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ORIGINAL PAPER

Statistical analysis of the temporal and spatial controls on tidal signal preservation in late-Holocene tidal rhythmites, Romney Marsh, Southeast England

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Abstract A hierarchical series of tidal periodicities are preserved within laminated tidal flat deposits at the barrier/back-barrier interface of Romney Marsh and the Dungeness Foreland in southeast England. The sedimentary record of the tidal signature, extracted from variations in sand layer thickness, was found to be severely truncated with neap-spring periods typically represented by five or less sand layers and possibly only alternate neap-spring periods present. Despite the low number of sand layers deposited in these higher frequency tidal cycles, semi-annual periods are clearly preserved but tend to contain less than the expected 6 months of sedimentation. Annual accumulation rates of around 0.2–0.3 m/year are indicated. Local emplacement of storm beaches is considered to have created the protected conditions suitable for tidal rhythmite preservation. Ongoing foreland progradation and infilling eventually restricted tidal inundation to the point where distinct sand laminae were no longer deposited. Here, in contrast with other systems, accommodation space was not limiting and tidal flat elevation is reflected as a more subtle control on spatial changes in the resolution of the tidal signal.

Keywords Tidal rhythmites · Late-Holocene · Romney Marsh · Dungeness · Coastal change

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Introduction

Approaches to resolving the nature and controls of Holocene coastal change focus primarily on palaeoenvironmental reconstruction. Often, limited evidence is provided on the nature and dynamics of depositional processes where extended minerogenic units merely represent the period of infilling between datable stratigraphic contacts with bounding organic deposits, and from which average linear sedimentation rates are determined. Even where advanced laboratory analytical work is completed, for example sediment geochemistry, the outcomes generally involve debates concerning sediment source and land–ocean interaction as a function of coastal morphology, sea-level and terrestrial sediment flux. Importantly, understanding the past dynamics of the coast is essential in resolving the local expression of regional controls on coastal evolution in response to the macro-scale drivers of relative sea-level, climate and sediment supply.

Laminated marine sediments have the potential to record evidence of sedimentary response to the prevailing tidal dynamics, over time periods spanning the semi-diurnal to many years, as systematic patterns of thickening and thinning laminae (e.g. Visser 1980; Kvale et al. 1989; Shi 1991; Archer 1994; Tessier et al. 1995; Kvale and Mastalerz 1998; Choi and Dalrymple 2004; Coueffe et al. 2004). Heterolithic tidal rhythmites consist of thin intercalated layers of sand and mud, which may be wavy, flaser or lenticular bedded (Archer et al. 1995). In siliciclastic intertidal systems, sands are typically laid down by the energetic flood and/or ebb currents, whilst a muddy layer accumulates under the low energy conditions around high water (Dalrymple et al. 1991; Nio and Yang 1991). Alternatively, where mud dominates, well-developed silty tidal rhythmites may occur, comprised of thin, planar laminated silts with clay drapes (Kvale et al. 1994; Archer 1998). Greater flow depths and longer durations of inundation lead to thicker layers, so the possibility exists for these laminated deposits to record the tidal signature associated with daily, neap-spring, lunar monthly and other cycles.

However, preservation of the tidal signal in a sedimentary sequence requires special or restricted (temporally and/or spatially) depositional conditions, i.e. protected, tide-dominated settings, with a high sediment supply and adequate accommodation space (Williams 1991; Allen and Duffy 1998a; Greb and Archer 1998; Choi et al. 2004; Coueffe et al. 2004). It is the variation in the height, and hence current speed and sediment transport capacity and competence, of tides at a particular location, generated by the interaction of a number of lunar and solar gravitational tide-raising forces (Kvale et al. 1995), which are responsible for the diagnostic cycles of layer thickness found in tidal rhythmites. The individual components of the total tide-raising force vary over periods ranging from less than a day to many years and each can be mathematically modelled as a sine wave with a its own amplitude, frequency and phase (Yang and Nio 1985). Due to their differing properties, the various sinusoidal components of the tide-raising force periodically reinforce or interfere with each other so creating the familiar tidal cycles such as neap-spring or solsticial-equinoctial (Kvale et al. 1999).

Importantly for this study, the complex nature of these interactions may cause significant variations in the height of, for example, successive twice daily tides (diurnal inequality), successive spring tides (the fortnightly inequality) and the neap and spring tides over semi-annual and annual periods. Consequently, the number and sediment transport potential of tides inundating any fixed point in the intertidal zone can vary greatly over several timescales even before non-tidal effects are taken into account. Short monitoring periods in modern settings and short sequences in the rock record are, therefore, potentially liable to be misrepresentative of longer-term patterns.

Research aims

Previous work on Romney Marsh extracted a tidal signal from laminated sediments, which rapidly infilled an extensive former tidal inlet: the Wainway (Stupples 2002a, b; Plater et al. 2002). Several metres of incomplete, though identifiable, neap-spring and lunar monthly deposits were shown to have accumulated over several years at rates approaching 0.5 m/year; the depositional period being defined on the basis of preservation of longer wavelength biannual equinoctial cycles within the laminae thickness time series. The sedimentary response of the Wainway to changes in coastal morphology showed a clear and primary control from tidal dynamics.

Similarly laminated sands and muds are widespread across Romney Marsh (Plater 1992; Long and Hughes 1995; Plater et al. 1999) where the range of Holocene depositional environments includes extensive back-barrier estuarine and lagoonal settings, as well as tidal creeks, interdigitating a series of gravel ridges and swales (Spencer et al. 1998; Plater et al. 1999). The aims of this paper are to:

1. Determine whether these protected back-barrier environments offer equal potential for laminated sediments to record a tidal signal within their varying layer thicknesses, or whether the conditions suitable for preservation of cyclic tidal rhythmites were restricted to the major tidal channels, such as the Wainway.
2. Explore temporal and spatial variability in the relative strength and significance of a tidal control on sedimentary response over the long-term (10^1 year).
3. Consider the relationship between sand and mud layer deposition in detail in order to assess the relative importance of seasonally driven meteorological, fluvial or biological non-tidal controls on sedimentation.
4. Develop a simple model based on predicted tidal heights from Dungeness to test the degree to which the cycles of layer thickness resemble patterns within the tide station data and so aid interpretation of any tidal signal encoded within the sediments.

If the rapid deposition of these laminated sediments is found to have been a consistent factor in the depositional history of the Marsh, then a revised interpretation of both the rate and nature of late-Holocene coastal change and the future response of contemporary analogues may be necessary.

Study sites and methods

The Romney Marsh depositional complex comprises several discrete areas of (mostly) former marshland in southeast England, the whole being protected from the sea by a series of gravel storm beaches, which form the Dungeness Foreland (Fig. 1). A suite of sub-, inter- and supra-tidal minerogenic and organic sediments accumulated in the lee of the gravel barrier through the Holocene driven by a combination of rising sea-level, barrier development and reorganisation, storminess and human intervention (Green 1968; Eddison 1983, 1998; Long and Innes 1995; Spencer et al. 1998; Plater et al. 1999; Waller et al. 1999; Stupples 2002b). Sample cores were collected across the Rye Bay, Romney Marsh and Dungeness field areas to investigate their depositional and landscape histories during the late-Holocene, primarily as a function of coastal morphology, relative sea-level rise, storm magnitude/frequency and sediment flux. Here we focus on the dynamic controls on sedimentation in the relatively long and well-preserved records from the barrier/back-barrier interface at Manor Farm and Boulderwall Farm (Fig. 1) where tidal sedimentation is considered to be a response to storm-driven changes in barrier morphology. The lithostratigraphy of the sedimentary sequences is combined with statistical analysis of the laminae thickness time series, detailed granulometric analysis, published palaeoenvironmental and chronological data and a consideration of the predicted tidal heights from Dungeness in an attempt to interpret the drivers of observed variations in layer thickness within the laminated sequences.

Lithostratigraphy and granulometric analysis

The sequences at Manor and Boulderwall Farms were investigated with a gouge corer and the sediments described according to the Troels-Smith (1955) classification before sample cores were recovered with a Stitz piston corer. Sites were levelled to UK ordnance datum (OD). Sample scrapes 5 mm wide were taken every 1–5 cm directly from a cleaned surface of the cores with a small spatula for particle size analysis. Due to the negligible amount of organic matter typically present in the sediments samples were not pre-treated with hydrogen peroxide (Allen 2000; Allen and Thornley 2004) prior to analysis in the Coulter LS130 laser granulometer.

Analysis of layer thickness

In the laboratory sample cores were cut into manageable lengths and a surface carefully cleaned to reveal the laminated structure. Lamination thickness was measured using a binocular microscope, with magnification up to 40×, mounted over a moving stage controlled by a micrometer. Layer thickness was adjusted for linear compaction before fast fourier transform (FFT) spectral analysis (Smith 1997), and simple smoothing, were applied to the resultant time series,

