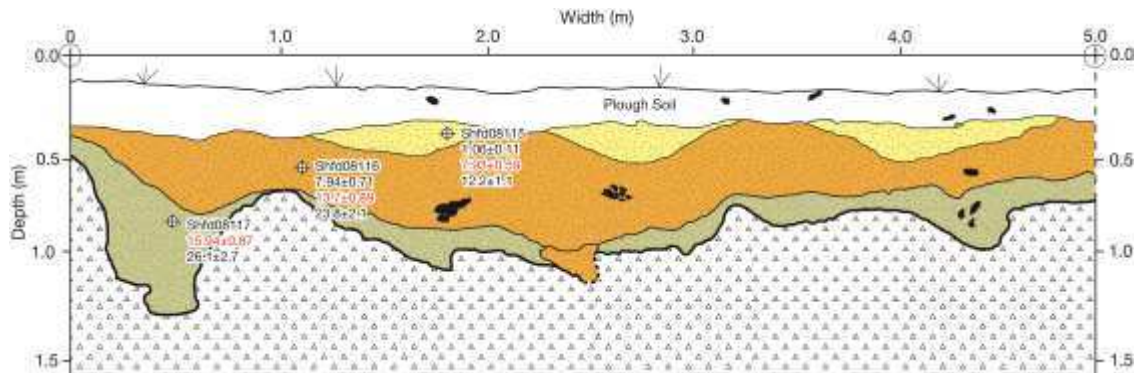


Figure 8 Section and samples from exposure through a stripe at Rectory House Farm with legend as Figure 5. Also shown are OSL component ages calculated from single grain data as extracted using finite mixture modelling. The age component representing largest proportion of data is highlighted in red. Components representing <10% of OSL data within a sample are not shown. Note the chalk diamicton grades downward into brecciated chalk.

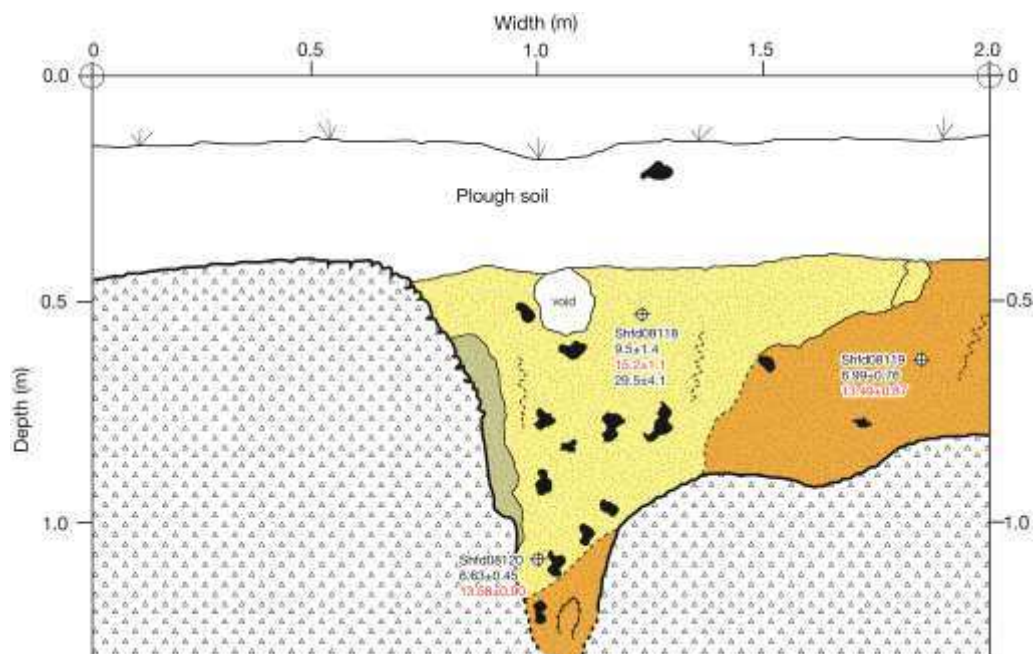


Figure 9: Section and samples from exposure through a stripe at Courtyard House Farm with legend cf. Figure 5. Also shown are OSL component ages calculated from single grain data as extracted using finite mixture modelling. Age component representing largest proportion of data are highlighted. Components representing <10% of OSL data within a sample are not shown. Note the chalk diamicton grades downward into brecciated chalk.

the measured OSL signal is an average of ~2000 grains masking variability of different age or differently bleached/mixed grains. Because of this replicate aliquot data may show less variability than reality or average results which do not reflect burial age (Rhodes 2007; Bailey and Arnold 2006; Arnold and

Roberts 2009). For aeolian sediments, such as the coversands, this standard aliquot approach is appropriate. However, OSL measurement at the single grain level enables measurement of true OSL variability within a sample and therefore a chance of examining and understanding the causes of this variability. This approach is therefore appropriate for sediments with complex depositional and post-depositional histories such as those incorporated by

cryoturbation into stripes. In the light of this, multiple samples per site were measured both at the standard single aliquot as well as single grain level as part of this research in order to better evaluate the reliability, consistency of ages produced.

Given the heterogeneous nature of the sediment within the periglacial features dose rates were determined via *in situ* gamma spectroscopy or where access made collected this data impossible were based on thick source beta counting (e.g. Ankjaergaard and Murray, 2007) using a low level Risø National Laboratories beta multicounter system GM-25-5. Attenuation due to water content was based on contemporary water content (Tables S1-S2). An assessment of three samples from Barnham Spinney (Shfd07119), East Farm, Barnham

(Shfd07202) and Brettenham Heath East (Shfd08003), using dose-rates determined by ICP-MS, beta-counting and field gamma spectrometry, found no evidence of disequilibria (Olley *et al.* 1996). As such it is assumed that the present-day measured radionuclide activities have prevailed throughout the period of sample burial. The cosmic dose component was estimated, following Prescott and Hutton (1994).

For details of OSL sample preparation to extract and clean quartz and for the single aliquot regenerative protocols applied for OSL measurement see supplementary information. All samples exhibited OSL decay curves dominated by the fast component and therefore rapidly bleachable, low thermal transfer (<5%) and good recycling. Dose recovery experiments (Murray and Wintle, 2003) undertaken for each site in all cases recovered laboratory doses to within 5% of the administered dose (see Supporting Information Table S3) indicating the appropriateness of the measurement methods employed. Multiple replicates of each sample were measured to give an indication of palaeodose (D_e) reproducibility and ensure measurements represented the true population of D_e values not a sub-sample.

