ABSTRACT: A statistical assessment of wave, tide, and river power was carried out using a database of 721 Australian clastic coastal depositional environments to test whether their geomorphology could be predicted from numerical values. The geomorphic classification of each environment (wave- and tide-dominated deltas, wave- and tide-dominated estuaries, lagoons, strand plains, and tidal flats) was established independently from remotely sensed imagery. To our knowledge, such a systematic numerical analysis has not been previously attempted for any region on earth.

The results of our analysis indicate that a relationship exists between the ratio of annual mean wave power to mean tidal power and the geomorphic development of clastic coastal depositional environments. Deltas and estuaries are associated with statistically significant differences in mean wave and tidal power. Statistically significant distinctions between populations of deltas, estuaries, strand plains, and tidal flats are also associated with river discharge and river flow rate (defined as discharge divided by open water area). Our results support the hypotheses of previous workers that wave, tide, and river power exert the principal control over the gross geomorphology and facies distribution patterns in clastic coastal depositional environments. Mean values and confidence limits of wave power, tide power, and river flow for the coastal depositional environments targeted in this study may provide a basis for the comparison of modern environments as well as constraints for paleo-reconstructions.

INTRODUCTION

The geomorphic evolution of different clastic coastal depositional environments (including deltas, estuaries, lagoons, strand plains, and tidal flats) is controlled by the relative importance of three main factors: sediment supply, physical processes, and sea level. In their reviews of this subject, Boyd et al. (1992) and Dalrymple et al. (1992) provided a synthesis and a ternary classification, emphasizing the geomorphic relationships that exist between different clastic coastal depositional environments over space and time (Fig. 1A–C). The conceptual wave–river–tide ternary classification, originally proposed by Cole and Wright (1975) and Gallaway (1975) for deltas, was adopted by Boyd et al. (1992) and applied to clastic coastal depositional environments (Fig. 1B, C). This new classification uses relative wave, tide, and river power to position each environment within the ternary diagram. Boyd et al. (1992) and Dalrymple et al. (1992) expanded this simple two-dimensional ternary diagram into a three-dimensional prism to incorporate the evolutionary relationships between the spectrum of clastic coastal depositional environments, where the $z$ axis represents relative time, with reference to changes in relative sea level and sediment supply (Fig. 1A).

Boyd et al. (1992) and Dalrymple et al. (1992) proposed the ternary prism (Fig. 1A, B) mainly as a means to portray the relative importance of the three processes. These workers plotted individual systems within the diagram on the basis of their perceived wave, tide, and river power, rather than based on measured values. To improve our understanding of the relative importance of these three key physical processes in governing the geomorphology of coastal depositional environments, the next logical step is to quantify the relative power (i.e., sediment transport capacity) of waves, tides, and rivers for a statistically significant number of cases. Therefore, the aim of this study was to test the hypothesis of Boyd et al. (1992) and Dalrymple et al. (1992) that wave, tide, and river power are the major controls on the geomorphology of modern clastic coastal depositional environments. This test was conducted by plotting a population of coastal depositional environments having a known geomorphology within a ternary diagram, with axes based on numerical estimates of wave, tide, and river power. The results provide not only the first calibration of the Boyd et al. (1992) and Dalrymple et al. (1992) model but also the first published continental-scale approach to the quantitative classification of clastic coastal depositional environments. In undertaking this work, we anticipate determining boundary conditions characteristic to each environment in the context of the existing ternary classification (Fig. 1A, B) and establishing the first quantitative approach for comparing coastal depositional environments of the same classification. As such, our approach provides the basis for identifying clastic coastal depositional environments most susceptible to changes in global wave climates as a result of global warming, and a mechanism for constraining paleo-environmental conditions for ancient coastal systems discovered in the rock record.

Quantification of Wave, Tide, and River Power

In the coastal zone, sediment erosion, transport, and deposition are physical processes that are closely related to the power of waves and tides (e.g., Swift and Thorne 1991). The geomorphology of clastic coastal depositional environments is strongly influenced by the relative contribution of waves and tides in governing the transport and deposition of available sediment (e.g., Davis and Hayes 1984). The ratio of wave power to tide power is thus used to classify each environment along the base of the ternary diagram (Fig. 1A).

