Facies evolution of Holocene estuaries and deltas: a large-sample statistical study from Australia

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Abstract

Selected geomorphic features and sedimentary facies were mapped in 283 of Australia’s wave- and tide-dominated estuaries and deltas to quantitatively evaluate established evolutionary facies models that depict the evolution of estuaries into deltas during stable sea level conditions. While diagnostic facies for wave- and tide-dominated estuaries and deltas approximate those specified by the models, statistical analyses of the data also reveal two additional insights regarding the evolution of estuaries to deltas. First, there is an offshore shift in the locus of sand accumulation between tide-dominated estuaries and deltas, associated with the onset of delta development. Second, the mean surface area of intertidal environments (i.e., intertidal flats, mangroves/melaleuca, saltmarsh/salt flat facies) is greater in wave-dominated deltas than in wave-dominated estuaries. Tidal penetration associated with the river establishing a more direct and permanent connection to the sea during late-stage development presents a natural impediment to continued formation of an alluvial plain and full development of the “classic” wave-dominated delta morphology. A notional evolutionary pathway for wave-dominated estuaries is developed from the distribution of facies that predicts the rate and susceptibility of geomorphic and habitat changes. The “classic” deltaic geomorphology may be unattainable for wave-dominated systems, except those with significant terrigenous sediment inputs. Our study is the first published example of geomorphic and sedimentary data assembled from a large number of wave- and tide-dominated estuaries and deltas across an entire continent.

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1. Introduction

Estuaries and deltas are common along modern coasts and are reasonably well represented in the geologic record because of the generally high preservation potential of their deposits (Dalrymple et al., 1992). Globally, estuaries are more abundant than deltas because of the relatively short time available for coastal sedimentation since the onset of the Holocene sea level highstand (Nichols and Biggs, 1985). However, given sufficient time, and under conditions of stable sea level and continuous sediment supply, all estuaries have the potential to infill their paleo-valleys and evolve into deltas (Dalrymple et al., 1992).

Geomorphic facies models (Walker, 1992) that depict changes to the distribution and abundance of
geomorphic and sedimentary environments in clastic coastal depositional environments have greatly increased our understanding of the evolution of estuaries into deltas (e.g., Galloway, 1975; Roy, 1984; Harris, 1988; Woodroffe et al., 1989; Dalrymple et al., 1992). Geomorphic facies models provide valuable information for classifying individual systems (e.g., Harris, 1988; Nichols et al., 1991; Boyd et al., 1992; Dalrymple et al., 1992; Cooper, 2001; Heap et al., 2001) and present a framework for examining the linkages between the structure and function of estuaries and deltas (e.g., Roy, 1994; Kench, 1999; Roy et al., 2001; Harris and Heap, 2003). For instance, changes to ecosystem health, turbidity, water quality and circulation, species diversity, faunal abundance, nutrient cycling and toxicant accumulation, as well as habitat fragmentation and loss have all been notionally linked to the predictable changes in the distribution and abundance of geomorphic and sedimentary environments associated with the evolution of estuaries (e.g., Eyre, 1994; Pollard, 1994; Heggie and Skyring, 1999; Heggie et al., 1999; Birch et al., 2001; Roy et al., 2001). Diagnostic combinations and abundances of facies might also indicate the position of a system along the estuary-delta evolutionary continuum (e.g., Roy, 1994; Roy et al., 2001). To date, these linkages have remained largely conceptual and untested. Part of the problem with testing these (or other) hypotheses is that the distribution and abundance of geomorphic and sedimentary facies for a large number and variety of estuaries and deltas have not been accurately quantified.

The purpose of this study is to evaluate the established evolutionary facies models by quantifying the changes to geomorphic and sedimentary facies associated with the evolution of estuaries into deltas under a stable sea level and tectonic setting in Australia. This was undertaken by calculating the areas and perimeters of eight diagnostic and commonly occurring geomorphic features and sedimentary facies in a large number of wave- and tide-dominated estuaries and deltas across an entire continent that span a broad range of climatic regimes, physical settings, and wave and tide conditions.

2. Geologic evolution of estuaries into deltas

Because of the close link between coastal geomorphology and the relative influence of waves and tides, two broad categories of estuaries and deltas can be distinguished: tide-dominated and wave-dominated, each possessing their own distinctive geomorphology represented by a unique assemblage of geomorphic and sedimentary environments (or facies). The geomorphic evolution of wave-dominated systems is reasonably well known, having been developed mostly from local case studies of wave-dominated estuaries, particularly from southeast Australia (e.g., Roy et al., 1980, 2001; Nichol and Murray-Wallace, 1992; Roy, 1994; Lessa and Masselink, 1995; Nichol et al., 1997). By contrast, our understanding of the geomorphic evolution of tide-dominated systems is less well known (e.g., Woodroffe, 1992; Mulrennan and Woodroffe, 1998).

