Geomorphology 221 (2014) 51–68

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

A sediment record of barrier estuary behaviour at the mesoscale: Interpreting high-resolution particle size analysis

David W. Clarke [a,*], John F. Boyle [a], Richard C. Chiverrell [a], Javier Lario [b], Andrew J. Plater [a]

[a] Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Roxby Building, Chatham Street, Liverpool, Merseyside, L69 7ZT, UK
[b] UNED-Universidad Nacional de Educación a Distancia, Madrid, Spain

ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form 21 May 2014
Accepted 27 May 2014
Available online 9 June 2014

Keywords:
Particle size distribution curves (PSDCs)
Particle size windows (PSWs)
Barrier estuary
Barrier regime
Coastal resilience
Mesoscale

ABSTRACT

At present, limited understanding of mesoscale (years–decades–centuries) back-barrier lagoon, barrier estuary behaviour is a critical shortcoming for resource managers and decision makers. In this paper, high-resolution particle size analysis of a sediment core from an intermittently open and closed barrier estuary is utilised to reconstruct a history of back-barrier environmental change at mesoscale temporal resolution. Sediments from Pescadero Marsh, California, were analysed for their particle size distribution at consecutive 2-mm intervals down-core. Site selection, informed by a time series of maps and aerial photographs coupled with a robust core chronology, ensured that the particle size data primarily reflect changing hydrodynamics of the back-barrier area over the European–American era (1850 to the present). Following more traditional plotting of particle size data and summary statistics, and statistical analysis of particle size end-members, visual analysis and categorisation of particle size distribution curves (PSDCs) provide an effective basis for the identification of recurring modal sizes and subpopulations. These particle size windows (PSWs) are interpreted as reflecting different modes of sediment transport and deposition, i.e., suspension and saltation loads, the varying prominence of which is interpreted as being modified by barrier integrity. When considered together, the down-core mean particle size (MPS) trend and individual PSDCs offer considerable insight into mesoscale system behaviour at subannual resolution over multiple years. This behaviour is expressed in the recurrence of characteristic barrier estuarine environments (closed lagoon, tidal lagoon, tidal marsh, and open estuary) and the overall barrier regime, and their persistence over the last c. 150 years. Subannual and multiannual fluctuations in back-barrier environmental configuration are seen to be superimposed on a longer-term quasi-stable barrier regime, demonstrating the value of the applied methodology with regard to bridging the estuarine evolution (long-term, stratigraphic) and process (short-term, geomorphic) knowledge bases. The documented behaviour suggests a level of innate morphological resilience in the system over the long term despite episodic disturbance by high-energy storms. Such empirical demonstrations of resilient behaviour in coastal environments are rare at the mesoscale.

1. Introduction

Estuaries and their associated environments are considered to be the most valuable biome on earth per unit area (Costanza et al., 1997). These environments play a significant role in global biodiversity, carbon storage, and food production while also offering diverse advantages at a local scale, e.g., fuel and fibre, flood regulation, recreational resources, etc. (Brevik and Homburg, 2004; Millennium Ecosystem Assessment, 2005). Over the coming centuries, modern estuarine environments will experience a number of stressors that may affect their functions and resource value. Stressors include sea-level rise, likely between 26 and 82 cm by 2100 (IPCC, 2013), changes in precipitation and temperature patterns (Seager and Vecchi, 2010), and increasing human population density in the coastal zone (Creel, 2003). Establishing the future trajectories of estuaries in the immediate term is of critical importance for the environmental management community.

