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Interpretation of radiocarbon dates from the upper surface of late-Holocene peat layers in coastal lowlands

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Abstract: Marine/brackish clastic sediments replace freshwater peats in the stratigraphic column of many coastal lowland areas bordering the North Sea during the late Holocene. Radiocarbon dates are routinely used to provide a chronology for this shift. We examine the assumptions underpinning this approach. The results of investigations from 13 sites in the Rye area of Romney Marsh, southeast England, are reported. Dates from apparently gradational contacts of a highly humified, laterally persistent, peat layer range from 3170–2840 cal. yr BP to 1290–1050 cal. yr BP. Multiple inundations or prolonged gradual inundation are nevertheless rejected, as discrete post-peat bodies of sediment are absent and because peat growth appears to have slowed-down or ceased at many sites in advance of inundation. Additionally in the Rye area, sharp contacts are widespread and the pollen assemblages rarely indicate the occurrence of transitional plant communities. A review of the dating evidence from other coastal lowland regions reveals that multiple dating of the upper surface of peat beds invariably produces diachronous results. As a consequence time-transgressive processes feature prominently as causal mechanisms underlying this shift. However, many of the dating difficulties recognized in the Rye area appear to apply to other regions. We conclude that radiocarbon dates from the upper surface of peat layers should in most instances only be regarded as limiting ages for the deposition of the overlying clastic sediments. New chronologies need to be built without *a priori* assumptions as to the underlying processes, ideally through the direct dating of the clastic sediments.

Key words: Late Holocene, coastal change, radiocarbon dating, peat accumulation, coastal lowlands, Romney Marsh, England.

Introduction

The late Holocene saw a profound change in the nature of sedimentation in the coastal lowlands that border the North Sea, marking the end of a protracted period of wetland development and peat accumulation, and the onset of a phase of predominantly minerogenic sedimentation as many estuaries and tidal inlets expanded (eg, Beets *et al.*, 1992; Waller 1994a; Brew *et al.*, 2000; Long *et al.*, 2000; Baeteman *et al.*, 2002, 2005; Behre, 2004). Over the last 50 years, radiocarbon dates from the upper surface of peat layers have been routinely used to provide a chronological framework for these events.

Such a sedimentary transition is described as a transgressive contact, and records the change from a predominantly freshwater to a marine environment. Where transgressive contacts can be traced between cores and sites, the lithostratigraphic boundary is referred to as a transgressive overlap (Tooley, 1978). The identification of these contacts/overlaps has formed the basis for studies of vertical and lateral trends in sea-level and coastal evolution. This methodology relies on the combined use of lithostratigraphic and biostratigraphic data to confirm the nature of the environmental changes associated with each contact. The accompanying vegetation succession should, under ideal conditions, include the demise of freshwater communities (typically fen carr or raised bog) and development of transitional reedswamp followed by saltmarsh communities, prior to the accumulation of intertidal mudflat deposits. Such a sequence indicates the gradual inundation that

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would be expected to accompany the progressive landward movement of vegetation communities associated with a retreating shoreline. A radiocarbon date from the transitional stages should provide a reliable date for the transgressive contact and an age for the inundation of the site.

Erosion of the peat surface is the most widely recognized problem in the dating of transgressive contacts. Workers attempt to overcome this potential problem by selecting sites where there is evidence for transitional communities and continuous sedimentation. The accuracy of radiocarbon dates from transgressive contacts will also be influenced by the timespan represented by the sample thickness, which in turn will be affected both by the rate of peat accumulation and any sediment compaction, and potentially by contamination (Törnqvist *et al.*, 1992).

Issues associated with dating are critical when considering the causal processes responsible for the shift away from organic to minerogenic sedimentation in the late Holocene. Coastal lowlands have the potential to be subject to both the gradual migration of the shoreline (eg, because of subtle adjustments in relative sea level) and geologically instantaneous events (eg, as a consequence of barrier breaching, storm surges and tsunami). A reliable chronology is essential to resolving the relative significance of these different types of coastal change.

Here we present the results of a detailed study from the Rye area of Romney Marsh where a laterally persistent peat is buried beneath several metres of minerogenic sediment. Emphasis is placed on determining the age(s) of the end of peat formation and whether the end of peat formation occurred as a result of gradual or abrupt changes in coastal processes and shoreline geometry. Our approach relies primarily on a combination of lithological, pollen and radiocarbon dating evidence that has been routinely used in previous studies of coastal change. The work is of wider methodological interest as it enables us to critically examine three assumptions that have underpinned studies of the late Holocene development of coastal lowlands:

(1) that radiocarbon dates from the surface of peat beds accurately date the end of peat formation;
(2) that radiocarbon dates from the surface of peat beds accurately date the onset of the deposition of the overlying marine/brackish sediments;
(3) that a series of radiocarbon dates from the upper surface of a layer of peat enable gradual and abrupt events to be distinguished.

Study area and previous work

Rye is situated on a promontory above the southwestern corner of the Romney Marsh depositional complex, adjacent to Walland Marsh and Brede Levels (Figure 1). To the south and east lie the sand and gravel beaches of Rye Harbour, which played a pivotal role in the growth and demise of both Rye and Winchelsea as major Mediaeval ports. The town of Old Winchelsea was situated on a gravel barrier that extended across what is today Rye Bay (Eddison, 1998). Old Winchelsea flourished in the early thirteenth century AD but was threatened by the sea from *c.* AD 1240 and the town was eventually relocated after AD 1288 when storms breached the barrier. An extensive tidal inlet subsequently expanded, extending northward to capture the river Rother (which had formerly flowed across Walland Marsh to New Romney) and westwards into the Brede valley.

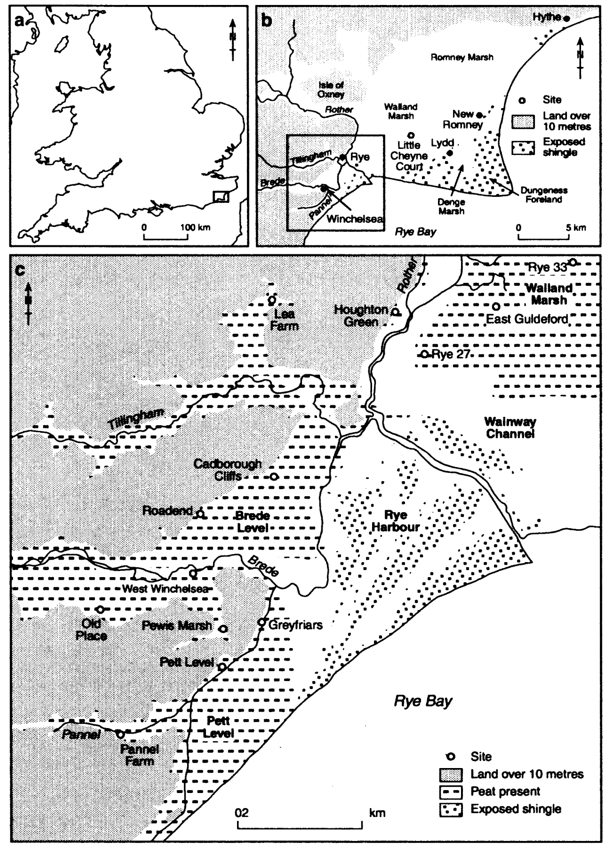

Figure 1 Location maps. (a) The UK, showing the location of the Romney Marsh depositional complex; (b) the Romney Marsh depositional complex showing the location of the study area and main towns; (c) the study area showing the sites mentioned in the text and the, largely subsurface, distribution of the extensive peat layer

