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Rapid Communication

Marine Isotope Stage 7–6 transition age for beach sediments at Morston, north Norfolk, UK: implications for Pleistocene chronology, stratigraphy and tectonics

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ABSTRACT: Optically stimulated luminescence age estimates for the Pleistocene beach at Morston, north Norfolk, UK, obtained by the single-aliquot regenerative-dose protocol, indicate a Marine Isotope Stage (MIS) 7–6 transition date. The view that the beach is of Ipswichian (MIS 5e) age, held virtually unanimously for the last 75 years, may now be discarded. The extant beach sequence lies up to ~5 m OD, yet global models suggest that MIS 7–6 sea levels were typically substantially below that of today. The explanation may lie with poorly understood regional tectonic movements. The MIS 7–6 date helps to constrain the ages of glacial deposits that bracket the beach sediments at Morston. The underlying Marly Drift till cannot be younger than MIS 8; this may also be true for the complex assemblage of glaciogenic landforms and sediments, including the Blakeney esker, in the adjacent lower Glaven valley. The well-established Late Devensian (MIS 2) age of the Hunstanton Till is not compromised by the date of the Morston beach. There is no indication of a proposed Briton's Lane glaciation during MIS 6 times. Copyright © 2009 John Wiley & Sons, Ltd.

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KEYWORDS: Pleistocene; beach deposits; Marly Drift; Hunstanton Till; Morston; Norfolk; East Anglia; optically stimulated luminescence (OSL) dating; MIS 7 and 6; sea level; tectonics.

Introduction

The Quaternary succession at Morston (TF 98714406; 52° 57′ 25″ N, 0° 57′ 24″ E) on the north Norfolk coast in eastern England (Fig. 1) preserves evidence of (in turn) glacial deposition, the accumulation of temperate beach sediments, cryoturbation associated with periglacial ground-ice formation, further glacial deposition, solifluction and, finally, weathering and pedogenesis (Gale *et al.*, 1988; Gale and Hoare, 2007a) (Figs 1(b) and 2). As with most British Quaternary sequences, although lithostratigraphic comparisons may be offered for the glaciogenic units, the chronology of deposition of each stratum and of the succession as a whole remains unclear.

The beach sediments at Morston consist of a sand body (units 2–6), which is not exposed under normal circumstances, overlain by rounded pebbles and cobbles of flint with a gravelly sand matrix (units 7–9) (Fig. 1(b)). Unit 5, a muddy sand with an impersistent band of very finely laminated mud, contains a temperate pollen assemblage with relatively abundant and diverse arboreal taxa (Gale *et al.*, 1988). Gale *et al.* (1988) concluded that units 2–9 were laid down during an (unspecified) interglacial. The beach deposits reach a maximum elevation of 5.03 m OD, but would once have attained a greater height as the gravelly base of the superjacent till (unit 10) denotes truncation of the underlying material (Gale and Hoare, 2007a, fig. 2).

With the exception of Gale *et al.* (1988) and Gale and Hoare (2007a), and perhaps Mitchell (1960), who quite specifically