OSL Data Analysis

If a sample contained grains relating to a number of depositional events of well-bleached wind-blown sediment that were incorporated into a periglacial feature the requirement of the finite mixture model (FMM; Galbraith and Green 1990; Galbraith *et al.* 1999) for peaks with equal σ should be met and consequently realistic D_e values should be able to be extracted using the model (Rodnight *et al.* 2005). Bateman *et al.* (2010) in applying FMM to single grain OSL from a sand-wedges in Arctic Canada showed that use of the extracted component which related to the most data (the dominant component) resulted in stratigraphically consistent ages not obtained by other approaches. Bateman *et al.* (2010) also showed that ages based on the dominant component and other minor components extracted by FMM coincided with climatic cool periods leading them to suggest that multiple phases of thermal contraction cracking were recorded within a single sample. This assumes multimodal D_e distributions are solely the response to different age grains, which were bleached before burial, and mixed together during sampling. Whilst beta heterogeneity could cause some of the spread in the D_e distributions it is unlikely to give rise to different modes within the data (Guérin *et al.* 2013). The approach of Bateman *et al.* (2010) has been adopted for this study. D_e components representing the most grains (dominant component) is considered to represent the age when the most grains in that sample were buried for the last time. In this context

this was either at the time of incorporation of coversand into the feature or when cryoturbation was sufficient to exhume sand grains to the surface. Minor D_e components within a sample that are younger than the dominant are considered either to reflect subsequent periglacial activity in which younger coversand or exhumed sand were mixed in or to reflect post-depositional disturbance which moved more recently deposited sand down profile (Bateman *et al.* 2003; 2007). Minor D_e components within a sample that are older than the dominant one are considered to reflect older phases of periglacial activity/coversand deposition in which not all grains were subsequently exhumed in later periglacial events. The latter might reflect subsequent events were less active or reflect the position of grains at depth or within structures (e.g. pipes) from which it is hard to move grains up profile.

OSL ages for each site are shown in Figures 5 – 9 and in Tables S1-S2. As per Bateman *et al.* (2010), at each site the resultant FMM component ages for all samples underwent cluster analysis using FMM with a sigma-b of 0.1 in order to see if phases of activity could be discerned (Table 1). These statistically extracted phases are used for guidance only.

Results

In order to assess D_e heterogeneity within samples, those from Barnham Spinney were measured both at the single aliquot and at the single grain level (Table S1). Figure 10 shows that as the number of grains measured simultaneously decreased from ~2000 to 100 to 1, so overdispersion and the mean D_e increased. This is attributed to the samples containing mixed D_e populations, with the single grain method identifying this, whereas the aliquots, through averaging effects masking it (Duller 2008). Thus the age of 7.18 ± 0.26 ka for sample Shfd07123 based on single aliquot measurements, at the single grain level, has multiple age components ranging from 3.01 ± 0.49 to 11.75 ± 0.84 ka (Figure 10d). As shown in Figure 5a, resultant ages based on 9.6 mm diameter single aliquot measurement would indicate that the burial ages for the sands in the patterned ground at Barnham Spinney are mostly between 5.8 and 8.3 ka, with only three samples providing ages which fall into a period when the palaeoclimate was cold enough for periglacial processes to be active. In contrast, Figure 5bc shows the single grain ages, which clearly reveals that each sample has older mean ages with younger age components. Thus, whilst single aliquot OSL data looks good with generally low OD and unimodal D_e distributions (Table S1) use of this data

Table 1 Cluster analysis of all age components (round to nearest ka) found within a site. Age components clustered into phases using Finite Mixture modelling with a sigma-b of 0.1

Site	Polygons				Stripes		Overall (ka)
	Barnham Spinney (ka)	Brettenham East (ka)	East Farm (ka)	Courtyard Farm (ka)	Rectory House Farm (ka)		
Phase 1	5-6	10-14	10-13	7-8	1	11-12	
Phase 2	10-11	25-30	20-23	14	4-5	20-22	
Phase 3	19-21	47-58	33-38	24-35	7-9	31-35	
Phase 4		71-92	67-75		16-18	55-60	

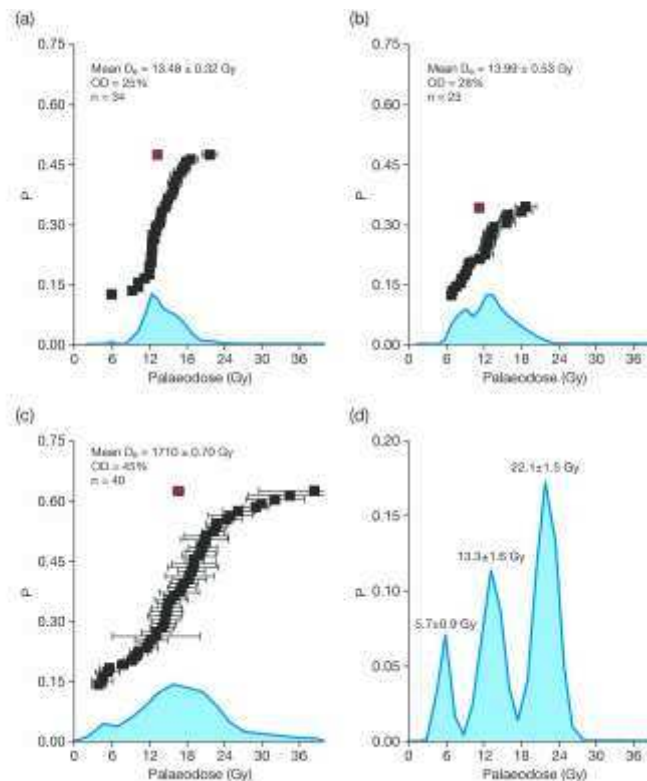


Figure 10 OSL data from sample Shfd07123 measured at different levels. (a) standard 9.6 mm diameter aliquot containing ~2000 grains; (b) small 2 mm diameter aliquot containing ~ 100 grains. (c) single grains. (d) components extracted from single grain data by finite mixture modelling run to minimise BIC with a sigma-b of 0.15. Peaks proportional to amount of data within each component (12%, 35% and 53% respectively). In Figures 10a-c black points represent individual aliquot/grain measurements and red point is the mean of dataset.

could lead to erroneous chronological interpretations. This might account for some of the age inconsistency issues noted by Kolstrup (2007a). Results from single grain measurements reveal true age complexity within samples and allow for more detailed chronological interpretations.