Previous stratigraphic investigations from the Rye area demonstrate the presence of a laterally extensive peat bed up to *c.* 6.5 m thick (Waller *et al.*, 1988; Long *et al.*, 1996). Widespread peat accumulation began *c.* 6500 cal. yr BP and, at a few locally favourable sites, may have continued until the present (Waller, 1993). Biostratigraphic investigations (pollen and macrofossils) indicate the peat largely accumulated in eutrophic communities, fen carr, in the valleys, with acidic communities including raised bog developing during the late Holocene over southern Walland Marsh (Waller *et al.*, 1999). The upper surface of the peat is usually highly humified and lacking in plant macrofossils, and diatom preservation in the peat and overlying clastic sediments is generally poor. In the study area the peat is overlain, frequently after sharp lithological contacts, by silty clays with frequent sand and mud laminae. Thinning landwards, locally this clastic material exceeds 4 m in thickness. Foraminiferal investigations from Old Place in the Brede valley (Marlow, in Waller, 1994b) indicate these clastic sediments were initially deposited in an intertidal environment followed by an upcore increase (sandflat/mudflat environment) and then decline in marine influence. Channels known to be active following the thirteenth-century AD breach in the barrier are lithologically distinct, being filled with grey silts and sands (Green, 1968; Waller *et al.*, 1988; Evans *et al.*, 2001).

Previously published dates from the upper surface of the peat in the Rye area range from *c.* 3200 to *c.* 1550 cal. yr BP, though some of this variation was thought to reflect erosional truncation (Long *et al.*, 1996). Three scenarios can be proposed. The Rye area may have experienced gradual inundation from the northeast as the consequence of an expansion in a back-barrier estuary. Dates for the end of peat formation on the adjacent Walland and Romney Marshes indicate this would have occurred after *c.* 2000 cal. yr BP; however, not all the data conform to such a pattern (Long *et al.*, 1998). Alternatively, given the historically documented events of the thirteenth century and with abrupt contacts widespread, it is possible that the peat surface across the study area was inundated rapidly as a consequence of the breaching of the coastal barrier near Rye. Finally, several phases of inundation, possibly resulting from different processes, may have occurred. However, neither the spatially and lithologically distinct post-peat bodies of sediment or the organic layers or soil horizons that might be expected to mark the intervening periods, have been detected.

Methods

As noted above, previous work has demonstrated that the upper contact of the peat in the Rye area is locally eroded. Effort was therefore directed towards the identification of sites that were likely to preserve lithologically gradational transgressive contacts. However, this has introduced a bias favouring sites located close to the upland edge. Lithostratigraphic data were collected from 11 sites by sinking a grid or transect of eight or nine boreholes (*c.* 50 m spacing) using a gouge auger, with the sediments recorded using the scheme of Troels-Smith (1955). In addition, an area where peat occurs close to and at the modern surface (Lea Farm, in the Tillingham valley) was investigated. This new information has been collated with previously collected borehole information from the Rye area derived from commercial schemes and earlier palaeoenvironmental research (Marlow, 1984; Waller *et al.*, 1988; Long *et al.*, 1996), and in total some 300 borehole logs are available.

Two of the sites, where the upper contact of the peat was found to be sharp (Table 1) in every borehole (*Limes superior* 2, 3 or 4), were rejected for further study. At the remaining nine sites where the contact appeared gradational (*Limes superior* 0 or 1) in one or more borehole, and at Lea Farm, core material was retrieved using a 'Russian' or mechanically operated piston corer. At one site (West Winchelsea) foraminiferal analysis was undertaken and the grain size characteristics determined for the upper clastic sediments. Here, however, we concentrate on the palaeoenvironmental changes occurring across the upper contact of the peat. Diatom analysis was not applied, since previous work on Walland Marsh indicated that their preservation was poor and palaeoenvironmental value limited (eg, Waller *et al.*, 1999; Evans *et al.*, 2001).

Pollen analysis was undertaken at all sites, with material generally extracted every 4 cm, though a closer sampling interval was used across stratigraphic boundaries. Standard preparation techniques (Moore *et al.*, 1991) were used to prepare 1 cm^3 of sediment with a minimum of 300 land pollen grains counted per sample. Nomenclature for the pollen taxa follows Bennett (1994). The full data set will be published elsewhere; here it is combined with data from three previously published sites in the area (Long *et al.*, 1996; Waller, 1998) and summarized using detrended correspondence analysis (DCA), which ordinates samples and taxa simultaneously. DCA was performed using the *CANOCO 4* program (ter Braak and Šmilauer, 1998) on a filtered data set comprising 28 samples. The samples selected are from immediately below the upper surface of the peat (all sites) and from the base of the overlying clastic deposits (not available for the pre-existing sites of Old Place, Rye 33 and Rye 27). In addition, at Pewis Marsh, Pannel Farm and East Guldeford, single samples are included from intervening organic silty clays (see Results section) from which the pollen assemblages are relatively well preserved and homogeneous.

Radiocarbon dates provide a chronology through the upper part of the peat deposit. Unfortunately the degree of peat humification prevented the selection of macrofossils and therefore conventional dates from bulk material were obtained. This necessitated the use of 4- to 5-cm-thick slices of core material. In a number of cases the humin and humic acid fractions were dated separately. The humin fraction consists of the actual, often heterogeneous, organic material, a proportion of which may be inwashed or intrusive. The humic acids are the products of *in situ* decay and while homogenous have been shown to be mobile in groundwater (A. Bayliss, personal communication, 2004). In most of the samples the dates from the humin and humin acid fraction were statistically indistinguishable and these results are therefore also presented as pooled means (Table 2). The new radiocarbon samples were processed and measured by Gas Proportional Counting at Groningen University, according to the methods described by Mook and Streurman (1983). In addition, dates from organic material, conventional dates on organic silty clays (Table 3) and Accelerator Mass Spectrometry (AMS) dates from *in situ* roots (Table 4), were collected from immediately above the main peat surface at five sites.

The calibrated date ranges quoted in the text (at the two sigma age range) were calculated by the maximum intercept method (Stuiver and Reimer, 1986), using the INTCAL98 data set (Stuiver *et al.*, 1998) and the program OxCal v. 3.9 (Bronk Ramsey, 1995, 2003).

