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Particle-size evidence of estuary evolution: A rapid and diagnostic tool for determining the nature of recent saltmarsh accretion

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A B S T R A C T

A conceptual model of saltmarsh sedimentation based on high-resolution particle-size analysis has been tested on short cores (c. 0.5 m) of known age from the Dee estuary, NW England, UK. Here, two components of the particle-size distribution (PSD) are interpreted as the traction load deposited by the faster tidal flow velocities ('fast tide') and the suspension load that settles during the turn of the tide ('slow tide'). The feasibility of this model for diagnosing the driving mechanism of estuary evolution in both time and space is tested with reference to historical evidence of saltmarsh accretion, up-core trends in dated saltmarsh cores, and the PSDs of present-day saltmarsh surface sediments. Cores that show an up-core progression from very fine-skewed to near symmetrical PSDs are interpreted in the context of estuary infilling due to a positive sediment budget (sediment surplus), whilst those that show a persistence of near-symmetrical, (very) poorly sorted, mesokurtic particle-size distributions in the fine to very fine silts size range are considered to be the result of 'slow tide' sedimentation. The influences of the two 'end-member' styles of saltmarsh accretion, i.e. (i) infilling due to sediment surplus and (ii) 'slow tide' settling linked to sea level, exhibit spatial and temporal trends as predicted, particularly in cores from mid- and lower saltmarsh locations. The upper saltmarsh cores also show evidence of estuary infilling due to 'slow tide' sedimentation at rates in excess of sea-level rise. The results confirm that the diagnostic approach can be applied as a 'pre-filtering' method for assessing the suitability of saltmarsh sediments for reconstructing sea-level trends, and for providing input data for improved estuary morphological modelling.

1. Introduction

Sea-level rise is one of the major concerns for coastal managers, environmentalists and geoscientists as it is likely to cause substantial losses of estuarine and coastal habitats and increases the risk of flooding (Orson et al., 1985; Reed, 1990, 1995; Cahoon et al., 2006). Thus, research into past coastal geomorphic responses to changing sea level must be undertaken at an appropriate resolution to establish the trajectory of change and the key forcing factors and relationships involved in order to better inform resource management decisions. Allied to this is research determining rates of sea-level rise for the last millennium from the same coastal geomorphic and sedimentary evidence base to establish any anthropogenically-induced accelerations (Edwards and Horton, 2000; Gehrels, 2000; Edwards et al., 2004; Gehrels et al., 2005; Edwards and Horton, 2006; Kemp et al., 2011) — not simply to quantify the significance of this forcing factor but to establish the consequent coastal environmental changes that come with accelerated sea-level rise (e.g., Pethick, 1993).

The particle size distribution (PSD) of sedimentary deposits has long been used as an indicator of flow strength, the characteristics of transport and deposition mechanisms, and the variability of these phenomena within the depositional environment (e.g. Allen, 2000). Summary statistical grain-size parameters including mean, median, mode, sorting (standard deviation), skewness and kurtosis (Inman, 1952; Folk and Ward, 1957) have been used to describe the PSD of sedimentary deposits, with the assumption that one or more of these parameters will accurately describe the key components of a given distribution and facilitate interpretation of the depositional environment (Friedman, 1961, 1967). Indeed, PSDs are particularly sensitive indicators of changes in flow regime in a wide variety of environments (e.g. Lario et al., 2002), and integrate the respective deceleration and acceleration of the flood and ebb tidal flow velocities at the turn of the tide (e.g. Stupples and Plater, 2007).

The present work aims to use PSD data from short cores (c. 0.5 m) to provide a diagnostic tool for determining the nature of recent saltmarsh accretion, distinguishing between: (i) estuary infilling due to a positive sediment budget (sediment surplus) and (ii) vertical accretion linked to sea-level rise. This is of considerable value to ecological transfer function studies of past sea level as it provides a rapid means for establishing the

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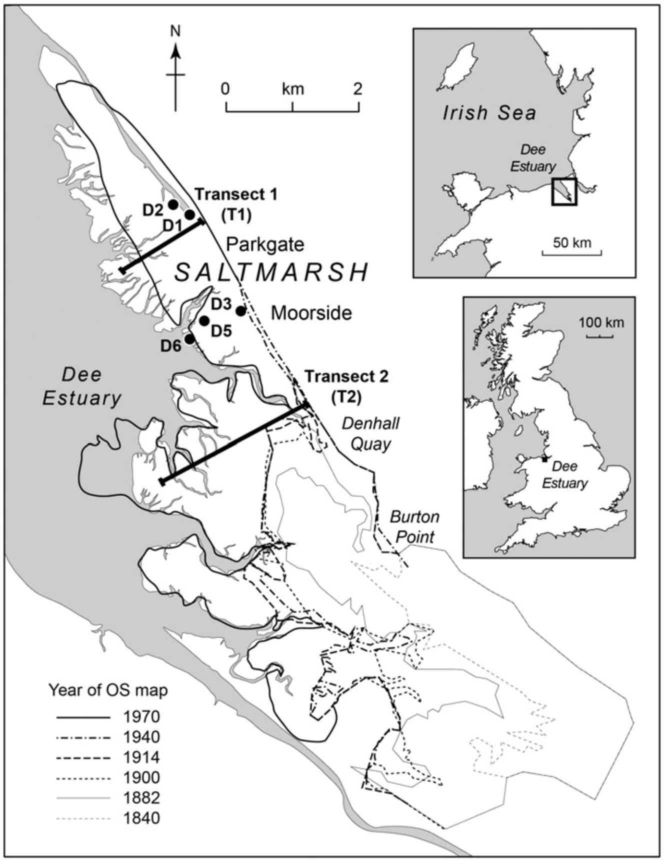

Fig. 1. The location and setting of the Dee estuary in eastern Irish Sea, UK, illustrating the saltmarsh surface sampling transects and core locations used in this study. The historical shorelines shown are derived from a time-series of OS map editions (Flint, 2007).

viability of any given saltmarsh core for recording evidence of historical sea-level rise. The diagnostic tool is developed and applied using statistical parameters and the shape of high resolution PSDs for saltmarsh sediment archives known to have been laid down by these two modes of accretion over the historical period in the Dee estuary, NW England (Fig. 1).

