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Classification of clastic coastal depositional environments

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ABSTRACT

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This paper proposes a new classification for clastic coastal environments which includes the full range of major depositional settings including deltas, strand plains, tidal flats, estuaries and lagoons. This classification includes both morphologic and evolutionary components and is based on dominant coastal processes. It has the potential to predict responses in geomorphology, facies and stratigraphy. The significance of this classification is its evolutionary capability, and its inclusion of all major clastic coastal depositional environments, making it more comprehensive than previous classifications.

We employ a ternary *process classification* with two axes. The first (horizontal axis) is defined as the relative power of wave versus tidal processes. The second (vertical) axis represents relative fluvial power (increasing upward). A ternary diagram defined by these axes can be used to illustrate the genetic process–response relationships between major coastal environments. The *evolutionary classification* combines the concept of two sediment sources (river and marine) with a relative sea-level parameter to classify embayed as well as linear and elongate/lobate shorelines. This approach identifies the evolutionary relationships between coastal sedimentary environments.

The new ternary approach to process classification can be applied to estuaries and lagoons to define wave and tide end-member facies models, each consisting of a tripartite facies zonation. The evolutionary classification is compatible with sequence stratigraphy because sediment supply and relative sea level are included, and serves as a starting point for more refined coastal stratigraphic analyses.

Introduction

Classification of coasts has been a standard approach for geomorphologists (Pethick, 1984) and most modern efforts date from Johnson (1919). These classifications concentrate on grouping morphological features and often employ a sea-level criterion to distinguish emergent from submergent coasts (e.g., Johnson, 1919; Valentin, 1952). Other classifications employ a genetic approach based on dominant processes, using non-marine versus marine processes (e.g., Shepard, 1973) or a range of marine processes such as Davies' (1980) use of wave type and tidal range. The approach of Curray (1964) employed the variables of sediment supply and relative sea level to distinguish regressive from transgressive coasts. Successful classifications based on structural controls such as those of Bloom (1978) and Inman and Nordstrom (1971) were usually employed only on a broad plate tectonic level.

From the mid part of the twentieth century, a more geological approach to coastal classification evolved. Sedimentologists began to organise information on the distribution and prediction of reservoir facies or organic source rocks in single depositional environments. Much early emphasis was placed on deltas (e.g., Fisher et al., 1969),

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culminating in Galloway's (1975) ternary classification based on wave, tide and river processes and the approach of Wright (1977) based on statistical analysis of many process variables. Models have now been established in many environments including alluvial (e.g., Miall, 1977), tidal inlets and barriers (e.g., Hayes, 1975), or continental shelves (e.g., Johnson and Baldwin, 1986). The most recent development in coastal models involves sequence stratigraphy (e.g., Posamentier and Vail, 1988) which places the coastal facies in a classification defined by transgressive and regressive stacking geometries and based primarily on relative sea-level variations.

The objective for this paper is to provide a classification for depositional coastal environments which includes the full range of major clastic depositional settings including deltas, strand plains, tidal flats, estuaries and lagoons. This classification includes both morphologic and evolutionary components and is based on dominant coastal processes. It has the potential to predict responses in geomorphology, facies and stratigraphy. The significance of this classification is its evolutionary capability, and its inclusion of all major coastal depositional environments, making it more comprehensive than previous classifications.

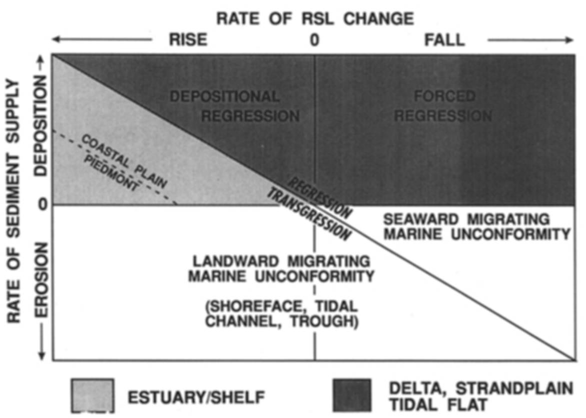

Fig. 1. A plot of relative sea-level rise and fall rates against erosion and deposition rates allows discrimination of transgressive from regressive coasts, and depositional coasts (upper half of figure) from erosional coasts (lower half of figure). Within the depositional field, this plot separates (transgressive) estuary/shelf environments from (regressive) deltas, strandplains and tidal flats. Each field represents equilibrium, long-term positions for the environments. Greater distance from the regression/transgression diagonal indicates increased rates of transgression/regression. When continued over a long period, high rates of transgression result in landward migration from the zone of coastal plain estuaries to that of piedmont estuaries. (Based on Curray, 1964.)

Coastal classification

General principles

The most effective method of classifying coastal stratigraphy is to use a subdivision into regressive and transgressive categories such as Reinson's approach (Reinson, 1984) or that of Frazier (1974). Curray's (1964) classification of transgressions and regressions has the potential to categorise most coastal environments. Curray used parameters of relative sea-level rise and fall plotted against erosion and deposition to identify several types of transgression and regression. The same approach can be used (Fig. 1) to broadly distinguish between two groups of depositional sedimentary environments—transgressive and regressive. When the rate of sediment supply exceeds the rate of relative sea-level rise, or sediment accumulates during a relative sea-level fall (area of darkest stipple on Fig. 1), regression results in the generation of elongate/lobate (delta) or linear (strandplain and tidal flat) shorelines (Fig. 2). The interaction between river sediment input and the ability of marine processes to redistribute that input determines if the coast will be elongate/lobate or linear (Fisher et al., 1969; Galloway, 1975). Deposition during relative sea-level fall (upper right quadrant, Fig. 1) has recently been investigated by Plint (1988) and termed "forced regression" by Posamentier et al. (1992). When the rate of relative sea-level rise exceeds the rate of sediment supply (area of light stipple on Fig. 1), transgression results in the generation of estuaries and lagoons on embayed coasts and the landward migration of the continental shelf on all linear (tidal flat and strandplain) coasts (Fig. 2). Coastal plain estuaries and lagoons are formed in a seaward location (Fig. 1) but if the transgression extends further inland it may encounter areas of higher relief and/or bedrock and produce piedmont estuaries and lagoons (e.g., Ricketts, 1991). Depending on the balance between relative sea level and erosion (lower half Fig. 1), coasts may experience either landward or seaward migrating marine unconformities produced by the shoreface (often termed ravinement surfaces), tidal channels or the troughs between shoreface ridges (Fig. 1). Conditions of net erosion will not be further considered here.