Table 1 Troels-Smith (1955) classification of lithostratigraphic boundary thicknesses

0	> 1 cm boundary area
1	< 1 cm and > 2 mm
2	< 2 mm and > 1 mm
3	< 1 mm and > 0.5 mm
4	< 0.5 mm

Results

Lithostratigraphy

The large borehole data base provides information on peat distribution and variations in the altitude of the upper surface. Tidal channels have cut through the peat in the lower Brede and Tillingham valleys and along the post-thirteenth-century AD route of the river Rother (Figure 1). Deep boreholes sunk in the Wainway Channel and along the edge of the Rye Harbour shingle show that peat is also absent from the seaward edge of the study area. The upper surface of the peat varies in altitude from 3.3 to −9.19 m OD. The highest altitudes are found at edge of the marshland where peat directly overlies the pre-Holocene surface. This suggests that differential compaction is likely to be responsible for some of the variation in altitude (Allen, 1999). However, there is also evidence for considerable erosional truncation as the lowest contacts (those below −2.5 m OD) are from sites where the transgressive contacts are sharp. Evidence for the redeposition of eroded peat in tidal channels has also been reported by Long *et al.* (1996).

Figure 2 displays the depth from the surface, altitude and nature of the upper surface of the peat at the 13 locations for which radiocarbon data are now available. Layers of black highly humified peat are recorded at ten of the locations.

Table 2 Conventional radiocarbon dates from the upper surface of the peat in the Rye area. Where the humin and humic acid (alkali acid) fractions were dated separately the age-estimate is also presented as a pooled mean

Site	Grid reference	Lab. code	Fraction	^{14}C age 1σ	Calibrated (cal. yr BP) 2σ	Altitude (m OD)
Pewis Marsh	TQ 90041684	GrN-27876	Humin	3500±30	3870–3640	−0.99 to −1.04
Pewis Marsh	TQ 90041684	GrN-27913	Humic acid	3380±80	3840–3440	−0.99 to −1.04
Pewis Marsh	TQ 90041684	Pooled mean		3485±28	3840–3680	−0.99 to −1.04
Pett Level	TQ 89991640	GrN-28109		3330±50	3690–3460	−0.96 to −1.00
Lea Farm	TQ 90862219	GrN-28055	Humin	3120±40	3450–3210	1.97 to 2.02
Lea Farm	TQ 90862219	GrN-28056	Humic acid	3080±90	3480–2990	1.97 to 2.02
Lea Farm	TQ 90862219	Pooled mean		3113±37	3440–3210	1.97 to 2.02
Rye 33	TQ 95742228	Beta-75454		2980±60	3350–2950	−0.25 to −0.29
Pannel Farm	TQ 88321513	GrN-28098		2880±60	3210–2840	1.00 to 1.04
Roadend	TQ 89701881	GrN-28106		2860±60	3170–2840	0.10 to 0.14
Greyfriars	TQ 90631688	GrN-28101	Humin	2940±40	3250–2950	−0.55 to −0.59
Greyfriars	TQ 90631688	GrA-24065	Humic acid	2730±40	2930–2750	−0.55 to −0.59
Greyfriars	TQ 90631688	Pooled mean		2837±28	3000–2850	−0.55 to −0.59
Cadborough Cliffs	TQ 90861939	GrN-28105		2480±60	2750–2350	−1.00 to −1.04
Houghton Green	TQ 92812218	GrN-28103		2500±40	2750–2350	2.17 to 2.21
Old Place 80	TQ 88051712	SRR-2893		1830±80	1950–1540	−1.15 to −1.18
Rye 27	TQ 93367214	Beta-75452		1740±60	1820–1520	−1.98 to −2.02
West Winchelsea	TQ 89541775	GrN-28734	Humin	1360±30	1310–1260	−1.99 to −2.03
West Winchelsea	TQ 89541775	GrN-28735	Humic acid	1300±60	1310–1060	−1.99 to −2.03
West Winchelsea	TQ 89541775	Pooled mean		1348±27	1310–1230	−1.99 to −2.03
East Guldeford	TQ 94342193	GrN-28104		1240±50	1290–1050	−0.70 to −0.74

Table 3 Conventional radiocarbon dates from the contact between the post-peat organic sediments and overlying marine/brackish sediments in the Rye area. Where the humin and humic acid (alkali acid) fractions were dated separately the age-estimate is also presented as a pooled mean

Site	Lab. code	Fraction	^{14}C age 1σ	Calibrated age (cal. yr BP) 2σ	Altitude (m OD)	Sediment dated
East Guldeford	GrN-2866		2040±70	2160–1860	−0.58 to −0.64	Organic-rich silty clay
Pett Level	GrN-28107	Humin	1900±60	1990–1700	−0.45 to −0.49	Organic-rich silty clay
Pett Level	GrN-28108	Humic acid	1880 ±100	2050–1650	−0.45 to −0.49	Organic-rich silty clay
Pett Level	Pooled mean		1895±51	1950–1700	−0.45 to −0.49	Organic rich silty clay
Pewis Marsh	GrN-27875	Humin	1870±35	1890–1710	−0.69 to −0.74	Organic-rich silty clay
Pewis Marsh	GrN-27910	Humic acid	1760±60	1830–1530	−0.69 to −0.74	Organic-rich silty clay
Pewis Marsh	Pooled mean		1842±30	1870–1700	−0.69 to −0.74	Organic-rich silty clay
Pannel Farm	GrN-28586	Humin	1640±50	1700–1410	1.34 to 1.39	Organic-rich silt
Pannel Farm	GrN-28587	Humic acid	1710±100	1870–1380	1.34 to 1.39	Organic-rich silt
Pannel Farm	Pooled mean		1654±45	1700–1410	1.34 to 1.39	Organic-rich silt

Occasional *Phragmites australis*, woody and herbaceous detrital remains occur, and a layer of peat with abundant *Sphagnum imbricatum* is preserved at East Guldeford. At Pewis Marsh and West Winchelsea, the lithology comprises woody and herbaceous detritus, while *Sphagnum* is found at Rye 33. The peat beneath the transgressive contacts at Roadend, Houghton Green and Old Place contains a silty/clay component (estimated at 25% or less). At none of the 13 sites is a transitional layer dominated by the macrofossil remains of *Phragmites* (indicative of reedswamp) present. At most a gradational boundary (in the sense that transitional sediment of >1 cm thickness) is recorded between the humified peats and the overlying sediments. However, at the pre-existing sites, Rye 27 and Rye 33, the peat contacts are described as abrupt (Long *et al.*, 1996).