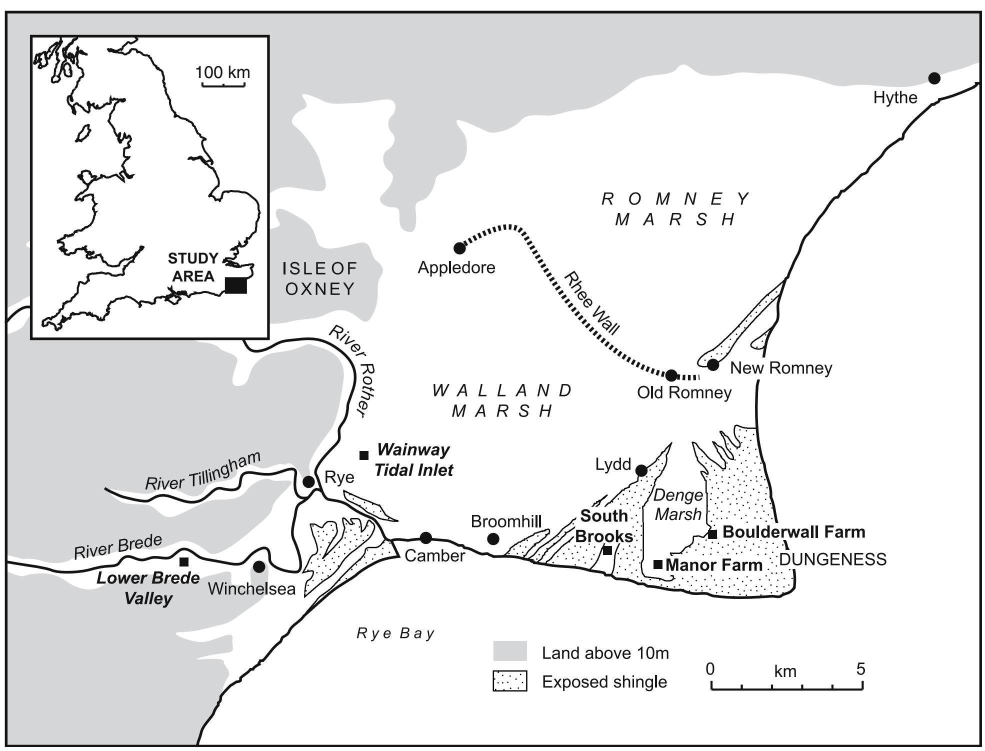

Fig. 1 The sample cores discussed in detail in this paper were recovered from two sites on Denge Marsh—an area of former marshland which interdigitates with the gravel beaches of the Dungeness Foreland: Manor Farm (TR 05928 18077, surface elevation 2.464 m *OD*) and Boulderwall Farm (TR 06181 19231, surface elevation 2.438 m *OD*). Other locations referred to in the text are also shown

using SPSS, Autosignal, Originpro and Excel, to break down the complex cycles of layer thickness into their constituent sinusoids (e.g. Martino and Sanderson 1993; Archer 1994). Periodograms generated by the FFT were smoothed using a Tukey–Hamming window, with a span of 5 data points, to create the spectral density plots. Predicted tidal elevations for Dungeness were computed using tidal constants and software of the national tidal and sea level facility at the Proudman Oceanographic Laboratory (Woodworth personal communication http://www.pol.ac.uk/ntslf/) and these data were similarly treated in an attempt to model the sedimentary record as a progressively truncated tidal signal.

Results and interpretation

Lithostratigraphy

A simplified tripartite sequence, comprising up to five lithostratigraphic units (Fig. 2), was recorded at all of the post-gravel sites across Dungeness: the basal gravel or saturated sand (little, if any, of which was recovered); an overlying laminated sandy-mud; and a subsurface mottled clayey-silt (e.g. Plater 1992; Long and Hughes 1995; Plater et al. 1999, 2002). The base of the sequence at Boulderwall Farm (Fig. 2) was typical of the majority of sites studied and was defined by a sharp contact with the gravel, which was not recovered. However, at Manor Farm (Fig. 2) a saturated silty-sand formed the basal deposit (unit 1) and gravel was not proved here. Overlying the gravel or silty-sand was a variably laminated sandy, clayey-silt (units 2 and 3), which occasionally coarsened to a well-laminated silty-sand. These laminated sediments fined-upwards slightly before grading into a heavily mottled clayey-silt (unit 4), with little structure other than a few sandy lenses or partings. The modern vegetation was rooted into this mottled sandy-mud and formed the typically thin soil (unit 5). Transitions between units were invariably gradational.

Laminations in units 2 and 3 varied in character from parallel, horizontal coarsely laminated sand-dominated couplets, to very thin, wavy sand stringers in a predominantly muddy deposit, i.e. heterolithic rhythmites (Fig. 3). Between these two endpoints was a spectrum of laminae types, including some startlingly clear sequences of pinstripe bedding (Fig. 3b, c), but most typical was a mud-dominated unit with thin, wavy, inclined and discontinuous layers of fine sand or coarse silt, which were not especially clearly defined to the naked eye, but allowed the cores to part easily and regularly (Fig. 3a), and were seen to be reasonably distinct when viewed under the microscope. Less typical were sand-dominated sections with subordinate, thin muddy layers or lenses (Fig. 3d, e). The more clearly laminated sections alternated every few centimetres with clean muds, or at least mud with just irregular sand stringers (Figs. 3d, e). Individual

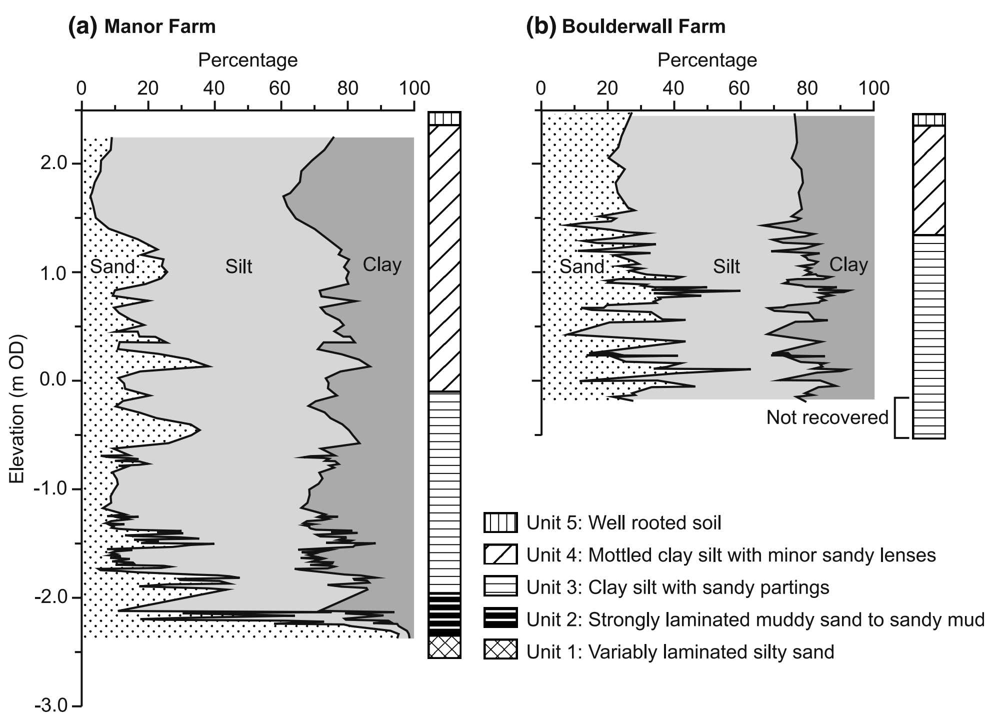

Fig. 2 Lithostratigraphy and sand:silt:clay percentages for Manor Farm (**a**) and Boulderwall Farm (**b**)

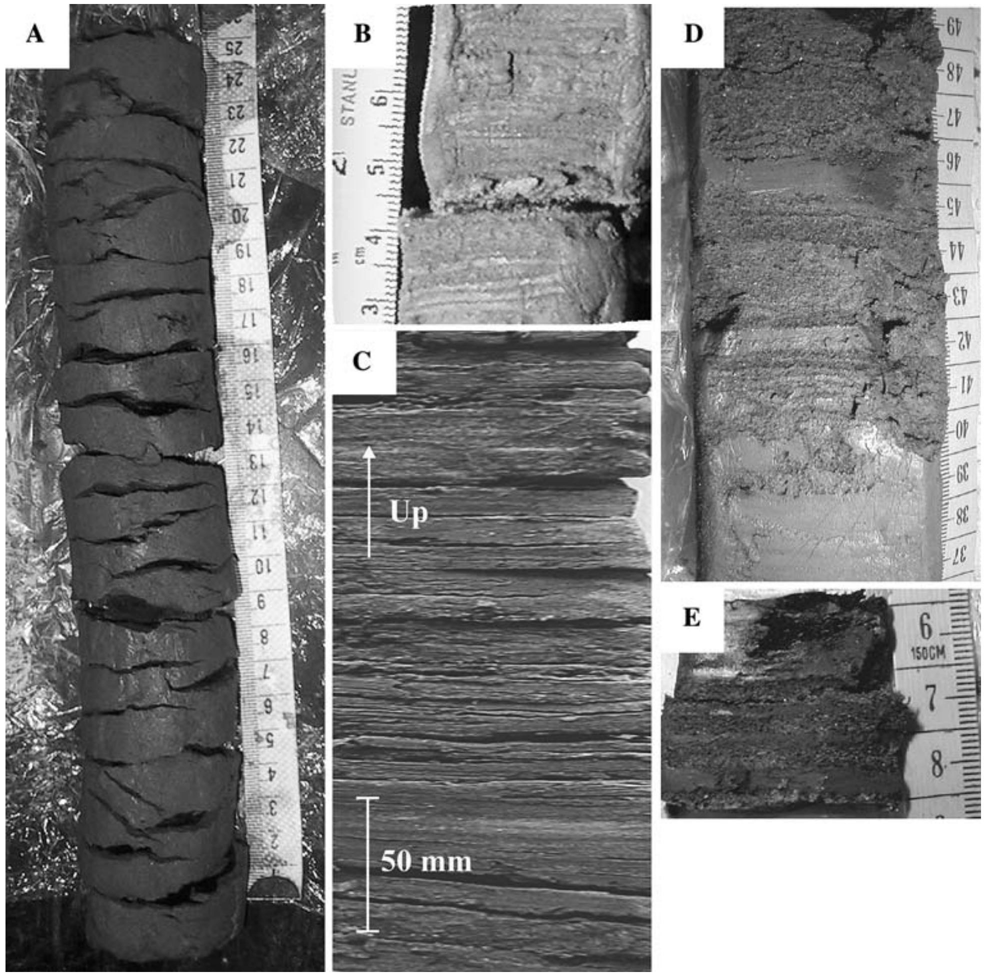

Fig. 3 An indication of the range of laminae types identified in the Dungeness sediments. **a** This mud dominated section of the Manor Farm core shows sand stringers allowing the apparently structureless core to part easily every 5–10 mm; additional structure was evident under the microscope. **b**, **c** Thinly interlaminated, mm-scale, sand and mud layers from the Lower Brede. **b** Near Winchelsea and the Wainway Channel. **c** Near Rye. **d**, **e** Coarser sand dominated laminae from South Brooks in the heart of the Dungeness Foreland. See Fig. 1 for locations

laminae were at the millimetre to sub-mm scale; thicker individual layers (>1 cm) of both sand and mud were also recorded at irregular intervals.

