Characterisation of estuary and adjacent beach sediments in the Gannel Estuary, South-West England

T.D.T. Oyedotun[1,2], H. Burningham[1] and J.R. French[1]

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This study presents results arising from an analysis of the spatial variation in sediment grain size within the Gannel Estuary, Cornwall, South-West England. Sediment samples acquired at the surface and at intervals to a depth of 15 cm were analysed using a *Malvern MasterSizer 2000* and the resulting distributions processed to yield a range of grain size statistics using the *GRADISTAT* software package. A principal component analysis, supported by a cluster analysis, shows that 76% of the variance in the grain size distribution across the samples is represented by fine-medium-coarse sand, and 17% is represented by the coarse/very coarse sand component. The comparison of grain-size statistics, and cluster analysis, reveals clear populations associated with the specific sub-environments of the beach and inner estuary. Importantly, this analysis shows that sediment characteristics can be discriminated clearly by sub-environments, but not on the basis of shallow depth below the surface.

[1] Coastal and Estuarine Research Unit, UCL Department of Geography,
University College London, Gower Street, London, WC1E 6BT, U.K.
[2] Department of Geography and Planning Sciences,
Adekunle Ajasin University, P. M. B. 001 Akungba-Akoko, Ondo State, Nigeria.
(E-mail: temitope.oyedotun.10@ucl.ac.uk; oyedotuntim@yahoo.com).

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Introduction

The nature of estuary sediments reflects the transport processes operating at local and regional scales as well as the longer-term evolution of estuary morphology (Anthony and Héquette, 2007). Grain-size remains the most important property to inform our understanding of these linkages as it provides fundamental information on sediment transport dynamics, the transport history and provenance of sediment supply through depositional conditions (Folk and Ward, 1975; Friedman, 1979; Blott and Pye, 2001). Grain-size trends, which may be primarily related to abrasion and selective sorting effects (Le Roux and Rojas, 2007), are naturally the result of sediment transport processes (Krumbein, 1938; Russell, 1939; Swift *et al.*, 1972; Stapor and Tanner, 1975; McCave, 1978; Harris *et al.*, 1990; Le Roux and Rojas, 2007).

Key grain size statistics (e.g. those relating to the average, sorting, skewness and kurtosis) have traditionally been obtained by sieve or settling techniques (Blott and Pye, 2001; Le Roux and Rojas, 2007). However, modern laser diffraction sediment size analysers permit much more rapid processing of large numbers of samples (Eshel *et al.*, 2004; Blott and Pye, 2006).

The aim of this study is to characterise and analyse size variation in the surface sediments of the Gannel Estuary, on the North Atlantic coast of Cornwall, South-West England. Specifically, the study investigates the variability in sediment characteristics within the estuary and on the adjacent beach with a view to elucidating the nature of the sedimentary exchanges that occur between these two environments.

Gannel Estuary

The Gannel Estuary is situated southwest of Newquay, between Pentire Point East and Pentire Point West, on the north coast of Cornwall, South-West England (Figure 1). This coastline is macrotidal (mean spring tide range of 6.4 m), and is exposed to a predominantly westerly wave climate with a 10% annual exceedance wave height of 2.5 - 3 m and a 1 in 50 year extreme offshore wave height of 20 m. Wave heights regularly exceed 5 m during the winter months and swells of 15 seconds or more are common (Royal Haskoning, 2011).

The Gannel is a ria estuarine system comprising sandy intertidal flats within a narrow valley merging with a large sandy beach-dune system (Crantock) at the seaward extent, especially towards the mouth of the estuary, and saltmarshes at the landward extent. Around 70% of the estuarine valley is intertidal (Davidson *et al.*, 1991). It has been suggested that the estuarine system (between the Devonian slate/sandstone headlands of Pentire Points East and West, Hollick *et al.*, 2006) functions as a self-contained sediment cell (Dyer, 2002). However, there may be weak and intermittent alongshore transport and some limited exchange of sediments between the bay and open coast, especially across the low intertidal, and during storm conditions (Royal Haskoning, 2011; see also Figure 1).