Process-based coastal classification

A simple yet effective ternary classification based on dominant processes has been employed by Galloway (1975) for deltas, and Johnson and Baldwin (1986) for continental shelves. Here we employ the same approach for all coastal environments by extending a ternary classification to deltas, estuaries, lagoons, strand plains and tidal flats (Fig. 3; see Zaitlin and Schultz, 1990, and Dalrymple et al., 1992, for earlier versions). We use two axes for this classification. The first (horizontal axis) is defined as the relative power of wave versus tidal processes. The second (vertical) axis represents relative fluvial power (increasing upward). A ternary diagram defined by these axes can be used to illustrate the genetic process relationships between major coastal environments, as shown in Fig. 3.

The terms estuary, barrier and strandplain (see Fig. 2) have a variety of connotations and for clarity we define our use of them here. We define an *estuary* in geological terms as the seaward portion of a drowned valley which receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave

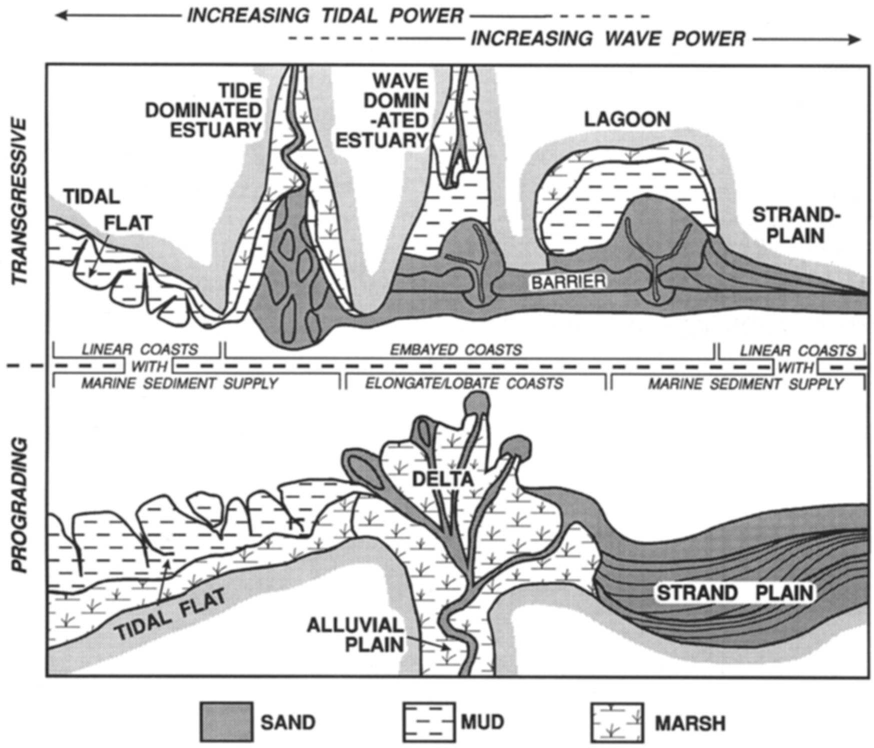

Fig. 2. The distribution of major coastal depositional features is shown here for both prograding (lower panel) and transgressive (upper panel) coasts. The figure is organised to show tidal power increasing to the left and wave power increasing to the right. Embayed coasts (estuaries and lagoons) are the transgressive counterpart of prograding elongate/lobate coasts (deltas) and are found in the centre of the figure. Deltas have a fluvial sediment source, estuaries have a mixed (both fluvial + marine) sediment source, and lagoons have only a marine sediment source. Further details of depositional sub-environments in estuaries may be found in Dalrymple et al., 1992. Progradation of linear or irregular coasts with marine (longshore and/or onshore) sediment supply, results in the generation of strandplains and tidal flats, which are replaced during transgression by the continental shelf.

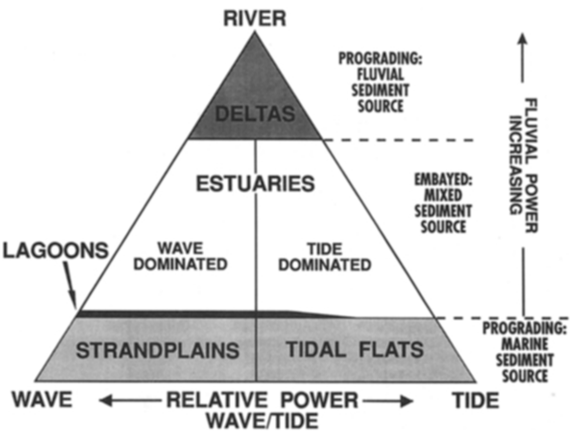

Fig. 3. Ternary process-based coastal classification modified after Dalrymple et al. (1992). The uppermost triangle is the delta field, the middle trapezoid is the estuary field, and the lower area contains a spectrum of prograding, straight coastlines, ranging from tidal flats to strand (beach-ridge) plains. Lagoons occupy a linear field lying between estuaries and prograding, straight coasts. The coastal environments are discriminated on the basis of relative wave versus tide power from left to right, and increasing fluvial power upward from the lagoon field. The fields are also discriminated on the basis of degree of coastal embayment, and sediment source.

and fluvial processes; the estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth (Dalrymple et al., 1992). We define a *barrier* as an elongate, shore-parallel sand body which may consist of a number of sandy units including beach, dunes, tidal deltas, washovers, and spits. Barriers separate lagoon and estuary embayments from the marine environment and are best classified as components of estuary and lagoon systems. They may be connected to the mainland at either end and breached by tidal inlets, forming barrier islands. Barriers are most often generated during transgression and are commonly underlain by more landward facies, such as those deposited in estuaries, lagoons and marshes. *Strandplains* are also shore-parallel sand bodies containing beaches and dunes but are found along prograded linear coasts and are not associated with embayments. Strandplains commonly preserve multiple shoreline positions and are underlain by more seaward facies such as the shoreface.