2.1. Evolution of tide-dominated estuaries

The gross geomorphology of tide-dominated estuaries (Fig. 1A) is comprised of a network of tidal channels, typically floored by coarse-grained sediment (e.g., sand), separated by tidal sand banks, intertidal flats, saltmarshes and salt flats (e.g., Woodroffe et al., 1989; Dalrymple et al., 1992; Harris et al., 1992; Chappell and Woodroffe, 1994; Mulrennan and Woodroffe, 1998). Fine-grained sediment (e.g., silt and clay) accumulates along the margins of the estuary as intertidal flats, mangrove, and in saltmarsh or salt flat environments. Tide-dominated estuaries are usually funnel-shaped because of the dominance of tidal currents throughout. The evolution of tide-dominated estuaries (Fig. 1A–C) is characterised by seaward progradation of all facies with the relative distribution and abundance of each facies remaining constant. Further sediment input during latter stages causes an expansion in the surface area of the tidal sand banks at the mouth, and their merging and interdigitation with the marginal intertidal flats, saltmarshes and salt flats (e.g., Harris, 1988; Woodroffe et
al., 1989, 1993; Allen and Posamentier, 1993). As a result, elongate tidal channels characterised by strong tidal currents develop throughout the system. In macrotidal systems, the funnel-shape of the estuary is generally preserved into the delta stage (Dalrymple et al., 1992).

2.2. Evolution of wave-dominated estuaries

The gross geomorphology of wave-dominated estuaries (Fig. 1D) is arranged into a tripartite facies zonation consisting of: a river-dominated bay-head delta and alluvial plain at the head; a low-energy...
central basin rimmed by intertidal environments (e.g., mangroves, tidal flats and saltmarshes); and a coast-parallel barrier and flood- and ebb-tidal deltas at the mouth. The evolution of wave-dominated estuaries (Fig. 1D–F) is characterised by the seaward progradation of the bay-head delta and landward expansion of the flood-tide delta, infilling the central basin (Roy et al., 1980, Roy, 1984, 1994; Lessa and Masselink, 1995; Nichol et al., 1996, 1997). Concomitant with these geomorphic changes in the distribution of facies is an increase in the area of fluvial bay-head delta, alluvial plain and flood tidal delta environments, and a reduction in the area of the central basin and intertidal environments and salt flats. This infilling continues until the central basin is completely filled and the bay-head delta and alluvial plain have prograded over the intertidal and flood-tide delta environments so that they are adjacent to the barrier, and the fluvial channel has a direct and permanent connection to the sea. At this stage, tides become less attenuated and penetrate further inland resulting in tidal ranges inside the basin that are similar to the open ocean. As the connectivity between the fluvial channel and tidal inlet increases, sediment transported by the river increasingly bypasses the basin and is exported to the sea, and the system becomes a delta. With increased sediment bypassing to the coast, the barrier may begin to prograde and a coastal protuberance can form adjacent to the mouth of the river (Roy et al., 1980).

2.3. Estuary-delta transition

Determining the point at which an estuary becomes a delta is not straightforward. Without knowledge of the sedimentary deposits or long-term sediment flux data, the geomorphic criterion of Dalrymple et al. (1992) can be used to distinguish between estuaries and deltas. Tide-dominated estuaries contain a straight-meandering-straight river channel profile near the head of the estuary (Fig. 1A–B) produced by convergence of seaward-directed river transported sediment and landward-directed tidally transported sediment (Dalrymple et al., 1992). In wave-dominated estuaries, a straight-meandering-straight river channel profile may develop during intermediate stages due to increased connectivity with the ocean (Fig. 1E). According to Dalrymple et al. (1992), the absence of the meandering morphology in both tide- and wave-dominated systems indicates that net bedload transport is seaward and the system is a delta (Fig. 1C,F).

3. Regional setting

The Holocene post-glacial sea-level history of Australia has seen a rise from a lowstand at ca. –130 m at 22–18 ka, followed by a rapid transgression towards a highstand at ca. +1.7 m about 6.5 ka (Larcombe et al., 1995), and a small regression to present-day elevations (Beaman et al., 1994). Since then, the present-day geomorphology of Australia’s wave- and tide-dominated estuaries and deltas has developed to variable degrees in response to the rate of sediment supply from fluvial and marine sources and the effects of wave and tide processes.

Australia’s coastal environment spans a wide range of physical settings, climate zones, and wave and tide conditions. In the north, wet and dry sub-tropical and tropical coasts are dominant and tide-dominated coastal depositional environments are most abundant (Fig. 2). In the south, temperate coasts are dominant and wave-dominated coastal depositional environments are most abundant. In the east, coastal catchments are generally small and densely spaced, with steep watercourses, due to the close proximity of the Great Dividing Range to the coast, the highest parts of which form a natural interfluve between the coastal and inland catchments.

Throughout Australia, coastal catchments are affected by highly variable rainfall dominated by ENSO and longer cycles (Schulmeister and Lees, 1995; Sturman and Tapper, 1996). Wet tropical catchments receive up to 4 m of rainfall each year (>8 m in the far north) most of which falls during the summer monsoon between December and April resulting in pronouncedly seasonal river flows. Temperate catchments receive much less rainfall (<1.5 m year\(^{-1}\)) and regularly experience droughts, especially during the summer (Erskine and Warner, 1988), resulting in perennial low river flows interspersed with significant flood events. Drought conditions are more widespread in southwest coastal catchments. The effect of this rainfall and river regime is an episodic and often significant supply of terrigenous sediment from coastal catchments to
Australia’s estuaries and deltas, at least during the late-Holocene. Total sediment discharge from rivers to the coast is estimated at \( \sim 150 \text{ Mt year}^{-1} \) (Harris, 1995). This figure is considered to be much higher than estimates of pre-colonisation discharge.