The energy of a gravity wave $E$, $J m^{-2}$ in the ocean is:

$$E = \frac{1}{8} (\rho g H^2)$$

where $\rho$ is the density ($kg m^{-3}$) of the sea water, $g$ is acceleration due to gravity ($m s^{-2}$), and $H$ is the wave height ($m$) (Soulsby 1997). The wave power (units $J m^{-1} s^{-1}$) is the energy times the wave group speed ($C_g = L/T$), where $L$ is the wavelength and $T$ is wave period. We have estimated wave “power” as the energy per wave period ($E/T$, units $J m^{-2} s^{-1}$) and ignored wavelength, which is complex to calculate for shallow-water waves (i.e., ocean tides). However, our “power” estimate accounts for the increase in near bed orbital velocity that occurs for decreasing period in waves of a given height (e.g., Soulsby 1997). Because ocean gravity swell waves and tides are both wave phenomena, the ratio of wave power to tide power can be estimated by:

$$\text{Power ratio} \approx \frac{\text{wave power}}{\text{tide power}} = \frac{K [H^2/T]_\text{wave}}{[H^2/T]_\text{tide}}$$

where $K$ is a dimensionless coefficient that corrects for the greater power of tidal waves over ocean gravity waves.

Calculation of the vertical axis (river power) of the ternary diagram (Fig. 1B) is a function of the fluid power ($P$, $N m^{-1} s^{-2}$) available to transport sediment (Swift and Thorne 1991):

$$P = U \tau$$
where $U$ is the mean river current ($\text{m s}^{-1}$) and $\tau$ is the bed shear stress ($\text{N m}^{-2}$). Although $U$ is proportional to the river discharge through the cross-sectional area of the river channel, the estimation of $\tau$ requires information on the shape of the velocity profile and bottom roughness characteristics (e.g., Sternberg 1972).

**Australian Clastic Coastal Depositional Environments**

Our study encompasses the clastic coastal depositional environments of the entire Australian continent to ensure that a wide range of environments is included in the analysis. Because the impetus for this study came about as an investigation into the “health” of Australia’s coastal waterways (Heap et al. 2001), the clastic coastal depositional environments considered in this paper are restricted to those associated primarily with Holocene terrigenous sediment sources. As such, extensive regions of the coastline, including most of southern and parts of western Australia, where transgressive wave-dune systems predominate, have not been considered.

Information on the wave, tide, and river regimes around the Australian coast have been discussed in relation to the evolution of depositional environments in numerous previous case studies. Examples include studies of macrotidal estuaries (e.g., Wright et al. 1973; Cook and Mayo 1978; Harris 1988; Woodroffe 1996); wave-dominated estuaries (e.g., Roy 1984); strand plains and cheniers (e.g., Roy et al. 1980; Rhodes 1982; Murray-Wallace et al. 1999); tidal flats (e.g., Semeniuk 1981); and deltas (e.g., Johnson 1982; Lees 1992; Jones et al. 1993; Woodroffe and Chappell 1993). However, to ensure that only consistently collected and comparable data are used in the analysis, we have recalculated the wave, tide, and river power for all Australian clastic coastal depositional environments considered in this study.

Previous systematic collations of information have been used to classify Australian clastic coastal depositional environments on the basis mainly of climate, freshwater discharge, and tidal range (e.g., Bucher and Saenger 1991, 1994; Eyre 1998; Digby et al. 1998). However, none of these studies included waves as a classification criterion. The distribution of continental shelf zones dominated by swell waves, tides, cyclone-induced currents, and intruding ocean currents was described by Harris (1995) on the basis of available published data, but this classification was not extended to the coastal zone. From these studies it is clear that Australia’s coastal environment spans a range of climatic zones (tropical to temperate) and contains examples from the complete spectrum of clastic coastal depositional environments of varying wave, tide, and river influence, and is therefore an appropriate location to carry out this study. We acknowledge, however, that by restricting our...
study to the Australian continent some clastic coastal depositional environments, such as those influenced by glacial processes and those associated with major river systems, are not represented, and our results may not be directly applicable in these situations.

**METHODS**

**Australian Database of Clastic Coastal Depositional Environments**

The database used in this study is the Australian Estuarine Database (AED; http://www.ozestuaries.org), which contains physical information for 780 Australian coastal waterways (Bucher and Saenger 1991; Digby et al. 1998). All of these waterways were identified as “estuaries” based on a definition similar to that proposed by Pritchard (1967), as: “semi-enclosed bodies of water and adjacent wetlands which have input both from marine inundation and terrestrial runoff” (Digby et al. 1998, p. 15). For a waterway to be contained in the AED, it also must be large enough to be shown on a 1:100,000 scale topographic map and have a catchment area of at least 15 km² (Digby et al. 1998).

These 780 coastal waterways span a range of climatic and oceanographic settings and display a range of geomorphic types. They include a range of clastic coastal depositional environments, together with other nondepositional environments such as rocky embayments and channels between islands and the coast that are not included in the Boyd et al. (1992) classification (Fig. 1C). Because in the present study we are concerned with the geomorphology of clastic coastal depositional environments, we have adopted the definitions of deltas, strand plains, lagoons, and tidal flats as summarized by Boyd et al. (1992) and for estuaries we have adopted the definition of Dalrymple et al. (1992).