In Fig. 3, the upper triangle is equivalent to the delta classification triangle of previous authors (e.g., Galloway, 1975; Wright, 1985), whereas the zone at the base is conceptually similar to the bivariate (wave/tide) classification of coasts developed by Hayes (1975, 1979). Deltas have an elongate/lobate shoreline with a fluvial sediment source and are followed during progradation by alluvial plains. Strandplains and tidal flats have a linear or irregular shoreline with a marine sediment source derived from either onshore or longshore transport. Other, less common, coastal environments such as marshes and mangrove swamps may also occur as components of other environments in Fig. 3 but are not plotted for simplicity. The trapezoidal area in the centre represents embayed coasts and provides a framework for the process classification of estuaries and lagoons. Estuaries receive a mixed river and marine sediment source. Lagoons represent an end member of the estuary spectrum where fluvial input is negligible. Lagoons therefore lie above and along the dividing line between estuaries and strandplains/tidal flats (Fig. 3), but are not commonly found in strongly tide-dominated settings where they are replaced by macrotidal embayments without barriers, and with a marine sediment source. The relative intensity of river, wave and tidal processes is listed for 42 examples in Table 1 and plotted on Fig. 4. Following Hayes (1975) and Dalrymple et al. (1992) we have subdivided estuaries into wave- and tide-dominated types, with the degree of river influence varying

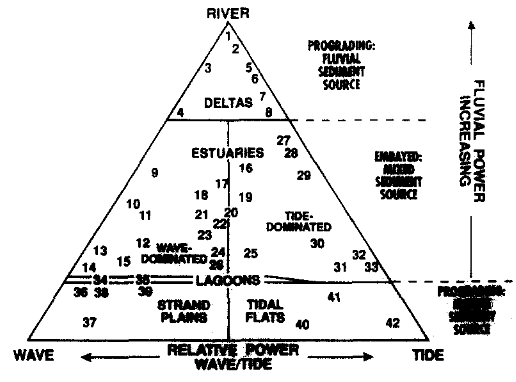

Fig. 4. Forty-two coastal examples, described in Table 1, illustrate the method of classifying coastal environments on a ternary diagram using wave, tide and river processes.

TABLE 1

Summary of depositional systems shown in Fig. 4 (relative intensity of tide, wave and river processes estimated from published literature or personal observations; Mod = moderate; Ext = extreme)

Number	Location	Tide	Wave	River	Reference
Deltas					
1	Mississippi Delta, USA	Low	Low	High	Wright, 1985
2	Chang Jiang Delta, China	Mod	Low	High	Chen et al., 1982
3	Ebro Delta, Spain	Low	Mod	High	Maldonado, 1975
4	Sao Francisco Delta, Brazil	Low	High	Mod	Coleman and Wright, 1975
5	Mahakam Delta, Indonesia	Mod	Low	High	Allen et al., 1979
6	Klang-Langat Delta, Malaysia	High	Low	Mod–High	Coleman et al., 1970
7	Fly River Delta, New Guinea	High	Low	High	Harris et al., 1992
8	Colorado Delta, Mexico	High	Low	Mod–High *	Meckel, 1975
Wave-dominated estuaries					
9	San Antonio Bay, USA	Low	Mod	Mod	Donaldson et al., 1970
10	Hawksbury Estuary, Australia	Low	High	Low–Mod	Roy et al., 1980; Roy, 1984
11	Lavaca Bay, USA	Low	Mod	Low–Mod	Wilkinson and Byrne, 1977
12	Miramichi River, Canada	Low–Mod	Mod	Low	Reinson, 1977; unpubl. observations
13	Lake Macquarie, Australia	Low	Mod–High	Low	Roy et al., 1980; Roy, 1984
14	Mgeni Estuary, South Africa	Low	High	Low	Cooper, 1988
15	Eastern Shore estuaries, Nova Scotia, Canada	Low	High	Low	Boyd et al., 1987; Honig and Boyd, 1992
Mixed-energy estuaries					
16	St. Lawrence River, Canada	Mod	Low–Mod	High	d'Anglejan and Brisebois, 1978
17	Gironde River, France	Mod–High	Mod–High	Mod	Jouanneau and Latouche, 1981; Allen, 1991
18	Raritan River, USA	Low–Mod	Low–Mod	Mod	Ashley and Renwick, 1983
19	Humber River, UK	Mod–High	Mod	Mod	unpubl. observations
20	James River, USA	Mod	Low–Mod	Mod	Nichols et al., 1991
21	Ogeechee River, USA	Mod	Mod	Mod	Dorjes and Howard, 1975; Greer, 1975
22	Chesapeake Bay, USA	Low–Mod	Low–Mod	Low–Mod	Biggs, 1967; Coleman et al., 1988
23	Delaware Bay, USA	Low–Mod	Low–Mod	Low–Mod	Knebel et al., 1989
24	Willapa Bay, USA	Mod	High	Low–Mod	Clifton, 1983; Clifton et al., 1989
25	Oosterschelde Estuary The Netherlands	Mod	Low	Low	Yang and Nio, 1989
26	Corio Bay, Australia	Mod–High	High	Low	unpubl. observations
Tide-dominated estuaries					
27	Cook Inlet, Alaska	High	Low–Mod	Mod–High	Bouma et al., 1980; Bartsch-Winkler and Ovenshine, 1984
28	Ord River, Australia	High	Low	Mod–High	Wright et al., 1973; 1975; Coleman and Wright, 1978
29	South Alligator, Daily and Adelaide Rivers, Australia	High	Low	Mod	Woodroffe et al., 1989
30	Severn River, UK	High–Ext	Mod	Low–Mod	Hamilton, 1979; Harris and Collins, 1985
31	Broad Sound, Australia	High–Ext	Low–Mod	Low	Cook and Mayo, 1977
32	Cumberland Basin, Canada	Ext	Low–Mod	Low	Amos et al., 1991
33	Cobequid Bay-Salmon River and Avon River, Canada	Ext	Low	Low	Lambiase, 1980; Dalrymple and Zaitlin, 1989; Dalrymple et al., 1990
Lagoons					
34	Smith Lake, Australia	Low	High	None	Unpubl. observations
35	Laguna Madre, USA	Low	Low–Mod	None	Fisk, 1959

TABLE I (continued)

Number	Location	Tide	Wave	River	Reference
Prograding strand plains					
36	Senegal "Delta"	Low	High	Low–Mod	Coleman and Wright, 1975; Wright, 1985
37	Shoalhaven River, Australia	Low	High	Low	Roy et al., 1980; Wright, 1985
38	Yaquina Bay, USA	Low–Mod	High	Low	Kulm and Byrne, 1967
39	Nayarit, Mexico	Low	High	Low	Curray et al., 1969
Prograding tidal flats					
40	Mont St. Michel Bay, France	High	Mod	Low	Larsonneur, 1988
41	Head of the German Bight	High	Low–Mod	Low–Mod	Reineck and Singh, 1980
42	East coast, Taiwan	High	Low	Low	Reineck and Cheng, 1978

* Before human interference.

from weak to strong in each estuarine category. The distribution of these major coastal types with respect to transgression/progradation, sediment supply, coastal geometry and wave/tide processes is shown in Fig. 2.