Upper meso- and macro-tidal ranges occur on the northern coasts while micro- to lower meso-tidal ranges occur on southern coasts (Harris, 1995). In the northwest, spring tidal ranges are typically \( >3.5 \text{ m} \) and can be \( >10 \text{ m} \) in some large embayments (e.g., King Sound; Fig. 2). In the south, spring tidal ranges are typically \(<3\text{ m} \) and are as little as \(0.8\text{ m} \) along the southern coast of Tasmania. In the south and west, significant wave heights (Hsig) are regularly \( >4 \text{ m} \), whereas Hsig along the northern coasts are generally \(<1.5 \text{ m} \). The lowest Hsig of \(<0.5 \text{ m} \) occur along the northeast coast because of the protection from ocean swells provided by the Great Barrier Reef (Fig. 2).

From the above summary, it is clear that Australia contains estuaries and deltas that are exposed to an almost complete spectrum of wave, tide and river influence, climatic regimes and physical settings,
and is therefore an appropriate location to carry out this study. We acknowledge that by restricting our study to the Australian continent estuaries and deltas affected by glacial processes or associated with large continental river systems (e.g., Mississippi River, USA) are not well represented. Our results may not be directly applicable in these specific cases. The abundance of estuaries over deltas in Australia probably also reflects the continent’s relatively arid climate, low relief, and relatively low sediment yield by world standards, factors that may skew the results of our study relative to the general geological past.

4. Methods

4.1. Classification of Australian coastal waterways

In order to determine the distribution and abundance of geomorphic features and sedimentary facies in Australia’s estuaries and deltas, an assessment of the geomorphology of 974 coastal waterways was undertaken by a visual inspection of aerial photographs, Landsat TM images and topographic maps (Heap et al., 2001). Only those systems with terrigenous sediment inputs were analysed. Each waterway was classified according to the principles of Boyd et al. (1992) and Dalrymple et al. (1992) as: tide- or wave-dominated estuaries, tide- or wave-dominated deltas, lagoons, strandplains or tidal flats/tidal creeks. Other waterway types including drowned river valleys and embayments were designated as “others” (Heap et al., 2001). Only the geomorphology visible at low tide was used to classify the waterways. As such, deeper subaqueous features, such as pro-delta environments, might not have been captured in some systems.

4.2. Geomorphic and sedimentary facies mapping

The spatial extent of eight diagnostic geomorphic features and sedimentary facies was then mapped for all of the tide- and wave-dominated estuaries and tide- and wave-dominated deltas identified in this study. The suite of facies identified for mapping was based on the terminology of Boyd et al. (1992) and Dalrymple et al. (1992), and previous geological studies of Australian coastal waterways such as those by Roy et al. (1980), Harris (1988), Woodroffe et al. (1989), Nichol (1991) and Roy (1994). Each facies represents distinct, easily recognisable geomorphic features or sedimentary facies present in Australia’s clastic coastal depositional environments (Table 1), notably: barrier/back-barrier (BBB), central basin (CB), fluvial bay-head delta (FBD), flood/ebb tidal delta (FED), intertidal flats (IF), mangrove/melaleuca (MAN), saltmarsh/salt flat (SM) and tidal sand banks (TSB). Flood-ebb tidal deltas more commonly refer to sand bodies associated with tidal inlets of wave-dominated systems. However, due to the objectives of the original study (see Heap et al., 2001; NLWRA, 2002), the term FED has been used in its broadest sense in this study and also includes sand bodies located at the mouth of tidal channels in tide-dominated systems.

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The boundaries of each facies were interpreted from the most recent colour aerial photographs available for each coastal waterway. Aerial photographs showing the geomorphology at low tide were used, where possible. The aerial photographs were flown between 1988 and 2000 and ranged in scale from 1:10,000 to 1:80,000. Each boundary was then digitised on to digital geo-referenced Landsat TM images or, where imagery was not available, digital 1:100,000 topographic maps (Heap et al., 2001). Comparison between aerial photographs and the digitised maps produced errors in the location of the boundaries to within ±10 m, causing errors in the areas of each facies of <10 km², and thus small relative to the total area of each system. The digitised boundaries were then imported into an ARCInfo™ geographical information system that computed the surface area and perimeter of each geomorphic and sedimentary facies. Individual facies areas are reported as percentages of the total facies area.

5. Results

5.1. Spatial distribution of estuaries and deltas around Australia

A total of 39 tide-dominated estuaries and 38 tide-dominated deltas were identified in our study (Fig. 2; Heap et al., 2001). Tide-dominated estuaries are most abundant on the northwest coast, while tide-dominated deltas are most abundant on the northeast coast. A total of 134 wave-dominated estuaries and 72 wave-dominated deltas were identified in our study (Fig. 2; Heap et al., 2001). They occur mostly along the southern coasts and are most abundant in the southeast, where >65% of these systems are found. Wave-dominated estuaries and deltas are sparse along the northern coasts, occurring in locations where the configuration and aspect of the coast locally produces relatively small tidal ranges. The distribution of tide- and wave-dominated estuaries and deltas in Australia corresponds strongly to the pattern of tide and wave dominance around the coast (cf. Harris, 1995; Fig. 2). A detailed treatment of the sedimentary characteristics and management implications associated with the distribution of tide- and wave-dominated clastic coastal depositional environments around Australia is presented in Harris et al. (2002).