An independent assessment of the geomorphology of the 780 waterways contained in the AED (Bucher and Saenger 1991; Digby et al. 1998) was undertaken in this study by a visual inspection of maps, nautical charts, LANDSAT-TM images, and aerial photographs (see acknowledgments). Each waterway was classified, following the principles of Boyd et al. (1992) and Dalrymple et al. (1992), as wave- or tide-dominated estuaries, wave- or tide-dominated deltas, lagoons, strand plains, or tidal flats (Fig. 1C). Only the geomorphology visible in the images was used to determine the classification. In cases where the waterway was judged to be an embayment, or a channel between an island and the coast, or where the diagnostic geomorphic features were ambiguous or unclear, a “mixed/other” category was used. This resulted in a total of 721 clastic coastal depositional environments targeted for further analysis.

**Quantitative Wave, Tide, and River Data**

To quantify the wave power around the Australian coast, heights and periods of surface gravity waves were estimated using the Australian Bureau of Meteorology’s regional atmospheric model. Surface wind speed estimates generated by this model provided input to the Wave Model, WAM (Hasselman et al. 1988; Komen et al. 1994) to yield estimates of mean wave height and period. These data are 6-hourly predictions of significant wave height (Hsig.) and mean wave period, gridded at a spatial resolution of 0.1° (11 km), for the period March 1997 to February 1998, inclusive. The gridding procedure employed a weighted inverse distance algorithm, which produces representative interpolations in situations where the original data are infrequent and irregularly distributed. The mean annual Hsig. and periods were then calculated for each coastal waterway by assigning the model grid value closest to the location of the waterway mouth.

To quantify the tidal power along the Australian coast, the maximum spring tidal range for 423 tide gauges located around Australia (Australian National Tide Tables 2000) was gridded at a spatial resolution of 0.1° (11 km) using an inverse distance algorithm with a weighting of 4. The maximum spring tidal range for each coastal waterway was then determined by assigning the model grid value closest to the mouth. Two tidal periods were used for the calculation of tidal power: diurnal and semi-diurnal. The difference between diurnal and semi-diurnal tides is defined in the Australian National Tide Tables (2000) on the basis of the ratio of four major tidal constituents as:

\[
\text{semidiurnal} = (K_1 + O_1)/(M_2 + S_2) < 0.5, \quad \text{and} \quad \text{diurnal} = (K_1 + O_1)/(M_2 + S_2) > 0.5,
\]

where \( K_1 \) is the lunisolar diurnal, \( O_1 \) is the principal lunar diurnal, \( M_2 \) is the principal lunar tidal component, \( S_2 \) the principal solar tidal component. The wave and tide power, derived here, are considered to best represent the conditions in situ measurements of river currents and boundary shear stress are not available for most Australian waterways. However, Digby et al. (1998) estimated the mean annual river discharge for the 780 Australian waterways contained in the AED as

\[
\text{mean annual discharge (m}^3\text{s}^{-1}) = [\text{catchment area (m}^2\text{)} \times \text{mean annual rainfall (m} \times \text{runoff coefficient}].
\]

The mean annual discharge was then divided by the open water area of each waterway, which was measured from LANDSAT TM images and, where available, from aerial photographs, to calculate river flow (m s⁻¹). River flow is proportional (but not equivalent) to river power (Equation 3).

Although we have calculated mean annual values for wave and tide power and river flow, it is important to note that the discharge of many Australian river systems is event-driven (Neil and Yu 1995; Wossen et al. 1996). The mean annual river flow does not reflect extreme river power values associated with flood events, when most, if not all, sediment transport occurs. Because of this, it is probable that the rate and degree of infilling of Australian coastal depositional systems by river-derived sediment are more closely associated with the frequency and duration of storms rather than with average annual sediment yield from the catchments. Al-

**Table 1.—Mean and standard deviation of the tide power, wave power, (dimensionless) wave/tide power ratio, mean annual river discharge, and river flow rates calculated for seven different clastic coastal sedimentary environments around Australia.**