Shell material was common and intact mollusc valves were occasionally preserved. Burrows, and more general disturbance, were present to some degree at all sites and ranged in severity from a slight blurring of the laminated structure to an almost complete reworking, notably in the muddiest section, which reduced the lengths of core suitable for statistical analysis.

Around 1.5 m of laminated material was recovered from Boulderwall Farm, and this paper concentrates on the section between 0.44 and 1.44 m *OD* which contained 96 sand/mud couplets. The laminated sequence recovered in the sample cores from Manor Farm was nearly 2.5 m long. Here, units 2 and 3 extended from approximately –2.4 to ~0.0 m *OD* and contained 596 sand/mud couplets. Spectral and granulometric analysis below are based on this complete sequence, but for clarity other figures concentrate on shorter sub-sections of the core and these are referred to accordingly in the text and figures.

Particle size analysis

The cyclical nature of the textural properties of the Romney Marsh tidal rhythmites has been shown previously (Stupples 2002a, b) and is evident in the sand:silt:clay proportions here (Fig. 2). Particle size distributions (Fig. 4; Stupples 2002b; Long et al. 2006) identify the typically bi- or tri-modal character of the sediments indicative of the amalgamation of several mm-scale sand-mud couplets in each sample. These distributions (Fig. 4) confirm the repetitive, cyclical character of the deposits, which are best defined by suites of curves bounded by relatively coarse and fine end-members, rather than single sample statistics such as mean or mode. With the exception of isolated coarser episodes at the base of Manor Farm and mid-core at Boulderwall (Fig. 2) such textural statistics, whilst showing subdued cycles of coarsening and fining, tend to be constrained within relatively narrow bands which remain consistent through the cores. It is important to note that the particle size work was not undertaken at the same resolution as the individual

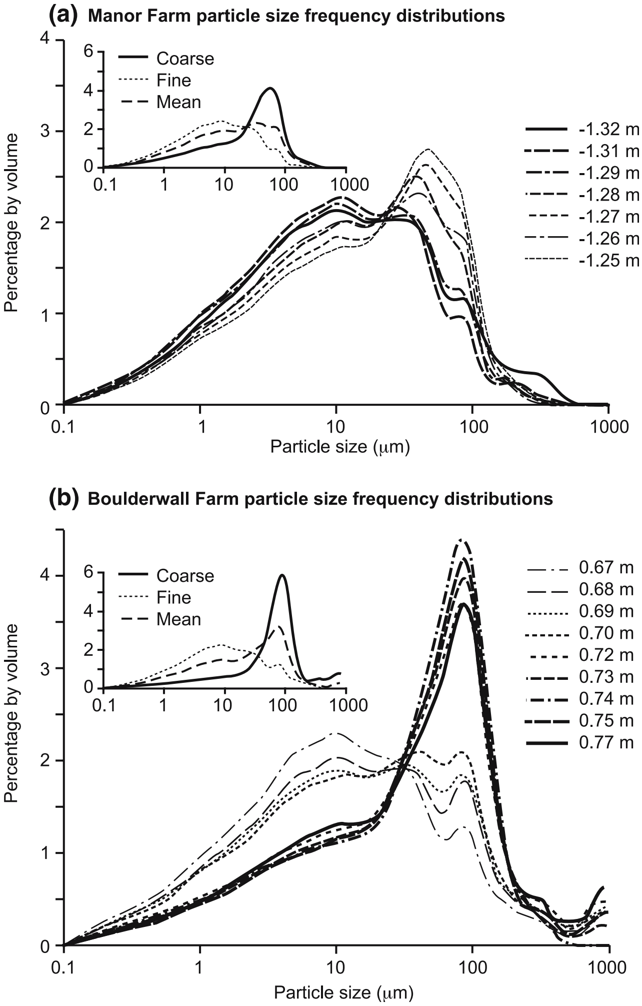

Fig. 4 Representative particle size frequency distributions highlighting cycles of coarse-fine-coarse deposits over core lengths of <10 cm at Manor Farm (**a**) and Boulderwall Farm (**b**). Insets show coarse and fine end-members, and the mean profiles, from the middle section (–1.53 to –0.53 m *OD*) of the longer Manor Farm sequence and 0.44–1.44 m *OD* at Boulderwall Farm

laminae thickness measurements. Hence, the particle size data represent a somewhat smoothed signal of sedimentary response in which any high-frequency variation is dampened.

Palaeoenvironmental context

The lithostratigraphic data—including composition, particle size trends, sedimentary structures and elevation—suggest that accumulation of the post-gravel deposits of Dungeness began at the lower end of the intertidal zone and that the laminated units form part of a broadly defined fining-upwards sequence typical of the development of an intertidal area from open channel or tidal flat to saltmarsh (Reineck and Singh 1980; Klein 1985; Reading and Collinson 1996). Unfortunately, allied palaeoecological data from diatom analysis are unable to resolve the environment of deposition for the marsh sediments in the region of Manor and Boulderwall Farms more accurately than an open tidal channel with fringing mudflats and saltmarshes (Plater 1992; Plater and Long 1995).

The Manor Farm core considered here was recovered from the bank of a sinuous ditch, probably the course of a former tidal creek, and this explains the relatively long sequence and also the absence of the basal gravel. At Boulderwall, the core was located in one of the regular swales between the gravel beach ridges (Plater et al. 1999), and hence has a clear basal gravel unit. At both sites, the sedimentary sequences record the creation and subsequent infilling of a series of back-barrier tidal embayments as the Dungeness Foreland prograded eastwards through the mid- to late-Holocene (Plater and Long 1995; Plater et al. 1999, 2002; Roberts and Plater 2005). Radiocarbon dates on articulated shells of *Cerastoderma edule* recovered from the Manor Farm stratigraphy reveal the laminated sequence to have been deposited around 1260–1050 cal. year BP (Plater et al. 2002). Similarly, ages obtained from palaeomagnetic secular variation dating of the marsh deposits from both Manor and Boulderwall farms are indicative of an extensive phase of marsh sedimentation during the period of 1100–400 years ago (Plater et al. 2006).

Laminae thickness analysis

In heterolithic rhythmites a more sensitive record of tidal periodicities should be preserved in the sand rather than the mud layers. The thickness of the latter is controlled by suspended sediment concentrations and slack water settling times, which are likely to be less effected by neap-spring (and other) cycles than the variations in current speed which control sand layer deposition (Dalrymple and Makino 1989; Dalrymple et al. 1991). It is the interpretation of the variation in sand layer thickness, which receives most attention here but the relationship between the patterns of varying sand and mud layer thickness will be considered below.

Sand layer time series

An examination of sand layer thickness from around the middle of the Boulderwall and Manor Farm sequences (Fig. 5) indicates a regular and repetitive thickening and thinning of the sand layers. A

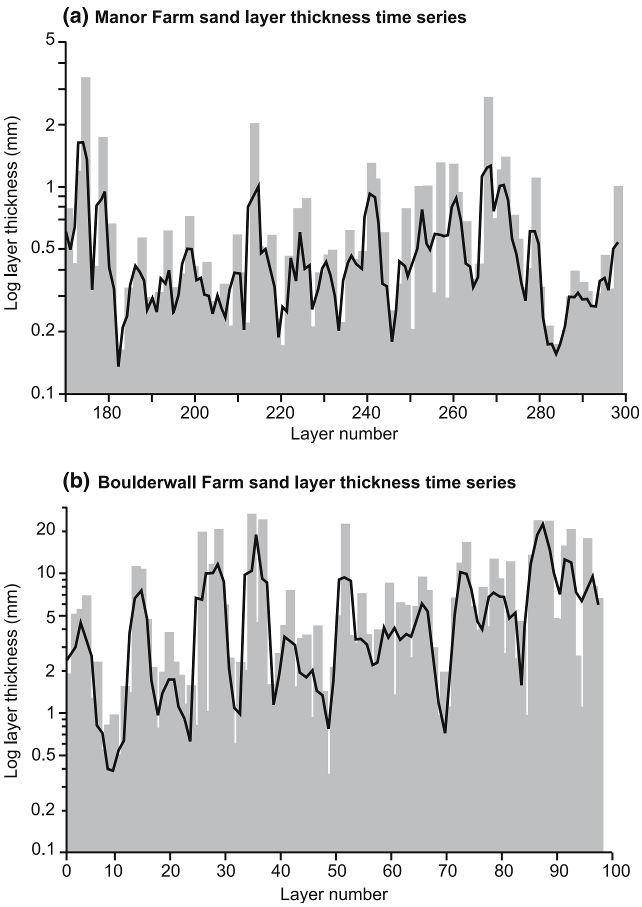

Fig. 5 High frequency variations in sand layer thickness in the unprocessed data (*bars*) and repeating cycles of <10 layers/cycle accentuated by 3 point moving average (*line*). **a** Manor Farm (layers 171–298, –1.40 to –1.16 m *OD* and –2.21 to 0.12 m *OD*, *n* = 596). **b** Boulderwall Farm (0.44–1.44 m *OD*, *n* = 96)

prominent thick layer recurs every 5–9 layers and nested within this period is a subsidiary pattern of moderately thicker layers occurring every 2–4 layers. Smoothing of the data accentuates the longer 5–9 layer cycle whilst the higher frequency 2–4 layer period is typified by the noisy, 'saw-tooth' appearance of the raw data (Fig. 5). The longer wavelength period appears to contain more layers/cycle at Manor Farm. Similarly, whilst the prominence of the higher frequency period varies along both cores, it is generally more clearly preserved at Manor Farm; this is perhaps reflected in mean sand laminae thickness being around 1 mm at Manor Farm whilst the Boulderwall sand layers where in excess of 5 mm thick on average.