5.2. Facies associations

Tide- and wave-dominated estuaries and deltas contain a diagnostic suite of geomorphic and sedimentary facies (Boyd et al., 1992), as indicated by the associations and probabilities \( F \) of occurrence of individual facies with each category (Fig. 3). Tidal sand banks, intertidal flats, mangroves/melaleuca and saltmarsh/salt flat facies are more strongly associated with tide-dominated systems \( (F \geq 0.9) \), with saltmarsh/salt flats facies occurring in all tide-dominated deltas mapped \( (F=1) \). Barriers, fluvial bay-head deltas and flood/ebb tidal deltas are more strongly associated with wave-dominated sys-

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**Fig. 3.** Matrix showing the probability of occurrence (numbers) and degree of association (shading) of geomorphic and sedimentary facies in Australia’s estuaries and deltas. The strength of association is determined by comparing the calculated probabilities \( F \) to the probability distribution for each facies: \( F<25th \) percentile = weak association; \( 25th \) percentile \(<F<75th \) percentile = moderate association; \( F>75th \) percentile = strong association. See Table 1 for definition of facies.
tems ($F \geq 0.7$), with central basins almost exclusively belonging to wave-dominated estuaries ($F \geq 0.8$). Mangroves/melaleuca facies are more strongly associated with deltas than estuaries (deltas: $F \geq 0.9$, estuaries: $F \leq 0.7$), a trend best shown by wave-dominated systems. Intertidal flats are strongly associated ($F \geq 0.9$) with all tide- and wave-dominated estuaries and deltas in Australia.

5.3. Facies areas

Significant variability exists in the surface areas of geomorphic and sedimentary facies comprising tide- and wave-dominated estuaries and deltas in Australia (Fig. 4). In tide-dominated estuaries and deltas (Fig. 4A), mangrove/melaleuca and salt-marsh/salt flat facies are most abundant and make...
up between 10% and 60% of the surface area for a total of 36 systems. All other facies generally comprise <20% of the surface area in these systems. Facies area distributions are positively skewed and contain several outliers and extreme values, except for mangrove/melaleuca and saltmarsh/salt flat facies, which have normal distributions and cover approximately the same area in both estuaries and deltas. Area distributions for flood/ebb tidal delta and tidal sand bank facies are similar with each comprising up to 20% of the surface area for approximately half of the tide-dominated systems in Australia. However, flood/ebb tidal delta facies comprise up to 20% of the surface area of tide-dominated deltas and tidal sand bank facies comprise an equal amount of the surface area of tide-dominated estuaries. Barrier, central basin and fluvial bay-head delta facies are not well represented in tide-dominated estuaries and deltas.

On average, mangroves/melaleuca and saltmarsh/salt flat facies combined cover more than two thirds of surface area of tide-dominated estuaries and deltas in Australia (Table 2). Flood/ebb tidal delta, intertidal flats and tidal sand bank facies almost equally divide the remaining area, with each facies covering on average between ~10% and 15%. On average, mangroves/melaleuca and saltmarsh/salt flat facies cover approximately 33% and 38% of the surface area of tide-dominated estuaries, respectively. While covering approximately the same total area, the abundance of these facies is reversed in tide-dominated deltas and tidal sand bank facies comprise 37% and 33% of the surface area of tide-dominated estuaries, respectively. Similarly, the abundance of flood/ebb tidal delta and tidal sand bank facies is also reversed between tide-dominated estuaries and tide-dominated deltas (Table 2).

In wave-dominated estuaries and deltas (Fig. 4B), greatest variability occurs in the areas of barrier, intertidal flats and mangrove/melaleuca facies, each of which comprise between <1% and >95% of the total area. The area distributions for barrier facies are similar for both wave-dominated estuaries and deltas. Individually, each facies (except for the mangrove/melaleuca facies) generally comprise <30% of the total surface area of wave-dominated estuaries and deltas. However, central basin facies occupy between 20% and 60% of the surface in 67 wave-dominated estuaries (i.e., 50% of the population). Flood/ebb tidal delta, intertidal flats, mangroves/melaleuca, saltmarsh/salt flat and tidal sand bank facies generally comprise less surface area in wave-dominated estuaries than wave-dominated deltas. Mangroves/melaleuca facies comprise <5% of the surface area for 118 (85%) wave-dominated estuaries but attain a maximum area of 70%. A total of 51 (70%) wave-dominated deltas contain mangroves/melaleuca facies of >5% coverage, but in 47 of these systems they comprise <40% of the total area. Area distributions for all facies present in wave-dominated estuaries and deltas in Australia are positively skewed, containing numerous outliers and extreme values. As such, facies areas in wave-dominated estuaries and deltas exhibit greater variability and range than facies areas in tide-dominated estuaries and deltas.