<table>
<thead>
<tr>
<th>Type of System</th>
<th>Tide Power (J m⁻² s⁻¹)</th>
<th>Wave Power (J m⁻² s⁻¹)</th>
<th>Wave/Tide Power Ratio</th>
<th>River Discharge (m³ s⁻¹)</th>
<th>River Flow (¹⁰⁶ m³ s⁻¹)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave-Delta</td>
<td>398 ± 437</td>
<td>181 ± 192</td>
<td>4.10 ± 10.5</td>
<td>19.2 ± 26.9</td>
<td>11.4 ± 18.6</td>
<td>81</td>
</tr>
<tr>
<td>Tide-Delta</td>
<td>828 ± 1190</td>
<td>42.8 ± 63.4</td>
<td>0.406 ± 0.794</td>
<td>33.4 ± 67.6</td>
<td>8.45 ± 16.2</td>
<td>69</td>
</tr>
<tr>
<td>Wave-Estuary</td>
<td>177 ± 280</td>
<td>318 ± 247</td>
<td>27.3 ± 52.9</td>
<td>26.6 ± 170</td>
<td>3.46 ± 10.5</td>
<td>145</td>
</tr>
<tr>
<td>Tide-Estuary</td>
<td>2244 ± 2220</td>
<td>41.7 ± 55.6</td>
<td>0.179 ± 0.338</td>
<td>55.5 ± 71.0</td>
<td>1.38 ± 5.11</td>
<td>99</td>
</tr>
<tr>
<td>Strandplain</td>
<td>969 ± 1260</td>
<td>127 ± 181</td>
<td>2.68 ± 5.81</td>
<td>1.68 ± 2.33</td>
<td>6.09 ± 11.8</td>
<td>43</td>
</tr>
<tr>
<td>Tidal Flat</td>
<td>1730 ± 2120</td>
<td>60.6 ± 74.1</td>
<td>0.450 ± 0.819</td>
<td>1.49 ± 2.25</td>
<td>2.84 ± 8.26</td>
<td>273</td>
</tr>
<tr>
<td>Lagoon</td>
<td>416 ± 1000</td>
<td>266 ± 202</td>
<td>1.41 ± 23.2</td>
<td>0.248 ± 0.259</td>
<td>0.503 ± 1.63</td>
<td>11</td>
</tr>
<tr>
<td>Other</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>59</td>
</tr>
</tbody>
</table>
Fig. 2.—Distribution of 721 different clastic coastal depositional environments around Australia based on the interpretation of aerial photographs and LANDSAT TM imagery. The 59 'mixed/other' coastal environments are not shown. Five regions are identified, on the basis of the combination and distribution of coastal depositional environments (see also Table 2).

RESULTS

Spatial Distribution of Coastal Depositional Environments

The visual inspection of the waterways resulted in the geomorphic classification of 721 clastic coastal depositional environments using the criteria of Boyd et al. (1992) and Dalrymple et al. (1992), and 59 cases of "mixed/other" types (Table 1). The data indicate that tidal flats are the most common coastal depositional environment in Australia (n = 273), followed by wave-dominated estuaries (n = 145), tide-dominated estuaries (n = 99), wave-dominated deltas (n = 81), tide-dominated deltas (n = 69), strand plains (n = 43), and lagoons (n = 11).

The spatial distribution of these environments around the coast exhibits a distinct zonation, such that five major coastal regions can be identified: southeast coast; southwest coast; northwest coast; Gulf of Carpentaria coast; and northeast coast (Figs. 2, 3; Table 2). The southeast and southwest coasts are wave-dominated environments, whereas the northern coastal areas (northwest, Carpentaria, and northeast) are mainly tide-dominated (Figs. 2, 3). Although wave-dominated estuaries occur almost exclusively in the southeast and southwest, wave-dominated deltas and strand plains are widely scattered across the southeast, northeast, Gulf of Carpentaria, and to a lesser extent in the northwest (Fig. 3). This pattern conforms to the general distribution of wave- and tide-dominated shelf environments described by Harris (1995), such that tide-dominated estuaries, deltas, and...
Fig. 3.—Maps showing the distribution of the seven different clastic coastal depositional environments around Australia based on the interpretation of aerial photographs and LANDSAT TM imagery. Note that the depositional environments targeted in this study are restricted to those influenced by Holocene terrigenous sediment; these environments are absent across most of southern and parts of western Australia.
Table 2.—Number (and percentage) of Australian clastic coastal depositional environments listed by geographical area.

<table>
<thead>
<tr>
<th></th>
<th>Southeast Coast</th>
<th>Southwest Coast</th>
<th>Northwest Coast</th>
<th>Gulf of Carpentaria Coast</th>
<th>Northeast Coast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave-Delta</td>
<td>81 (27%)</td>
<td>27 (13%)</td>
<td>4 (5%)</td>
<td>14 (17%)</td>
<td>35 (43%)</td>
</tr>
<tr>
<td>Tide-Delta</td>
<td>49 (10%)</td>
<td>0 (0%)</td>
<td>11 (16%)</td>
<td>24 (35%)</td>
<td>34 (49%)</td>
</tr>
<tr>
<td>Wave-Estuary</td>
<td>145 (79%)</td>
<td>18 (12%)</td>
<td>0 (0%)</td>
<td>7 (6%)</td>
<td>6 (4%)</td>
</tr>
<tr>
<td>Tide-Estuary</td>
<td>99 (21%)</td>
<td>51 (52%)</td>
<td>17 (17%)</td>
<td>29 (29%)</td>
<td></td>
</tr>
<tr>
<td>Strandplain</td>
<td>43 (9%)</td>
<td>9 (21%)</td>
<td>4 (9%)</td>
<td>21 (49%)</td>
<td>9 (21%)</td>
</tr>
<tr>
<td>Tidal Flats</td>
<td>273 (44%)</td>
<td>95 (35%)</td>
<td>80 (29%)</td>
<td>86 (32%)</td>
<td></td>
</tr>
<tr>
<td>Lagoon</td>
<td>11 (3%)</td>
<td>8 (73%)</td>
<td>1 (9%)</td>
<td>1 (9%)</td>
<td>0</td>
</tr>
</tbody>
</table>

