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Letter

Coastal lagoons: Geologic evolution in two phases

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ABSTRACT

Estuaries formed globally when river valleys and bays were inundated by the rising sea towards the end of the Holocene post-glacial marine transgression and have been supplied with sediment ever since. Coastal lagoons, estuaries that are partially or wholly cut off from marine influence, are said to *evolve* through sedimentation from an immature, unfilled state to a mature, filled state at a rate dependent on sediment supply. The existence of numerous examples of lagoons that remain unfilled worldwide, however, despite thousands of years of sedimentation, suggests that a discontinuity in the geologic evolution of lagoons occurs before maturity is reached. Presented here is a hypothesis that geologic evolution takes place in two phases which are defined by changes in physical processes. The early phase aligns with the traditional view but ends when a depth threshold is reached. In the late phase, sedimentation is inhibited by the local energy regime and can only proceed if the lagoon surface area is reduced. Validation of the existence of these two distinct process-based phases of geologic evolution will improve the reliability of predictive models for lagoon shoreline changes and rates of basin fill as well as reduce the risk of misinterpreting past conditions from the geological record.

1. Background

The low-relief shorelines of estuaries tend to support densely populated coastal communities as well as important wetland habitats. The latter are often the focus of conservation efforts (Jennerjahn and Mitchell, 2013), act as flood buffers during storm surges (Townend and Pethick, 2002), have the potential to store large quantities of greenhouse gases (Chmura et al., 2003; Saintilan et al., 2013), are under pressure due to human interventions (Elliott and Whitfield, 2011) and face future impacts from sea level rise and other climate change effects (Saintilan and Williams, 1999; McCarthy et al., 2001; Syvistki et al., 2005). Complexity and variability reign in estuarine environments (Roy et al., 2001) however, and this hampers efforts to understand drivers of change in estuaries and on their shorelines. Coastal lagoons, a comparatively less complex and more narrowly defined category of coastal water body, are therefore the focus of the evolutionary model described herein.

Unlike many types of estuaries, coastal lagoons have only restricted or intermittent connections to the ocean and, in order to maintain that restricted connection, also tend to have low freshwater input relative to their size (Harris, 2008). Their energy regimes are dominated by internally generated wind waves (Ward and Ashley, 1989; Bird, 1994; Harris, 2008). The low energy regime and reduced influence from ocean waves, tides and fluvial discharge provide an opportunity to study a reduced number of processes in an otherwise complex environment, so coastal lagoons are appealing natural laboratories for investigating processes operating in coastal water bodies. The formal definition of coastal lagoons adopted here is "inland water bodies… separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets which remain open at least intermittently, and have water depths which seldom exceed a few metres. A lagoon may or may not be subject to tidal mixing, and salinity can vary from that of a coastal fresh-water lake to a hypersaline lagoon, depending on the hydrologic balance" (Kjerfve, 1994). Schematisation of an idealised coastal lagoon is provided in Fig. 1.

Coastal lagoons on the southeastern Australian coast occur on gently sloping substrates where, following the stabilisation of sea level at least 6000 years ago, transgressive coastal sand barriers were able to form at the mouths of flooded river valleys and coastal inlets, partially or wholly isolating low energy, lagoonal environments (Roy, 1984; Bird, 1994). In other parts of the world lagoons formed in similar circumstances, though sources of sediment for barrier formation vary (Bird, 1994). As with estuaries more broadly, coastal lagoons are considered temporary features over geologic timescales because they are naturally filled over time through sedimentation (Ward and Ashley, 1989; Bird, 1994; Nichols and Boon, 1994). Lagoons intercept sediment conveyed by rivers from landwards catchments to the ocean until such time as accommodation space within lagoon basins is exhausted. The lagoon system then acts as a sediment pathway rather than a sink, as sediment is delivered directly to the coast, and the system is referred to as a delta (Roy, 1984; Roy et al., 2001; Heap et al., 2004).