There is also a sense of some longer cycles of thickening and thinning (Figs. 5, 7) delineated by relatively sharp, but short lived, declines in layer thickness which recur every 15–20 layers (sometimes less) at Boulderwall, but is of a longer wavelength covering perhaps 20–30 layers (occasionally more than 50) at Manor Farm.

Spectral density plots

Harmonic analysis of the sand layer time series (Fig. 6) shows clusters of powerful spikes in spectral density with approximately the same periods identified in the raw and smoothed data above. In the shorter Boulderwall sequence a longer 6–8 layers/cycle period is relatively well-defined and clearly dominant over a spike at 5 layers/cycle and a cluster of higher frequency spikes with less than 4 layers/cycle. There are also broad maxima in spectral density at around 14 and 32 layers/cycle respectively; the former being coincident with the longer wavelength patterns identified above. The Manor Farm spectrum is closely comparable but the peaks in spectral density are a little more clearly defined, reflecting the longer data set, and there is a different relationship between the power of the various periodicities. There are two broad spikes in spectral density centred on 13 and 16 layers/cycle and 2 equally powerful but much sharper peaks in the range 3–4 layers/cycle. There is a small cluster of spikes centred on 8 layers/cycle, a further spike at 5 layers/cycle and a broader peak at 22 layers/cycle.

The contrast between the two sites is the distribution of power across the spectra, i.e. the relative importance of the various harmonic components in the overall signal. At Boulderwall, power is concentrated in the middle of the spectra around 8 layers/cycle but at Manor Farm power is concentrated at the high (<4 layers/cycle) and low (>12 layers/cycle) frequency ends. Both spectra also contain a large number of subsidiary peaks suggesting, as do the raw and smoothed data, that these time series are composed of a continuum of harmonic elements in the range of wavelengths 2–10 layers/cycle, some of which are more dominant than others. Furthermore, this dominance is temporally (and spatially) variable, with the result that interference between cycles of different frequency generates the complex spectra typical of these sediments.

The sedimentary tidal signal

Interpretation of laminated marine sediments must take into account both the possibility that the layers were not derived from predominately tidal processes (Kvale and Archer 1990; Park et al. 1995; Allen and Duffy 1998a; Allen 2004; Fan et al. 2004) and also that,

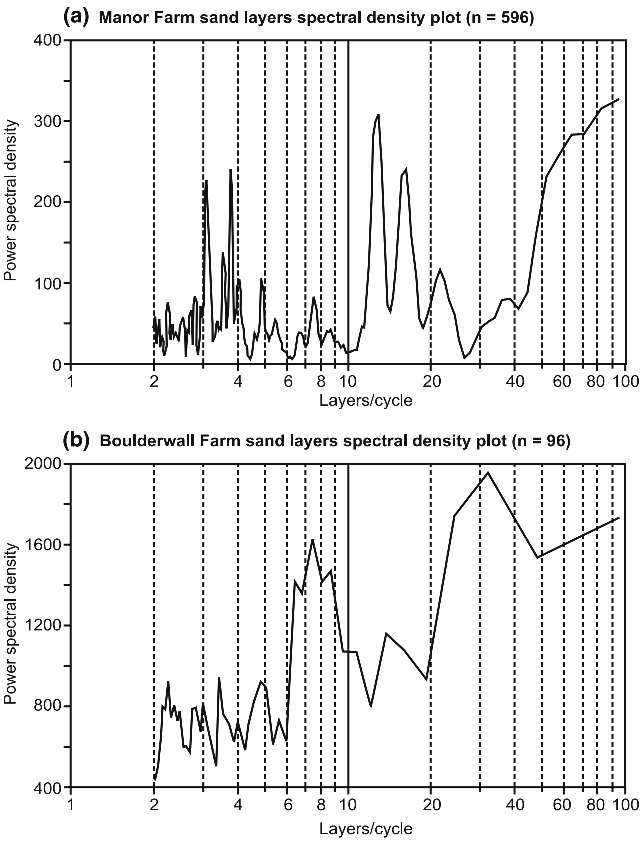

Fig. 6 Spectral density plots from sand layers at **a** Manor Farm (–2.21 to 0.12 m *OD*, *n* = 596) and **b** Boulderwall Farm (0.44–1.44 m *OD*, *n* = 96). Prominent peaks in spectral power occur at approximately the same wavelengths at each site but their relative strength differs

even if a tidal control is proven, there are several orders of nested, sinusoidal variation (Kvale et al. 1995; 1999), which may, or may not, be preserved and potentially confused with each other (Greb and Archer 1998; Tessier 1998). Lithostratigraphic and palaeoenvironmental evidence has already been presented which is indicative of a strong tidal control on deposition at these sites, and other work on Romney Marsh supports this conclusion regarding the back-barrier minerogenic sediments of the area (Plater 1992; Long and Hughes 1995; Spencer et al. 1998; Plater et al. 1999, 2002; Stupples 2002a, b; Long et al. 2006). Furthermore, one of the diagnostic attributes of a tidal control on sedimentation is the presence of repetitive, nested cycles of thickening then thinning within a laminated sequence (Kvale and Archer 1991; Nio and Yang 1991; Kvale et al. 1994, 1999) such as those described here (Figs. 5, 6, 7).

By following the convention applied in previous studies of correlating nested cycles of sand layer thickness with the comparably hierarchical tidal cycles, and with reference to previous analysis of tidal rhythmites from this area (Stupples 2002a, b; Plater et al. 2002), it is possible to deduce which of the various tidal harmonics are most likely to be responsible for the patterns of laminae thickness recorded at Dungeness. The two most important tidal harmonics, in terms of their amplitude, flow velocity and, hence, influence on sediment transport capacity, are the neap-spring and lunar monthly periods (Dalrymple 1992; Archer 1996; Archer and Johnson 1997; Kvale et al. 1999, 1995). It is these periods that we propose are expressed in the dominant cycles of layer thickness accentuated by the smoothed lines in Fig. 5, with wavelengths of less than 10 layers/cycle. It is also possible that the occasional 'saw tooth' appearance of alternating thick and thin layers in the unprocessed data (Fig. 5) is driven by a diurnal inequality in the height of successive tides.

The longer wavelength (>15 layers/cycle) periods (Fig. 7) are best explained in terms of the twice yearly cycles in tidal energy, driven by the changing alignment of earth, moon and sun, which results in the enhanced equinoctial tides twice each year (Martino and Sanderson 1993; Kvale et al. 1994, 1999; Greb and Archer 1998). Around 3.5 years sedimentation (7 semi-annual periods) are recorded in the metre-long Boulderwall Farm core whilst around 11 years are preserved in the entire 2.33 m-long Manor Farm series (Fig. 7). This indicates accumulation rates of the order of 0.2–0.3 m/year, which is a little lower than the 0.4–0.5 m/year previously obtained from infilled Wainway tidal inlet (Stupples 2002a, b).

The number of layers preserved in these neap-spring to annual cycles may seem unrealistically small given that the potential number of tides in the same periods is likely to be an order of magnitude greater in a semi-diurnal system such as Dungeness. However, even in relatively long and (apparently) perfectly preserved laminated sequences the number of layers recorded over any particular depositional cycle, such as the neap-spring fortnight, does not match the number of tides theoretically capable of inundating the site, and neither is this number constant in time or space (Brown et al. 1990; Williams 1991; Martino and Sanderson 1993; Greb and Archer 1998; Staub et al. 2000; Choi et al. 2001, 2004; Coueffe et al. 2004). For each high tide, a range of depositional outcomes may be envisaged: at the low energy extreme a site not being flooded at all or non-deposition, to the accumulation of mud only (perhaps over several tides), to the preservation of a well-defined sand-mud couplet, to erosion of intervening mud layers allowing amalgamation of sand layers from two or more tides, to extensive erosion of some or all of a previously deposited sequence