Beyond internal OSL checks such as dose recovery test, evaluating the reliability of age data from sediment which probably does not conform to the principle of superposition is difficult. All OSL results showed no indication of grain saturation and did not produce high D_e values indicative of sediment ages being near the upper limits of the OSL technique. Calculated dose rates within and between sites also show a high degree of consistency, reflecting the common sediment sources and free-draining nature of

the sampled sites. For the polygon sites, samples with the oldest dominant age component generally appear lower within the stratigraphy of the feature than the samples with the youngest dominant age component (e.g. Figure 5b, Figure 7). For the stripe sites, dominant age components at Rectory House Farm do confirm to noted changes within the sand (Figure 8) or have a good degree of consistency, as per Courtyard House Farm (Figure 9). As such there is no reason to suspect the OSL ages do not reflect true burial ages. At Barnham Spinney three age clusters were found at 5-6 ka, 10-11 ka and 19-21 ka. Some single grain component ages clearly show that some of the uppermost sediment is much younger (Middle Holocene; Figure 5a). These component ages mostly occur in samples taken just below the plough horizon

Table 2: Summary periglacial activity based on pre Holocene OSL age components and categorized by time-periods determined by cluster analysis. Note Hint indicates 1 age component in that time period at a site, Minor = 1-2 age components in that time period at a site, Major = 3+ age components in that time period at a site. Note also that number of age components (n) found for stripe sites is lower and this is reflected when comparing relative activity to the patterned ground sites.

Site	n	Loch Lomond (GS1)	LGM (GS2)	Pre-LGM/Post Upton Warren (GS3)	30-40 ka (OIS 3)	40-70 ka (OIS 4)	85-95 ka (OIS 5b)
Patterned Ground							
Barnham Spinney	15	Major	Major				
East Farm Barnham	12	Hint	Minor	Hint	Major	Major	Minor
Brettenham Heath	15	Hint	Minor	Minor	Hint	Major	Minor
Stripes							
Rectory Farm	6	Minor	Hint	Minor			
Courtyard Farm	4	Minor	Hint	Hint			
Manor Farm	3	Hint		Hint		Hint	

where in-filled burrows were noted when sampling. Mid Holocene ages do not show when only the ages based on the dominant D_e are used (Figure 5a). It is therefore interpreted that these young ages show minor post-depositional disturbance or reworking of some sand within the upper most sediment during the warm Middle Holocene, as reported elsewhere (Bateman and Godby 2004). A second age cluster (10-11 ka), found in 8 of the 10 samples, dominates in terms of OSL data the results from the uppermost sediments below the plough soil. In term of timing this falls at the Younger Dryas Stadial (GS1) – Holocene transition when temperatures were rapidly ameliorating and when presumably stadial periglacial activity gave way to permafrost thaw, active-layer deepening and other more temperate processes. During this phase the Barnham Spinney polygon was still active and/or subject to coversand deposition. The final age cluster (19-21 ka) is coincidental with the peak climatic intensity of the Late Devensian cold Substage (GS2a20.9-22.9 ka cf. Lowe *et al.* 2008). All samples (except one) below ~0.5 m from the surface contain this age component suggesting that the whole feature was active with cryoturbation and/or coversand deposition. Since no age components are older than this, it would also appear that this is when this feature was initiated.

The Brettenham East site revealed four clusters of ages at 10-14 ka, 25-30 ka, 47-58 ka and 71-92 ka of which the latter two dominate the single grain D_e data. Only one age component falls within the Younger Dryas Stadial and only two minor age components could be considered within the errors of GS2. Thus it would appear little if any sediment was added or reset at this site during/post GS2 or during the Younger Dryas Stadial. Four samples had age components which contributed to an age cluster of 25-30 ka, a period of cooling (GS3; 23.5-27.5 cf. Lowe *et al.* 2008) after the Upton Warren Interstadial. As the samples contributing to this cluster are from the uppermost and intermediate sediments they are interpreted as indicating at least partial activation or brief coversand deposition at Brettenham East at this

time. All samples had age components which contributed to an age cluster of 47- 58 ka. This is centred on the early part of the Middle Devensian Substage (MIS 3), when global temperatures were variable between full-glacial and interstadial events (e.g. Johnsen *et al.* 2001). It would appear, based on the OSL ages, that the whole feature was aggrading with coversand or actively cryoturbating then. The final cluster is quite broad (71-92 ka) and is probably an artefact of the finite mixture modelling in that it is made up of four age components from a disparate range of stratigraphic positions including both near-surface sediment and the sample augered from a sand-filled pipe. The lowest in terms of depth of these ages is at ~69-70 ka, the start of cooling associated with the Early Devensian (MIS 5/4 transition) and the other two between ~89-94 ka centre on MIS 5b a time of cool interstadial temperatures and indicates the initiation of incorporation of coversand into polygons at this site was post MIS 5c.

The East Farm samples show four clusters of ages. An age cluster between 10-13 ka based on two near-surface samples which coincides with the Younger Dryas Stadial and which is interpreted as dating limited re-activation of the feature and/or coversand deposition. The three uppermost samples contain age components which cluster between 20-23 ka, coincident with the GS2a and therefore also indicating limited re-activation/coversand deposition then. Three samples for the upper/intermediate sediment contribute to an age cluster of 33-38 ka, which falls within the Middle Devensian Upton Warren Interstadial (later part of MIS 3), when climates were thought to be cool and highly variable (e.g. Johnsen *et al.* 2001). A final cluster of 67-75 ka is probably an artefact of the finite mixture modelling in that it is made up of four age components, two between 60 and 64 ka, and two from basal sediment between 89 and 98 ka. The former two age components occur at a time of cold near-glacial temperatures post MIS 4. The latter