Previous research on the Gannel Estuary has primarily focused on the impact of mining on sediments and sedimentation (Reid and Scrivenor, 1906; Bryan *et al.*, 1980; Pirrie *et al.*, 2000a, b). Historical siltation of the estuary mouth has been attributed to a combination of sediment release from

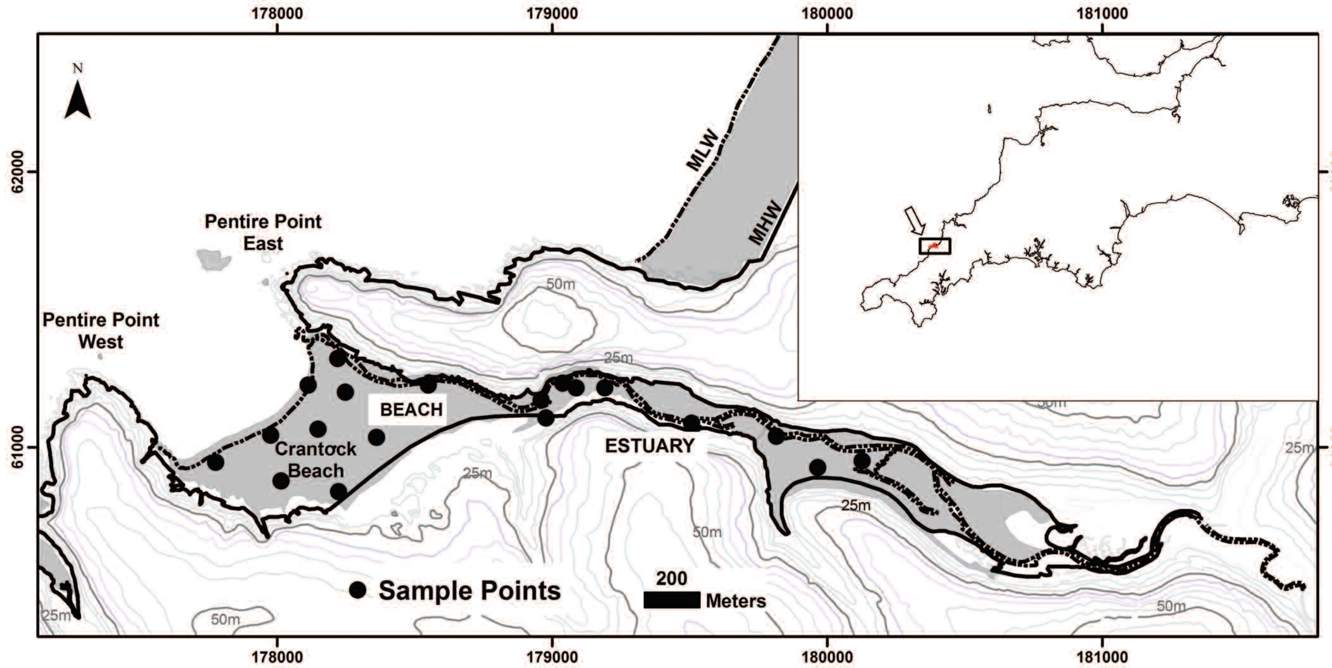

Figure 1. *The Gannel Estuary showing the location of sediment sample points and (inset) its situation in South-West England.*

mine works in the catchment supplemented with marine-derived shell-rich sand (Reid and Scrivernor, 1906), implying that sediments throughout the mouth comprise a mixed population from these two sources. Heavy metal contamination research in estuaries in South-West England (including the Gannel), has confirmed the strong sedimentary link to mining waste. Pirrie *et al*. (2000a) reported high concentrations of Pb (8,500 ppm) and Zn (1,600 ppm) in the Gannel, attributed to mining activity in the late 1800s.

Methodology

A total of 19 short cores (length <15 cm) were collected in October 2011 from the Gannel-Crantock intertidal zone (Figure 1) using a 65 mm diameter tube. Sample locations were positioned using a hand-held Global Positioning System (GPS), (±4 m). Cores were sliced at 1 cm vertical intervals and grain size distributions of these subsamples were analysed using a *Malvern MasterSizer 2000* particle analyser (Malvern, 1999), which computes the grain size distribution across the range 0.02-2,000 µm. No sediment coarser than sand (>2,000 µm) was present. Folk and Ward (1957) grain size statistics (median (D_{50}), sorting (spread of the distribution) and skewness (asymmetry of distribution)) were calculated using *GRADISTAT* software (Blott and Pye, 2001). Principal component analysis (PCA) was used to reduce the grain size distributions across all samples into a smaller number of key variables. Hierarchical cluster analysis (using Euclidean distance and average linkage, which produced the strongest cophenetic correlation of 0.74) was applied to the grain size distributions to organise samples into groups comprising similar sedimentological characteristics. Calculations were undertaken in *Matlab*.