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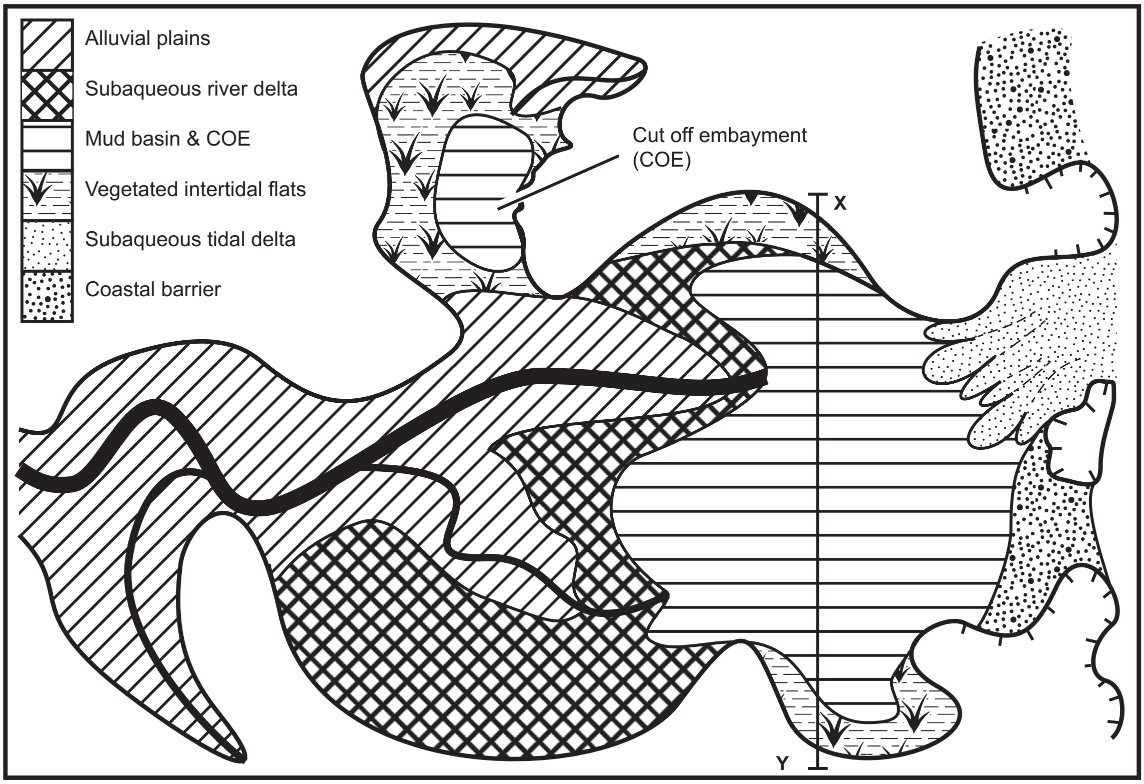

Fig. 1. An idealised coastal lagoon displaying major geomorphic units. The central mud basin and fringing intertidal flats are the focus of the model of geologic evolution presented here. Cut off embayments exhibit analogous behaviour on smaller scales. Other geomorphic units that make up coastal lagoons have the potential to act as system constraints whose position and extent influence where the threshold depth lies through their control on wind fetch, but are otherwise excluded from the present scope. Vertical line X–Y represents the cross section used in Fig. 3. Figure adapted from source (Roy et al., 2001).

Geologic evolution of coastal lagoons from unfilled to filled (delta) states has been described as a "seamless progression" that proceeds according to the rate of sediment supply (Roy et al., 2001). The persistence of a large number of coastal lagoons along several coastlines despite up to 6000 years of sediment supply suggests that sediment supply is not the only control on their geologic evolution. Examples are numerous on the southeastern Australian (Roy et al., 2001) and Texas coasts (Price, 1947). This paper presents the hypothesis that a threshold can be reached in the natural geologic evolution of coastal lagoons that changes the trajectory of ongoing evolution. It is argued here that: (i) geologic evolution of coastal lagoons through sedimentation is divided into two distinct phases, each affected by different factors; (ii) the threshold between the two phases is directly related to the local wind regime; and (iii) recognition of lagoon maturity in relation to this threshold will improve interpretation of past infill rates from the geological record and prediction of future geologic evolution. The rationale leading to the development of these arguments is presented and further research to validate the arguments is proposed.

2. Accommodation space within coastal lagoons

The geologic evolution of coastal lagoons is typically expressed in terms of the rate of basin fill through sedimentation. It is thus helpful to consider lagoon fill in terms of maturity (Roy et al., 2001). *Immature* lagoons are newly inundated depositional basins in which the entire volume of the water body is available to accommodate sediment; *mature* lagoons (or deltas) are entirely filled with sediment, accommodation space has been exhausted, and river discharge flows directly to the coast. Most processes operating within lagoons affect maturity through the creation and consumption of accommodation space. Relative sea level rise for example, creates accommodation space for deposition; whereas reduced sediment supply will reduce the rate at which accommodation space is consumed (Nichol et al., 1994).

The term *accommodation space*, as used here, refers to the total subaqueous volume of coastal lagoon basins available for sediment deposition. *Effective* accommodation space, on the other hand, is the proportion of total accommodation space that is available for sediment deposition given the specific combination of sediment properties and energy regime within a coastal lagoon. The volume of *effective* accommodation space is less than the volume of total accommodation space. This is because once basin sedimentation comes near to occupying the *total* accommodation space, hydrodynamic processes such as waves and currents periodically exceed some critical sheer stress and may prevent deposition or, where the bed consists of unconsolidated sediment, cause entrainment (Roy and Peat, 1976). *Effective* accommodation space may be exhausted by ongoing sediment deposition but, in the absence of any mechanism to alter sediment properties or energy regime, some *total* accommodation space remains because its consumption is inhibited by the energy regime. The rate of consumption of accommodation space in coastal lagoons and estuaries has previously been described as dependent on rates of sediment supply (Roy et al., 1980; Boyd et al., 1992; Dalrymple et al., 1992). The identification of a number of coastal lagoons not actively infilling (Price, 1947; Roy and Peat, 1976) however, suggests that the assumption of supply-dependent fill is only valid up to a certain point in the evolutionary trajectory. This point appears to be reached well before *total* accommodation space is exhausted (i.e. before the system matures into a completely filled delta) and is assumed here to coincide with the exhaustion of *effective* accommodation space.

For 31 oval, enclosed tidal basins on the Texas coast, maximum basin depth has been correlated to average width (Price, 1947). This dataset is presented in Fig. 2. The depth–width ratios appear to have been maintained over time, despite up to 10 ft of eustatic sea level rise, suggesting