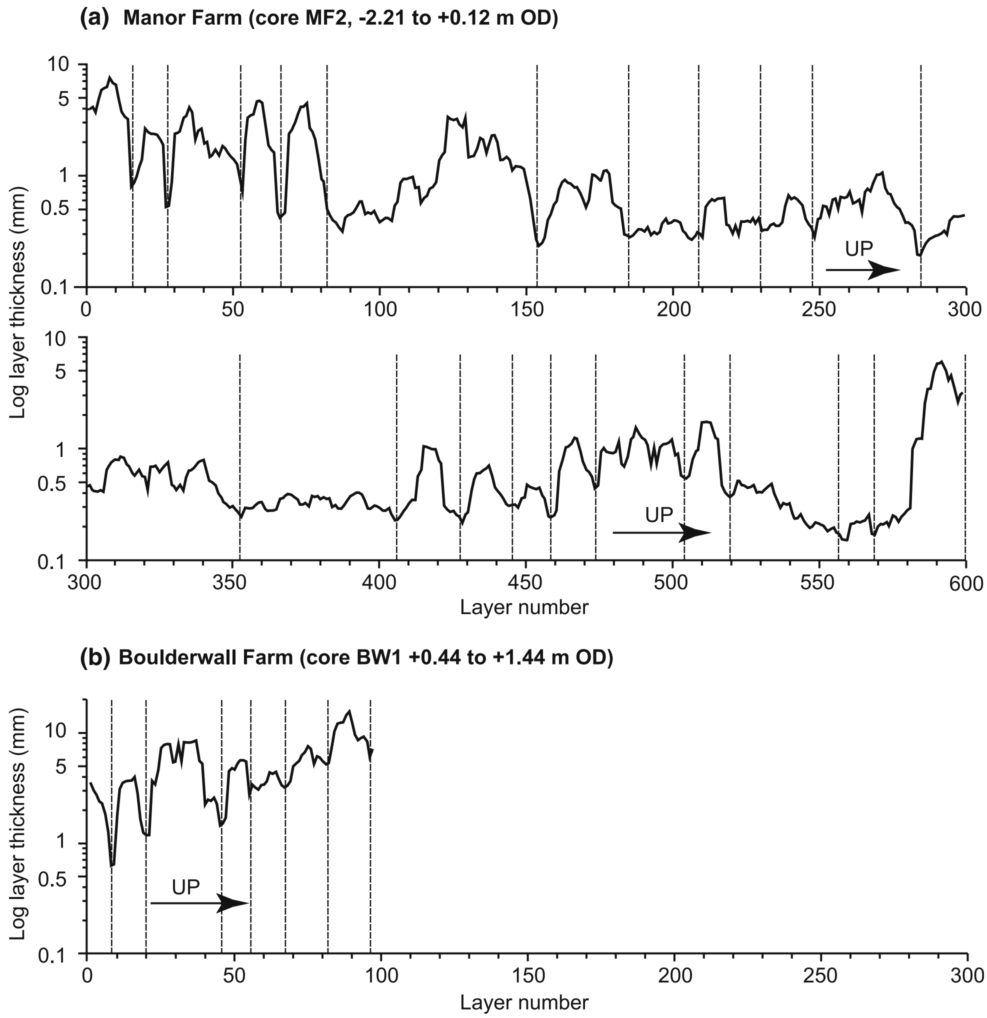

Fig. 7 Sand layer thickness from **a** Manor Farm (–2.21 to 0.12 m *OD*) and **b** Boulderwall Farm (0.44–1.44 m *OD*) sequences smoothed by 7 point moving average to highlight semi-annual cycles in sand layer thickness. Notice that these longer period patterns tend towards being symmetrical, and alternately higher and lower, as anticipated from a consideration of changing tidal heights over equivalent time periods (Martino and Sanderson 1993; Kvale et al. 1994, 1995, 1999, Tessier 1998). *Vertical lines* illustrate the bi-annual periodicity in tidal energy, hence the cores record approximately 11 years of sedimentation at Manor Farm (**a**) and around 3.5 years at Boulderwall Farm (**b**)

at the high energy end (Dalrymple and Makino 1989; Dalrymple et al. 1991; Martino and Sanderson 1993; Archer and Johnson 1997; Kvale et al. 1995, 1999; Archer 1998). The possible implications of this partial dislocation of tides and layers is the misidentification of one periodicity as another, especially when relying heavily on statistical analysis of laminae thickness time series alone (Tessier 1998). This problem is addressed in the following section where a theoretical model is generated to test the hypothesis that a tidal signal composed of incomplete neap-spring, lunar monthly and semi-annual cycles, with wavelengths comparable to those recorded in the laminae thickness series, could be generated from a simple truncation of the predicted tidal heights time series from Dungeness. This process will not only aim to add confidence to the general interpretation of the sedimentary tidal signal presented above but will hopefully lead to a more detailed understanding of the main temporal controls on this signal.

Tidal record threshold modelling

The number of laminae preserved in the proposed neap-spring/lunar monthly and semi-annual/annual cycles of layer thickness in the post-gravel sediments of Dungeness is equivalent to only a small percentage of the theoretical number of high tides in the same periods at a semi-diurnal site. In the models below (Figs. 8, 9, 10) each high tide of the predicted Dungeness tide station data is equated to a single sand layer with tidal height being proportional to sand layer thickness. As elevation increases so tidal flooding frequency declines (Archer 1994, 1995; Kvale et al. 1995; Archer and Johnson 1997; Choi et al. 2001) and this simple relationship may be used as a proxy to model the incomplete cycles of sand layer thickness in the Dungeness tidal rhythmites. We wish to test whether the straightforward reduction in the number of tides inundating a site is sufficient on its own (i.e. without distortion of the signal by non-tidal effects) to generate

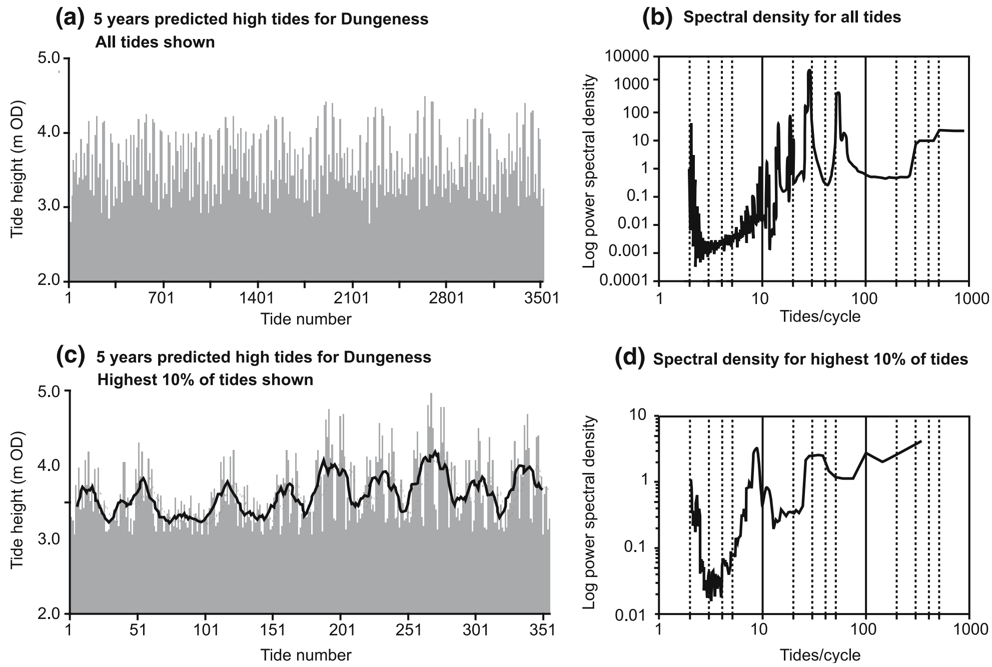

Fig. 8 Pattern of predicted high tides for Dungeness over a 5-year period. All tides (**a**, **b**) and time series truncated to include highest 10% of tides only (**c, d**). Smoothed line (11 point moving average) accentuates truncated semi-annual periods in the 10% scenario (**c**)

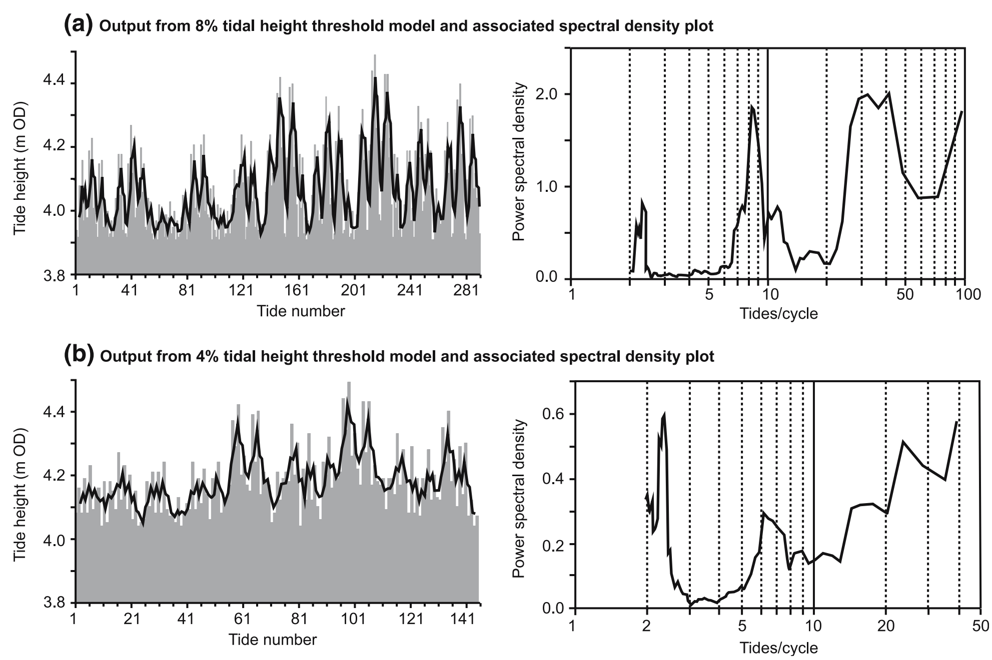

Fig. 9 Dungeness tide models with thresholds set to reflect proposed annual periods at **a** Manor Farm (8%). **b** Boulderwall Farm (4%). High tide records acting as a proxy for sand layer deposition. *Smoothed lines* (7 point moving average) highlighting truncated semi-annual cycles

high and low frequency patterns comparable to those recorded in the sand layer thickness data and to identify the principal harmonic components of this tidal signal as it changes through time at a particular site.

The time series of predicted high tides from Dungeness for an arbitrary 5 year period was selected and the percentage of high tides theoretically inundating the site was first reduced, in sequence, from 100 to 50% and then 10% in order to inform our understanding of the tidal signal and the impact of changing intertidal elevation on the resolution of this signal. A 5 year record is sufficient to identify annual cycles in the data without obscuring the higher frequency periods when the series are plotted (Figs. 8, 9); this time span is also comparable to the lengths of tidal rhythmite records typically extracted from Romney Marsh sediments (Stupples 2002a, b; Plater et al. 2002; Long et al. 2006). An attempt was then made to replicate the tidal signature encoded within the sand laminae thickness cycles using thresholds derived from