Results

Median (µm), sorting (standard deviation expressed in µm units) and skewness values of sediment samples (sites identified in Figure 1) from both estuary and beach environment are summarised in Figure 2. Median grain size is consistently variable through the shallow stratigraphies examined here, but sediment recovered from the two sub-environments show marked differences. The bulk of the samples (76%) can be classified as moderately to well sorted sand, while about 24% of samples can be described as poorly to extremely poorly sorted sand or silt. Sediment size sorting improves with an increase in grain size. The more poorly sorted sediments are classified as silt/fine sand and the moderately to well sorted sediments are classified as medium/coarse sand.

The data presented in Figure 2 reveal little systematic variation in grain size parameters with depth. However, differences between the estuarine and beach sub-environments are evident, with the estuarine samples being finer, less well sorted, and more strongly negatively skewed (Figure 2). Differences between estuary and beach environments are significant (99.9% level) for both the median grain size and skewness (Table 1).

Differences in the sediment population, and evidence for mixed sediment sources (e.g. the likely input of mining waste derived sediment *vs*. the contribution from the marine environment), may explain the differences in grain size texture, but these summary statistics are often blunt tools with which to compare sediments with complicated grain size distributions. Multiple modes are particularly difficult to account for in summary statistics, but the full distribution allows recognition of these sub-populations (Figure 3). The difficulty with distribution data is that they are not readily comparable (sample to sample), but multivariate statistics can be used to derive a smaller number of variables that comprise the majority of the variance in the data, in addition to exploring differences and associations in the data for the grouping of similar characteristics.

Principal component analysis of the grain size distribution in this study derived two principal components (PCs) that together account for approximately 93% of the variance (Figure 4). PC1 explains 76% of the variance and is dominated by the medium sand (MS) part of the distribution, and to a lesser extent coarse/very coarse sand (CS/VCS) and some fine sand (FS), but a distinct lack of material smaller than fine sand. PC2, accounting for 17% of the variance, relates to a coarse component, specifically the presence of coarse and very coarse sand (VCS), and the lack of a fine-medium sand component.

Comparison of these first two principal components in a bivariate plot shows that sub-environment (estuary or beach) is a clear discriminator of sediment characteristics (Figure 5a),