At some of the sites adjacent to the upland edge organic clayey silts occur between the peat and the overlying, frequently laminated, silty clays. At three of the sampled

Table 4 AMS radiocarbon dates from the post-peat marine/brackish deposits in the Rye area. Duplicate samples were submitted and the results are also presented as pooled means

Site	Lab. code	^{14}C age 1σ	Calibrated age (cal. yr BP) 2σ	Altitude (m OD)	Dated material
West Winchelsea	GrA-25302	1170±35	1180–970	−1.82 to −1.92	Fine herbaceous rootlets within clay
West Winchelsea	OxA-13460	1297±28	1290–1170	−1.82 to −1.92	Fine herbaceous rootlets within clay
West Winchelsea	Pooled mean	1248±22	1270–1120	−1.82 to −1.92	Fine herbaceous rootlets within clay
Pannel Farm	GrA-2591	395±35	520–320	1.40 to 1.45	*Phragmites* rhizomes within clay
Pannel Farm	OxA-13227	356±36	510–320	1.40 to 1.45	*Phragmites* rhizomes within clay
Pannel Farm	Pooled mean	376±25	510–320	1.40 to 1.45	*Phragmites* rhizomes within clay

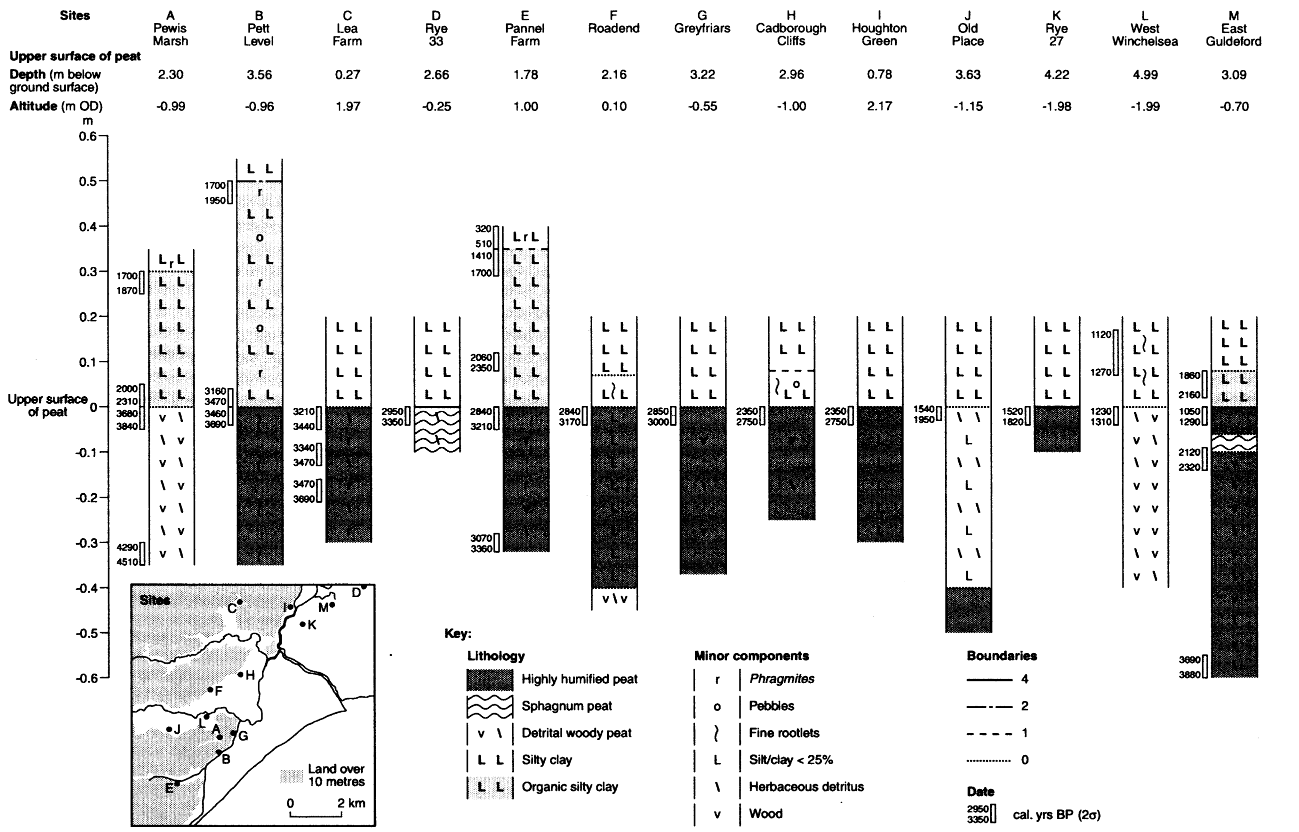

Figure 2 Litho- and chronostratigraphy across the upper contact of the peat at the 13 radiocarbon dated sites from the Rye area. The major change in lithostratigraphy has been used as the baseline ('upper surface of the peat'), with information on the altitude and the depth (from the ground surface) of this baseline provided in tabular form. The sites are ordered chronologically, their geographical location is shown in the inset

locations Pannel Farm, Pewis Marsh and Pett Level this intervening deposit is in excess of 10 cm thick (Figure 2). Marine/brackish indicators are absent and the site stratigraphies suggest that this material is derived from the adjacent slopes. The Pett Level deposit is heterogeneous within and between boreholes. Other components in this sediment include peaty pockets (particularly above the main peat), sand, small angular fragments of sandstone, woody detritus and humified *Phragmites* rhizomes. In addition, two pottery sherds were recovered from this intervening deposit *in situ* (at depths from the surface of 381 and 388 cm) in adjacent boreholes. They date from the twelfth to mid-thirteenth century AD and mid thirteenth to fourteenth century AD (L. Barber, personal communication, 2004). Organic clay also occurs above the peat at East Guldeford (Figure 2). Here the biostratigraphic evidence (see below) suggests the layer was deposited under marine/brackish conditions.

We find no lithostratigraphic evidence above the main peat bed/organic clays-silts that marine/brackish conditions were interrupted by periods of freshwater or no deposition. Intercalated peats or other surfaces indicative of breaks in sedimentation are absent, though laterally impersistent upcore variations in the lithology of the clastic deposits are ubiquitous.

Biostratigraphy

The DCA species biplot (Figure 3a) shows that a number of distinct wetland communities are represented by the samples selected. Taxa indicative of fen/marginal aquatic vegetation (Cyperaceae, *Filipendula*, *Sparganium emersum*-type) are distinguished from bog (*Calluna vulgaris* and *Sphagnum*) on axis 1. Axis 2 differentiates the former from assemblages dominated by *Myrica gale* and *Salix*. *Alnus glutinosa* occupies a central position in the DCA. This position is likely to reflect the over-representation of *Alnus* in the regional pollen rain (Huntley and Birks, 1983), with values >10% TLP even recorded from sites where the lithostratigraphy demonstrates the presence of raised bog. Pollen likely to be derived from upland vegetation types (eg, *Quercus*, *Corylus avellana*-type, *Pteridium aquilinum* and *Plantago lanceolata*) similarly occupies a central position. The central position of the Poaceae may reflect the occurrence of this family in a number of wetland communities (potentially both herbaceous fen and bog) though a dry-land contribution is also likely.