Tidal flats occur mostly adjacent to tide-dominated shelves, wave-dominated estuaries, lagoons, and deltas, and strand plains occur mostly adjacent to wave-dominated shelves (Fig. 2). However, each of the five coastal regions contains a distinct mixture of coastal depositional environments.

The southeast coast contains 79% of Australia’s wave-dominated estuaries but also significant numbers of wave-dominated deltas, strand plains, and lagoons plus some tide-dominated environments (Table 2). This mixture of environments distinguishes this region from the southwest coast, where there are also mainly wave-dominated estuaries, but only one wave-dominated delta and no strand plains; the southwest coast lacks progradation coastal depositional environments. There are no tide-dominated coastal depositional environments on the southwest coast.

The northwest coast is characterized by the largest number of tide-dominated estuaries (n = 51). These are supplemented with significant numbers of tidal flats and some tide-dominated deltas. Wave-dominated environments are rare, with only 9 out of 166 environments being wave-dominated (Table 2).

The Gulf of Carpentaria coast is characterized by the largest number of strandplains (n = 21). This region also has significant numbers of tidal flats, tide-dominated estuaries, and tide-dominated deltas. However, the greater influence of waves in this region relative to the northwest coast is manifest by the occurrence of wave-dominated estuaries and wave-dominated deltas (Fig. 2; Table 2).

The northeast coast is differentiated from the Gulf of Carpentaria coast by its abundance of both wave- and tide-dominated deltas (n = 69) but fewer strand plains (Fig. 3; Table 2). The northeast and Gulf of Carpentaria coasts are similar in that the total number of tide-dominated environments (tide-dominated estuaries, deltas, and tidal flats) is about three times as large as the total number of wave-dominated environments (wave-dominated estuaries, deltas, strand plains, and lagoons). Hence, although these coastal regions are classed as being mainly tide-dominated, there is a greater mixture of wave- and tide-dominated environments on the northeast and Gulf of Carpentaria coasts than in any of the other three regions (northwest, southwest, and southeast; Figs. 2, 3; Table 2).

Wave, Tide, and River Power

A plot of wave and tidal power shows that Australia’s clastic coastal depositional environments are partitioned into two populations (Fig. 4) that are distinguished by environments that display wave-dominated geomorphology (wave-dominated deltas and estuaries, strand plains, and lagoons) and environments that display a tide-dominated geomorphology (tide-dominated deltas and estuaries, tidal flats). A line of best fit separating these two populations can be drawn with a slope of 3.2. This slope was used as the coefficient K in Equation 2 to center the distribution of coastal depositional environments at a wave/tide power ratio of 1 (i.e., Log (W/T) = 0).

Coastal depositional environments that display wave-dominated geomorphology number 280, with a mean annual wave power of between 1.56 × 10⁻³ and 1.190 J m⁻² s⁻¹ (average = 246 ± 235 J m⁻² s⁻¹). Tidal power for these environments ranges from 7.9 to 6000 J m⁻² s⁻¹ with an average of 327 ± 621 J m⁻² s⁻¹. Coastal depositional environments that display tide-dominated geomorphology number 441, with a mean annual wave power of between 2.47 × 10⁻³ and 497 J m⁻² s⁻¹ (average = 53.6 ± 69.2 J m⁻² s⁻¹). Tidal power for these environments ranges from 31.6 to 10,900 J m⁻² s⁻¹ with an average of 1,700 ± 2,070 J m⁻² s⁻¹.

A statistical t-test analysis of the data demonstrates that the average wave and tide power of wave-dominated environments are significantly different (at 95% confidence limits) from the average wave and tide power of tide-dominated environments (Fig. 4). The differences between the average wave/tide power ratios for wave-dominated environments (5.23 ± 12.9, n = 280) are also statistically significant compared with tide-dominated environments (0.119 ± 0.231, n = 441).

In order to investigate whether there are statistically significant differences in the mean values of tidal power, wave power, river flow, and river discharge between the seven clastic coastal depositional environments (Fig. 4).
1B), a one-way analysis of variance (ANOVA) was calculated using the statistical software package STATISTICA® (Fig. 5; Table 1). The ANOVA indicated that there are significant differences between category means for tidal power, wave power and river flow. 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 (highlighted cells in Fig. 6). These tests provide a statistical check on the significance of the relationships between the geomorphology of each of the seven clastic coastal depositional environments and wave power, tide power, river discharge, and river flow. The significant differences also confirm situations where a positive correlation exists between the independently derived geomorphology and wave, tide, and river values. Interestingly, no significant differences were identified between the mean river discharges of the seven coastal depositional environments.