Evolutionary coastal classification

Stratigraphic implications and problems resulting from the evolution of coastal systems, such as estuary infilling, mean that a process-based classification needs to be augmented by an evolutionary classification. Figure 5, modified after Dalrymple et al. (1992) shows one attempt to combine process and temporal aspects conceptually by extending the triangle of Fig. 3 with a third dimension, *relative time*, to form a triangular prism. In the context of coastal evolution, including estuary creation and infilling, relative time may be best expressed in terms of transgression and progradation. Thus, changes which occur during progradation (including estuary filling) are shown by movement toward the back of the prism, whereas changes associated with transgression (including progressive flooding of estuaries) are represented by movement toward the front face (Fig. 5). This approach has the advantage of linking depositional environments with shoreline behaviour through time, but also experiences two problems. Firstly, the rate at which different systems progress in either direction is not constant in real time because the rate of filling (or flooding) is dependent on the ratio of sediment supply to the size of the palaeovalley, other variables being constant. As a result, individual systems will be spread out within the volume of the prism at any instant in real time (e.g., today). Secondly, the relative intensity of river, wave and tidal processes is not an accurate guide to transgres-

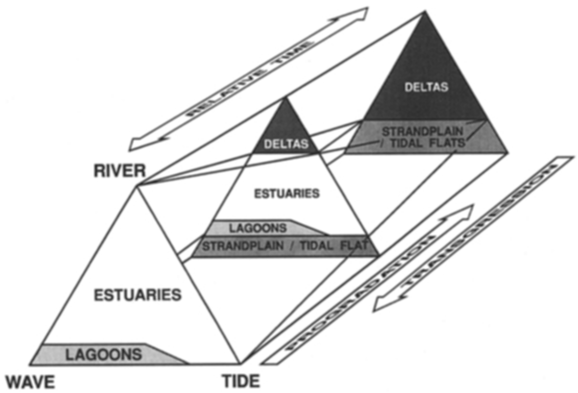

Fig. 5. One possible evolutionary classification of coastal environments. The long axis of the three-dimensional prism represents relative time with reference to changes in relative sea level and sediment supply: transgressions are shown by movement toward the front of the prism, whereas progradations are represented by movement toward the back face. Following Galloway (1975), the three corners of the triangular prism correspond to depositional conditions dominated by fluvial, wave and tidal processes; mixed-energy conditions are indicated by points within the prism (see Fig. 3). Deltas occupy the uppermost area; the intermediate, wedge-shaped space contains all estuaries and lagoons; the bottom wedge represents non-deltaic, prograding coasts. During a sea-level cycle, a coastal area will track forward and backward through the prism by an amount determined by the interplay between the rate of relative sea-level change, the sedimentation rate and basin size. It will maintain a constant position relative to the corners if the controlling process variables remain unchanged.

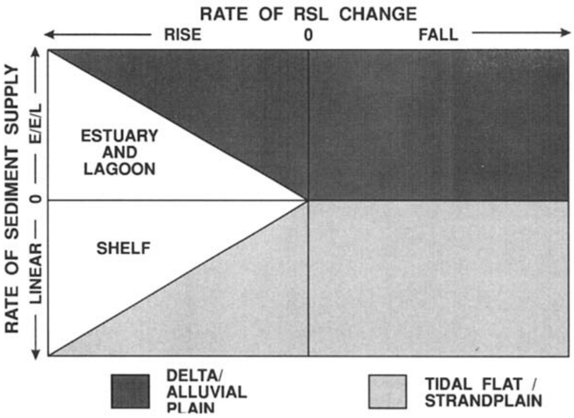

Fig. 6. This figure shows coastal evolution for equilibrium positions of estuaries and lagoons, deltas/alluvial plains, and strandplains/tidal flats. The upper half of the figure shows RSL rise and fall and transgression/regression on river coasts with embayed, elongate or lobate shorelines. The lower half shows the same relationships for linear coasts away from the influence of river mouths. The diagonal lines represent division between conditions of regression and transgression, emphasising the generation of estuaries and lagoons only under transgressive conditions.

sion or progradation, because shoreline migration is largely a function of sediment supply and relative sea level.

The earlier classification of Dalrymple et al. (1992) can be extended to an evolutionary classification that combines the concept of rate of sediment supply on two types of coast (linear and embayed-elongate/lobate coasts) with relative sea level in a modified version of Curray's (1964) diagram (Fig. 6). Unlike Curray's original diagram which classified types of regression and transgression, this new version can be used to identify the evolutionary relationships between coastal sedimentary environments. Although values plotted on Fig. 6 may not define coastal environments at every point in time due to disequilibrium, long-term equilibrium positions of estuaries, deltas and alluvial plains, strandplains and tidal flats, and the continental shelf are accurately represented. Figure 6 shows that *the presence or absence of rivers is a critical factor in classifying coasts*. During progradation, when river deposition dominates over marine redistribution, deltas form elongate/lobate shorelines. During transgression, embayed river palaeovalleys become the sites of estuaries, which are seen to form only under conditions of relative sea-level rise. Away from river mouths, where more linear coasts are found, transgression or progradation causes strand/plain tidal flat environments to alternate with the continental shelf.

Estuary evolution

Variation in morphology and evolution of deltas, barriers and tidal flats has been covered extensively elsewhere (for example in Davis, 1985). However, estuaries and lagoons have received comparatively little study (as discussed by Clifton, 1982; Frey and Howard, 1986) and we present a more detailed treatment of their evolution here (Fig. 7A).