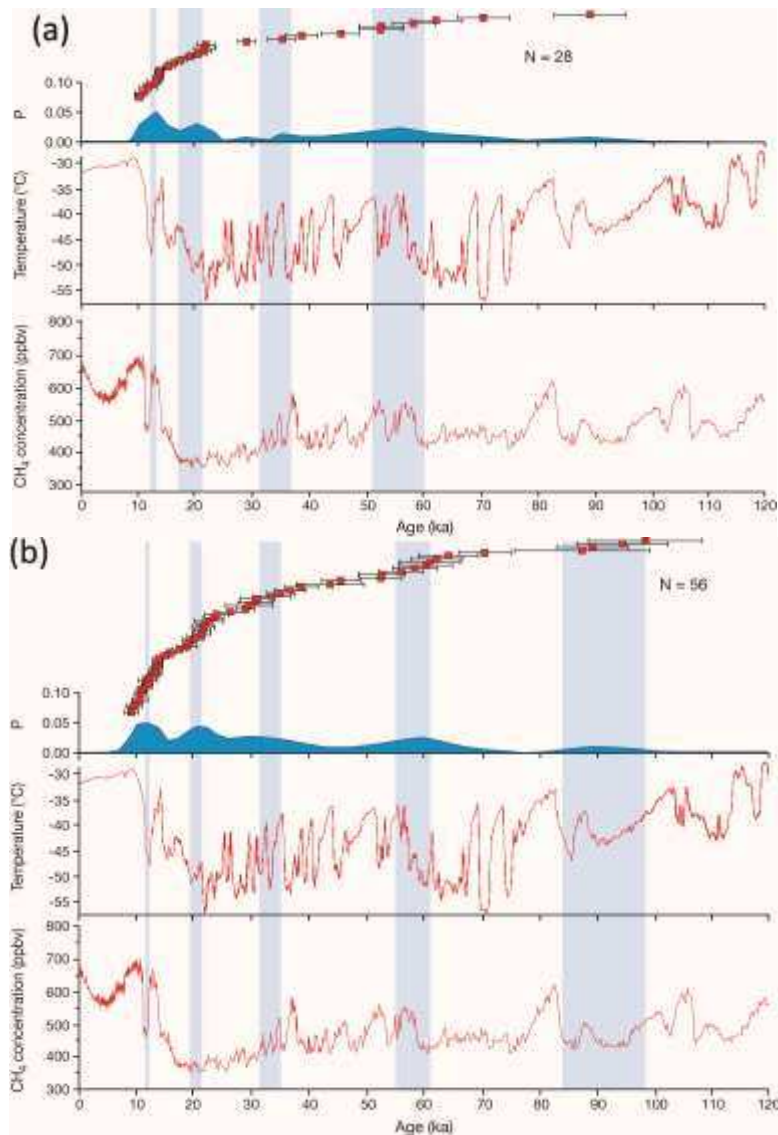


Figure 11: Single grain OSL ages from the periglacial structures of East Anglia plotted against the composite oxygen isotope record from Greenland (redrawn from Johnsen *et al.* 2001) and the Epica Dome C Antarctic methane record (redrawn from Louergue *et al.* 2008). Shaded rectangles represent cluster analysis of the OSL age data carried out using finite mixture modelling with a sigmaB of 0.1 and component numbers reflecting those which reduced the BIC as close as possible to zero. (a) Ages based on the dominant D_e component extracted using finite mixture modelling for each sample. (b) Ages based on all D_e components extracted using finite mixture modelling for each sample.

is within the Early Devensian MIS 5b, a time of cool interstadial temperatures and indicates the initiation of incorporation of coversand into polygons at this site. The Courtyard Farm site has two samples with a Middle Holocene age cluster (7-8 ka) taken to indicate post-depositional disturbance by burrowing animals. All samples have an age component indicating that the stripe was actively incorporating coversand just prior to or within the Younger Dryas Stadial. Whilst no GS2 ages were found, one age component indicates sand incorporation into the feature around 30 ka, possibly indicating this was when the feature was initiated.

At Rectory House Farm, two recent age clusters (~1 ka and 7-9 ka) were identified. The former is from the uppermost sample just beneath the

plough soil, whilst the latter is in the same sample and the one found just below it. Both are assumed to represent minor post-depositional disturbance. Again all samples have an age component indicating the stripe was actively incorporating coversand just prior to or within the Younger Dryas Stadial. Additionally the lower two samples also contain a post-Upton Warren Interstadial age cluster, indicating that this stripe was actively incorporating coversand prior to the GS2, although no GS2 age sediment was dated.

The single sample from the Manor Farm stripe shows an age component around the start of the Younger Dryas Stadial, one post-Upton Warren Interstadial and an age component centred on 55 ka (Middle Devensian, early MIS 3), as well as a much

younger age component assumed to represent Mid-Holocene, post-depositional disturbance.

Discussion

Our results show that no sample is older than the Devensian Stage. This is not an artefact of the dating technique, which has been successfully applied to much older sediment in the region. For example, Pawley *et al.* (2008) reported ages of up to 500 ka for north Norfolk glacial meltwater sediments, and Gibbard *et al.* (2009) reported a luminescence age of 160 ka from the Tottenhill sands and gravels. Additionally no sample showed any sign of having reached the limit of the technique, with grains in saturation. As such this would appear to agree with the hypothesis of Rose *et al.* (1985) that the periglacial deposits and associated structures are all of Devensian age.

Whilst ruling out poly-cyclic activity at the glacial-interglacial timescale, the range of ages extracted from the sites does indicate poly-cyclic activity *within* the Devensian Stage. As summarised in Table 2, at all sites sediments date to more than one discrete time-period, indicating multiple phases of development. It would also appear that the timing of coversand deposition and assumed pattern activity varied substantially across the region. All sites indicate activity during the Younger Dryas Stadial, GS2 (except Manor Farm) and Pre-GS2 period (GS3; except Barnham Spinney). However, it varies as to whether this time-period is based on a single age-component (i.e. relatively little sampled sediment from one place) or most of the ages at a site (i.e. the majority of sediment throughout the feature). Additionally, whereas Barnham Spinney apparently only developed during the GS2, both East Farm Barnham and Brettenham Heath started to accumulate sediment in the earliest Devensian (MIS 5b). This is also reflected in the relatively simple stratigraphy of the Barnham Spinney sequence compared to that of East Farm and Brettenham Heath. There is also an apparent contrast between the age of the polygon and stripe sands, as sand dated from the stripes is dominated by ages less than 30 ka.

The different records at Barnham Spinney and East Farm sites are of note because they are only 0.5 km apart. It seems unlikely that these differences relate to climate as this would have been the same at both sites, as is the geological context. Instead, microclimatic variations may have affected periglacial activity (e.g. Mackay, 1993a, 1993b) or coversand deposition varied and at times was of such thickness that all active-layer processes were confined within the sand. Further work to elucidate the formational processes associated with these features is needed.

When these new data from all sites are combined and compared to long-term proxies of palaeo-temperature (the Greenland oxygen isotope record; Johnsen *et al.* 2001 and the Vostok Methane sequence; Loulergue *et al.* 2008), there is a clear association of periglacial sediment dating from cold phases (Figure 11). This is particularly the case when all age components (not just dominant ones) are used (Figure 11b) and for phases which have a large number of age components (e.g. Younger Dryas and around the GS2 Stadials). The regional record shows an association of periglacial activity with the latter part of the Younger Dryas Stadial (activity phase centred on 11-12 ka) and the cold period of time leading up to and including the GS2a. The latter activity phase is centred on 20-22 ka. During both of these times, mean annual air temperatures are thought to have been $< -8^{\circ}\text{C}$ in central England (with mean monthly temperatures of the coldest month at around -26°C to -20°C Atkinson *et al.* 1987; Huijzer and Vandenberghe 1998). Since the Younger Dryas Stadial is well constrained temporally (ages cluster between 11 and 12 ka), it would appear that activity occurred predominantly within the latter part. This can be attributed to when activity ceased and active-layer thickening took place, as the OSL data provide burial not initiation ages. Likewise, the phase centred on the GS2a Stadial (20-22 ka) coincides not only just when temperatures are thought to have been at their lowest but also, based on the oxygen isotope record, when temperatures were beginning to warm and permafrost potentially starting to degrade. An activity phase which occurs after 37 ka (centred on 35-31 ka) is less well-defined. It coincides with a period of overall cooling (based on the methane record) but also one typified by multiple intense cold periods interspersed with warm periods. On average, mean annual air temperatures are thought to have been between -8°C to -2.5°C in central England with mean monthly temperatures of the coldest month around -27°C to -10°C (Huijzer and Vandenberghe 1998). The phase of periglacial activity centred around 55-60 ka falls within the latter part of the Early Devensian Substage cold period associated with MIS 4. Mean annual air temperatures for the period 74-59 ka are thought to have been between around -8°C in central England with mean monthly temperatures of the coldest month around -20°C (Huijzer and Vandenberghe 1998). The oldest phase of activity that the data show is based on only a limited number of age components but can be associated with the cool stadial periods within the earliest Devensian (MIS 5). Thus, in addition to a clear association of the reconstructed East Anglian periglacial activity phases with cold climatic periods, there is also an indication that the preserved periglacial sediments relate more to the latter parts of cold-climatic periods, with initiation occurring