Plotting the data on ternary diagrams (Figs. 7A, B) illustrates a strong separation of coastal depositional environments along the x axis (wave/tide power ratio). Tide-dominated environments plot almost without exception on the right side of the diagram and wave-dominated estuaries and lagoons clearly plot on the left side. However, strand plains and wave-dominated deltas exhibit much scatter around the center of the ternary diagram, indicating that they occur where the wave/tide power ratio is close to 1.

There is generally wide scatter for all environments along the vertical (river discharge/river flow) axes (Figs. 7A, B). The separation of the different populations varies, depending upon which parameter (river discharge or river flow) is used. For river discharge, deltas and estuaries plot as overlapping and widely scattered groups, but strand plains, lagoons, and tidal flats all have a mean annual discharge $< 10^7$ m³ s⁻¹ (Fig. 7A). As noted above, no significant differences were identified between the mean annual river discharges of the seven coastal depositional environments based on Schefee’s test (Fig. 6).

Nearly all deltas have a mean annual river flow of $> 1 \times 10^{-7}$ m s⁻¹ (Fig. 7A), which corresponds to deltas being significantly different from estuaries and tidal flats based on Schefee’s test (Fig. 6). Estuaries, strand plains, and tidal flats exhibit a wide scatter against mean annual river flow (Fig. 7B), whilst lagoons have a mean annual river flow of $< 1 \times 10^{-7}$ m s⁻¹ (Fig. 7B).

DISCUSSION

The hypothesis of Boyd et al. (1992) and Dalrymple et al. (1992), that wave, tide, and river power controls the geomorphology of clastic coastal depositional environments is generally supported by the results of our study. A clear relationship exists between the ratio of mean annual wave power to mean annual tidal power (i.e., the wave/tide power ratio) and the geomorphology of coastal depositional environments (Fig. 4). There are also statistically significant differences in the mean annual wave power, mean tidal power, and mean annual river flow between the seven types of clastic coastal depositional environments targeted in our study (Figs. 5, 6).

Our results show that most clastic coastal depositional environments plot on either the wave- or tide-dominated side of the ternary diagrams (Fig. 7). An exception to this are the strand plains, which have the widest scatter in terms of wave/tide power ratio, and they tend to plot towards the center rather than on the wave-dominated half of the ternary diagram (Fig. 7), as expected (Fig. 1B). We have not separated chenier-ridge complexes from strand plains, because of the difficulty in discriminating between the two in the remotely sensed images used. Hence these depositional environments are plotted together, even though they may be associated with different wave/tide power regimes. Wave-formed chenier ridges are separated by fine-grained, tidal-flat deposits and are generally considered to be more “mixed” wave/tide environments (e.g., Dalrymple 1992), which probably explains their scattered distribution in the ternary diagram (Fig. 7).

An interesting observation is that the matrix of statistically significant differences between clastic coastal depositional environments (Fig. 6) shows that not all environments are differentiated by the same independent variables, either separately or in combination, and that some environments are not differentiated by any of the variables. For example, the differences between wave-dominated deltas, tide-dominated estuaries, and tidal flats...
were significant for all three of the independent variables (wave power, tide power, and river flow; Figs. 5, 6). On the other hand, there was no statistically significant difference between strand plains and tide-dominated deltas, wave-dominated deltas, or lagoons identified by any of the independent variables (Fig. 6). For the other three environments, however, it appears that there may be some other factor (or factors) that controls the geomorphology.

One variable that is not accounted for in the Boyd et al. (1992) and Dalrymple et al. (1992) classification (Fig. 1) is the initial volume of the incised valley. It is implied in the diagram (Fig. 1A) that all valley systems start out having a comparable volume (accommodation space), which is then filled with river and marine sediment under a steady sea level. However, some valleys are larger than others, depending on a wide range of geological parameters, and hence they do not infill at the same rate. Valleys having identical wave, tide, and river power may have already infilled and become deltas (where the accommodation space was relatively small), or they may still be estuaries (where the accommodation space was relatively large). Hence variations in the initial volume of incised valleys may explain some of the scatter exhibited by the data (along the vertical axes) in Figs. 7A and 6B. Nevertheless, the results of the present study suggest that there are statistically significant differences between groups of clastic coastal depositional environments based on river discharge and river flow.