2. Conceptual model of saltmarsh accretion

2.1. Factors influencing saltmarsh sedimentation

A saltmarsh is an emergent part of the intertidal area where fine sediment that has been transported by water is stabilized by vegetation (Boorman et al., 1998). Saltmarshes are usually found within temperate and high latitudes along the coasts where wave action is relatively low, allowing saltmarsh plants to become established and survive (Friedrichs and Perry, 2001). As the flooding tide crosses the saltmarsh, the vegetation operates to dampen the incoming flood currents and waves sufficiently to enhance settling (e.g. Stumpf, 1983; Leonard and Luther, 1995; Möller et al., 1999; Bouma et al., 2005; Neumeier and Amos, 2006). By reducing the flow velocity, turbulent intensity and total turbulent kinetic energy (TKE) – dependent upon plant architecture, size and spacing – the vegetated canopy also serves to reduce the potential resuspension of sediment from the saltmarsh surface both within and around the vegetation (Neumeier and Ciavola, 2004; Leonard and Croft, 2006). Hence, on saltmarshes dominated by allogenic inputs of mineral matter (as opposed to in situ organic sedimentation), sediments are deposited as a settling lag (Postma, 1961). The saltmarsh will accrete at rates determined by sea level, with the altitude of the saltmarsh surface being determined by sediment supply, the product of the duration and frequency of tidal flooding (hydroperiod, cf. French, 1993), and shallow subsidence (Cahoon et al., 1995). Taking a simplistic view, increasing saltmarsh elevation relative to the prevailing high water level decreases tidal flow velocity (cf. Boon, 1975) as well as the number of times the surface in flooded, thereby increasing the relative proportion of fine-grained sediment deposition towards the head of the saltmarsh (e.g. Beeftink et al., 1977).

Field observations show that the flow velocity of the flooding tide over the saltmarsh increases as the tide transitions from a hydraulically efficient channel flow to a relatively inefficient flow over the vegetated saltmarsh surface, thus generating a water surface slope and a velocity 'pulse' (e.g. Bayliss-Smith et al., 1979; French and Stoddart, 1992; French et al., 1993; Allen, 1994). The same effect occurs to a greater extent on the ebb. The interaction between the velocity pulse, creek flow turbulence and the presence of flocculated particles account for the decrease in the grain size and the rate of sediment deposition away from the channel margin (Allen, 1994, 1996). In this respect, proximity to the point of tidal ingress over the saltmarsh also plays an important role in determining the characteristics of sedimentation.

The deposition of tidal deposits in relation to the frequency and duration of tidal inundation is perhaps best considered with reference to the phase-lag between idealised sinusoids of flow velocity and tidal height (e.g. Elliott and Gardiner, 1981). Here, maximum and minimum tidal heights (high and low water, respectively) are characterised by negligible flow velocity at slack water as the tidal vector turns. Similarly, maximum tidal flow velocities are experienced around mid-tide on both the rising (flood tide, directed onshore) and falling (ebb tide, directed offshore) tides. However, tidal creeks and saltmarshes are subject to marked tidal asymmetry (Postma, 1967; Ridderinkhof, 1997) whereby maximum tidal discharges and flow velocities (both flood and ebb) are shifted towards the time of the high-tide slack water (Boon, 1975). Consequently, the strongest tidal flows are experienced by the upper part of the intertidal zone, which are then supplemented by shallow water tidal constituents; as the flood tide rises onto the upper part of a tidal flat (saltmarsh) it is characterised by flow velocities that fall from their maximum to virtually zero at high tide (see Fig. 5 in Boon, 1975).

Interpretation of saltmarsh sedimentation has been largely done in the context of settling from suspension (and re-suspension) with limited consideration of different sediment transport modes, although considerable attention has been paid to the origins, composition and fate of different grain sizes — and especially large 'flocs' (French et al., 1993; Graham and Manning, 2007). Indeed, Woolnough et al. (1995) explicitly consider different grain size populations but again only from the perspective of settling and thus differential settling velocity. Whilst sediment deposition is a continuum determined by the relationship between fall velocity and turbulent up-currents, tidal deposition can be associated with two modes of sediment transport. The first of these modes is the 'traction load', in this case a combination of particles rolling and sliding along the bed, moving in a series of short hops, and, especially, in intermittent suspension (cf. Yang, 1986). In essence, this load includes sediments transported by the 'surface creep' and 'saltation' mechanisms described by Visher (1969), and represents the 'coarse' component of the deposited saltmarsh sediment — the mean grain size of which will decrease as flow velocity decreases. The second mode is the suspension load whereby turbulent flow is sufficient to maintain 'fine' grain sizes within the water column. Again, as flow velocity decreases, progressively finer particles settle to the bed. (Nb. The terms 'coarse' and 'fine' grain sizes are used in a relative sense in the conceptual model, and are not intended to relate, respectively, to non-cohesive and cohesive grains.) This process is aided by flocculation, enhancing the settling of fine particles that would otherwise require several hours to settle (Pejrup, 1988; Van Leussen, 1988). These flocs demonstrate a significant level of interaction with the saltmarsh vegetation canopy, creek margin/estuary mixing processes, turbulent shear and particle composition (Manning, 2004), and play an important role in saltmarsh sedimentation and morphodynamics (Graham and Manning, 2007).