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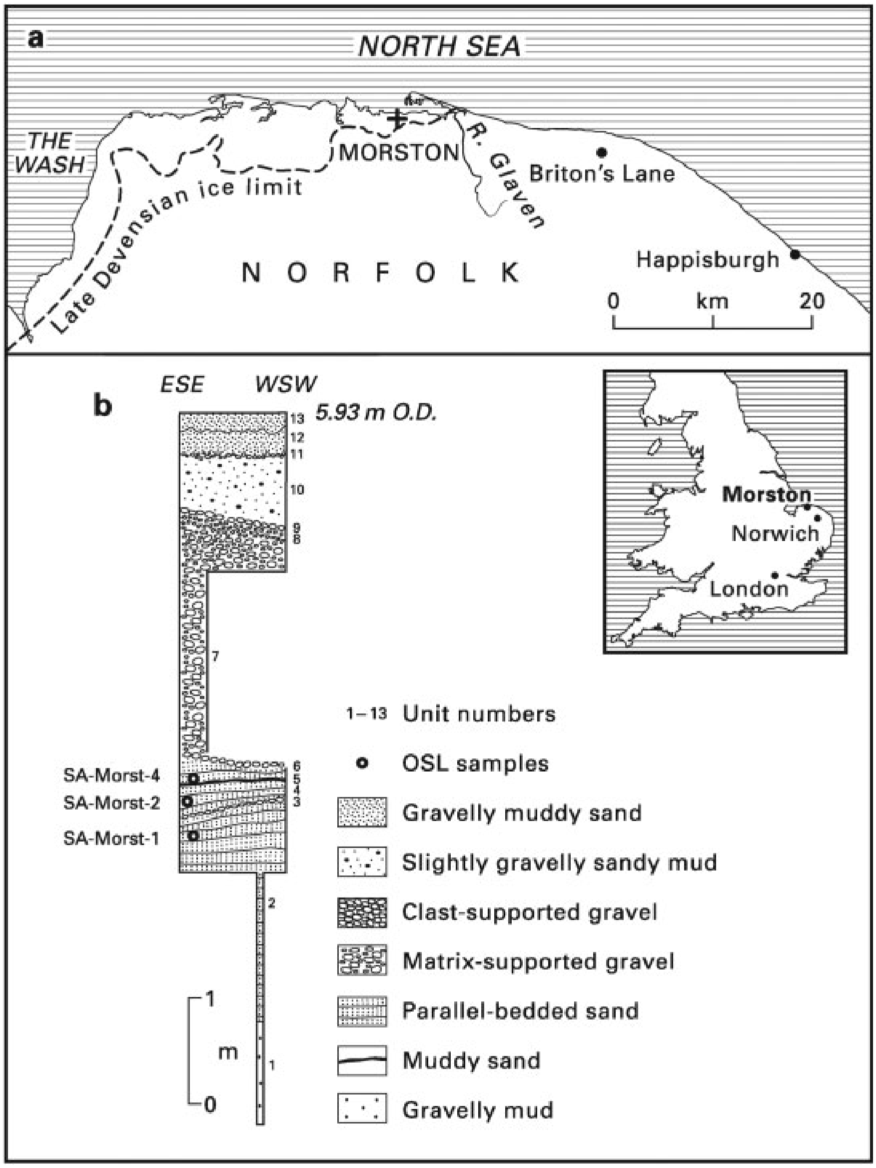

Figure 1 (a) Location of sites referred to in the text. The maximum extent of Late Devensian ice is taken from Pawley *et al.* (2008, fig. 1c). (b) Quaternary succession at Morston, north Norfolk (Gale *et al.*, 1988, fig. 2), showing the position of the OSL sample points

avoided assigning the deposit to a particular temperate stage, the Morston beach has been consistently regarded as of last interglacial age (Solomon, 1932; Straw, 1960; West, 1970; Turner, 1973; Bowen, 1980, 2003; Lewis, 1999; Pawley *et al.*, 2008).

Despite the significance of this ancient beach to the timing of Quaternary events in a region with little chronometric control, no attempt has previously been made to establish its age. The successful determination of a date for this episode would also help to constrain the nature and timing of other events in northern East Anglia and throughout Britain. It may also provide clues to questions of relative sea level and of neotectonics.

Dating the Morston beach sediments

Field procedure

The sequence described by Gale *et al.* (1988) was re-excavated on 5 March 2007 to reveal the uppermost ~0.77 m of the beach sands (units 2–6). Three samples for optically stimulated luminescence (OSL) analysis were collected in vertical succession (Fig. 1(b)) by hammering lengths of black opaque plastic pipe into the freshly cleaned face.