The biplot for the sites suggests that their DCA scores primarily reflect spatial rather than temporal trends (Figure 3b). Towards the end of peat formation there was a shift away from the eutrophic communities (largely fen carr) that dominated the region in the mid-Holocene (Waller, 1994b) and several of the sites (Roadend, Greyfriars, Cadborough Cliffs) included in this analysis are dominated by *Myrica* pollen, which suggests vertical or spatial isolation from the influence of groundwater (Wheeler, 1980). Bog vegetation (with *Sphagnum* and *Calluna*) became established to the east of the modern course of the river Rother (Rye 27, 33 and East Guldeford). After *c.* 3500 cal. yr BP eutrophic communities (fen carr and open herbaceous fen) were largely confined to the upper valleys (eg, Pannel Farm, Lea Farm).

Stratigraphic context has surprisingly little influence on position in the DCA site biplot. The samples above and below the upper surface of the peat at Roadend and Houghton Green are virtually indistinguishable. The origin of pollen in clastic sediments is more complex than from peats with, in addition to the contemporaneous pollen rain, grains likely to be reworked from earlier sediment stores and potentially transported over long distances. This may be reflected by many of the samples from above the contacts having more central positions in the

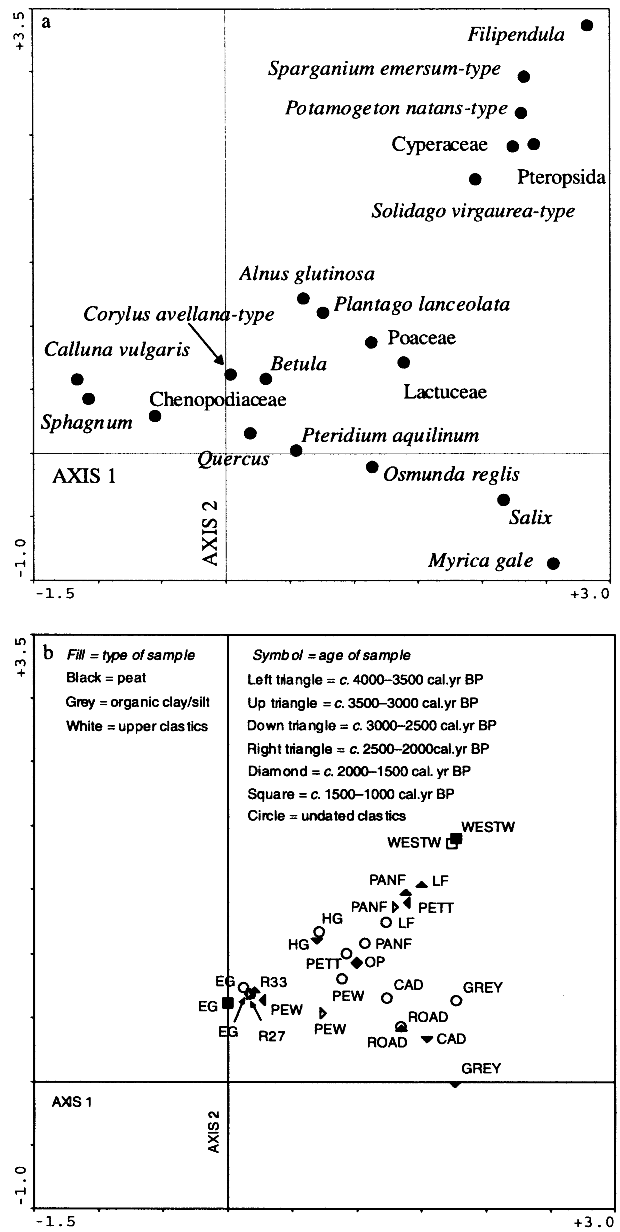

Figure 3 (a) Plot of the DCA scores for taxa occurring at >2% total land pollen in more than 5 samples. (b) Plot of the DCA scores for sites. CAD, Cadborough Cliffs; EG, East Guldeford; GREY, Greyfriars; HG, Houghton Green; LF, Lea Farm; PANF, Pannel Farm; PETT, Pett Level; PEW, Pewis Marsh; OP, Old Place; ROAD, Roadend; R33, Rye 33; R27, Rye 27; WESTW, West Winchelsea

DCA plot. However, the similarity of the assemblages above and below the contacts at most sites suggests that a large proportion of the pollen deposited in the sediments immediately above the peat was derived from the preceding vegetation. This suggests that the peat-forming vegetation remained in close proximity and contributed contemporaneous pollen (indicating continuous sedimentation). Taxa associated with marine/brackish conditions (eg, Chenopodiaceae) only occur in the samples from above the contact at low frequencies (<2% TLP). The position of the Chenopodiaceae in the DCA plot, close to the bog group, is because the only high values of this family occur in the intervening organic clay at East Guldeford (where they attain a maximum 14% TLP).

These biostratigraphic data do not conform to the idealized vegetation sequence that one might expect to be associated with transgressive contacts. The clearest evidence for rising water levels and the establishment of open and potentially transitional communities prior to marine/brackish inundation comes from West Winchelsea where high *Alnus* frequencies are replaced immediately below the transgressive contact by an assemblage dominated by Cyperaceae, *Filipendula* and aquatics. In addition, at Old Place high Poaceae values replace *Alnus* in the upper silty peat, and Chenopodiaceae values rise at East Guldeford prior to the deposition of the organic clays. The DCA position of the Pett Level peat sample reflects an abundance of Pteropsida spores rather than open transitional communities, while at Pannel Farm high Poaceae and Cyperaceae values are maintained from *c.* 3200 to 1600 cal. yr BP. There is no indication in the pollen record of the development of transitional communities at the remaining sites where peat is directly overlain by clastic sediments (Greyfriars, Cadborough Cliffs, Roadend and Houghton Green).

Chronology

Information on the accumulation rates of the peat and organic clays-silts is provided by the sites with a series of dates, though the calculated rates will be underestimates as a result of compaction. Linear interpolation within sedimentary units of similar lithology suggests, away from the raised bog (where peat growth was decoupled from the ground water-table) rates of *c.* 0.3–0.4 mm/yr after 4000 cal. yr BP, compared with >2.5 mm/yr for the mid-Holocene in the Brede and Pannel valleys (Waller, 1993, 1994b). Exceptions to this trend occur at Lea Farm and Pannel Farm, which each experienced periods of relatively rapid of peat accumulation during the late Holocene. However, both these phases coincide with pollen stratigraphic changes indicative of anthropogenic interference (including woodland clearance) on the adjacent uplands, which may locally have increased run-off and hence promoted accelerated peat accumulation.