Figure 7A is drawn to show the net tendency of an estuary to be generated or infill from transgression/regression at both ends of the embayment (barrier or mainland shorelines), and thus approximates the sequence stratigraphy concept of accommodation. The rate of infilling or regression is partially a function of embayment volume, a larger embayment taking longer to infill for the same sediment volume supplied. This is depicted on Fig. 7A by transgression/regression boundaries of variable slope between the estuary generation and infill fields. Steeper boundaries occur for embayments of larger volume. This may be expressed as:

$$E = K(R_S/R_{RSL})$$

where E is an estuary evolution index, R_S is the rate of sediment supply, R_{RSL} is the rate of relative sea-level change and K is an empirical constant determined by the geometry of the estuary. For values of $E > 1$, estuaries infill and for $E < 1$, estuaries expand.

One of the parameters determining estuary volume is the coastal plain gradient, which may be broadly placed in a plate tectonic framework. A rise in sea level on a flat coastal plain passive margin such as the Gulf of Mexico generates a long estuary with a large volume, while an equivalent rise on a steep, active-margin coast such as the US Pacific coast will only generate a small estuary volume. Thus, the lines of variable slope

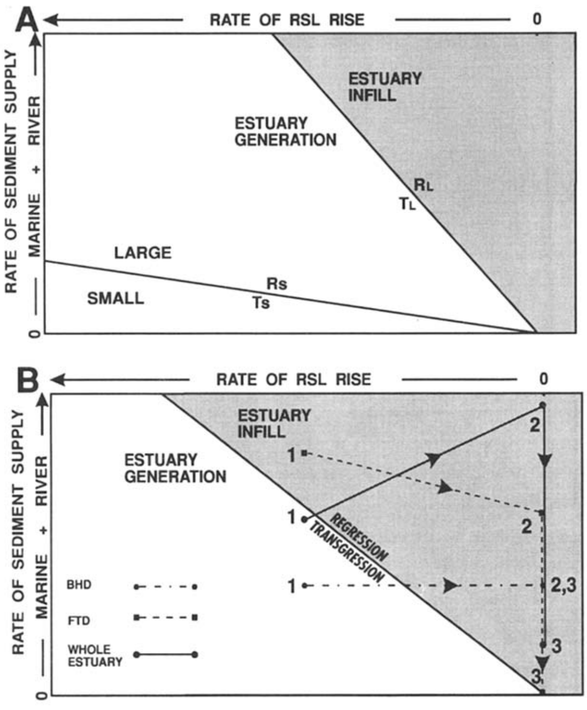

Fig. 7. A. Here rate of relative sea-level rise is plotted against rate of marine plus river sediment supply to classify equilibrium positions of estuary generation or infill. This figure is similar to the upper left-hand corner of both Figs. 1 and 5. The diagonal lines separate zones of transgression (T) from regression (R) for two situations: small volume estuaries (R_S / T_S), and large volume estuaries (R_L / T_L). Wave-dominated estuaries receive marine and river sediment and have two shorelines capable of regression/transgression, the bay-head delta shoreline and the flood tidal delta shoreline. Tide-dominated estuaries also receive sediment from two sources but only prograde the landward shoreline. Lagoons have only a marine sediment source. B. An example of the use of A, for the wave-dominated microtidal Wapengo Inlet on the south coast of New South Wales (data from Nichol, 1991). Regression/transgression of both bay-head delta (*BHD*) and flood tidal delta (*FTD*) shorelines is shown. The sum of these two shoreline migration rates, normalised with respect to shoreline length determines if the estuary as a whole (solid line for whole estuary) expands or infills. Net transgression and hence estuary expansion was occurring around 7 ka (*1* solid line), followed by rapid infilling around 6.2 ka (*2*) mainly due to flood tidal delta progradation, and then a period of slower infill from 1.5 ka to present (*3*) dominated by bay-head delta progradation.

on Fig. 7A could also be labelled as coastal plain gradients ranging from flat to steep.

Following Dalrymple et al. (1992), we recognise a fundamental division between wave-dominated estuaries, tide-dominated estuaries, and lagoons. *Wave-dominated estuaries* are more geomorphologically complex, and are separated by a barrier (sand plug) from the marine environment. They have two sources of sediment (marine and river) and can be infilled from, and experience transgression/regression at, both ends of the embayment. Landward sediment is supplied by rivers to bay-head deltas while marine sediment is transported into the estuary by eolian, tidal and wave processes, forming flood tidal deltas and washovers. *Lagoons* experience the same evolutionary trends as wave-dominated estuaries except for the absence of landward-derived infill from a river sediment source.

Tide-dominated estuaries (like wave-dominated estuaries) have both a marine and a river sediment source, but infilling only occurs by progradation of the landward margin of the embayment. In true tide-dominated estuaries such as the Bay of Fundy (Dalrymple et al., 1990, 1992) or the Severn Estuary (Harris and Collins, 1985) no bay-head delta forms, and progradation occurs through tidal sand bars, estuarine tidal flats and marsh in the marine environment passing directly landward into an alluvial plain. Marine sediment often experiences a bedload parting seaward of tide-dominated estuaries. Marine sediment moving into the estuary is transported as bedload moving landward as tidal sand bars along the estuary floor. Further marine sediment is supplied by longshore drift moving landward along the margins of the estuary. These two sediment sources combine to prograde only the landward margin of the estuary.

The use of the estuary evolution diagram (Fig. 7A) under complex conditions of relative sea-level rise followed by stillstand under variable sediment supply regimes in both flood tidal deltas and bay-head deltas is illustrated in Fig. 7B. Wapengo Inlet (Nichol, 1991) experienced rapid rates of relative sea-level rise prior to the establishment of the current stillstand around 6.5 ka (Thom and Chappell, 1975). This microtidal, wave-dominated setting received a relatively constant fluvial sediment supply both prior to and since stillstand, and a rapid flood tidal delta sediment supply until 6 ka.

Wapengo Inlet, being wave-dominated, experiences infill and growth from both bay-head and flood tidal delta sources. Three paths are plotted on Fig. 7B, each path defining a shoreline history. The data points on each path are rate of sediment supply plotted against relative sea-level rise. Their distance from the regression/transgression line on Fig. 7B is proportional to their rate of shoreline migration. The first (dashed) line represents landward progradation of the flood tidal delta shoreline from time 1 (7 ka) to 2 (6.2 ka) to 3 (1.5 ka to present). The second (dot and dashed) line represents transgression and subsequent progradation of the bay-head delta shoreline. The third (solid) line represents the evolution of the whole estuary and is derived by summing the migration rates of the flood tidal delta and bay-head delta shorelines, normalised with respect to shoreline length. The whole estuary evolution path shown on Fig. 7B identifies whether the estuary will be expanding or infilling. As shown here, the estuary was expanding around 7 ka and has since undergone infilling.