The geomorphology of Holocene barrier estuary environments is largely well understood over the macroscale (centuries–millennia) in terms of forcing, response, and resultant landform evolution, and also over the microscale (seconds–years) in terms of the process-response of sediment dynamics and landform morphodynamics. What is less well understood is their intermediate or mesoscale (years–decades–centuries) 'behaviour' (Cooper et al., 2007; Cooper, 2009), particularly for coarse clastic barriers and their associated intertidal environments with respect to sea-level rise (e.g., Jennings et al., 1995; Orford et al., 1995). This is a critical shortcoming as the mesoscale has become

* Corresponding author. Tel.: +44 151 794 2843.
E-mail address: d.w.clarke@hotmail.co.uk (D.W. Clarke).

http://dx.doi.org/10.1016/j.geomorph.2014.05.029
0169-555X/

the typical timescale of interest for decision makers (Cooper and McKenna, 2008; McKenna et al., 2008; Cooper, 2009). For many coastal systems written records, maps, and aerial photographs provide an initial basis for the understanding of mesoscale behaviour, yet these records are fragmented, variable in quality and of limited duration (Cooper, 2009). Improving our understanding of meso-scale coastal system behaviour has been identified as a challenge in the field of coastal geomorphology (French and Burningham, 2009).

In recent years, high-resolution analysis of the coastal sediment record has been a focus of many attempts to supplement historical records (cf. French and Burningham, 2009). The temporal resolution of sediment-based palaeoenvironmental reconstruction is limited by achievable sampling resolution and the sensitivity of the sediment archive to short-term change. Particle size analysis has successfully identified subannual variation in depositional processes in estuarine environments (Allen, 1990; Mohd-Lokman and Pethick, 2001; Allen and Haslett, 2002; Allen, 2004; Dark and Allen, 2005; Allen and Haslett, 2006, 2007; Stupples and Plater, 2007; Allen and Dark, 2008). High-resolution particle size analysis as a proxy for mesoscale hydrodynamic variability in a barrier estuary and lagoon environment is the focus of this study.

Barrier systems account for ~15% of the world's coastline, being best developed on micro- and mesotidal coasts (Fitzgerald et al., 2008) and, in the case of barrier islands, where storms have an important influence (Pilkey et al., 2011). Various drivers influence the behaviour of barrier subenvironments (cf. Fitzgerald et al., 2008), the relative importance of which may change through time, thus leading to barrier and back-barrier evolution (Roy et al., 1994). In barrier estuaries, the nature of back-barrier depositional environments is largely dictated by the coherence, or the openness, of the barrier system. This is demonstrated by Molinaroli et al. (2009) using modern sediments from lagoons with differing hydrodynamic parameters. Alternatively, Schneider et al. (2010) contrasted sedimentation in a number of estuarine environments over the late Holocene, demonstrating distinct sedimentary regimes between sites driven by barrier formation and low magnitude/high frequency barrier opening events. Similarly, Spencer et al. (1998) and Lario et al. (2002) diagnosed past periods of more open and more closed barrier conditions using bivariate plots of particle size summary statistics. This approach allowed the identification of abrupt changes in barrier integrity and aperiodic high-energy events embedded in late Holocene evolutionary sequences. A similar approach to clarifying past back-barrier environments and identifying extreme events was employed by Switzer et al. (2005). These studies highlight the potential for high-resolution, back-barrier estuarine core records of particle size distribution data to be excellent subannual archives of late Holocene environmental change. As such, consecutive time series of particle size data may be used to investigate mesoscale disturbance, response and recovery behaviours, or 'barrier regime'.

The study is conducted on a barrier estuary located at Pescadero in San Mateo County, California (Fig. 1). The Pescadero site incorporates an intermittently open sand barrier, a back-barrier lagoon, barrier estuary, and extensive wetlands ranging from salt marsh to freshwater reedswamp.

This paper seeks to examine whether chronological sequences of mesoscale environmental change in a barrier estuary back-barrier wetland, driven by variations in barrier coherence, can be reconstructed from the sediment record given a suitable core location (i.e., a consistent environment of deposition over the period of record, not heavily influenced by channel migration or land use), an adequate chronology, a sufficiently rapid sedimentation rate, and an appropriately fine sampling resolution. Environmental interpretations are informed by the varying prominence of different depositional processes expressed in the particle size distributions of consecutive core samples. Through this process, we seek to illustrate the wealth of readily interpretable palaeoenvironmental information available in particle size distribution curves. This information is often overlooked when particle size analysis is employed in palaeoenvironmental reconstructions.