Laboratory procedures

OSL measurements were carried out on quartz grains (180–212 μm) using the single-aliquot regenerative-dose protocol. For further details of sample preparation and the protocol used to calculate the equivalent dose (D_e), see Spencer and Robinson (2008). The sample D_e values are skewed due, most probably, to partial and/or heterogeneous bleaching of the grains during transport and deposition. Finite age modelling of the distributions for each sample was conducted to determine the true burial age (see, for example, Galbraith *et al.*, 1999; Rodnight *et al.*, 2006).

Results

In order to determine a depositional age using OSL methods, both the equivalent dose (D_e), representing the amount of

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Figure 2 A previously unpublished photograph of the middle portion of the Morston sequence taken by Hallam Ashley FRPS in 1953 or 1954 (Norwich Castle Museum Accession Number NWHCM : 2004.3.3927). The greater part of the ~2 km long section is at present (2008) overgrown and the exact position of the image could not be located. Beach gravels (believed to be equivalent to Gale *et al.*'s, 1988, units 7–9) lie partially within a narrow, steep-sided channel cut into sands (units 2–6). (Units 10–13 appear to have been removed artificially from this site.) The erosional form may be compared to that of scour or rip channels (see, for example, Mathers and Zalasiewicz, 1996, especially fig. 4, and references therein)

radiation absorbed by a sediment since deposition, and the environmental dose rate must be known (Stokes, 1999). The D_e results are summarised in Table 1; the data are presented as radial plots in Fig. 3, with the finite age model (FAM), mean and median D_e values included for comparison. Note that the calculation of uncertainty in finite age modelling (quoted as a relative standard error) includes the uncertainty value for each aliquot used, whereas the mean and median uncertainty values are standard errors that reflect the range of all aliquot values, but not the uncertainty attributed to each aliquot.

The calculation of an environmental dose rate for a sample requires a knowledge of its water content, as this affects the attenuation of the radioactive decay products of U, Th and K (Adamiec and Aitken, 1998). In determining this property, most investigations employ the water content of the sample at the time of its receipt in the laboratory, with an uncertainty of ~5–10% to take account of variability through time. The laboratory pore water content of the Morston samples is shown in Table 1. In freely draining sediments that have spent a relatively large proportion of time above the water table, such measurements provide a reasonable estimate of the historical water content. However, sites such as Morston that lie close to modern sea level will have a more varied, but unknown, history.

In order to derive a time-averaged figure for water content, an estimated value was assigned to separate eustatic sea-level ranges derived from Thompson and Goldstein's (2006) high-resolution curve (Fig. 4(b)). The sediment grain-size and sorting characteristics of the Morston beach sands (Gale *et al.*, 1988, fig. 4, sample 2) suggest a porosity of ~45% and a saturated water content of ~30% (Pryor, 1973; Urish and McKenna, 2004). A value of 30% was thus adopted for periods when sea level was above 0 m OD. A figure of 20% was assumed for sea levels between 0 m and −10 m, and 5% for periods when sea level was below −10 m. The time-averaged water content, based on these assigned values, is 14.6%; a 10% uncertainty means that almost the entire range of possible water content values is incorporated within this figure. Based on a time-averaged value of 15 ± 10%, the calculated ages of the Morston sediments are 180 ± 19 ka (SA-Morst-1), 184 ± 21 ka (SA-Morst-2) and 191 ± 19 ka (SA-Morst-4) (Table 1). These age estimates are 8–10% older than those determined using the laboratory water contents of SA-Morst-2 and SA-Morst-4, and 3% older than that determined for SA-Morst-1.

Interpretation

Marine Isotope Stage 7–6 transition age for the beach sediments

Radiometric calibration of the orbitally tuned SPECMAP timescale suggests that the MIS 7–6 transition has a U–Th age of 179.2 ka. This date is ca. 10 ka more recent than the $\delta^{18}O$ shift in the SPECMAP record at 189.6 ka (Thompson and Goldstein, 2006). MIS 7 might therefore be considered to incorporate this ca. 10 ka period, previously regarded as part of the MIS 6 glacial episode (Henderson *et al.*, 2006). The statistically indistinguishable OSL ages of the Morston samples (Table 1) overlap the conventionally accepted and revised terminations of MIS 7 (Fig. 4(a)). The age estimates lie within the Wolstonian Stage 'complex' of the British terrestrial sequence (Bowen, 1999).