There is no relationship between the age of the upper surface of the peat and depth from the surface or altitude (Figure 2). At Pewis Marsh, Pett Level and Pannel Farm, with intervening sediments present, the radiocarbon dates from the upper surface of the peat cannot reliably date the onset of marine/brackish conditions. The date from Lea Farm, which lies beyond the inland limits of marine/brackish sedimentation, shows that peat accumulation ceased here 3400–3240 cal. yr BP. At Pewis Marsh an early end to peat formation is also indicated (3840–3680 cal. yr BP) with the overlying slope-derived material accumulating (between 2310–2000 and 1870–1700 cal. yr BP) after a considerable hiatus (Figure 2). A similar age range is indicated for the bulk of the latter deposit at Pannel Farm though there is no lithological evidence of a break in sedimentation here. We suspect this is also the case at Pett Level, however, given the heterogeneous nature of the post-peat deposits here and the evidence of human disturbance, all the dates from this site should be treated with caution.

With their abrupt contacts, Rye 33 and Rye 27 have probably suffered erosional truncation. The dates from these sites (3350–2950 cal. yr BP and 1820–1520 cal. yr BP), in the absence of a strong biostratigraphic signal, must be considered unreliable and, at best, minimum ages for inundation (Long *et al.*, 1996).

The uppermost date from East Guldeford records a considerable age inversion. When combined with the high Chenopodiaceae pollen values in the corresponding pollen assemblage, this suggests that the organic matter in the apparently transitional organic clay was probably reworked during the marine inundation. However, the presence of this layer does not demonstrate that erosion occurred at the site itself and, given that a rise in Chenopodiaceae pollen (suggesting the proximity of marine/brackish sediment) occurs prior to the end of peat accumulation, the date of 1310–1230 cal. yr BP from the transgressive contact could accurately reflect the timing of marine/brackish inundation.

The oldest of the remaining dates from the upper surface of the peat lie in the range *c.* 3200–2350 cal. yr BP. They are from sites situated on the edge of Walland Marsh, Brede Levels and Pett Level (Houghton Green, Roadend, Greyfriars and Cadborough Cliffs). Younger dates exist from sites in the Brede valley and Levels at Old Place (1950–1540 cal. yr BP) and West Winchelsea (1310–1250 cal. yr BP) where, in both cases, there is evidence of the development of open communities prior to marine inundation. The Old Place date is consistent with dates of *c.* 2000–1500 cal. yr BP obtained from the top of the slope-derived deposits at Pewis Marsh, Pannel Farm and Pett Level and the potentially eroded contact at Rye 27. The West Winchelsea date conforms to the date for the end of peat formation at East Guldeford and is consistent with an assay (1270–1120 cal. yr BP) obtained from fine rootlet material in the overlying clay (Table 4). There was no evidence that the rootlets penetrated the peat and similar dates were obtained from the humin and humic acid fractions. The date obtained (Table 4) from the *Phragmites* rhizomes at Pannel Farm (pooled mean, 510–320 cal. yr BP) is considerably younger than that from the immediately underlying organic sediment (1700–1410 cal. yr BP) and this material is considered likely to be intrusive.

Discussion

The late-Holocene evolution of the Rye area

First, we consider whether the radiocarbon dates from the surface of the peat bed in the Rye area can be used to date (1) the end of peat formation and (2) the deposition of the overlying clastic sediments.

The consistency of the radiocarbon dates, both in terms of stratigraphic position and the dating of the different fractions, suggests that the dates obtained accurately reflect the age of the samples submitted. However, in terms of establishing the end of peat formation the precision of the dates is suspect for several reasons. The decline in the rate of sediment accumulation, the complete cessation of peat growth at some sites and the highly humified nature of the peat (with the deposits frequently 2 m or more below the ground surface making it unlikely that this is the result of recent lowering of the water-table) suggest that many sites experienced a long period of slow or no sediment deposition.

The calibrated dates from immediately beneath apparently marine/brackish clastic sediments appear to fall into four age brackets (Figure 4); *c.* 3200–3000 cal. yr BP, *c.* 2700–2350 cal. yr BP, *c.* 2000–1500 cal. yr BP and *c.* 1300–1100 cal. yr BP. Care is required in interpreting such groupings, however, since some age clustering, such as that between *c.* 2700 and 2350 cal. yr BP, may reflect variations in the production of atmospheric radiocarbon through time rather than any time-specific process. The sites dating to between *c.* 3200–3000 cal. yr BP and *c.* 2700–2350 cal. yr BP (Rye 33, Roadend, Greyfriars, Cadborough Cliffs and Houghton Green), derive from the eastern (seaward) side of the study area and the similarity of the pollen assemblages above and below the upper surface of the peat at four of these sites suggests continuous sedimentation. However, we consider that these dates do not accurately reflect the timing of the marine/brackish inundation. As well as the absence of transitional communities there is no evidence of a sedimentary response at landward sites to marine inundation at this time (indeed peat formation had ceased at Lea Farm beyond the inland limits of marine sedimentation) and deposits that might define the end of such a phase of sedimentation are also absent. The consistent stratigraphic position of the marine/brackish sediments, overlying the intervening slope deposits at sites marginal to the upland, strongly suggests that inundation occurred after *c.* 1750 cal. yr BP. The similarity of the pollen assemblages and the low values of marine/brackish indicators at these sites suggest an initial post-peat phase of slope-wash/fluvial deposition, though such a phase is difficult to distinguish lithostratigraphically.

Five sites yielded dates of between *c.* 2000 and 1500 cal. yr BP, but they too must be treated with caution. We have noted

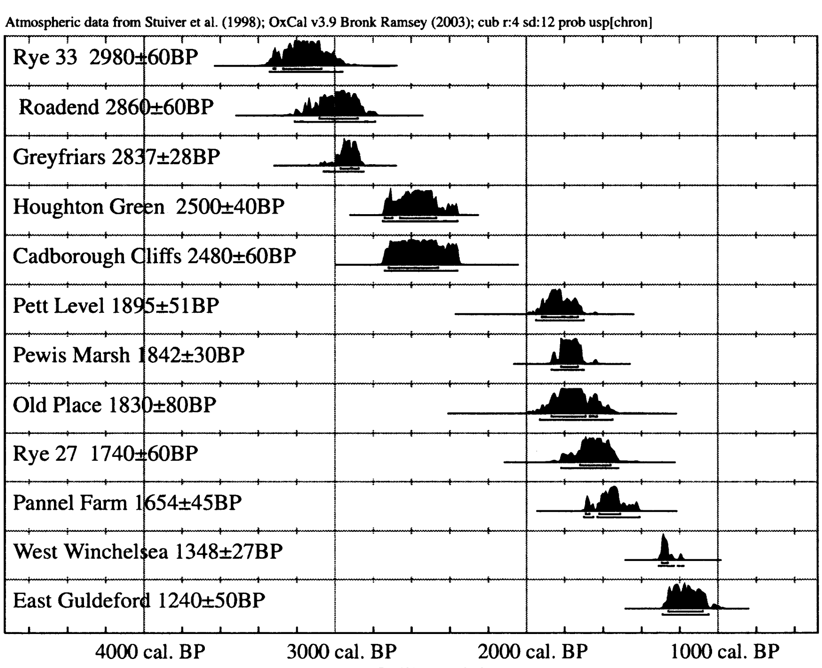

Figure 4 The radiocarbon dates from immediately beneath apparently marine/brackish clastic sediments in the Rye area