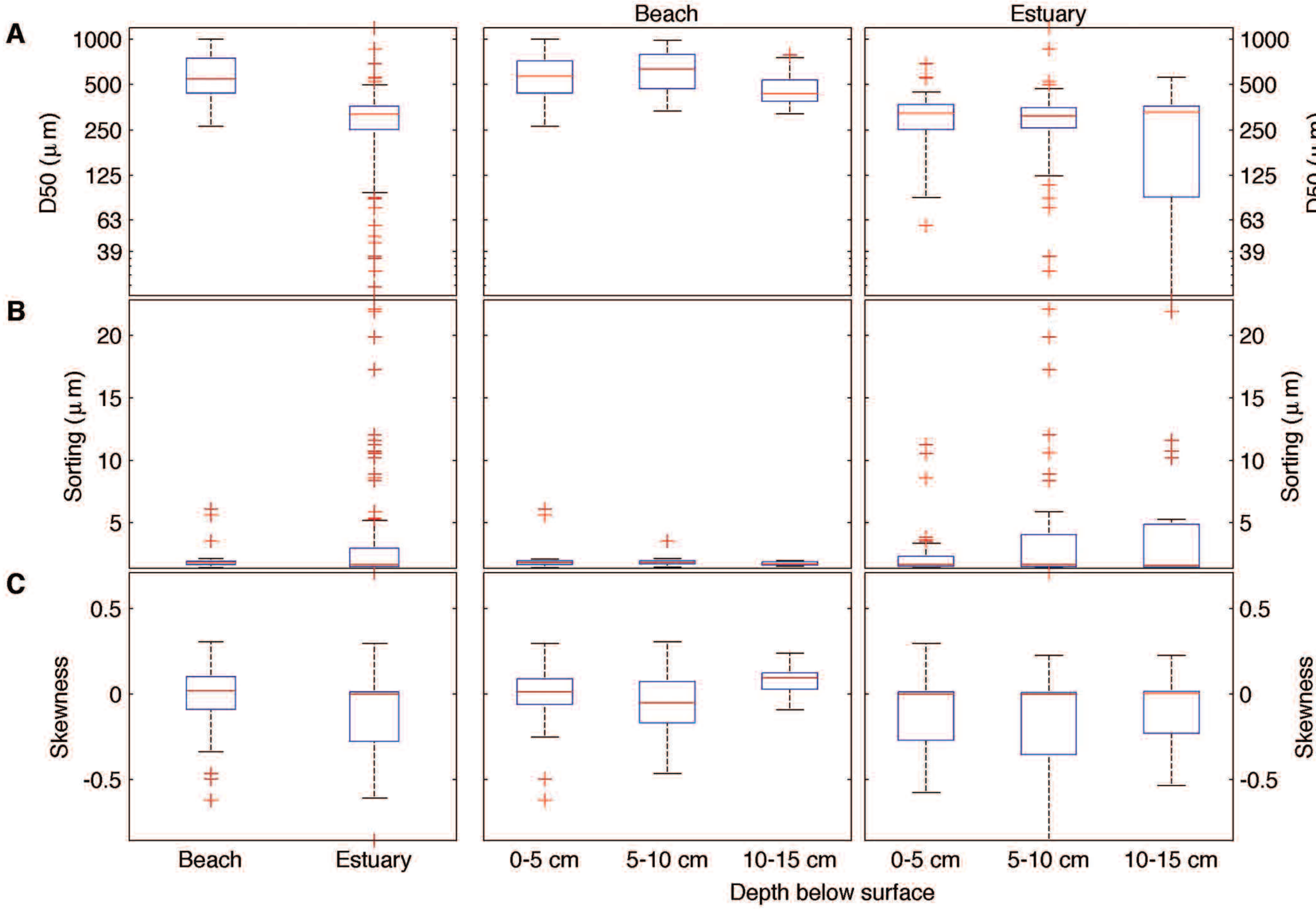

Figure 2. *Grain-size statistics for samples collected from points identified in Figure 1: (**a**) median (**b**) sorting and (**c**) skewness.*

Parameter	Sub-environment[1]	Depth (cm)
Median	<0.001	0.03
Sorting	0.25	0.5
Skewness	<0.001	0.04

[1] Beach *vs*. estuary

Table 1. *p values for Kruskal Wallis analysis of variance (difference of medians).*

whilst stratigraphic depth is not (Figure 5b). Hierarchical cluster analysis of the grain size distributions facilitates a more formal grouping of samples comprising similar grain size distributions. The separation of samples identified in the PCA is clarified in the clustering of samples into 5 groups; all but 2 samples (both mid-depth, estuarine samples) are within clusters 1, 2 and 4, which can be described as environment-specific groupings (Figure 5). Cluster 1 refers to medium to high values on both PC1 and PC2, indicating a dominance of the coarser grain sizes and small contribution of finer material to these distributions. This cluster generally characterises the beach environment. Cluster 2 refers to high PC1 and low PC2 values, which corresponds to a dominance of fine and medium sand in

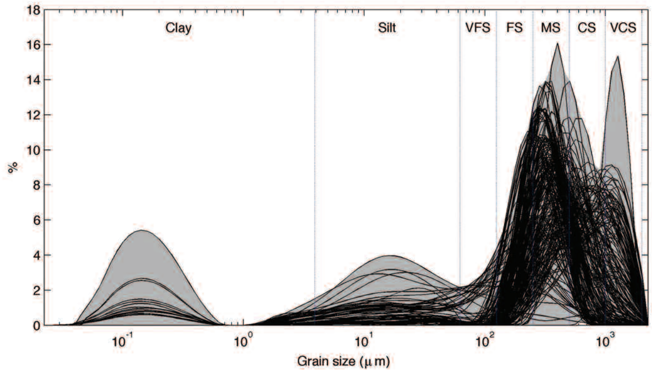

Figure 3. *Envelope of grain size distributions measured for the Gannel-Crantock sediment samples.*