Global sea level and the Morston results

The elevation of the extant beach sequence (up to 5.03 m OD) is at odds with the high-resolution curve that suggests that the contemporaneous eustatic sea level was typically below modern datum (Fig. 4(b)). The explanation may lie with poorly

Table 1 Summary of results of the OSL and dosimetric measurements for the Pleistocene beach sediment samples, Morston, north Norfolk

Sample and laboratory code	N^a	U (ppm)	Th (ppm)	K (%)	H_2O content[b] (%)	Cosmic dose rate[c] (mGy a^{-1})	Total dose rate (mGy a^{-1})	D_e[d] (Gy)	FAM age[d] (ka)
Upper; SA-Morst-4	39	0.33 ± 0.01	1.22 ± 0.04	0.35 ± 0.01	15 ± 10 (4.1)	0.1990	0.70 ± 0.03	124.2 ± 9.6	191 ± 19
Middle; SA-Morst-2	41	0.34 ± 0.01	1.28 ± 0.04	0.48 ± 0.01	15 ± 10 (3.1)	0.1845	0.82 ± 0.03	137.5 ± 13.0	184 ± 21
Lower; SA-Morst-1	28	0.31 ± 0.01	1.39 ± 0.04	0.54 ± 0.02	15 ± 10 (10.9)	0.1808	0.82 ± 0.03	143.0 ± 12.0	180 ± 19

[a] Number of replicated D_e estimates.
[b] Time-averaged moisture content; the laboratory water content of the Morston samples, expressed as a percentage of the oven-dry mass, is given in parentheses.
[c] Cosmic dose rate calculated assuming constant burial depth using method described by Prescott and Hutton (1994). Uncertainty taken as 10%.
[d] D_e and ages calculated using the finite age model with uncertainty presented as two relative standard errors (Galbraith *et al.*, 1999).