2. Barrier and back-barrier processes and stressors

Back-barrier environments by definition feature some degree of regular water exchange with the ocean through inlets or breaches in the barrier system (Fitzgerald et al., 2008). These inlets may be multiple or singular and relatively short- or long-lived, in any case inlet opening or closure results from wave, tide, current, stream flow and storm action, variations in sediment supply or a combination of these factors (Cooper, 1994). Barrier inlet closure events—driven by longshore transport, wave overtopping, sediment overwashing, and onshore bar migration—usually accompany low stream flow combined with the largest regularly experienced waves (Ranasinghe et al., 1999; Baldock et al., 2008). Storms or unusually intense wave action are the primary mechanisms responsible for marine breaching, while fluvial breaching often results from elevated back-barrier water level causing piping and liquefaction in combination with reduced sediment supply to the barrier (Kraus, 2003). The depth of a barrier inlet relative to the tidal frame can significantly affect the hydrodynamics of the back-barrier area (Pethick, 1984; Woodroffe, 2007). Ephemeral barrier breaches generally open to approximately mean sea level, while more permanent inlets become deeper (Kraus, 2003). Breaching in present-day barrier estuarine systems may also be manual with artificial breaching performed to alleviate flood risk in the back-barrier, to aid navigation, to manage salinity and water quality, and to allow the free migration of marine organisms (Kraus et al., 2002). Human activity can also indirectly impact barrier opening regimes by altering catchment hydrology and morphology (Woodroffe, 2002).

Over multiannual and longer timescales, climatic cycles (e.g., ENSO) may be an important control on barrier coherence (Komar, 1997; Allan and Komar, 2002, 2006; Masters and Aiello, 2007; Ruggiero et al., 2010). Furthermore, events of lower frequency but extreme magnitude (i.e., large storms, tsunami, seismic activity) may be responsible for large-scale barrier depletion or shifts in relative sea level capable of impacting the barrier regime on a centennial scale (Cooper, 2002; Woodroffe, 2002; Masters and Aiello, 2007; Houser et al., 2008).

An 'intermittently closed or open lake or lagoon' (ICOLL) (Ranasinghe and Pattiaratchi, 1998; Ranasinghe et al., 1999; Dye and Barros, 2005; Gale et al., 2006; Haines et al., 2006; Everett et al., 2007) describes barrier estuary environments characterised by aperiodic closure. Many ICOLLs occur where highly seasonal streamflow is the dominant control on opening and closure, i.e., western North America, Australia, and South Africa (Elwany et al., 1998; Cooper, 2001; Roy et al., 2001). Such systems can be further distinguished as seasonally open tidal inlet (SOTI) environments (Ranasinghe and Pattiaratchi, 1998). The majority of the small drowned river valley barrier estuary systems found on the central coast of California, including the study site, are best classified as SOTI due to their observed seasonal behaviour linked to interacting river flow, wave climate and beach erosion (cf. Elwany et al., 1998). With respect to Pescadero, the back-barrier environment is characterised by two end-member states: 'closed lagoon' and 'open estuary'. The closed lagoon state emerges when barrier inlets (with respect to tidal ingress) are absent and water levels in the back-barrier area rise to create a non-tidal lagoonal pool. The open estuarine state occurs when the barrier inlet or inlets are sufficient to lower the water levels and allow tidal exchange with the back-barrier. Under these conditions the lagoonal pool is reduced to a tidal channel and the area it had covered becomes intertidal. Between these two end-member states a continuum exists in which a tidal lagoon and wetland will exist covering a reduced portion of the back-barrier area. Within the tidal lagoon, the tidal wave is distorted and attenuated tidal action inundates and exposes marginal areas (Carter, 1989; Roy et al., 1994; Woodroffe, 2002).

In barrier estuaries the lagoonal state is a low-energy sedimentary environment, with settling from suspension the primary process of sedimentation (Nichols, 1999). Clastic mud and autochthonous organic material from fluvial sources dominate the sediments accreted (Woodroffe, 2002). Wind-derived waves may locally and periodically increase depositional energy in lagoonal waters; however, the main sources of