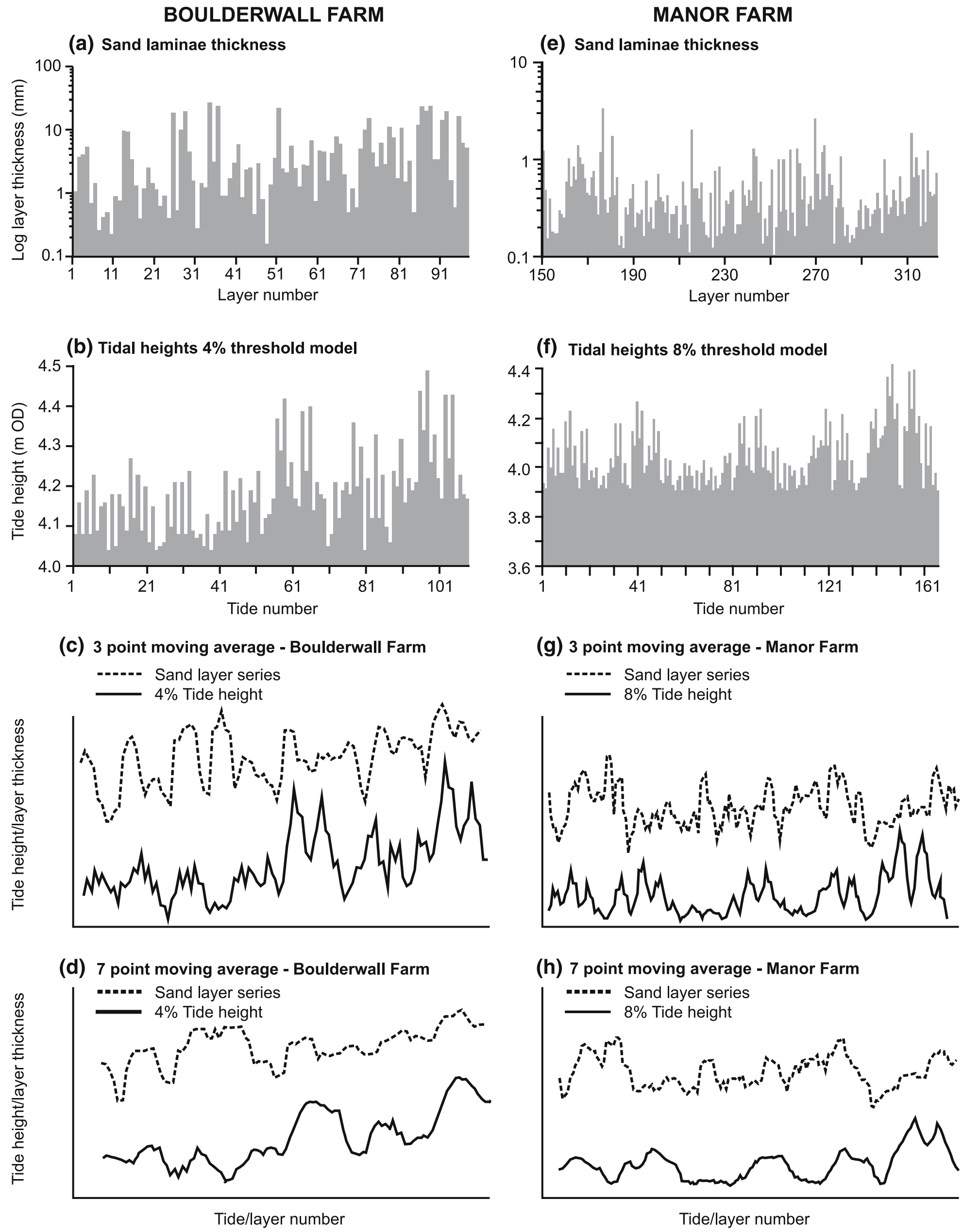

Fig. 10 Good agreement in the principal harmonic characteristics of the sedimentary tidal signal and models based on truncated tide station data in the raw data (**a**, **b**, **e**, **f**), and the smoothed data at the neap-spring/lunar monthly level (**c**, **g**) and over semi-annual periods (**d**, **h**). Boulderwall Farm 0.44–1.44 m *OD*, Manor Farm –1.43 to –1.11 m *OD* with both sand layer series, and associated models, covering periods of about 3–3.5 years

a consideration of the semi-annual periodicities identified at Manor and Boulderwall Farms (Fig. 7). The resulting time series were plotted and spectral analysis completed as for the layer thickness data (Figs. 8, 9).

Dungeness tidal patterns

There are around 706 high tides in a complete year and the bar chart of predicted high tides (Fig. 8) shows, amongst other things, a well-developed fortnightly inequality between successive spring tides and a symmetrical and repetitive rise and fall in the spring tide height twice each year. Ten such semi-annual peaks in tidal height can be seen in the plot of the complete data set and they are also alternately a little higher and lower. Strong well-defined peaks in spectral density (Fig. 8) are seen at around 28, 54 and 2 tides/cycle representing in decreasing order of power: neap-spring, lunar monthly and diurnal inequality respectively. A number of subordinate spikes are also evident in the range 10–20 tides/cycle and a broadly defined peak between 200 and 1,000 tides/cycle is also present. The latter is an amalgamation of the annual and semi-annual equinoctial peaks in tidal elevation and these two long wavelength components of the tidal elevation time series are poorly resolved in the frequency domain (though not the time domain) due to a combination of the relatively short length of the record with respect to annual cycles and the smoothing inherent in the spectral density plot; the former is driven by subordinate tide-raising forces.

Reducing the number of tides to the highest 50% (not shown) has little effect on the plot of tide height—both the fortnightly inequality and the ten equinoctial peaks remain obvious. However, the spectral density plots lose power across all frequencies and there is a broadening and splitting of the peaks in spectral density associated with the principle harmonic components of the tide (Kvale et al. 1995; Choi et al. 2001; Choi and Dalrymple 2004). This trend continues when only the highest 10% of tides (Fig. 8) are included but now the third equinoctial peak is poorly defined and the higher frequency pattern is becoming more irregular. This loss of resolution is reflected in the spectral density plot with a further loss in power across the frequency range, increasingly broad and poorly defined (though still identifiable) 1st–3rd order spikes and a continued shift in power towards the longer wavelength end of the spectrum with semi-annual to annual peaks broad but still recognisable.

Statistical significance of spectral density peaks

Significance levels (not shown) associated with the spectral peaks change as the length of the series are reduced but, more importantly, periods which are well defined in the time domain, i.e. the raw or smoothed data, do not necessarily generate statistically significant peaks in the frequency domain, i.e. on the spectral density plots. For example, the neap-spring and lunar monthly periods in the entire tidal heights series (Fig. 8a, b) have significance levels in excess of 99.9% i.e. less than a 1 in 1,000 chance that they could be derived from a random white noise signal. However, the significance level associated with the two longest wavelength periods is 50% or less for the same data set. As the series is truncated so the resolution and significance of the spectral peaks declines at the neap-spring/lunar monthly level but the annual and semi-annual periods become more statistically significant relatively. Finally, the highest frequency, diurnal inequality, harmonic remained below the 50% significance level in the 100, 50 and 10% scenarios despite being clearly and demonstrably preserved in the data. This trend continues in the models of the sedimentary signal discussed below—demonstrably present cycles do not necessarily generate statistically significant spectral peaks—and this adds confidence to our interpretation of the laminae thickness time series despite the complex character of the time series and resultant spectral density plots, and also to the connections made between the modelling process and the sedimentary signal.

Modelling the sedimentary tidal signal

Semi-annual and annual periods identified in the smoothed sand layer thickness data (Fig. 7) suggest that in the longer Manor Farm sequence around 54 sand layers were deposited during an average year (596 layers in 11 years). The shorter Boulderwall sequence indicates an annual period of around 30 layers/cycle (96 layers in less than 3.5 years). These figures equate to approximately 8 and 4%, respectively, of the predicted 706 annual high tides (Fig. 9).

Harmonic analysis (Fig. 9) supports the periodicities identified above with a continuing shift in power towards the higher frequency end of the spectrum and a loss in power across all frequencies as the number of tides (i.e. layers) in the modelled time series declines. Both examples retain a sharp, powerful spike at 2–3 layers/cycle and also 2 poorly defined peaks in the range 15–40 layers/cycle—the wavelengths of which decline steadily from 8 to 4% model. In the middle of the spectra 2 further peaks are well-defined in the range 6–12 layers/cycle. A number of subsidiary periodicities are also present between these five principal harmonics.

There is a striking resemblance in the dominant periodicities evident, in both the unprocessed and smoothed data, when the 8% (Manor Farm) and 4% (Boulderwall Farm) threshold models are compared directly with the associated sand laminae thickness series from the two sites (Fig. 10). In both modelled scenarios (Fig. 10b, c, f, g) a noticeably higher tide recurs every 3–9 tides approximately, with the highest frequency variations in the 4% model and a predominance of slightly longer periods in the 8% model. Within these cycles there is also a strong impression that tides tend to be alternately higher and lower which generates the jagged profile also typical of the raw laminae thickness plots (Fig. 10a, b, e, f). Superimposed on these higher frequency patterns is a clear, symmetrical 10–40 tide repeating cycle of increasing, then decreasing, tidal range which, when smoothed, again closely resembles the similarly smoothed sand layer thickness plots (Fig. 10d, g). However, only 9 of the 10 semi-annual cycles have been clearly preserved in these truncated data sets.

A close examination of the tidal height datasets reveals which of the twice-daily tides remain after application of the thresholds and consequently which of the tidal harmonic components are driving the temporal cycles of changing tidal height, and hence are most likely to be preserved in the sedimentary tidal signal. The tidal signal generated by the 8% threshold model contained 57 truncated neap-spring sequences each comprising between 1 and 9 individual tides. Those periods with more than 5 tides typically recorded the semi-diurnal pattern of alternate high and low spring tides, the shorter records only the highest daily spring tides. A further and more significant effect of the threshold has been that, within each semi-annual cycle, only alternate neap-spring cycles are represented. Five, occasionally six, alternate lunar months were present in each semi-annual cycle although the more complete records did preserve several consecutive, but still severely truncated, neap-spring periods. Each semi-annual period comprised 20–37 tides and the alternately higher and lower character of these equinoctial cycles was generally clearer than in the 4% model but became less so in the years when the lowest number of high tides was recorded. The 4% threshold model generated a series of 35 severely truncated neap-spring cycles comprising between 1 and 7 tides each. Each semi-annual cycle contains just 3 or 4 of these truncated neap-spring periods totalling 9–23 tides. Only alternate neap-spring cycles are represented here also and, within these, only 1 tide per day is typically recorded in the 1–4 tide neap-spring periods, but the slightly longer records of 4–7 tides tend to record both daily tides.