**River Discharge and Flow**

In Australia, river discharge is larger for deltas and estuaries than for strand plains and tidal flats but does not vary significantly between deltas and estuaries (Fig. 5; Table 1). The mean annual river discharge is not significantly different between the seven clastic coastal depositional environments (Fig. 6). However, a statistical t-test demonstrates that the mean annual river discharge for deltas and estuaries combined ($28.5 \pm 113 \text{ m}^3 \text{s}^{-1}$, $n = 394$) is significantly different (at the 95% confidence level) from the mean annual river discharge of strand plains and tidal flats combined ($1.51 \pm 2.26 \text{ m}^3 \text{s}^{-1}$, $n = 316$; Fig. 6A). Furthermore, lagoons have a significantly lower river discharge rate than any other environment (Fig. 5; Table 1). This result is consistent with the view of Boyd et al. (1992), that strand plains, lagoons, and tidal flats occur along coastlines that do not have any significant river input (Fig. 1C). In our study, these environments were found not to have incised valleys, but contained small drainage areas that extended only as far as the immediately adjacent hinterland.

Despite significant overlap in the populations, statistically significant differences do occur between mean annual river flow values for some of the different environments (Figs. 5, 6). Most significantly, wave- and tide-dominated deltas can be discriminated from wave- and tide-dominated estuaries (Figs. 6, 7B). Although the difference in mean annual river flow rate between the seven coastal depositional environments is scattered...
**FIG. 7.**—Triangular classification diagrams of Australian clastic coastal depositional environments plotting log wave/tide power ratio versus: **A)** log mean annual river discharge, and **B)** log mean annual river flow. The slope of the line in Fig. 4 was used as a correction coefficient ($K$) in Equation 2 for plotting the data so that all the data in the ternary plot was centered on a wave/tide power ratio = 1. Note the Murray–Darling River (Fig. 2) has a mean annual discharge of 2,032 m$^3$ s$^{-1}$ and plots beyond the limit of the ternary diagrams.
(Figs. 5, 7B), a t-test indicates that the combined mean annual river flow for wave- and tide-dominated deltas ($1.0 \times 10^{-5} \pm 1.8 \times 10^{-5}$ m s$^{-1}$, $n = 150$) is significantly different from the combined mean annual river flow rate of estuaries, strand plans and tidal flats ($2.9 \times 10^{-6} \pm 8.8 \times 10^{-6}$ m s$^{-1}$, $n = 571$) at the 90% confidence level. The infilling of estuaries to form deltas results in a smaller open water area, and it follows that deltas should have a larger river flow rate than estuaries (given a similar river discharge). However, tidal creeks and lagoons associated with tidal flats and strand plains also have small open water areas and they exhibit a wide range of river flow rates (i.e., large standard deviations), depending on the size of their catchment areas (Table 1). Some strand plains, with small open water areas, have river flow rates similar
to some deltaic systems (Fig. 6). Hence, the type of depositional environment and their stage of development may explain some of the scatter in the river-flow data.

Dalrymple et al. (1992) suggested that the river sediment load (and not necessarily the water discharge) exerts the most control over the geomorphology of clastic coastal depositional environments. If this is true, then river power plays only a secondary role in controlling the geomorphology of coastal depositional environments. Testing of this hypothesis must await the development of a reliable database containing sediment yields for Australia’s river catchments, which is currently not available (Harris 1995; Wasson et al. 1996).

**Flux of River Sediment to the Coast**

The distribution of different geomorphic classes of clastic coastal depositional environments provides insight into the flux of river sediment to the coast during the Holocene. In Australia estuaries are more common than deltas, which is also true globally and is attributed to the relatively brief time available in the Holocene for estuaries to infill under a steady sea level (Nichols and Biggs 1985). The abundance of estuaries over deltas in Australia also probably reflects the continent’s relatively arid climate, low relief, and hence relatively low sediment yield (Milliman and Syvitski 1992).

Two-thirds of all Australia’s deltas and nearly half of the prograding strand plains and tidal flats are located on the northeast and Gulf of Carpentaria coasts. The abundance of these progradational coastal depositional environments (Fig. 1C) indicates that the hinterland of this region has a relatively high sediment yield in comparison with other regions of the continent. Geological investigations of the postglacial evolution of the northeast margin of Australia (e.g., Harris et al. 1990; Woolfe et al. 1999; Dunbar et al. 2000) have revealed that this margin has been characterized by significant input of fluvioclastic sediment during most of the Holocene associated with the dominant quasi-monsoonal climate regime in the region (e.g., Suppiah 1992).