On average, central basin facies cover more than one third of the surface area of all wave-dominated estuaries in Australia (Table 2). Barrier and fluvial bay-head delta facies comprise more than a quarter of the remaining area with flood/ebb tidal delta, intertidal flats, mangroves/melaleuca and saltmarsh/salt flat facies comprising 37% and 33% of the surface area of tide-dominated deltas, respectively. Similarly, the abundance of flood/ebb tidal delta and tidal sand bank facies is also reversed between tide-dominated estuaries and tide-dominated deltas (Table 2).

Table 2
Mean facies areas for Australian estuaries and deltas (% of total area)

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<tr>
<td>T-Dom. Est.</td>
<td>0.48</td>
<td>0.33</td>
<td>2.48</td>
<td>3.58</td>
<td>9.75</td>
<td>33.69</td>
<td>37.59</td>
<td>12.09</td>
<td>39</td>
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<tr>
<td>T-Dom. Del.</td>
<td>0.36</td>
<td>0</td>
<td>0</td>
<td>14.06</td>
<td>11.77</td>
<td>36.82</td>
<td>32.81</td>
<td>4.18</td>
<td>38</td>
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<tr>
<td>W-Dom. Est.</td>
<td>15.53</td>
<td>38.44</td>
<td>12.48</td>
<td>9.11</td>
<td>9.36</td>
<td>2.83</td>
<td>11.56</td>
<td>0.68</td>
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<tr>
<td>W-Dom. Del.</td>
<td>11.77</td>
<td>0.51</td>
<td>3.52</td>
<td>10.87</td>
<td>20.25</td>
<td>28.47</td>
<td>19.79</td>
<td>4.82</td>
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See Table 1 for definitions of facies.
Paleovalley dimensions are unknown for most of Australia’s wave-dominated estuaries and deltas. However, differences in the initial shape and volume of the paleovalley probably have largely contributed to the significant variability exhibited by the facies by delimiting the amount of accommodation space available for development during the Holocene (cf. Heap and Nichol, 1997; Roy et al., 2001). Variability in areas of mangrove/melaleuca environments strongly reflects climate, with largest areas occurring in the few wave-dominated estuaries located in the north (e.g., Maroochy River). Modifications by humans have also contributed to the variability displayed by facies in wave-dominated estuaries and deltas. In particular, mangrove/melaleuca, intertidal flats and flood/ebb tidal delta environments have been extensively reduced in area in systems on the southeast coast for urban development and to maintain safe navigation. Less modified systems contain proportionally larger areas of these environments.

In order to investigate whether there are statistically significant differences in the mean surface areas of the geomorphic and sedimentary facies between tide- and wave-dominated estuaries and deltas (Table 2), a one-way analysis of variance (ANOVA) was calculated using the statistical software package STATISTICA™. The ANOVA indicated that there are significant differences between means for the facies surface areas for tide- and wave-dominated estuaries and deltas. The Scheffe’s test was then applied as a post-hoc comparison to determine which combinations of means in the ANOVA were significantly different from each other at the 95% confidence limit (shaded cells in Fig. 5). These tests provide a statistical check on the significance of the facies relationships and surface areas between tide- and wave-dominated estuaries and deltas. The significant

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Fig. 5. Matrices showing the results of the Scheffe’s test indicating combinations of tide- and wave-dominated estuaries and deltas in Australia where statistically significant differences in the mean areas (shaded boxes) of each facies exist. See Table 1 for definitions of facies.
differences also confirm situations where a positive correlation exists between the facies areas and the independently derived geomorphic classifications.

6. Discussion

Geological investigations of tide- and wave-dominated estuaries and deltas have traditionally been based on detailed data collected from one or, at most, several examples. By contrast, we derive our findings from detailed geomorphic and sedimentary data acquired from 283 examples of tide- and wave-dominated estuaries and deltas. To our knowledge, our study is the first published example of geomorphic and sedimentary data assembled from a large number of systems spanning an entire continent. An advantage of our study compared with traditional smaller-scale localised studies is that it captures the variation in geomorphology of coastal waterways using a consistent methodology.

Several findings were highlighted by our study. First, diagnostic facies contained in Australian tide- and wave-dominated estuaries and deltas approximate those predicted by published geomorphic facies models for tide- and wave-dominated estuaries and deltas in general. Second, changes to the distribution and surface area of geomorphic and sedimentary facies associated with the evolution of Australian tide- and wave-dominated estuaries into deltas generally reflect those predicted by established geomorphic evolutionary models. Third, the surface area of tidal sand bank facies in Australian tide-dominated estuaries is greater than in tide-dominated deltas. Finally, the surface area of intertidal environments (i.e., intertidal flats, mangroves/melaleuca, saltmarsh/salt flat) is greater in wave-dominated deltas than in wave-dominated estuaries. We consider the significance of each of these findings in turn, with the last two representing additional insights into the nature of the estuary-delta transition.