This case study illustrates the disequilibrium or hysteresis conditions under which most estuaries exist and the finite lag time required for transition between equilibrium conditions. For the past 1500 years, Wapengo Inlet has existed in the zone of estuary infill at position 3, line 3 on Fig. 7B. However, because of the size of Wapengo Inlet compared to the rate of filling, the estuary continues to exist and will remain an estuary for several thousand years more before being completely filled and evolving into a prograding strand plain or delta.

Discussion

The relationship between the lag time for transition between equilibrium states and the length of time spent at the equilibrium positions will determine if an estuary accommodation volume is filled in one relative sea-level-driven cycle of sedimentation, or if the original estuary volume will contain multiple fills. The relative distances of the bay-head delta and flood tidal delta paths from the regression/transgression line will determine the relative volumes of these two facies in the final estuarine fill (e.g., Fig. 7B).

The approach taken in Figs. 1, 3 and 6 can be applied to most coastal settings but is best suited to embayed coastlines with both marine and river sediment input. It should be regarded as describing only the coastline and not extending to the continental shelf or to terrestrial environments. In particular, this approach does not describe situations in which river incision and non-marine unconformities are generated. Nor does it specifically apply to non-depositional coasts (e.g., fjords) or non-clastic (e.g., carbonate) shorelines.

There are two main advantages of this new coastal classification. The first is the inclusion of all important clastic coastal depositional environments and identification of the relationship between them. The model does this by using both process and evolutionary criteria. The second advantage is the opportunity to now generate facies models for estuarine and lagoon environments. These environments, particularly estuaries, have long been regarded as complex and difficult subjects for facies models because of the variety of processes and resulting facies deposited in a small area. However, the new ternary approach to process classification can be employed to define wave and tide end-member facies models, each consisting of a tripartite facies zonation (Dalrymple et al., 1992). The evolutionary approach is compatible with sequence stratigraphy because sediment supply and relative sea-level variables are included, and serves as a starting point for more refined coastal stratigraphic analyses.

Conclusions

(1) A new coastal classification has been constructed, based on both process and evolutionary criteria.

(2) The process model uses river, tide and wave parameters; the evolutionary model uses rate and source of sediment input, shoreline shape and rate of relative sea-level change to classify the response of delta, strand plain, tidal flat, lagoon and estuarine environments.

(3) The new classification provides the basis for an estuarine facies model. It also provides a

framework for understanding incised valley fill styles and constructing sequence stratigraphic models in coastal settings.

References

Allen, G.P., 1991. Sedimentary processes and facies in the Gironde estuary: a Recent model of macrotidal estuarine systems. In: D.G. Smith, G.E. Reinson, B.A. Zaitlin and R.A. Rahmani (Editors), Clastic Tidal Sedimentology. Can. Soc. Pet. Geol. Mem., 16: 29–40.

Allen, G.P., Laurier, D. and Thouvenin, J., 1979. Etude Sedimentologique du Delta de la Mahakam. Compagnie Française des Pétroles, Notes et Memoires, 15, 115 pp.

Amos, C.L., Tee, K.T. and Zaitlin, B.A., 1991. The post-glacial evolution of Chignecto Bay, Bay of Fundy, and its modern environment of deposition. In: D.G. Smith, G.E. Reinson, B.A. Zaitlin and R.A. Rahmani (Editors), Clastic Tidal Sedimentology. Can. Soc. Pet. Geol. Mem. 16: 59–90.

Ashley, G.M. and Renwick, W.H., 1983. Channel morphology and processes at the riverine–estuarine transition, the Raritan River, New Jersey. In: J.D. Collinson and J. Lewin (Editors), Modern and Ancient Fluvial Systems. Int. Assoc. Sedimentol., Spec. Publ., 6: 207–218.

Bartsch-Winkler, S. and Ovenshine, A.T., 1984. Macrotidal subarctic environment of Turnagain and Knik Arms, upper Cook Inlet, Alaska: sedimentology of the intertidal zone. J. Sediment. Petrol., 54: 1221–1238.

Biggs, R.B., 1967. The sediments of Chesapeake Bay. In: G.H. Lauff (Editor), Estuaries. Am. Assoc. Adv. Sci. Publ., 83: 239–260.

Bloom, A.L., 1978. Geomorphology. Prentice Hall, Englewood Cliffs, N.J.

Bouma, A.H., Rappeport, M.L., Orlando, R.C. and Hampton, M.A., 1980. Identification of bedforms in lower Cook Inlet, Alaska. Sediment. Geol., 26: 157–177.

Boyd, R., Bowen, A.J. and Hall, R.K., 1987. An evolutionary model for transgressive sedimentation on the eastern shore of Nova Scotia. In: D.M. Fitzgerald and P.S. Rosen (Editors), Glaciated Coasts. Academic Press, New York, N.Y., pp. 88–114.

Chen, J.Y., Yun, C. and Xu, H., 1982. The model of development of the Chang Jiang estuary during the last 2000 years. In: V.S. Kennedy (Editor), Estuarine Comparisons. Academic Press, New York, N.Y., pp. 655–666.

Clifton, H.E., 1982. Estuarine deposits. In: P.A. Scholle and D. Spearing (Editors), Sandstone Depositional Environments. Am. Assoc. Pet. Geol. Mem., 31: 179–189.

Clifton, H.E., 1983. Discrimination between subtidal and intertidal facies in Pleistocene deposits, Willapa Bay, Washington. J. Sediment. Petrol., 53: 353–369.

Clifton, H.E., Phillips, R.L. and Anima, R.J., 1989. Sedimentary facies of Willapa Bay, Washington: a comparison of modern and Pleistocene estuarine facies. Can. Soc. Pet. Geol. Field Guide, 2nd Int. Symp. Clastic Tidal Deposits, Calgary, Alta., 62 pp.

Coleman, J.M. and Wright, L.D., 1975. Modern river deltas: variability of processes and sand bodies. In: M.L. Broussard (Editor), Deltas—Models for Exploration. Houston Geol. Soc., Houston, Tx., pp. 99–149.