Wave-dominated estuaries that occur on the southeast coast are only partially filled with postglacial sediment, most of which is marine-derived siliciclastic sediment (e.g., Roy 1984; Nichol and Murray-Wallace 1992; Nichol et al. 1994; Nichol et al. 1997). The part of the southeast region that borders the Great Australian Bight (Fig. 2) is drought-dominated and receives little or no runoff (e.g., Erskine and Warner 1988). Clastic coastal depositional environments in the southeast regions of Australia are thus characterized mostly by partially filled lagoons, also indicating the dominance of marine sediment deposition in these systems. In contrast, coastal systems throughout southern and western Australia are dominated by marine-derived sediment from carbonate sources, including the adjacent shelf and coral reefs (e.g., Short in press). Similarly, published case studies from clastic coastal depositional environments of the northwest coast (e.g., Woodroffe et al. 1989; Woodroffe and Chappell 1993; Woodroffe 1996) show that the (mainly) tide-dominated estuaries found here are also only partially filled with marine-derived Holocene sediment. The abundance of estuaries and lagoons containing ample accommodation space and marine-derived sediment along the southwest, southeast, and northwest coasts of Australia implies that these margins have been characterized by moderate to low flux of terrigenous sediment during the Holocene.

**The Relative Influence of Wave and Tide Power on Coastal Geomorphology**

An important factor that plays a role in determining the geomorphology of clastic coastal depositional environments is the relative power of waves and tides, acting separately and in combination. As noted by Davis and Hayes (1984), it is possible, for example, for a coastal environment to be wave-dominated even along macrotidal coasts, if the wave power is great enough. An interesting result of our analysis is that both wave-dominated and tide-dominated deltas have significantly lower mean wave and tidal power than wave-dominated and tide-dominated estuaries (Figs. 5, 6). In other words, our results suggest that deltas are formed in lower-energy environments than estuaries. This may be because the higher-energy systems tend to lose more sediment to the adjacent shelf and coastal areas, thus inhibiting delta development. Delta sediment may be smeared out along the coast where the receiving basin is characterized by relatively high wave or tide power.

The average tidal power for the 780 coastal environments (1,200 J m$^{-2}$ s$^{-1}$) is greater than the average wave power (130 J m$^{-2}$ s$^{-1}$; see Fig. 4) because power is a function of the wave height squared (Equation 2). Hence the absolute value of fluid power expended around Australia is highest on the macrotidal northwest coast (Fig. 2), which is characterized by transgressive tide-dominated estuaries and tidal flats, with strong tidal currents and continuously turbid water (e.g., Wright et al. 1973; Semeniuk 1981). Tide-dominated deltas are most abundant and best developed in central and north Queensland (Fig. 2), where the coast is characterized by upper-micro to lower-meso ranges and a broad, shallow-gradient, progradational coastal plain (Hopley 1982; Belperio 1983). Wave power along this coast is attenuated by the Great Barrier Reef, which acts to block out long-period swell waves generated in the Coral Sea (Hopley 1982; Hopley 1984). The distribution of tide-dominated deltas suggests that they are confined to coasts where tidal power is relatively weak, allowing sediment supplied by rivers to be deposited close to the river mouth, and thus permitting the delta to prograde seaward (e.g., Galloway 1975).

Wave-dominated deltas are also generally found along relatively low-energy coasts. The formation of deltas on the northeast Queensland coast is probably facilitated by the sheltering effect of the Great Barrier Reef as mentioned above (Hopley 1982; Orpin et al. 1999). In contrast, the high-energy exposed southeast coast has relatively few deltas.

The mean values and bounding limits of tide power, wave power, river discharge, and river flow predicted by our study (Table 1; Fig. 5) may prove useful for the characterization of paleoenvironments. If an ancient deposit is interpreted as a tide-dominated estuary, for example, then it might be inferred (from Fig. 5) that the mean annual river discharge into the estuary was at least ~1 m$^3$ s$^{-1}$, that its tidal power was at least ~100 watts m$^{-2}$, whilst its wave power was probably less than ~100 watts m$^{-2}$. Taken together with information from the fossil record, these values might provide a means of testing the validity or otherwise of basic environmental interpretations.

**Climate Change and the Stability of Coastal Depositional Environments**

Our results show that many Australian coastal depositional environments are poised along the wave–tide power boundary (Figs. 4, 7) and may be likely to change from one geomorphic state to another with changes to the wave/tide power ratio. Geomorphic changes resulting from an increase in wave power are likely to be most obvious for tide-dominated environments. The most significant change would be the replacement of existing shore-normal features (e.g., tidal sand banks) with shore-parallel features (e.g., barriers and beach ridges). Coastal depositional environments that presently contain permanently open tidal inlets may become subject to intermittent or complete closure, and prograding environments may begin to recede because of increased alongshore sediment transport.

Significant attention has focused on the rise in global sea level induced by anthropogenic greenhouse warming and the effects this may have on the coastal zone (e.g., Daniels 1992; MacDonald and O’Connor 1996). Another apparent response to the warming of the Earth’s atmosphere is a change in the ocean wave climate, manifested as increased wave heights associated with more intense storm events (e.g., Carter and Draper 1988; WASA 1998; Gulev and Hasse 1999; Allan and Komar 2000; Greve...
REFERENCES


Received 2 October 2001; accepted 9 April 2002.