Despite significant variability in the areas of geomorphic and sedimentary facies in Australia’s tide- and wave-dominated estuaries and deltas, the fact that the facies distributions are generally the same as those specified by the models supports our geomorphic classifications. The facies data also verify the strong link between geomorphology and the influence of waves, tides and rivers (e.g., Galloway, 1975; Boyd et al., 1992; Dalrymple et al., 1992). Detailed explanations of the climatic, tectonic and oceanographic controls on the distribution and abundance of geomorphic and sedimentary facies in tide- and wave-dominated estuaries and deltas around Australia are presented in Heap et al. (2001), Roy et al. (2001) and Harris et al. (2002).

While it is clear that certain facies are strongly associated with individual categories, it is also true that all but two facies are associated with all estuaries and deltas. The distribution of facies in Australia reveals that there are very few “pure” tide- and wave-dominated estuaries and deltas and that the majority of systems have geomorphology that reflects a “mixed” tide/wave influence. Facies most strongly associated with tide-dominated systems also have a high probability of occurrence in wave-dominated systems ($F \geq 0.7$; Fig. 3), but the opposite trend is not reflected in tide-dominated systems by facies strongly associated with wave-dominated systems ($F \leq 0.3$; Fig. 3). This facies distribution indicates that tides have a significant influence on the overall geomorphology of tide- and wave-dominated estuaries and deltas.

Quantitative estimates of tide, wave and river influence around Australia (Harris et al., 2002) reveal that annually tides exert more power per unit area of coastline than swell waves. Because much of the Australian coast is not exposed to a high-energy swell wave regime (Davis, 1972; Heap et al., 2001; NLWRA, 2002), the geomorphic and sedimentary facies in Australian systems reflect the generally greater role tides play in shaping coastal features. This trend is best shown by the prevalence of tide-dominated estuaries and deltas located on the northwest coast, where upper meso- to macro-tidal ranges occur, and the Gulf of Carpentaria and northeast coasts, where the regional wave energy is persistently low except during tropical cyclones. Notwithstanding the extra power exerted on the coast, tides are likely to shape the overall geomorphology of estuaries and deltas because they penetrate further inland, particularly in wave-dominated systems where the fluvial channel has established a direct connection with the tidal channels. Significant tidal inundation is also a feature of wave-dominated estuaries and deltas that contain breakwaters and groynes installed to mitigate unstable entrance conditions. In such cases, the works artificially provide relatively unrestricted access for the tidal wave into the inlet.
and enhance tidal inundation. In Australia, tide-dominated estuaries and deltas cover more than three times the surface area (average = 97.3 km²) of wave-dominated estuaries and deltas (average = 31.1 km²), which we infer to be a direct result of the larger tidal ranges and generally low-gradient coastal topography across the north of the continent.

Despite the significant difference in area between tidal sand bank and flood/ebb tidal delta facies in tide-dominated estuaries and deltas, the mean areas of the remaining facies are not significantly different from each other (Fig. 5). This implies that, except for these two facies, there is a general seaward progradation of facies associated with the evolution of tide-dominated systems with the relative proportions of each facies remaining relatively constant (Figs. 4B and 5). Significant differences in the mean areas of the central basin and fluvial bay-head delta facies between wave-dominated estuaries and wave-dominated deltas (Fig. 5) support the hypothesis that the evolution of wave-dominated systems is characterized by infilling of the central basin and development of the alluvial plain (cf. Roy, 1984; Lessa and Masselink, 1995). The mean areas of flood/ebb tidal deltas in wave-dominated estuaries and deltas are not significantly different from each other, which indicates that the evolution of wave-dominated estuaries is principally dominated by the expansion of the alluvial plain rather than marine sand bodies. This result is consistent with a strong statistical relationship between water area and degree of infilling (as measured by the combined fluvial bay-head delta and alluvial plain area) for 68 of Australia’s wave-dominated estuaries (Roy et al., 2001).

6.1. Insights into the evolution of tide-dominated estuaries and deltas

The data reveal that there is the switch in dominance between sand accumulating as tidal sand banks in tide-dominated estuaries and flood/ebb tidal deltas in tide-dominated deltas, as shown by the significant differences in the areas of these facies (Fig. 5). This change in abundance indicates that the relative area of tidal sand banks declines with increasing maturity, with a shift towards deposition of sand as sub-aqueous sand bodies located seaward of the tidal channels and attached to the banks (i.e., islands) (Fig. 6). Ultimately, the shifting tidal sand banks become stable because of subaerial sediment deposition and vegetation, eventually forming discrete islands separating a network of elongated tidal channels (e.g., Fig. 6). Enhanced penetration and amplification of tidal currents in the elongated channels during late-stage development is the most likely mechanism for the transfer of sand from the tidal channels to the delta front (Fig. 6). Because both tidal sand banks and flood/ebb tidal delta facies occur in similar abundances in tide-dominated systems, the total abundance of sand facies does not change between the estuary and delta stages (Table 2, Fig. 4B). This implies there is an offshore shift in the locus of sand accumulation, a result consistent with the geomorphic criterion of net offshore bedload transport associated with tide-dominated deltas (Dalrymple et al., 1992). It follows that the distribution and relative abundance of these two geomorphic and sedimentary facies might also be used as an additional geomorphic criterion for recognising and differentiating between tide-dominated estuaries and deltas.