Coleman, J.M. and Wright, L.D., 1978. Sedimentation in an arid macro-tidal alluvial river system: Ord River, Western Australia. J. Geol., 86: 621–642.

Coleman, J.M., Gagliano, S.M. and Smith, W.G., 1970. Sedimentation in a Malaysian high tide tropical delta. In: J.P. Morgan (Editor), Deltaic Sedimentation—Modern and Ancient. SEPM Spec. Publ., 15: 185–197.

Coleman, S.M., Berquist, C.R., Jr. and Hobbs, C.H., III, 1988. Structure, age and origin of the bay-mouth shoal deposits, Chesapeake Bay, Virginia. Mar. Geol., 83: 95–113.

Cook, P.J. and Mayo, W., 1977. Sedimentology and Holocene history of a tropical estuary (Broad Sound, Queensland). Aust. Bur. Miner. Resour. Geol. Geophys., Bull., 170, 206 pp.

Cooper, J.A.G., 1988. Sedimentary environments and facies of the subtropical Mgeni Estuary, southeast Africa. Geol. J., 23: 59–73.

Curray, J.R., 1964. Transgressions and regressions. In: R.L. Miller (Editor), Papers in Marine Geology, Shepard Commemorative Volume. Macmillan, New York, N.Y., pp. 175–203.

Curray, J.R., Emmel, F.J. and Crampton, P.J.S., 1969. Holocene history of a strand plain, lagoonal coast, Nayarit, Mexico. In: A. Ayala-Castanares and F.B. Phleger (Editors), Coastal Lagoons, A Symp. Univ. Nacional autónoma de Mexico, Ciudad Universitaria, pp. 63–100.

Dalrymple, R.W. and Zaitlin, B.A., 1989. Tidal sedimentation in the macrotidal, Cobequid Bay—Salmon River estuary, Bay of Fundy. Can. Soc. Pet. Geol. Field Guide, 2nd Int. Symp. Clastic Tidal Deposits, Calgary, Alta., 84 pp.

Dalrymple, R.W., Knight, R.J., Zaitlin, B.A. and Middleton, G.V., 1990. Dynamics and facies model of a macrotidal sand-bar complex, Cobequid Bay—Salmon River estuary (Bay of Fundy). Sedimentology, 37: 577–612.

Dalrymple, R.W., Zaitlin, B.A. and Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. J. Sediment. Petrol. (in press).

d'Anglejan, B. and Brisebois, M., 1978. Recent sediments of the St. Lawrence middle estuary. J. Sediment. Petrol., 48: 951–964.

Davies, J.L., 1980. Geographical Variation in Coastal Development. Longman, London.

Davis, R.A., Jr., 1985. Coastal Sedimentary Environments. Springer, New York, N.Y., 2nd ed.

Donaldson, A.C., Martin, R.H. and Kanes, W.H., 1970. Holocene Guadalupe delta of Texas Gulf Coast. In: J.P. Morgan (Editor), Deltaic Sedimentation—Modern and Ancient. SEPM Spec. Publ., 15: 107–137.

Dörjes, J. and Howard, J.D., 1975. Estuaries of the Georgia coast, U.S.A. Sedimentology and biology. IV. Fluvial–marine transition indicators in an estuarine environment, Ogeechee River—Ossabaw Sound. Senckenbergiana Marit., 7: 137–179.

Fisher, W.L., Brown, L.F., Scott, A.J. and McGowen, J.H., 1969. Delta Systems in the Exploration for Oil and Gas. Bur. Econ. Geol., University of Texas, Austin, 78 pp.

Fisk, H.N., 1959. Padre Island and the Laguna Madre flats, coastal south Texas. In: 2nd Coastal Geography Conf. Coastal Studies Institute, Louisiana State University, Baton Rouge, pp. 103–151.

Frazier, D.E., 1974. Depositional episodes: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf Basin. Bur. Econ. Geol., University of Texas, Austin, Circ., 74-1, 28 pp.

Frey, R.W. and Howard, J.D., 1986. Mesotidal estuarine sequences: a perspective from the Georgia Bight. J. Sediment. Petrol., 56: 911–924.

Galloway, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: M.L. Broussard (Editor), Deltas—Models for Exploration. Houston Geol. Soc., Houston, Texas, pp. 87–98.

Greer, S.A., 1975. Estuaries of the Georgia coast, U.S.A. Sedimentology and biology. III. Sandbody geometry and sedimentary facies at the estuary–marine transition zone, Ossabaw Sound, Georgia: a stratigraphic model. Senckenbergiana Marit., 7: 105–135.

Hamilton, D., 1979. The high-energy, sand and mud regime of the Severn estuary, S.W. Britain. In: R.T. Severn, D. Dineley and L.E. Hawker (Editors), Tidal Power and Estuary Management. Colston Pap., 30: 162–172.

Harris, P.T. and Collins, M.B., 1985. Bedform distribution and sediment transport paths in the Bristol Channel and Severn Estuary. Mar. Geol., 62: 153–166.

Harris, P.T., Cole, A.R. and Short, S.A., 1992. A preliminary study of sedimentation in the tidally dominated Fly River delta, Gulf of Papua. Cont. Shelf Res., 12 (in press).

Hayes, M.O., 1975. Morphology of sand accumulations in estuaries: an introduction to the symposium. In: L.E. Cronin (Editor), Estuarine Research, Vol. II. Academic Press, New York, N.Y., pp. 3–22.

Hayes, M.O., 1979. Barrier island morphology. In: S.P. Leatherman (Editor), Barrier Islands from the Gulf of Mexico to the Gulf of St. Lawrence. Academic Press, New York, N.Y., pp. 1–28.

Honig, C. and Boyd, R., 1992. Estuarine sedimentation on the Eastern Shore of Nova Scotia. J. Sediment. Petrol. (in press).

Inman, D.L. and Nordstrom, C., 1971. On the tectonic and morphologic classification of coasts. J. Geol., 79: 1–21.

Johnson, D.W., 1919. Shore Processes and Shoreline Development. Wiley, New York, 584 pp.

Johnson, H.D. and Baldwin, C.T., 1986. Shallow siliciclastic seas. In: H.G. Reading (Editor), Sedimentary Environments and Facies. Blackwell, Oxford, pp. 229–282.