above the abrupt contact at Rye 27 but, in addition, three of the dates from this interval (Pewis Marsh, Pannel Farm and Pett Level) are from the surface of the slope-wash deposits. The erosion and movement of material off the slopes is likely to be related to land-use activities. We note that the bulk of these sediments date from the late Iron Age/Roman period (*c.* 2200–1750 cal. yr BP), when the pollen evidence indicates that agricultural activity, including cultivation, was at its most intense and the iron industry was also active in the region (Cleere and Crossley, 1995). Deposition of the slope-wash deposits ceased at the end of the Roman occupation, which marks both the end of the iron industry and a decline in cultivation. If valid, this hypothesis implies that sediment supply was shut-off at this time rather than an immediate change in depositional environment. That some of the late-Holocene pollen assemblages are dominated by herbaceous taxa (eg, Pannel Farm and Old Place) is probably also indicative of conditions on the uplands during the Roman period rather than the presence of transitional communities at these sites. The continued or renewed growth of peat in the lower Brede (eg, at West Winchelsea where marine/brackish indicators are absent until immediately beneath the contact), and the incorporation of Mediaeval pottery sherds into the slope wash deposits at Pett Level, also argue against these dates as reliable age estimates for dating the onset of marine/brackish sedimentation.

In contrast, several lines of evidence suggest that the dates of *c.* 1300–1100 cal. yr BP from East Guldeford and West Winchelsea are accurate in determining the timing of marine/brackish inundation. At East Guldeford, the rise in Chenopodiaceae pollen prior to the end of peat formation suggests the proximity of marine/brackish conditions, whilst a similar date (1040–890 cal. yr BP) exists for the inundation of the raised bog at Little Cheyne Court, some 4 km to the east (Waller *et al.*, 1999). At West Winchelsea the transitional pollen assemblage spans the contact and the dates obtained from the rootlets in the post-peat sediments are stratigraphically consistent.

In summary, most of the dates from this analysis are unreliable for dating the end of peat formation and for the deposition of the overlying clastic sediments. In particular, a slow-down or total cessation in peat accumulation leads us to suggest that the dates, with the exception of those from East Guldeford and West Winchelsea, are not reliable for either purpose.

The above discussion forms a basis for re-evaluating the scenarios outlined in the introduction as to the timing and processes responsible for the inundation of the peat surface in the Rye area. We consider it unlikely that the study area experienced gradual or multiple inundations from as early as *c.* 3200 cal. yr BP. In addition, from evidence mentioned above, the absence of any relationship between the altitude of the contact and age argues against the inundation of low lying sites ahead of topographically higher sites. It remains possible that the study area was inundated after *c.* 2000 cal. yr BP as a result of the enlargement of a backbarrier estuary. Gradual inundation starting *c.* 1300 cal. yr BP is supported by the occurrence of transitional communities at West Winchelsea. Although the radiocarbon dates imply West Winchelsea was inundated before East Guldeford, flooding along tidal channels could have enabled the initial incursion to penetrate beyond the raised bog. However, we consider it more likely that rapid inundation of the study area occurred as a consequence of the breaching (or an enlargement of an existing breach) of the coastal barrier near Rye. Transitional communities are, aside from West Winchelsea, absent and erosional truncation appears widespread. Barrier breaching and the development of a wide tidal inlet is the most likely explanation for the carving out of a large area of peat and associated sediments in the immediate vicinity of Rye.

While the evidence discussed above indicates the initial inundation was pre-thirteenth century AD, the bulk of the post-peat sediments may have been deposited following the changes in shoreline configuration associated with the thirteenth-century AD storms. For example, the deposit with the twelfth- and thirteenth-century AD pottery at Pett Level is overlain by >3 m of material that includes laminated silts and clay. While the sherds are likely to have been incorporated into the slope deposits as a consequence of human activity, possibly connected to peat extraction for fuel or salt making (cf. Behre *et al.*, 1979), the overlying deposits are undisturbed. In addition, at Old Place (Marlow, in Waller, 1994b) and West Winchelsea, foraminiferal investigations confirm a shift from intertidal to deeper, probably, subtidal conditions during the initial stages of the deposition of the post-peat sediments. Given the date of peat inundation, a likely explanation for the sudden increase in environmental energy is the breakdown of the barrier system associated with the thirteenth-century AD storms.

The evidence from northwest European coastal lowlands

The Rye study demonstrates the difficulties in interpreting bio- and chronostratigraphic data from peat contacts of late Holocene age, especially from sites close to the upland edge. Slow, or non-deposition of organic material prior to inundation, humification of the upper levels of the peat, and possible mixing by animal or human activity, all reduce the potential resolution of bio- and chronostratigraphic data from this period.

A review of the evidence from coastal lowland areas bordering the southern North Sea suggests these difficulties are commonplace. The age range of dates from the upper peat contact from the Romney Marsh deposition complex as a whole is similar to that obtained from the Rye area (Long *et al.*, 1998), although the slope-derived material is absent from most of these sites. A diachronous end to the protracted mid-Holocene period of peat formation is also indicated for the other major coastal lowland areas in southern England. For example, for Southampton Water dates range from *c.* 5200 to 3200 cal. yr BP (Long *et al.*, 2000), for the Thames from *c.* 4600 to 2350 cal. yr BP (Devoy, 1979; Sidell *et al.*, 2000), with a range of *c.* 4100 to 2350 cal. yr BP at Silvertown alone (Wilkinson *et al.*, 2000), and for the East Anglian Fenland from *c.* 2900 to 1700 cal. yr BP (Waller, 1994a). In all cases authors comment on, at least from some locations, the highly humified nature of the peat and the evidence for erosional truncation.