sometime earlier. This would support the hypothesis that a thick active layer was required to explain the large size of the patterned ground to establish the polygons/troughs. Alternatively it may reflect periods of rapid climate change which induced landscape instability and enhanced coversand movement and deposition.

Comparison of the periods when East Anglian polygons and stripes appeared to have been most intensively active (1) ~55-60 ka, (2) ~31-35, (3) ~20-22 and (4) ~11-12 ka (taken from clusters shown in Figure 11) with dated coversand and relict sand wedges elsewhere in NW Europe shows strong agreement. In the UK, the most recent period of coversand deposition occurred during the Younger Dryas Stadial and is represented in the coversands of Lincolnshire, Lancashire and west Norfolk (Bateman, 1995; Bateman, 1998; Hoare *et al.* 2002; Baker *et al.* 2013). Older fluvio-aeolian coversand on low-angle fans in north Lincolnshire has yielded OSL ages of *c.* 18 to 14 ka (Bateman *et al.* 2000). On the Isle of Thanet in Kent, where chalkland polygons and stripes very similar to those in the present study were examined, three phases of coversand deposition were identified at *c.* 24–21 ka, *c.* 15.5 ka, and *c.* 12 ka (Murton *et al.* 2003). This is coincident with two of the three activity phases found in East Anglia. The identified phases in East Anglia also coincide with the Older Coversand I and II, and Younger Coversand II of the European coversand chronology (Bateman and Van Huisstenden 1999; Koster 2005, fig. 2) although spatial asynchronicity of the transition between Older and Younger Coversand deposition has been noted (Kolstrup 2007b).

Relict sand wedges from Jutland and NE Germany have provided luminescence ages of 19.4 ± 1.5 ka, 24 ± 2 ka, 32 ± 3 ka 33 ± 2 ka and 53 ± 5 ka (Böse 1992; Christiansen 1998; Mejdahl *et al.* 1992), encompassing three of the four active phases in East Anglia (phases 1-3). In France, Guhl *et al.* (2013) published OSL ages of 27.4 ± 5.5 ka and 32.9 ± 3.3 ka for two sand wedges, indicating periglacial activity at the MIS 3/GS3 boundary. Bertran *et al.* (2011, 2013) dated sand wedges to 25.5 ± 2.2 , 26.6 ± 1.8 ka, 26.7 ± 1.5 , 27.7 ± 1.7 ka and 34.3 ± 2.8 ka, and concluded that a major phase of periglacial wedge network developed in the period 25-36 ka. They also identified another significant phase of sand-wedge formation between 19 and 16 ka, with some ice-wedge pseudomorphs thought to be of around 60 ka in age. Again this broadly corresponds to three of the four activity phases found in East Anglia (phases 1-3). In The Netherlands, Kasse *et al.* (2007) found two units with occasional relict sand wedges. Unit A, where wedges are often truncated, provided OSL dates of between 28.8 ± 2.4 ka and 24.4 ± 1.8 ka, a time period not identified for the patterned ground of East Anglia.

However Unit B, containing large well-preserved wedges was OSL dated between 25.2 ± 2 ka to 17.2 ± 1.2 ka. As in neither case was sand within wedges directly dated, the wedges must have formed within these periods. In Belgium, Buylaert *et al.* 2009 found 14 relict sand wedges, with OSL dated mostly between 22 and 14 ka, possibly in two phases, although one wedge dated to 36 ± 4 ka. This corresponds well to activity phases 2 and 3 presented in this paper. The lack of older wedges Buylaert attributed to sampling bias and/or erosion and/ or less favourable conditions. Northwest of Paris, France, sand-filled polygonal patterns about 20 to 30 m diameter (twice that of the features described in the present study and apparently lacking stripes) are thought to have initiated by thermal contraction cracking during the Saalian glaciation (~260 ka), with repeated episodes of periglacial activity and aeolian deposition during the Saalian and Weichselian, although these features have not been dated (Thiry *et al.*, 2013). We know of no relict patterned ground features directly comparable in size and morphology in northern and central Europe to those in East Anglia.

The NW continental patterned ground and wedge development record apparently diverges from the East Anglian record during the latter part of GS2b and *c.* (20.9-14.7 ka cf. Lowe *et al.* 2008) and G11. Widespread NW European periglacial activity dates to the period 18-14 ka but only limited evidence for it exists in East Anglia. This might reflect the fact that much of the NW continental record is based on buried features found within sediment (mostly coversand) which was extensively aggrading at this time. This would have allowed for rapid wedge development and a higher preservation potential compared to the superficial deposits of East Anglia developed in a non-aggrading brecciated chalk landscape. Another reason is that during this period both France and The Netherlands are thought to have become free of continuous permafrost (Huijzer and Vandenberghe 1998) whereas glacial ice may have only reached the northern part of East Anglia just after 17 ka (Clark *et al.* 2012). This would have caused a strong north-south thermal gradient across East Anglia and possibly prevented permafrost degradation, as seen in The Netherlands and France. Persistence of permafrost in East Anglia could account for further patterned ground activity within the Younger Dryas Stadial period.

Bertran *et al.* (2013) discussed the relationship of cold periglacial episodes in France with Heinrich events (e.g. Hemming 2004). It was thought that climatic cooling allowed sea-ice formation in the Bay of Biscay, limiting the thermal buffering effect of the ocean. Despite uncertainty about the exact timings of Heinrich events and the spread of the OSL data presented here, East Anglian periglacial activity

phases 1, 3 and 4 would appear to occur at and just after H6, H2 and H0 respectively. However activity phase 2 appears prior to H3 and evidence of periglacial activity associated with H5, H4 and H1 appears weak or absent. Given that throughout the period global sea-levels were lowered by at least 50 m (Waelbroeck *et al.* 2003), the North Sea basin and much of the English Channel would have been non-marine and thus any additional sea ice forming at coasts during Heinrich events would have had only a limited effect on East Anglian climate.