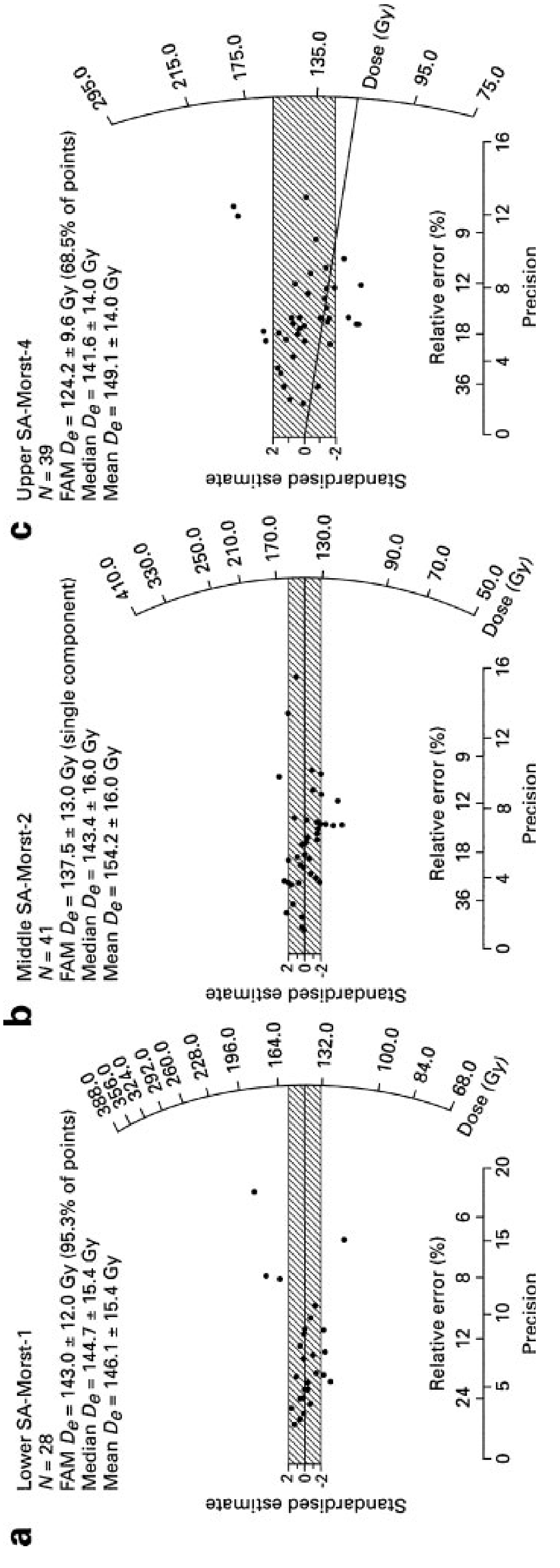

Figure 3 Radial plots of the equivalent dose values obtained using the single-aliquot regenerative-dose protocol from the lower (a), middle (b) and upper (c) samples of Pleistocene beach sediments, Morston, north Norfolk. All uncertainties are expressed to two standard errors

understood regional tectonic movements. Read *et al.* (2007) described Middle Pleistocene sands at Chapel Hill (TG 228046), 4 km south of Norwich, Norfolk, at elevations up to 28.5 m OD. These, they alleged, are of shallow marine origin and indicate >30 m of uplift in the Norwich area since their

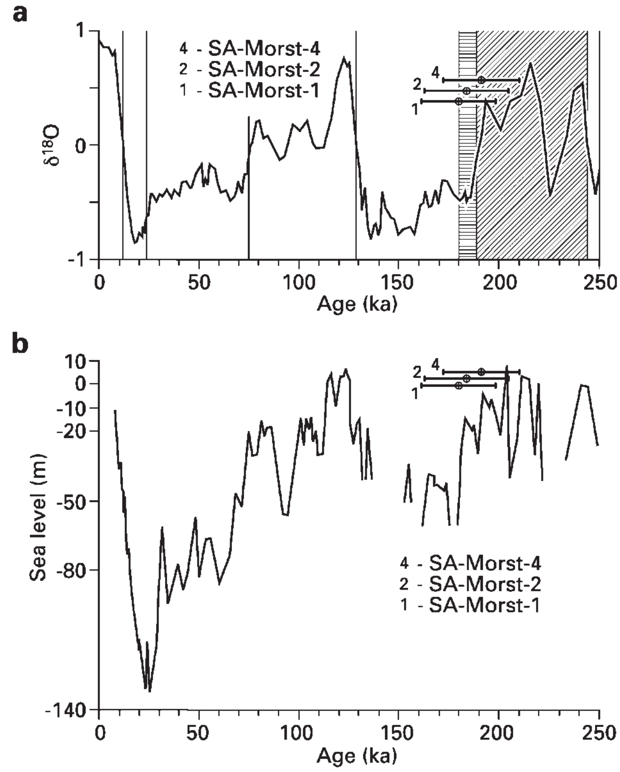

Figure 4 The Morston OSL ages at two relative standard errors (Table 1) plotted against (a) the stacked SPECMAP benthic $\delta^{18}O$ record on the SPECMAP timescale (after Thompson and Goldstein, 2006, fig. 2c) (the conventional MIS 7 interval is emphasised by diagonal shading; horizontal shading indicates the probable ca. 10 ka extension to this event; see text for elaboration) and (b) Thompson and Goldstein's (2006, fig. 4) high-resolution sea-level curve. The Morston samples were separated vertically by only 0.508 m between 0 and 1 m OD, but are more widely spaced in the figure to avoid congestion

deposition (see also Leeder, 2008). Note, however, that the crucial faunal assemblages in the Chapel Hill sands may have been derived (Read *et al.*, 2007; J. E. Whittaker, pers. comm., 17 November 2008).