Discussion

Temporal variation in the sedimentary tidal signal

The manner in which the predicted pattern of high tides for Dungeness is modified as elevation within the tidal frame increases (Archer 1994, 1995; Kvale et al. 1995; Archer and Johnson 1997; Choi et al. 2001) points towards the possible sensitivity of the depositional system to the magnitude of the fortnightly and diurnal inequalities in tidal range. As elevation increases and the number of tides inundating the site falls the model predicts that neap-spring, and effectively lunar monthly, periods are increasingly represented by fewer days of tidal flooding (a proxy for declining sand laminae formation), which may themselves be further restricted (in the 4% scenario) to the 3 or 4 months around the time of the semi-annual maximum in tidal energy. An indication that occasionally an entire semi-annual cycle can be effectively removed from the record under these conditions is that only 9 of the 10 semi-annual peaks are recorded by the 4% threshold model. Conversely, relatively small increases in flooding frequency (sand deposition potential) can have considerable impacts on the completeness and complexity of tidal patterns likely to be recorded at a particular location. So, the 8% threshold models predict greater resolution of high frequency periodicities with semi-diurnal tides recorded more often, more layers per neap-spring period, and more neap-spring periods contributing (sometimes consecutively) to the signal. The consequence of this is longer wavelength semi-annual and annual periods and an overall increase in the complexity of the tidal signal.

Boulderwall farm

Applying the results of the modelling to the patterns of sand laminae thickness seen in the sample cores it can be deduced that the Boulderwall sediments record a relatively simple and repetitive pattern of short (<5 layers/cycle) neap-spring periods. The very high frequency alternation of thick and thin layers, which occurs sporadically along the sequence can be attributed to a combination of occasional preservation of the diurnal inequality and, at the other extreme, neap-spring periods in which less than 3 sand layers were preserved. The 6–8 layers/cycle period indicated on the spectral density plot (Fig. 6) and highlighted by the 3 point smoothing (Fig. 5) certainly reflects occasional periods when a slightly longer neap-spring record accumulated, but also probably relates to the creation of a spurious fortnightly inequality derived from the pattern of symmetrical semi-annual cycles that often contained only 3 or 4, alternate, neap-spring periods i.e. the lunar monthly cycle was not preserved in the sand layers. This may be seen as a form of natural aliasing—the misrepresentation of one periodic component as another (Smith 1997)—which is typically caused by an inappropriate sampling frequency but here is a natural element of the sand layer thicknesses time series, and is driven by the character of the depositional system.

Manor Farm

At Manor Farm results of the threshold modelling process suggest that the longer, and more complex, higher resolution record is also based on truncated neap-spring cycles of 2–5 layers. The less prominent spikes at 6–8 layers/cycle suggest the presence of occasional longer neap-spring records and also, as suggested by the 8% threshold scenario, the occasional preservation of a now genuine fortnightly inequality between successive spring tides. The lower power of these mid-frequency periodicities on the spectral density plots, in comparison to Boulderwall where the period is predominately an artefact of the severely truncated sedimentary record of tidal inundation, is consistent with this interpretation. At Manor Farm the signal is influenced to a relatively greater extent by the increased preservation potential of the neap-spring period. The variable longer period cycles (>14 layers/cycle) reflect systematic changes in this preservation potential, and also in the number of layers contained within individual neap-spring periods. This generates semi-annual and annual periods with a wider range of wavelengths here than at Boulderwall, and this too is consistent with results of the threshold modelling process.

Controls on deposition

Resolution of the sedimentary tidal signal

Whilst there are subtle spatial differences in the resolution of the preserved tidal signal, patterns of layer thickness and texture are relatively consistent through the laminated units at each site. Consequently, there appears to have been little significant temporal change in depositional conditions during tidal rhythmite accumulation (Coueffe et al. 2004). This contrasts with clear examples of sediments fining and/or layers thinning and becoming less numerous upwards as elevation increases and so accommodation space and flooding frequency decline (Archer and Johnson 1997; Greb and Archer 1998; Allen 2004; Dark and Allen 2005).

Assuming that there has been no change in tidal range or sea-level since deposition then accumulation of the laminated units occurred several metres below the level of the highest tides at both sites. So, whilst position within the tidal frame must, by definition, have been an important control on the resolution of the tidal signal preserved here, elevation/accommodation space alone was probably not the sole limiting factor on the number of layers deposited in any particular tidal cycle at each site. Whilst the simple elevational threshold model works well in terms of its ability to generate patterns comparable to those recovered from the sediments, an additional and similarly restrictive process or control must have contributed to limiting the formation (or preservation) of sand laminae, and hence the low number of layers deposited during neap-spring and longer periods at the two sites. It may be that only the highest few percent of tides were capable of sand transport, or perhaps more likely as the sand recovered here is composed primarily of very fine to fine grades of which the former is the more abundant, were energetic enough to overtop the gravel barrier with sufficient force to deposit a continuous sand sheet across the back-barrier intertidal zone. Lower tides may have resulted in a lenticular bedded sandy mud rather than more clearly defined and extensive sand and mud laminae (Reineck and Singh 1980; Klein 1985; Dalrymple 1992)—the range of sedimentary structures recovered from these sediments tends to support this (Fig. 3). This scenario probably reduces the likelihood of a sample core recovering a complete tidal signal although, as the sand layer thickness series clearly show, the fundamental thickening and thinning pattern is recorded.

In addition, given the textural evidence of sediment primarily composed of bi- or tri- modal muds, it may be that the sediments record a more complete record of tidal inundation than is recoverable from the sand layers alone. The majority of tides inundating a site may have left what, on subsequent consolidation, are seen to be silty (rather than heterolithic) tidal rhythmites (Archer 1998). However, in the wet, unconsolidated marsh cores these fine structures are not evident, although their presence is suggested by the ease with which the cores may be split even when there appears to be no well-defined sand layers present (Fig. 3a). Other possible mechanisms for the truncation of tidal cycles recorded in rhythmite sequences include erosion of thinner sand laminae, amalgamation of thicker sands due to erosion of intervening muds and disturbance of the thinnest layers by some physical or biological reworking (Greb and Archer 1995; Kvale et al. 1995; Archer and Johnson 1997; Choi and Park 2000; Li et al. 2000; Fan et al. 2004).

The upper limit of rhythmite preservation

The top of the laminated units at these and other sites at the barrier/back barrier interface tends to be at elevations more than 1 m lower than in the former tidal channels (Stupples 2002a, b; Long et al. 2006). An abrupt, rather than gradual, change from laminated to mottled sediments is common across the marsh and is also reported from the Bay of Mont-Saint-Michel (Tessier 1998). More generally, the results of rhythmite analysis here and in the upper intertidal area of the Bay of Mont-Saint-Michel are remarkably similar both in terms of the number of layers accumulating each year and the number of tides with which this equates, i.e. 3–5% of high tides (Tessier 1998). At the French site, the upper limit for rhythmite preservation is related to the non-linear decline in tidal inundation as elevation increases up the intertidal zone, but as elevation/accommodation space appear not to be restrictive at the Dungeness sites, it might be suggested that the extent of barrier progradation was the main control, acting in place of, but with the same effect as, the more typical restricting factor of elevation/accommodation space.

We propose that initial emplacement of the gravel storm beach at each site provided the protective embayment required for deposition of the finer grained minerogenic sediments. However, ongoing barrier progradation finally, and perhaps quite suddenly, restricted the frequency and intensity of tidal flooding to the extent that significant sand transport was no longer possible by individual tides and heterolithic tidal rhythmite accumulation ceased. A relatively uniform marshwide response is indicated with barrier progradation acting as both initiator of, and final control on the extent of, tidal rhythmite accumulation. Whilst availability of accommodation space appears not to be the ultimately limiting factor as it is elsewhere (Archer and Johnson 1997; Archer 1998; Tessier 1998; Stupples 2002a, b) tidal flat elevation remains significant in controlling spatial variation in the resolution of the preserved signal at across the marsh.

The back-barrier tidal signature

In summary, the tidal signal preserved in the sand layer thickness variations of the heterolithic tidal rhythmites at Boulderwall and Manor Farms was dominated by a severely truncated neap-spring cycle, with a subordinate diurnal inequality occasionally preserved. Due to the highly punctuated nature of deposition suggested from the threshold models it is proposed that the lunar monthly period is either absent, or at least only sporadically preserved, in the sand layer thickness series and only alternate neap-spring phases are typically represented. Complexity arises at both sites not only from the apparently punctuated pattern of deposition over the month–year timescale but also from considerable variation within the higher frequency periodicities. The wavelength of successive neap-spring cycles changes continually and the diurnal inequality may also be preserved at times, causing further confusion with the neap-spring periods of only 2–3 layers and, inevitably, interference on the spectral density plots. These variable, high frequency cycles generate the typically complex Dungeness spectra and drive the noisy character of the tidal signal (Martino and Sanderson 1993; Kvale et al. 1995; Choi et al. 2001). The longer wavelength periods can, despite the counter-intuitively small number of layers which they contain, be reasonably assigned to annual/semi-annual cycles comprising as few as three alternate neap-spring periods centred around the equinoctial peaks in tidal energy. These periods are best identified in the smoothed plots of sand layer thickness (Fig. 7).

Evidence from other studies also supports this interpretation despite the small number of layers deposited by each neap-spring cycle. The tidal range in Rye Bay is currently around 6.7 m. (Admiralty Tide Tables 2006) which is less than half that recorded at Mont-Saint-Michel and the Bay of Fundy, and even here complete neap-spring cycles are not preserved, or at least not consistently. Periodicities of 15–25 layers per fortnight are reported from the Bay of Fundy (Dalrymple and Makino 1989; Dalrymple et al. 1991) and 10–12 at the French site (Tessier et al. 1995; Tessier 1998). In addition, rhythmites from the Carboniferous of eastern USA (Archer 1996) have neap-spring cycles of only 8–9 layers/cycle, resulting from deposition relatively high in the tidal frame. This suggests that the interpretation of the high frequency cycles here is reasonable

Comparing patterns of sand and mud layer thickness

Although there is certainly some sense of cyclicity in the mud layer thickness data (Fig. 11), it is expressed as broader peaks (i.e. groups of several similarly thick layers) recurring every 10–20 layers whilst the higher frequency periods seen in the sand layers are not well developed. As anticipated above these data do little to aid interpretation of the cyclic nature of sedimentation here, but when compared to the sand layer thickness records a significant relationship becomes apparent.