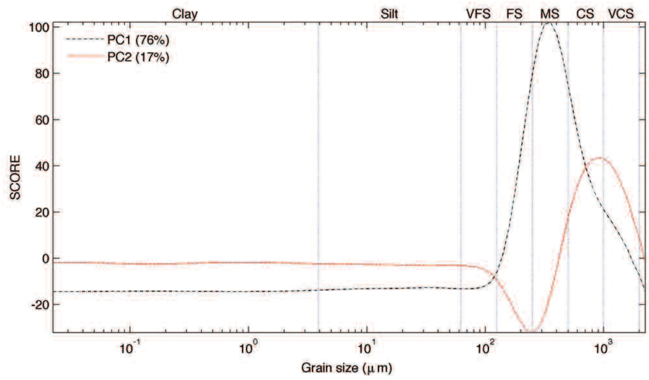

Figure 4. *Principal component scores in relation to the grain size distribution (see text for explanation).*

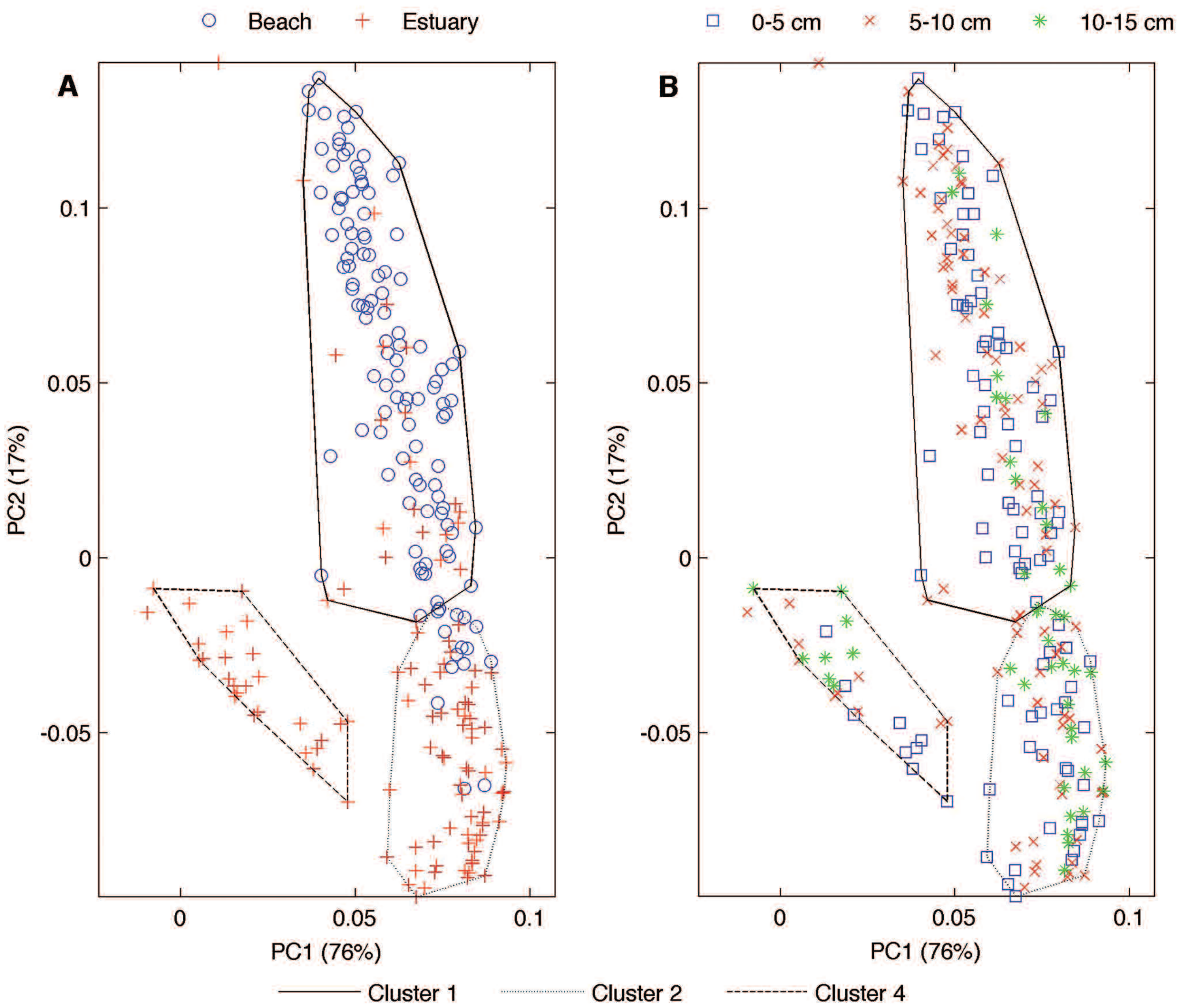

Figure 5. *Combined plots of PCA and cluster analysis of the grain size distribution for (**a**) the relative sub-environment (beach vs. estuary) and (**b**) relative stratigraphic depth.*