6.2. Insights into the evolution of wave-dominated estuaries and deltas

Variability in the relative abundances of geomorphic units and sedimentary facies in Australia’s wave-dominated estuaries and deltas makes them unsuitable for quantifying the location of a wave-dominated estuary on the estuary-delta continuum (cf. Roy et al., 2001). Independent of size, the point at which a wave-dominated estuary becomes a wave-dominated delta does not reliably coincide with any combination or abundance of facies, except for the absence of a central basin.

The areas of barrier and flood and ebb-tidal delta facies in Australian wave-dominated deltas are not significantly different from those in wave-dominated estuaries (Fig. 5). This is largely a function of the ratio of wave power to sediment supply in southeast Australia, where most wave-dominated estuaries occur. Sand is not exported to the coast in sufficient quantities to result in large volumes of sediment being reworked back onshore by waves despite increased sediment bypassing during late stage development (cf. Roy et al., 1980; Thom, 1983; Fig. 1F). Very few deltas in this region contain distinct coastal protuberances. Previous sediment transport studies (e.g., Wright and Short, 1983; Harris and Coleman, 1998;
Roy, 1999) have also demonstrated that the relatively high mean annual wave power in the southeast produces strong bottom return currents and significant alongshore transport of sand. The facies area data from southeast Australian wave-dominated deltas indicate that the combined rates of offshore and alongshore transport in the long term are at least equal to the rate of sand supplied to the coast by rivers. Greatest quantities of sand are exported to east coast rivers during high-magnitude floods (e.g., Roy, 1977; Hacker, 1988). So it may also be the case that sufficient quantities of river-borne sand are deposited far enough offshore to be lost from the coastal sediment budget further reducing the amount of sand accumulating in barrier and beach environments.

Interestingly, our data also reveal that intertidal environments (i.e., tidal flat, mangroves/melaleuca, saltmarsh/salt flat facies) comprise on average 24% and 69% of the total facies area in wave-dominated estuaries and wave-dominated deltas, respectively (Fig. 6). As discussed above, facies data from Australian systems indicate that valley infilling is dominated by progradation of the alluvial plain (Roy et al., 2001), so the most likely reason for the presence of significantly larger areas of intertidal environments in wave-dominated deltas is that there has been insufficient time since the onset of the Holocene highstand for rivers to develop alluvial plains that prograde all the way to the coast. Analysis of available data indicates that this explanation might not be so straightforward.

While reliable estimates of terrigenous sediment loads are not available for all Australian rivers, a recent study of Australian waterways (Harris et al., 2002) has demonstrated that mean annual fluvial discharge under natural conditions is a good first approximation of the influence of rivers on the geomorphology of coastal waterways. Our data reveal that even in cases where wave-dominated deltas are subject to very high fluvial discharge and almost continuous sediment input they contain substantial...
areas of intertidal environments. Thus, larger areas of intertidal environments in wave-dominated deltas are almost certainly the product of raised water levels in the channel(s) caused by a reduction in tidal attenuation as the river establishes a more direct connection with the sea during late-stage development, followed by a long phase of vertical accretion (Fig. 1; Roy et al., 1980). Expansion of intertidal environments in wave-dominated systems may represent an equivalent “big swamp” phase, recognised in tide-dominated systems (e.g., Woodroffe et al., 1993; Mulrennan and Woodroffe, 1998). Subaerial levees in several wave-dominated deltas in southeast Australia also point to the presence of impounded water behind barriers with very constricted outlets (Roy, 1994).

Although our simple statistical analyses reveal that the geomorphology and facies distribution in Australia’s estuaries and deltas is similar, there are other important differences that cannot be neglected. Estuaries are more commonly associated with incised valleys than deltas (Walker, 1992), although this trend is not apparent with Australian systems because most estuaries and deltas occupy drowned bedrock valleys cut into Cainozoic and older rocks. Only on the northeast coast and eastern and southern coasts of the Gulf of Carpentaria, do present-day deltas typically occur in a broad, shallow-gradient coastal plain comprised of pre-Holocene and Holocene alluvial and coastal deposits. Estuaries contain deposits that reflect both terrestrial and marine sediment inputs and exhibit a transgressive stratigraphy, whereas deltaic deposits are mainly terrigenous and exhibit a regressive stratigraphy (Dalrymple et al., 1992). In estuaries flood/ebb tidal delta sands are underlain by a tidal ravine-ment surface and landward estuarine and fluvial facies and in deltas tidal sand bank sands are underlain by prodelta and shelf muds (e.g., Walker, 1992). Coarsest sediment in estuaries is associated with the fluvial bay-head delta, but in deltas the coarsest sediment fines towards the mouth.