Conclusions

Intensive sampling and the application of single grain OSL with FMM analysis has provided for the first time an insight into the timing and longevity of relict patterned ground development in East Anglia. Results show that:

- OSL measurements should be made at the single grain level in such contexts to avoid erroneous results.
- East Anglian coversand deposition coincided with patterned ground development.
- Chalkland patterned ground in East Anglia is not the result of multiple glacial cycles but repeated activity *within* the Devensian Stage.
- some East Anglian coversand deposition and periglacial activity can be dated back to stadials within the Early Devensian (MIS 5) but it was widespread during the Late Devensian, particularly in the Younger Dryas and GS2a Stadials.
- there is coincidence of activity and the end of climatic cold-phases during GS2a and the Younger Dryas, possibly indicating that active-layer deepening or enhanced coversand deposition was key for development but not during earlier initiation of some patterns.
- there is poly-cyclicality and variability in the relative importance of different periglacial phases within sites and spatial variability between sites.
- post-depositional bioturbation and solution as well as sediment remobilisation during the Holocene has added complexity to the periglacial structures that are preserved.

As a result it would seem that the East Anglian patterned ground developed in Chalk bedrock forms not only a spatially extensive but also

significant archive of Devensian Stage periglacial activity within the NW European context. Further work is required to relate the timing of coversand deposition and polygon activity to the processes of their formation and their environmental and climatic controls.

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References

- Ankjaergaard C, Murray AS. 2007. Total beta and gamma dose rates in trapped charge dating based on beta counting. *Radiation Measurements* **42**: 352-359.
- Arnold LJ, Roberts RG. 2009. Stochastic modelling of multi-grain equivalent dose (De) distributions: Implications for OSL dating of sediment mixtures. *Quaternary Geochronology* **4**: 204-230.
- Atkinson TC, Briffa KR, Coope GR. 1987. Seasonal temperatures in Britain during the past 22,000 years, reconstructed using beetle remains. *Nature* **325**: 587-592.
- Bailey RM, Arnold LJ. 2006. Statistical modelling of single grain quartz De distributions and an assessment of procedures for estimating burial dose. *Quaternary Science Reviews* **25**: 2475-2502.
- Baker CA, Bateman MD, Bateman P, Jones H. 2013. The aeolian sand record in the Trent Valley. *Mercian Geologist* **18**: 108-118.
- Ballantyne CK, Harris C. 1994. *The periglacial of Great Britain*. Cambridge University Press, Cambridge; 330 pp.
- Bateman MD. 1995. Thermoluminescence dating of the British coversand deposits. *Quaternary Science Reviews* **14**: 791-798.
- Bateman MD. 1998. The origin and age of coversand in north Lincolnshire, UK. *Permafrost and Periglacial Processes* **9**: 313-325.
- Bateman MD, van Huissteden J. 1999. The timing of Last Glacial periglacial and aeolian events, twente, Eastern Netherlands. *Journal of Quaternary Science* **14**: 277-283.
- Bateman MD, Murton JB, Crowe W. 2000. Reconstruction of the depositional environments associated with the Late Devensian and Holocene coversand around Caistor, N. Lincolnshire, UK. *Boreas* **16**: 1-16.
- Bateman MD, Frederick CD, Jaiswal MK, Singhvi AK. 2003. Investigations into the potential effects of pedoturbation on luminescence dating. *Quaternary Science Reviews* **22**: 1169-1176.
- Bateman MD, Godby SP. 2004. Late-Holocene Inland Dune Activity in the UK: A case study from Breckland East Anglia. *The Holocene* **14**: 579-588.