the grain size distribution. This cluster largely represents estuarine sediments, although several beach samples also exist in this group. Cluster 4 refers specifically to low PC1 and PC2 values, representing those samples containing a mix of fine material (silt and very fine sand) and limited coarser component: cluster 4 comprises entirely estuarine samples.

The principal component and cluster analyses of the Gannel sediments reveal that the beach environment is predominantly characterised by a mixture of medium-coarse sand while the estuarine intertidal is characterised by a mixture of medium-fine sand and finer material. However, there is some clear overlap in sediment populations from these sub-environments, evidenced in clusters 1 and 2 (Figure 5a). This implies that there is at least some sediment exchange (sand) between beach and estuary and that this is contemporary, given that it is evidenced by sediments at, and close to, the surface.

Stratigraphically, there appears to be a high degree of consistency in the PC-based sample clustering from surface through to 15 cm deep (Figures 5b and 6). This further supports the inference that both the compartmentalisation and partial exchange between beach and estuarine sub-environments can be attributed to the contemporary process regime. These results also suggest that sediment characterisation in this physical context is relatively insensitive to the sampling depth within the near-surface zone.

Discussion

The grain-size distributions of the sandy intertidal deposits in the Gannel system exhibit heterogeneity in the mixing of sand populations across the main beach and estuary sub-environments. As found in earlier studies in other systems (e.g. Folk & Ward, 1957; Flemming, 1988; Anthony and Héquette, 2007), grain size analysis reveals the existence of multiple sediment sub-populations. In the Gannel Estuary, the medium to coarse/very coarse sand population (cluster 1) is found across the beach environment, at surface and down to 10-15 cm depth (Figures 5 and 6). In contrast, a fine sand/silt population (cluster 4) is present in the estuary, again consistently evident from surface through to 10-15 cm depth. The spatial analysis reveals that this population is found just landward of the narrowest part of the Gannel estuarine valley, at the boundary between beach and estuary (Figure 6). The medium-fine sand population (cluster 2) is found throughout the estuarine valley, and crops up at depth in the beach environment.

Despite this compartmentalisation, it is clear that the sediment populations are found at other geographical and stratigraphical locations beyond their dominant sub-environment (Figure 6). Interaction between estuarine and coastal processes leads to the mixing of these sediment populations. Beach-type sediments (cluster 1) are found