Very similar results to those from the Rye area have been also been reported from Belgium. From the Scheldt basin, Denys and Verbruggen (1989) report multiple dates from the top of a late-Holocene peat ranging from *c.* 2550 to 1190 cal. yr BP. In the lower Scheldt, a mesotrophic fen was replaced by 'heathland', with *Myrica*, in the upper black levels of the peat. Very low accretion rates initially prevailed in the post-peat period with 10–30 cm of peaty clay deposited prior to the thirteenth century AD (Denys and Verbruggen, 1989). More recently, from the coastal plain, Baeteman *et al.* (2002) report radiocarbon dates from the top of the uppermost peat bed ranging *c.* 3830–1520 cal. yr BP and large age differences between the peat dates and shell dates from the overlying clastic deposits. Baeteman *et al.* (2002) suggest, as we suspect for the Rye area, that the late-Holocene evolution of Belgian coastal plain was characterized by long periods of slow sedimentation alternating with short periods of high-energy conditions. In contrast, the presence of thin intercalated peats and peaty soils from the western Netherlands (eg, Jelgersma *et al.*, 1979; Zagwijn, 1989) and East Frisian coast (eg, Behre, 2004; Streif, 2004) suggest areas over which sedimentation was more continuous or the sedimentary record is more complete. Nevetheless, locally, for example parts of the East Frisian coast, the upper surface of the 'Upper Peat' (which formed from 3500 to 2300 cal. yr BP), is described as frequently eroded (Behre, 2004) and optical dates from a site in the outer coastal area indicate that the bulk of the overlying clastic sediments were deposited after *c.* 1600 cal. yr BP (Bungenstock *et al.*, 2004).

Methodological implications and recommendations

The data from the Rye area and other coastal lowlands can be used to critically examine the three assumptions that have underpinned the conventional dating strategies outlined in the introduction.

(1) That radiocarbon dates from the surface of peat beds accurately date the end of peat formation

Determining accurate dates for the end of peat formation in the late Holocene is made extremely difficult by the very low rates of relative sea-level rise (Long *et al.*, 2000; Waller and Long, 2003). Not only does the timespan represented in radiocarbon samples increase but peat preservation is almost universally poor, a problem exacerbated in some regions by reclamation and modern drainage. In the Rye area this has forced a reliance on bulk dates, the reliability of which, if the sediment matrix contains a high clastic content, can additionally be questioned (Berendsen and Stouthamer, 2000). AMS dating may appear an attractive option. However, there are dangers in this approach if the degree of humification prevents the isolation of individual macrofossils. The bulk-dating of small samples may lead to highly inaccurate age determinations if the upper surface of the peat has been affected by even a limited degree of intrusion or surface reworking, or if the sediment has experienced aerobic conditions and mixing prior to inundation (A. Bayliss, personal communication, 2004).

The ubiquity of diachronous dates from the surface of late-Holocene peats, even for small areas, is striking. Some difference in the timing of the end of peat formation is likely, given the continued accumulation of organic material in favoured, landward locations. However, we suspect that this range largely reflects the lack precision of the dates combined with differential erosion of a peat surface which accumulated slowly.

(2) That radiocarbon dates from the surface of peat beds accurately date the onset of the deposition of the overlying marine/brackish sediments

Evidence for erosion of the peat surface is widely reported from the coastal lowland areas that border the North Sea. Lithological analysis alone will, however, not always be sufficient to establish sites where sedimentation has been continuous. Given that some erosion and reworking is always likely during the initial stages of inundation, there is the potential (as at East Guldeford) for pseudo-transitional sediment (finely interspersed peat within a clastic matrix) to be deposited.

Mixed microfossil assemblages may also result from reworking and, as noted previously for the Rye area, the more sensitive indicators of coastal environments (eg, diatoms, testate amoebae) are often poorly preserved in fen–reedswamp conditions (eg, Roe *et al.*, 2002). Where pollen or plant macrofossils are utilized, evidence of the presence communities indicative of higher water levels (eg, herbaceous fen, reedswamp) across the upper surface of the peat would appear to be a necessity in defining gradational, continuous sedimentation. Most convincing is sediment that is rich in the remains of *Phragmites*, as this taxon is tolerant of brackish conditions and survives into the early stages of clastic sedimentation. Although *Phragmites* macrofossil remains have been recorded above and below the peat contacts in the Rye area, deposits dominated by *Phragmites* have not, a situation which, given the highly humified nature of the peat reported, clearly applies to many other coastal lowland areas.

Humified peats produce a reliance on pollen analysis. Unfortunately the lack of taxonomic precision with pollen identifications means that, while the presence of open communities can readily be detected, the likely dominants (eg, the Poaceae and Cyperaceae) cannot be distinguished to species level. In these circumstances it is very difficult to determine the precise nature of the community and its relationship to the contemporary tidal datum. Although rising water levels might appear to be a requirement for the development of such communities and they would not be expected to persist naturally over long periods, such communities are also created and maintained by human activity.

There are a number of additional potential problems associated with the standard approach to the interpretation of transgressive contacts. The avoidance of abrupt contacts, as practised in this analysis, introduces a significant bias against sites that have been rapidly inundated, but not necessarily eroded. We know, for example, that raised bog communities were extensive across Walland Marsh during the late Holocene. These bog communities generate highly compressible organic sediments that can dewater and lose volume quickly, effectively collapsing once tidal inundation occurs. In such circumstances transitional communities will be absent. Nevertheless the age obtained from below the contact may still provide a reliable date for the end of peat formation and the deposition of the overlying clastic sediment.

Interpretations based on single dates from the upper contact of peat layers in coastal lowland situations must also be treated with caution. A vertical series of dates is preferable, enabling detection of reworked material and determination of the rate of peat accumulation. However, a period of very slow or no peat growth, immediately prior to inundation, is clearly likely to be difficult or impossible to determine by radiocarbon dating.

(3) That a series of radiocarbon dates from the upper surface of a layer of peat enable gradual and abrupt events to be distinguished

Given the problems outlined above (and for certain periods that associated with the variable production of atmospheric radiocarbon), spatial series of radiocarbon dates collected from the upper surfaces of late-Holocene peat layers are likely to provide misleading data regarding patterns of coastal change and hence driving mechanisms of shoreline evolution. That this approach has been used for well over 50 years in northwest European coastal lowlands, including by the current authors, suggests that many models of coastal change now require critical reappraisal. In particular, it seems likely that samples from the top of abruptly buried peat layers of late Holocene age will yield variable radiocarbon ages. Because of this, we question the assumption of time-transgressive processes and suspect that the importance of geologically instantaneous events has been considerably underestimated.

We conclude that many radiocarbon dates collected from the top of late-Holocene coastal peat layers only provide limiting ages for the overlying clastic sediments. Only where continuous environmental change is clearly and unambiguous demonstrated by the presence of well-defined transitional communities established with a variety of palaeoenvironmental proxies, can real confidence be placed on the associated radiocarbon dates (Tooley, 1978). Such dates are rare and the conditions to produce them will not arise with abrupt events. The radiocarbon dating of material within the clastic layers themselves provides a partial way forward (eg, Baeteman *et al.*, 2002) though problems detecting reworking suggest the direct dating of sediment by optical methods (eg, Bungenstock *et al.*, 2004) may prove a more attractive alternative. New chronologies must be built without *a priori* assumptions as to the underlying processes.

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