Regional stratigraphy

The OSL age estimates from Morston have considerable significance for our understanding of regional stratigraphy, and they provide an opportunity to reconcile some of the contrasting stratigraphic models recently put forward.

The earlier of the glacial episodes recorded at Morston is represented by the Marly Drift (unit 1 of Gale *et al.*, 1988), a till that is the subject of considerable chronological debate (Gale and Hoare, 2007b). Straw (1965) noted the interdigitation of Blakeney esker sands and gravels with Marly Drift towards the north-western end of the esker (TG 017438) in the adjacent lower Glaven valley (see also Ehlers *et al.*, 1987). If this interfingering is a primary feature of the stratigraphy, the Marly Drift and the complex assemblage of glaciogenic deposits, including those of the esker (Gale and Hoare, 2007b), outwash plains, kames and ridges, that dominate the Glaven valley, can be no younger than MIS 8. The preservation of beach sediments at Morston suggests that, with the exception of the Late Devensian ice sheet, whose progress was halted by the gently rising ground that characterises the coast hereabouts, the deposits have not been overrun by ice. Indeed, all pre-MIS 2 glacial sediments in north Norfolk (with the possible exception of the Happisburgh Till) may date from MIS 12 (Pawley *et al.*, 2008; Phillips *et al.*, 2008).

Hamblin *et al.* (2000, 2005) proposed a Briton's Lane Formation, comprising the sediments of the Cromer Ridge, the Blakeney esker and the Glaven valley kames (a correlation rejected by Gale and Hoare, 2007b, on lithological grounds) of MIS 6 date. This unit, apparently indicative of the glaciation of a substantial part of north Norfolk (Hamblin *et al.*, 2005) left no trace in the Morston succession and failed to remove the beach sediments. A periglacial episode in which ground-ice disrupted the original gravel fabric of units 7–9 of the beach during the interval MIS 6–2 is, however, preserved at the site (Gale and Hoare, 2007a).

Unit 10 at Morston (Fig. 1(b)), the Hunstanton Till (Gale *et al.*, 1988), has been assigned to the Late Devensian (MIS 2) on the basis of its correlation with the Skipsea Till of Holderness, East Yorkshire (Catt and Penny, 1966; Penny *et al.*, 1969) and with the sedimentary record of Glacial Lake Sparks in southern Fenland (West, 1993; West *et al.*, 1999). This age is not compromised by the date of the Morston beach. A significant disconformity thus exists between the Morston beach sediments (MIS 7–6) and the superjacent till (MIS 2). The fortuitous location of the site at the southern limit locally of Late Devensian ice (Fig. 1(a)) may explain why the sequence escaped serious glacial erosion (Gale and Hoare, 2007a).

Conclusions

Despite being long overlooked, the Morston succession is of considerable importance within the East Anglian record, itself one of the most significant Quaternary sequences in the world, yet one in which there is relatively little chronometric control. We show here that the beach sediments at Morston date from a late MIS 7–early MIS 6 interval, thus finally rejecting the long-held but unfounded view that assigned it to the last temperate substage (Ipswichian, MIS 5e). The modestly positive elevation of the Morston beach and the negative sea levels of MIS 7–6 times are difficult to resolve, but clearly have important implications for the tectonic history of the region. The preservation of the beach sediments at Morston may be connected with their deposition at the close of a MIS 7–6 transgression and the limited capacity for the reworking of coastal deposits during the regressive phase (Fig. 4(b)). The Marly Drift and, possibly, the glaciogenic landforms and sediments of the lower Glaven valley date from a glaciation no younger than MIS 8. There is no evidence in support of a proposed Briton's Lane glaciation during MIS 6 (*contra* Hamblin *et al.*, 2000, 2005). The age of the beach sediments provides a lower bracket on the MIS 2 date of the Hunstanton Till.

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