Plots of both unprocessed (Fig. 11a) and smoothed (Fig. 11b, c) sand and mud layer thickness data show the two series to be slightly out of phase with each other. Although not a direct inverse relationship, as sand layers thicken, muds thin, and vice versa, and this relationship is apparent both at the level of the individual tides over several layers (neap-spring, Fig. 11a) and over the longer semi-annual periods (Fig. 11b, c). This suggests a distinction between tides, which inundated the site and deposited only mud and those which left distinct sand laminae.

From a consideration of the results of the tidal heights threshold modelling, preservation of distinct

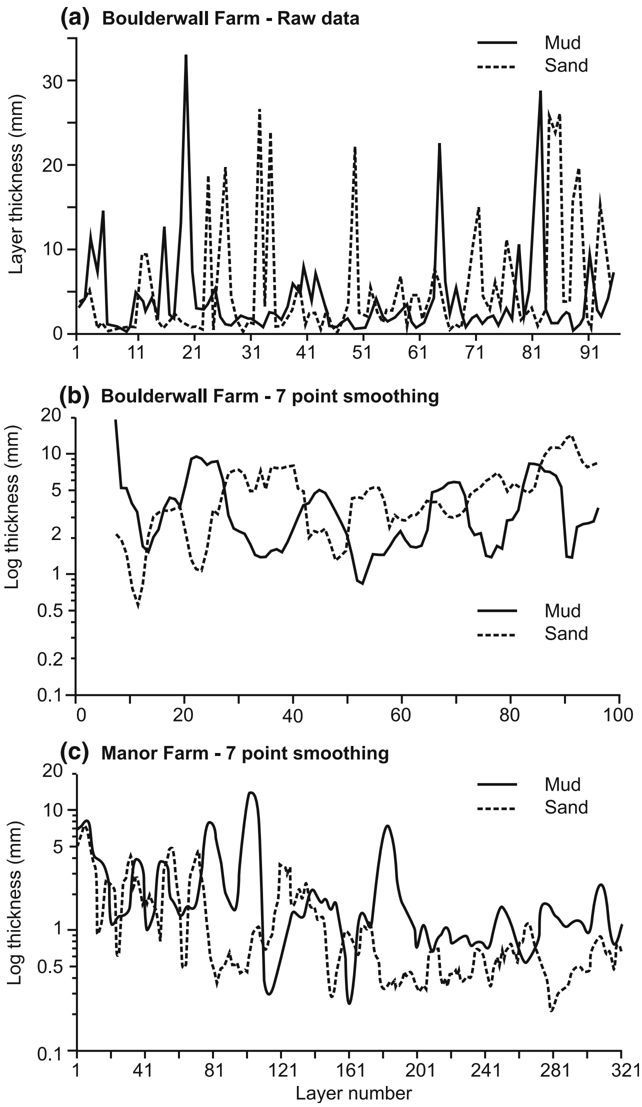

Fig. 11 Sand and mud signals out of phase over neap-spring (**a**), to semi-annual periods (**b**, **c**)

heterolithic rhythmites—sands intercalated with thin mud drapes—was typically restricted to just a few tides every other neap-spring period around the highest spring tides. Moving away from the period of high spring tides deposition shifts to an increasingly mud-dominated phase, initially perhaps very thin sand stringers are preserved then possibly silty rhythmites, and finally undifferentiated mud as the length and energy of inundation declined. This out of phase relationship would be reinforced at this temporal scale if sand layer deposition was indeed restricted to alternate neap-spring periods as more-or-less uninterrupted mud would have accumulated during the intervening 2–3 weeks.

Over semi-annual periods the relationship follows the same principles but now the solsticial-equinoctial cycle of tidal range is superimposed. Williams (1991) found an inverse relationship between layer thickness and the number of layers per neap-spring periods over these semi-annual cycles in an incredibly well-preserved sequence of Upper Proterozoic rhythmites which records over 60 years of apparently continuous deposition. This was interpreted as representing the distinction between the enhanced equinoctial tidal range, when the exceptionally energetic spring tides deposited thicker layers but neap tides were too weak to deposit recognisable laminae, and the lower tidal range at solstices that deposited a more complete neap-spring record of thinner layers as spring tides were less energetic, but neaps more so, at this time. In the much lower resolution Dungeness system this relationship is evident in the out of phase character of the long wavelength cycles of sand and mud layer thickness and is perhaps also reflected in the subtle spatial change in the resolution of the tidal signal preserved at Manor and Boulderwall Farms respectively. Moving away from the equinoctial peaks in tidal energy the opportunities for sand layer deposition starts to decline and the opportunities for uninterrupted accumulation of mud rises accordingly. As tidal flat altitude was not restrictive and sediment supply was not limiting, at least in terms of the availability of a continuous range of particle sizes, then the key control on heterolithic rhythmite formation here was the variation in tidal height, and hence flow velocity, over daily to annual periods.

Non-tidal influences on patterns of sedimentation

If sedimentation were dominated by a purely seasonal signal, generated by some non-tidal fluvial, meteorological or other factor, then the sand and mud layer thickness signals are more likely to be in phase and it seems unlikely that the out-of-phase relationship between sand and mud thickness described above would be evident at the higher frequency neap-spring level (Fig. 11a). In addition, the symmetrical appearance of the proposed semi-annual cycles (Figs. 7, 11b, c) in both smoothed sand and mud layer series is strongly indicative of a tidal control, non-tidal influences are typified by a skewing of these semi-annual cycles (Kvale et al. 1994). The alternate higher and lower semi-annual peaks in the smoothed layer thickness plots, more particularly from Boulderwall, is also seen in the Dungeness tide station data at this wavelength and is typical of other sedimentary sequences in which long tidal rhythmite records have preserved semi-annual and annual periodicities (Martino and Sanderson 1993; Kvale et al. 1994, 1995, 1999; Tessier 1998).

A seasonal influence on the clarity of the tidal signal preserved in the sedimentary record (Van den berg 1981; Brown et al. 1990; Dalrymple et al. 1991; Kvale et al. 1994; Park et al. 1995; Allen and Duffy 1998a, b; Li et al. 2000; Allen 2004; Fan et al. 2004; Staub et al. 2000; Dark and Allen 2005) such as storm incidence, biological activity or river discharge cannot, of course, be entirely ruled out. For example, periods when sand and mud layer thickness patterns tend towards being in-phase with each other perhaps suggest that the longer period elements of the tidal signal were occasionally modified by some other factor. However, and more importantly, the fundamental higher frequency pattern of thickening and thinning sand layers remains intact throughout the sand layer time series at both sites. Similarly, sections of these and other cores were certainly disrupted to some extent by bioturbation but in these two cases at least, not to the extent where the sedimentary structures were destroyed.

Clusters of sand-dominated laminae are clearly indicative of a higher energy period of sedimentation, winter storms for example, but whilst such pulses of coarser material are often recorded in the Romney Marsh sediments (Fig. 2), they do not recur with any regularity and again, of most significance here, do not override the general cycles of thickening and thinning. Results of contemporary monitoring (Allen and Duffy 1998a, b) and studies of laminated Holocene sequences (Allen 2004; Dark and Allen 2005) in the Severn Estuary seem to demonstrate the importance of non-tidal meteorologically driven factors in moderating the strong tidal influence on sedimentation in the mid- to upper intertidal zone. Consequently, whilst individual mm-scale laminae in the Holocene Severn Estuary sequences are ascribed to deposition from individual tides, longer period cyclicities are driven by seasonal changes in wind wave activity and water temperature leading to cm-scale annual banding of an alternately finer (summer) and coarser (winter) character (Allen 2004; Dark and Allen 2005). These patterns are defined on the basis of detailed textural profiles; and whilst annual band widths are reported, the mm-scale laminae of which they are comprised were not measured so any higher frequency cycles preserved in the layer thickness data cannot be determined. In contrast, annual banding developed under a predominately tidal control, such as the upper intertidal deposits in the Bay of Mont-Saint-Michel (Tessier 1998), are not characterised by this well-defined textural distinction of regularly alternating fine/coarse bands. Textural profiles (Fig. 2) from Manor and Boulderwall Farms are similarly not indicative of a strong seasonal control on sedimentation.

Conclusions

This study has combined several lines of new evidence—lithostratigraphy, granulometry, a theoretical consideration of how and why tidal patterns at Dungeness change through time, and statistical analysis of actual and modelled sedimentary tidal signals—supported by previously published research, to illustrate that depositional palaeoenvironments capable of preserving heterolithic tidal rhythmites developed at the barrier/back-barrier interface in the lee of gravel storm beaches deposited during the eastward progradation of the Dungeness Foreland. Deposition of the laminated units at the Boulderwall and Manor farm sites was primarily controlled by initial creation of a protected embayment behind the barrier and ended when progradation effectively distanced and sealed-off the sites from regular, energetic tidal inundation. Here, tidal flat elevation, modified by the degree of protection offered by the protecting storm beach, controlled the site-specific resolution of the tidal signal encoded within the sediments. Temporal change at individual sites reflected variations in tidal flow velocity, and hence sand transport capacity, over daily to annual periods.

The sensitivity of the system to relatively small changes in flooding frequency, and support for interpretation of the principle cyclic components within the sand layer thickness data (e.g. neap-spring) despite the small number of layers preserved in each, was derived from a detailed consideration of the effect of truncating the predicted high tide time series from Dungeness via successive elevation thresholds. This modelling suggests that only a small percentage of high tides need to be preserved in the sedimentary record to allow extraction of the tidal signal and hence estimation of deposition rates. Patterns within the textural evidence, the relationship between the sand and mud layer thickness time series, point to the likelihood that more tidal inundations are recorded in the sedimentary record than is apparent from the sand layers alone. In mud-dominated sections the system may have shifted from deposition of heterolithic to silty rhythmites and whilst these fine structures were not visible they are suggested by the multi-modal particle size distributions.

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