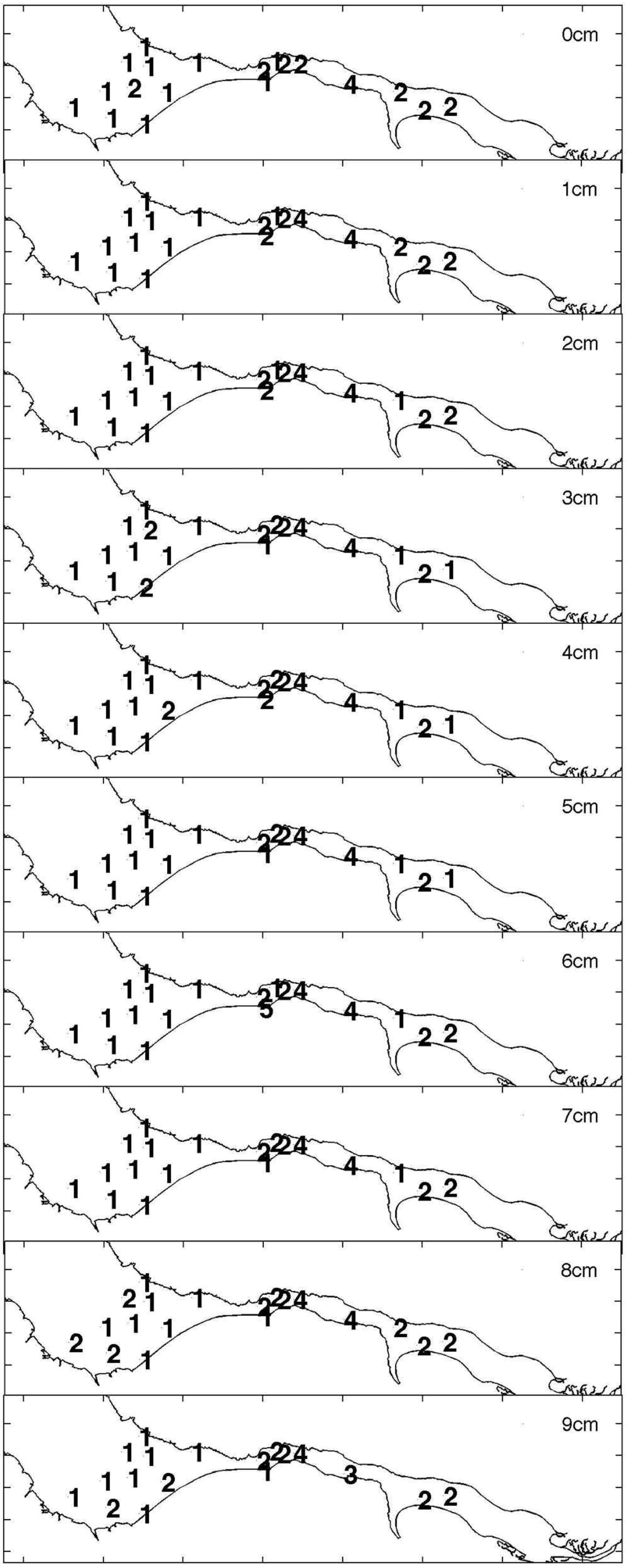

Figure 6. *Depth variation in the distribution of sediment sub-populations within the estuary and the beach. Numbers refer to the clusters identified in Figure 5.*

occasionally within the estuary, and estuary-type sediments (cluster 2) occur in places on the beach. Only the very fine material (cluster 4) retains a very consistent spatial and sub-environment association.

The spatial sedimentology presented here concurs with many previous studies of sediments in beach and estuary environments. The energy regime in the Gannel is at a maximum within the beach environment, which is dominated by high energy wave-driven processes. Here, the sediment population is characterised by medium-coarse sands. Energy levels decrease within the estuarine environment: although the system is macrotidal, the tidal prism here is limited by the narrow accommodation space, and open coastal waves are unable to propagate into the estuary. In this lower energy zone, a finer sediment population exists, and in places very fine material is also found. It is possible that selective transportation of the finer sand populations towards the estuary, which results from a probable washing of the sands towards the mouth of the estuary (Reid and Scrivenor, 1906), from a marine carbonate source (Merefield, 1982) or from heterogeneous shell-sand drifted in by the sea (Reid and Scrivenor, 1906), drives the compartmentalisation observed (Anthony and Héquette, 2007). At the beach, these hydrodynamic processes have led to the deposition of the coarser sand population, and removal of the finer population, leading to a moderately well sorted sand population.

The results clearly show that the contemporary sedimentary processes are consistent over a depth of 10 to 15 cm. The sedimentological discrimination demonstrated here is present throughout the centimetre-scale units. This could be the result of contemporary sediment activation (transport mechanisms) occurring throughout the near-surface profile. Alternatively, this may indicate significant consistency in the processes responsible for transport and deposition over the sedimentary timescale associated with the accretion of this profile. It is clear that a consistent sedimentary interpretation is achieved irrespective of where a sediment sample is obtained within 10 to 15 cm of the intertidal surface.

Conclusions

Sediments from the Gannel estuarine system can be classified sedimentologically into clear groupings that reflect both estuarine and beach sub-environments. There is some degree of homogeneity in the sediment populations occurring across these two sub-environments, but also a suggestion of mixing between beach and estuary.

Sediments across the beach are coarser, and moderately well sorted. Most of the samples within the estuary are finer, more poorly sorted, and negatively skewed. The size-sorting concept discussed by Flemming (1988), which suggests that sediment sorting improves with decreasing grain size, is not supported by the data presented here, which indicate a beach environment that is better sorted but coarser than the rest of the estuarine system.

The above findings are consistent across the top 15 cm of the sediment profile. This is a useful result in that it implies a robust chararactisation of estuarine and adjacent beach environments can be obtained through spatial sampling of the surface sediment.

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