6.3. Evolutionary pathway for wave-dominated estuaries and deltas

Facies data from Australian wave-dominated estuaries and wave-dominated deltas makes it possible to construct a notional evolutionary pathway for their evolution (Fig. 7). Initially, geomorphic and facies area changes are moderately fast due to infilling of the central basin and expansion of intertidal environments. The rate of change increases during intermediate stages to a point where the where additional infilling causes the river to establish a more direct connection to the sea. After this point, the rate of change decreases as more river-derived sediment is bypassed to the ocean. During late stages, a permanent direct connection between the river channel and sea precludes further development of the alluvial plain and allows tides to propagate landward, and the system adopts a stable morphology. This becomes a natural impediment to the development of the “classic” delta geomorphology consisting of a fully developed alluvial plain extending seaward to a subaerial barrier, as predicted by the models, and might in fact be unachievable (i.e., asymptotic). Given the generally low relief, relative aridity and great antiquity of the

Fig. 7. Notional evolutionary pathway for wave-dominated estuaries to wave-dominated deltas based on facies area data from Australian systems. Initially, changes in the facies areas are rapid due to sediment deposition in the large central basin and the system is susceptible to geomorphic changes. The facies areas change more rapidly as the central basin reduces in area and the geomorphology becomes increasingly susceptible to change. Changes to the facies areas slow once the river has established a permanent connection with the ocean and a relatively stable geomorphology is adopted. The “classic” deltaic geomorphology, as predicted by the models, may be unattainable for all systems except those with significant terrigenous sediment inputs.
Australian continent it is likely that, apart from a few of the larger rivers (e.g., Bega, Clarence and Hunter Rivers), most of Australia’s wave-dominated estuaries may never attain the classic delta geomorphology.

Simple perimeter/area ratios (Table 3) offer further insights into the evolution of wave-dominated estuaries to wave-dominated deltas, with mean ratios for intertidal environments being significantly different at the 95% confidence level for Australian systems. Lower average perimeter/area ratios of intertidal environments in wave-dominated deltas point to their expansion during late stage development associated with the additional penetration of tidal currents. As such, intertidal flats, mangroves/melaleuca and saltmarsh/salt flat facies are generally less fragmented in wave-dominated deltas than wave-dominated estuaries. Increased habitat connectivity in wave-dominated deltas may indicate that they are less vulnerable to environmental pressures such as increased sedimentation.

### 7. Conclusions

Diagnostic facies contained in Australian tide- and wave-dominated estuaries and deltas approximate those specified by published geomorphic facies models. Changes to the distribution and surface area of geomorphic and sedimentary facies associated with the evolution of estuaries to deltas generally reflect those predicted by the models with two significant exceptions. First, late-stage development of tide-dominated deltas is associated with an offshore migration of the sand facies, caused by increased strength of tidal currents. Second, intertidal environments are more widespread in wave-dominated deltas than wave-dominated estuaries.

Facies in Australian tide- and wave-dominated estuaries and deltas indicate that tides generally play a greater role than waves in shaping the overall geomorphology and habitats. Significant variability in the relative abundance of facies in wave-dominated estuaries and deltas makes them unsuitable for quantifying the location of a system on the estuary-delta continuum. While the evolution of wave-dominated estuaries and deltas in Australia is characterised by the development of the alluvial plain, enhanced penetration of tides during late-stage development associated with the river establishing a more direct and permanent connection to the sea presents a natural impediment to full development of the delta morphology. The mature form of wave-dominated deltas contains significant areas of intertidal environments. A notional evolutionary pathway for wave-dominated estuaries begins with rapid changes in the facies areas due to sediment deposition in the large central basin, and the system is susceptible to geomorphic changes. Facies areas change more rapidly as the central basin reduces in area and the geomorphology becomes increasingly susceptible to change. Once the river has established a direct and permanent connection with the ocean, changes to the facies areas slow and a relatively stable geomorphology is adopted. Perimeter/area ratios indicate that habitats are more connected in wave-dominated deltas and thus may be less vulnerable to environmental pressures.

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**Table 3**

Average perimeter to area ratios for Australian estuaries and deltas

<table>
<thead>
<tr>
<th>Facies</th>
<th>BBB</th>
<th>CB</th>
<th>FBD</th>
<th>FED</th>
<th>IF</th>
<th>MAN</th>
<th>SM</th>
<th>TSB</th>
<th>IE</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-Dom. Est.</td>
<td>1.46</td>
<td>0.18</td>
<td>0.53</td>
<td>3.45</td>
<td>15.95</td>
<td>11.12</td>
<td>11.16</td>
<td>9.32</td>
<td>12.16</td>
<td>39</td>
</tr>
<tr>
<td>T-Dom. Del.</td>
<td>2.26</td>
<td>0.00</td>
<td>0.00</td>
<td>4.29</td>
<td>15.81</td>
<td>14.33</td>
<td>16.43</td>
<td>16.41</td>
<td>13.12</td>
<td>38</td>
</tr>
<tr>
<td>W-Dom. Est.</td>
<td>10.15</td>
<td>8.43</td>
<td>17.22</td>
<td>18.07</td>
<td>31.33</td>
<td>9.51</td>
<td>19.31</td>
<td>7.25</td>
<td>28.94</td>
<td>134</td>
</tr>
<tr>
<td>W-Dom. Del.</td>
<td>12.01</td>
<td>0.47</td>
<td>2.84</td>
<td>13.99</td>
<td>29.31</td>
<td>16.12</td>
<td>20.41</td>
<td>16.52</td>
<td>24.61</td>
<td>72</td>
</tr>
</tbody>
</table>

See Table 1 for definitions of facies.

* Significantly different at 95% confidence level.
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References