- Bateman MD, Murton JB. 2006. The Chronostratigraphy of Late Pleistocene Glacial and Periglacial Aeolian Activity in the Tuktoyaktuk Coastlands, NWT, Canada. *Quaternary Science Reviews* 25: 2552-2568.
- Bateman MD, Boulter CH, Carr AS, Frederick CD, Peter D, Wilder M. 2007. Preserving the palaeoenvironmental record in Drylands: Bioturbation and its significance for luminescence-derived chronologies. *Sedimentary Geology* 195: 5-19.
- Bateman MD. 2008. Luminescence dating of periglacial sediments and structures. *Boreas* 37: 574-588.
- Bateman MD, Murton JB, Boulter CH. 2010. The Source of De variability in periglacial sand-wedges: depositional processes v. measurement issues. *Quaternary geochronology* 5: 250-256.
- Bertran P, Bateman MD, Hernandez M, Mercier N, Millet D, Tastet J-P. 2011. Inland aeolian deposits of southwest France: facies, stratigraphy and chronology. *Journal of Quaternary Science* 26: 374-388.
- Bertran P, Andrieux E, Antoine P, Coutard S, Deschodt L, Gardère P, Hernandez M, Legentil C, Lenoble A, Liard M, Mercier N, Moine O, Sitzia L, Van Vliet-Lanoë B. 2013. Distribution and chronology of Pleistocene permafrost features in France: Database and first results. *Boreas* (in press).
- Boreham S, White TS, Bridgland DR, Howard AJ, White MJ. 2010. The Quaternary history of the Wash fluvial network, UK. *Proceedings of the Geologists' Association* 121: 393-409.
- Böse M. 1992. Late Pleistocene sand-wedge formation in the hinterland of the Brandenburg stade. *Sveriges Geologiska Undersökning*, 81: 59-63.
- British Geological Survey. 2010. *Thetford, England and Wales Sheet 174, Bedrock and Superficial Deposits. 1:50,000*. British Geological Survey, Keyworth, Nottingham.
- Buylaert JP, Ghysels G, Murray AS, Thomsen KJ, Vandenberghe D, De Corte F, Heyse I, Van den haute P. 2009. Optical dating of relict sand-wedges and composite-wedge pseudomorphs in Flanders, Belgium. *Boreas* 38: 160-175.
- Catt JA. 1977. Loess and coversands. In *British Quaternary Studies: Recent Advances*, Shotton, F.W. (ed.) Oxford University Press, Oxford, 221-229.
- Chorley RJ, Stoddart DR, Haggitt P, Slaymaker HO. 1966. Regional and local components in the areal distribution of surface sand facies in the Breckland, eastern England. *Journal of Sedimentary Petrology* 36: 209-220.
- Christiansen HH. 1998. Periglacial sediments in an Eemian-Weichselian succession at Emmerlev Klev, southwestern Jutland, Denmark. *Palaeogeography, Palaeoclimatology, Palaeoecology* 138: 245-258.
- Clark CD, Hughes ALC, Greenwood SL, Jordan C, Sejrup HP. 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* 44: 112-146.
- Clayton K. 2000. The Landform Changes Brought About by the Anglian Glaciation In *The Quaternary of Norfolk and Suffolk: Field Guide*, Lewis, S. G., Whiteman, C. A., and Preece, R. C. (eds.). Quaternary Research Association, London.
- Duller GAT. 2008. Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. *Boreas* 37: 589-612.
- England AC, Lee JA. 1991. Quaternary deposits of the eastern Wash Margin. *Bulletin of the Geological Society of Norfolk* 40: 67-99.
- Evans R. (1975). Air Photographs for Soil Survey in Lowland England: Soil Patterns. *Photogrammetric Record* 7: 302-322.
- Fish PR, Whiteman CA. 2001. Chalk micropaleontology and the provenancing of Middle Pleistocene Lowestoft Formation Till in eastern England. *Earth Surface Processes and Landforms* 26: 953-970.
- Galbraith RF, Green PF, 1990. Estimating the component ages in a finite mixture. *International Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation Measurements* 17: 197-206.
- Galbraith RF, Roberts RG, Laslett GM, Yoshida H, Olley JM. 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Part 1. Experimental design and statistical models. *Archaeometry* 41: 339-364.
- Gibbard PL, West RG, Andrew R, Pettit M. 1992. The Margin of a Middle Pleistocene Ice Advance at Tottenhill, Norfolk, England. *Geological Magazine* 129: 59-76.
- Gibbard PL, Pasanen AH, West RG, Lunkka JP, Boreham S, Cohen KM, Rolfe C. 2009. Late Middle Pleistocene glaciation in East Anglia, England. *Boreas* 38: 504-528.
- Gibbard PL, West RG, Boreham S, Rolfe CJ. 2012. Late Middle Pleistocene ice-marginal sedimentation in East Anglia, England. *Boreas* 41: 319-336.
- Guérin G, Murray AS, Jain M, Thomsen KJ, Mercier N. 2013. How confident are we in the chronology of the transition between Howieson's Poort and Still Bay? *Journal of Human Evolution* 64: 314-317.
- Guhl A, Bertran P, Zielhofer C, Fitzsimmons KE. 2013. Optically Stimulated Luminescence (OSL) dating of sand-filled wedge structures and their fine-grained host sediment from Jonzac, SW France. *Boreas* 42: 317-332.
- Hallet B, Prestrud S. 1986. Dynamics of periglacial sorted circles in western Spitsbergen *Quaternary Research* 26: 81-99.
- Hallet B, Waddington ED. 1992. Buoyancy forces induced by freeze-thaw in the active layer: implications for diapirism and soil circulation. In *Periglacial geomorphology*, Dixon JC and Abrahams AD (eds.). John Wiley & Sons: Chichester, 251-279.
- Hemming SR. 2004. Heinrich events: Massive late pleistocene detritus layers of the North Atlantic and their global climate imprint. *Reviews of Geophysics* 42: article No RG1005.
- Hoare PG, Stevenson CR, Godby SP. 2002. Sand sheets and ventifacts: the legacy of aeolian action in west Norfolk, UK. *Proceedings of the Geologists' Association*, 113: 301-317.
- Huijzer B, Vandenberghe J. 1998. Climatic reconstruction of the Weichselian Pleniglacial in northwestern and central Europe *Journal of Quaternary Science* 13: 391-417.
- Johnsen SJ, Dahl-Jensen D, Gundestrup N, Steffensen JP, Clausen HP, Miller H, Masson-Delmotte V, Sveinbjörnsdóttir AM, White J. 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. *Journal of Quaternary Science* 16, 299-307.
- Kasse C, Vandenberghe D, De Corte F, Van Den Haute P. 2007. Late Weichselian fluvio-aeolian sands and coversands of the type locality Grubbenvorst (southern Netherlands): sedimentary environments, climate record and age. *Journal of Quaternary Science*, 22: 695-708.
- Kolstrup E. 2004. Stratigraphic and Environmental Implications of a Large Ice-wedge Cast at Tjæreborg Denmark. *Permafrost and Periglacial Processes*, 15: 31-40.
- Kolstrup E. 2007a. OSL dating in palaeoenvironmental reconstructions. A discussion from a user's perspective. *Estonian Journal of Earth Sciences* 56: 157-166.
- Kolstrup E. 2007b. Lateglacial older and younger coversand in northwest Europe: chronology and relation to climate and vegetation. *Boreas* 36: 65-75.
- Koster EA 2005. Recent advances in luminescence dating of late Pleistocene (cold-climate) aeolian sand and loess deposits in Western Europe. *Permafrost and Periglacial Processes* 16: 131-143.
- Lee JR, Rose J, Hamblin RJO, Moorlock BSP, Riding JB, Phillips E, Barendregt RW, Candy I. 2011. The glacial history of the British Isles during the Early and Middle Pleistocene: implications for the long-term development of the British Ice Sheet, In *Quaternary glaciations: extent and chronology*, Ehlers J, Gibbard PL, Hughes PD (eds.). Elsevier: Amsterdam, 59-74.
- Loulergue L, Schilt A, Spahni R, Masson-Delmotte V, Blunier T, Lemieux B, Barnola J-M, Raynaud D, Stocker TF, Chappellaz J. 2008. Orbital and millennial-scale features of atmospheric CH₄ over the past 800,000 years. *Nature* 453: 383-386.
- Lowe JJ, Rasmussen SO, Björck S, Hoek WZ, Steffensen JP, Walker MJC, Yuf ZC, the INTIMATE group. 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol

- recommended by the INTIMATE group. *Quaternary Science reviews* **27**: 6-17.
- Mackay JR. 1980. The origin of hummocks, western Arctic coast *Canadian Journal of Earth Sciences* **17**: 996-1006.
- Mackay JR. 1993a. The sound and speed of ice-wedge cracking, Arctic Canada. *Canadian Journal of Earth Sciences* **30**: 509-518.
- Mackay JR 1993b. Air temperature, snow cover, creep of frozen ground, and the time of ice-wedge cracking, western Arctic Coast *Canadian Journal of Earth Sciences* **30**: 1720-1729.
- Mayer J, Sutton G. 1997. Eastern England. In *Regional climates of the British Isles*, Wheeler D, Mayer J. (eds.). Routledge: London, 343.
- Mejdahl V, Shlukov AL, Shakhovets SA, Voskovskaya LT, Lyashenko MG. 1992. The effect of shallow traps: possible source of error in TL dating of sediments. *Ancient TL* **10**: 22-25.
- Met Office. 2006. *Weather and climate, Past weather, UK, Averages, 1971-2000* [online]. Available from: <http://www.metoffice.gov.uk/climate/uk/averages/19712000/index.html> [Accessed 23/11/13]
- Moorlock BSP, Booth SJ, Hamblin RJO, Pawley SJ, Smith NJP, Woods MA. 2008. *Geology of the Wells-next-the-Sea district - a brief explanation of the geological map, Sheet Explanation of the British Geological Survey. 1:50 000 Sheet 130 (England and Wales)*. British Geological Survey, Keyworth, Nottingham.
- Murray A S, Wintle AG. 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements* **37**: 377-381.
- Murton J B, Bateman M D, Baker C A, Knox R, Whiteman CA. 2003. The devensian periglacial record on Thanet, Kent, UK. *Permafrost and Periglacial Processes* **14**: 217-246.
- Murton JB, Kolstrup E. 2003. Ice-wedge casts as indicators of palaeotemperatures: precise proxy or wishful thinking? *Progress in Physical Geography* **27**: 155-170.
- Murton JB, Peterson R, Ozouf J-C. 2006. Bedrock fracture by ice segregation in cold regions *Science* **314**: 1127-1129.
- Murton JB, Ballantyne CK. (submitted). Periglacial and permafrost conceptual ground model. In *Periglacial and Glacial Engineering Geology*, Griffiths (ed.). Engineering Group of the Geological Society: London.
- Nicholson FH. 1969. *An investigation of patterned ground: Vols. 1 and 2*. Unpublished PhD, University of Bristol, Bristol.
- Nicholson FH. 1976. Patterned Ground Formation and Description as Suggested by Low Arctic and Sub Arctic Examples. *Arctic and Alpine Research* **8**: 329-342.
- Olley JM, Murray A, Roberts RG. 1996. The effects of disequilibrium in the uranium and thorium decay chains on burial dose rates in fluvial sediments. *Quaternary Science Reviews* **15**: 751-760.
- Pawley SM, Bailey RM, Rose J, Moorlock BSP, Hamblin RJO, Booth SJ, Lee JR. 2008. Age limits on Middle Pleistocene glacial sediments from OSL north Norfolk, UK. *Quaternary Science Reviews* **27**: 1363-1377.
- Pawley SM 2006. *Quaternary glaciations of north and west Norfolk*. Unpublished PhD Thesis, Royal Holloway University of London., pp. 453.
- Perrin RMS, Davies H, Fysh MD. 1974. Distribution of Late Pleistocene Aeolian Deposits in Eastern and Southern England. *Nature* **248**: 320-324.
- Perrin RMS, Rose J, Davies H. 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. *Philosophical Transactions of the Royal Society of London* **B287**: 535-570.
- Peterson R A, Krantz WB. 2003. A mechanism for differential frost heave and its implications for patterned-ground formation. *Journal of Glaciology* **49**: 69-80.
- Phillips I, Sparks BW. 1976. Pleistocene vegetational history and geology in Norfolk - with an appendix on non-marine mollusca from Swanton Morley. *Philosophical transactions of the Royal Society of London Series b* **275**: 215-286 .
- Prescott JR, Hutton JT. 1994. Cosmic-Ray Contributions to Dose-Rates for Luminescence and ESR Dating - Large Depths and Long-Term Time Variations. *Radiation Measurements* **23**: 497-500.
- Rhodes EJ. 2007. Quartz single grain OSL sensitivity distributions: implications for multiple grain single aliquot dating. *Geochronometria* **26**: 19-29.
- Rodnight H, Duller GAT, Tooth S, Wintle AG. 2005. Optical dating of a scroll-bar sequence on the Klip River, South Africa, to derive the lateral migration rate of a meander bend. *Holocene* **15**: 802-811.
- Rose J. 2009. Early and Middle Pleistocene landscapes of eastern England. *Proceedings of the Geologists' Association* **120**: 3-33.
- Rose J, Kemp RA, Whiteman CA. 1985. The Early Anglian Barham Soil of Eastern England In *Soils and Quaternary Landscape Evolution*, Boardman J. (ed.). Wiley: Chichester, 250p.
- Rothera S. 2000. *Breckland: NA 46*. English Nature.
- Ruddiman W, McIntyre A. 1981. The North Atlantic Ocean during the last deglaciation *Palaeogeography, Palaeoclimatology, Palaeoecology* **35**: 145-214.
- Scheib AJ, Lee JR. 2010. The application of regional-scale geochemical data in defining the extent of aeolian sediments: The Late Pleistocene Loess and coversand deposits of East Anglia, UK. *Quaternary Newsletter* **120**: 5-14.
- Scheib AJ, Lee JR, Breward N, Riding JB. 2011. Reconstructing flowpaths of the Middle Pleistocene British Ice Sheet in central-eastern England: the application of regional soil geochemical data. *Proceedings of the Geologists' Association* **122**: 432-444.
- Thiry M, van Oort F, Thiesson J, Van Vliet-Lanoë B. 2013. Periglacial morphogenesis in the Paris basin: insight from geophysical survey and consequences for the fate of soil pollution. *Geomorphology* **197**: 34-43.
- Waelbroeck C, Labeyrie L, Michel E, Duplessy JC, McManus JF, Lambeck K, Balbon E, Labracherie M. 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quaternary Science Reviews* **21**: 295-305.
- Watt AS. 1955. Stone Stripes in the Breckland. *Geological Magazine* **92**: 173-174.
- Watt AS, Perrin RMS, West RG. 1966. Patterned Ground in Breckland - Structure and Composition. *Journal of Ecology* **54**: 239-258.
- West RG. 1961. The glacial and interglacial deposits of Norfolk. *Transactions of the Norfolk and Norwich Naturalists' Society* **19**: 365-375.
- West RG. 1963. Problems of the British Quaternary. *Proceedings of the Geologists Association* **74**: 147-186.
- West RG, Dickson CA, Catt JA, Weir AH, Sparks BW. 1974. Late Pleistocene Deposits at Wretton, Norfolk II. Devensian Deposits *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **267**: 337-420.
- West RG. 2007. The Little Ouse River, the Waveney River and the Breckland: a joint history. *Transactions of the Suffolk Naturalists' Society* **b43**: 35-39.
- West RG. 2009. *From Brandon to Bungay. An exploration of the landscape history and geology of the Little Ouse and Waveney Rivers*. Suffolk Naturalists' Society: Ipswich, 106 p.
- West RG, Williams RBG. 2012. The value of temporary sections: gravels at Rushford, Suffolk. *Transactions of the Suffolk Natural History Society* **48**: 157-160.
- Williams RGB. 1964. Fossil Patterned Ground in Eastern England. *Buletyn Peryglacjalny* **14**: 337-349.
- Williams, RBG. 1968. *Periglacial Climate and its Relation to Landforms: a study of southern and eastern England during the Last Glacial Period*. Unpublished PhD Thesis, University of Cambridge.
- Williams RBG. 1987. Frost weathered mantles on the Chalk. In *Periglacial Processes and Landforms in Britain and Ireland*, Boardman J. (ed.). Cambridge University Press: Cambridge, 127-133.