Jouanneau, J.M. and Latouche, C., 1981. The Gironde Estuary. Contributions to Sedimentology 10, Schweizerbart, Stuttgart, 115 pp.

Knebel, H.J., Fletcher, C.H., III and Kraft, J.C., 1988. Late Wisconsinan–Holocene paleogeography of Delaware Bay; a large coastal plain estuary. Mar. Geol., 83: 115–133.

Kulm, L.D. and Byrne, J.V., 1967. Sediments of Yaquina Bay, Oregon. In: G.H. Lauff (Editor), Estuaries. Am. Assoc. Adv. Sci. Publ., 83: 226–238.

Lambiase, J.J., 1980. Sediment dynamics in the macrotidal Avon River estuary, Bay of Fundy. Can. J. Earth Sci., 17: 1628–1641.

Larsonneur, C., 1988. La Baie du Mont Saint-Michel: un modèle de sedimentation en zône tempérée. Université de Caen, Caen, 85 pp.

Maldonado, A., 1975. Sedimentation, stratigraphy, and development of the Ebro Delta, Spain. In: M.L. Broussard (Editor), Deltas—Models for Exploration. Houston Geol. Soc., Houston, Texas, pp. 311–338.

Meckel, L.D., 1975. Holocene sand bodies in the Colorado Delta area, northern Gulf of California. In: M.L. Broussard (Editor), Deltas—Models for Exploration. Houston Geol. Soc., Houston, Texas, pp. 239–265.

Miall, A.D., 1977. A review of the braided river depositional environment. Earth Sci. Rev., 13: 1–62.

Nichol, S.L., 1991. Zonation and sedimentology of estuarine facies in an incised valley, wave-dominated, microtidal setting. In: D.G. Smith, G.E. Reinson, B.A. Zaitlin and R.A. Rahmani (Editors), Clastic Tidal Sedimentology. Can. Soc. Pet. Geol. Mem., 16: 41–58.

Nichols, M.M., Johnson, G.H. and Peebles, P.C., 1991. Modern sediments and facies model for a microtidal coastal plain estuary, the James estuary, Virginia. J. Sediment. Petrol., 61: 883–889.

Pethick, J., 1984. An Introduction to Coastal Geomorphology. Arnold, Baltimore, Md., 260 pp.

Plint, A.G., 1988. Sharp based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea level. In: C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross and J.V. Van Wagoner (Editors), Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral., Spec. Publ., 42: 357–370.

Posamentier, H., Allen, G.P., James, D.P. and Tesson, M., 1992. Forced regression in a sequence stratigraphic framework: concepts, examples and exploration significance. Am. Assoc. Pet. Geol. Bull. (in press).

Posamentier, H.W. and Vail, P.R., 1988. Eustatic controls on clastic deposition II—sequence and systems tract models. In: C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross and J.V. Van Wagoner (Editors), Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral., Spec. Publ., 42: 125–154.

Reineck, H.-E. and Cheng, Y.M., 1978. Sedimentologische und faunistische Untersuchungen an Watten in Taiwan. I. Aktuogeologische Untersuchungen. Senckenbergiana Marit., 10: 85–115.

Reineck, H.-E. and Singh, I.B., 1980. Depositional Sedimentary Environments. Springer, New York, N.Y., 2nd ed., 549 pp.

Reinson, G.E., 1977. Tidal current control of submarine morphology at the mouth of the Miramichi estuary, New Brunswick, Canada. Can. J. Earth Sci., 14: 2524–2532.

Reinson, G.E., 1984. Barrier island and associated strand plain systems. In: R.G. Walker (Editor), Facies Models. Geosci. Can., Repr. Ser., 1: 119–140.

Ricketts, B.D., 1991, Lower Paleocene drowned valley and barred estuaries, Canadian Arctic Islands: aspects of their geomorphological and sedimentological evolution. In: D.G. Smith, G.E. Reinson, B.A. Zaitlin and R.A. Rahmani (Editors), Clastic Tidal Sedimentology. Can. Soc. Pet. Geol. Mem., 16: 91–107.

Roy, P.S., 1984. New South Wales estuaries: their origin and evolution. In: B.G. Thom (Editor), Coastal Geomorphology in Australia. Academic Press, New York, N.Y., pp. 99–121.

Roy, P.S., Thom, B.G. and Wright, L.D., 1980., Holocene sequences on an embayed high energy coast: an evolutionary model. Sediment. Geol., 26: 1–19.

Shepard, F.P., 1973. Submarine Geology. Harper and Row, New York, N.Y., 3rd ed.

Thom, B.G. and Chappell, J., 1975. Holocene sea level relative to Australia. Search, 6: 90–93.

Valentin, H., 1952. Die Küsten der Erde. Petermanns Geogr. Mitt. Ergänzungh., 246, 118 pp.

Wilkinson, B.H. and Byrne, J.R., 1977. Lavaca Bay—transgressive deltaic sedimentation in a central Texas estuary. Am. Assoc. Pet. Geol. Bull., 61: 527–545.

Woodroffe, C.D., Chappell, J.M.A., Thom, B.G. and Wallensky, E., 1989. Depositional model of a macrotidal estuary and flood plain, South Alligator River, Northern Australia. Sedimentology, 36: 737–756.

Wright, L.D., 1977. Sediment transport and deposition at river mouths: a synthesis. Bull. Geol. Soc. Am., 88: 857–868.

Wright, L.D., 1985. River deltas. In: R.A. Davis, Jr. (Editor), Coastal Sedimentary Environments. Springer, New York, N.Y., 2nd ed., pp. 1–76.

Wright, L.D., Coleman, J.M. and Thom, B.G., 1973, Processes of channel development in a high-tide-range environment: Cambridge Gulf—Ord River delta, Western Australia. J. Geol., 81: 15–41.

Yang, C.S. and Nio, S.D., 1989. An ebb-tidal delta depositional model—a comparison between the modern Eastern Scheldt tidal basin (southwest Netherlands) and the Lower Eocene Roda Sandstone in the southern Pyrenees (Spain). Sediment. Geol., 64: 175–196.

Zaitlin, B.A. and Schultz, B.C., 1990. Wave-influenced estuarine sand body, Senlac heavy oil pool, Saskatchewan, Canada. In: J.H. Barwis, J.G. McPherson and J.R.J. Studlick (Editors), Sandstone Petroleum Reservoirs. Springer, New York, N.Y., pp. 363–387.