

PERSPECTIVE

ESTUARINE FACIES MODELS: CONCEPTUAL BASIS AND STRATIGRAPHIC IMPLICATIONS¹

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ABSTRACT: The nature and organization of facies within incised-valley estuaries is controlled by the interplay between marine processes (waves and tides), which generally decrease in intensity up-estuary, and fluvial processes, which decrease in strength down-estuary. All estuaries ideally possess a three-fold (tripartite) structure: an outer, marine-dominated portion where the net bedload transport is headward; a relatively low-energy central zone where there is net bedload convergence; and an inner, river-dominated (but marine-influenced) part where the net transport is seaward. These three zones are not equally developed in all estuaries because of such factors as sediment availability, coastal zone gradient and the stage of estuary evolution.

Two distinct but intergradational types of estuaries (wave- and tide-dominated) are recognized on the basis of the dominant marine process. Wave-dominated estuaries typically possess a well-defined tripartite zonation: a marine sand body comprised of barrier, washover, tidal inlet and tidal delta deposits; a fine-grained (generally muddy) central basin; and a bay-head delta that experiences tidal and/or salt-water influence. The marine sand body in tide-dominated estuaries consists of elongate sand bars and broad sand flats that pass headward into a low-sinuosity ("straight") single channel; net sand transport is headward in these areas. The equivalent of the central basin consists of a zone of tight meanders where bedload transport by flood-tidal and river currents is equal in the long term, while the inner, river-dominated zone has a single, low-sinuosity ("straight") channel.

These facies models and their conceptual basis provide a practical means of highlighting the differences and similarities between estuaries. They also allow the predication of the stratigraphy of estuarine deposits within a sequence-stratigraphic context.

INTRODUCTION

Estuaries which occupy drowned valleys are extremely common along modern transgressive coasts and were presumably equally abundant during past transgressions. They are highly efficient sediment traps (Meade 1972; Biggs and Howell 1984), and their deposits have high preservation potential because of their location within paleovalleys (Demarest and Kraft 1987). Thus, estuarine systems should be widely represented in the geological record.

Ancient estuarine deposits have not, however, been widely recognized (Clifton 1982; Zaitlin and Shultz 1990). Part of the problem has been the absence of a standardized terminology, but the major impediments have been the complexity of estuarine systems and the lack of a unifying model which 1) puts the facies variations between estuaries in perspective, and 2) is predictive. A valuable model for wave-dominated estuaries has been developed by Roy et al. (1980), and there are individual case studies of tide-dominated systems (Dalrymple et al. 1990; Allen 1991), but no comprehensive synthesis of the entire spectrum of estuarine types exists.

The purposes of this paper are to propose a conceptual framework for estuarine classification and to develop facies models for estuaries which will be of use to geologists. This is done in four steps: 1) examination of the definition of estuaries and their relationship to other coastal depositional systems in order to produce a classification of estuaries; 2) development of two idealized, end-member models of estuarine sedimentation; 3) examination of the nature and causes of local deviation from these general models; and 4) discussion of the stratigraphic implications. Although the concepts and models are based on modern estuaries and processes, our objective is to develop an approach which can be applied to the rock record in a sequence-stratigraphic context. Thus, our focus differs from that of most previous classifications.

ESTUARY DEFINITIONS

The most widely-used definition of estuary is that given by Pritchard (1967) which is based on salinity, with the requirement that "... seawater is measurably diluted with fresh water derived from land drainage". Thus, an estuary would occupy the area at a river mouth where salinities range from approximately 0.1‰ to 30–35‰ (Fig. 1). Although this definition is useful when dealing with chem-

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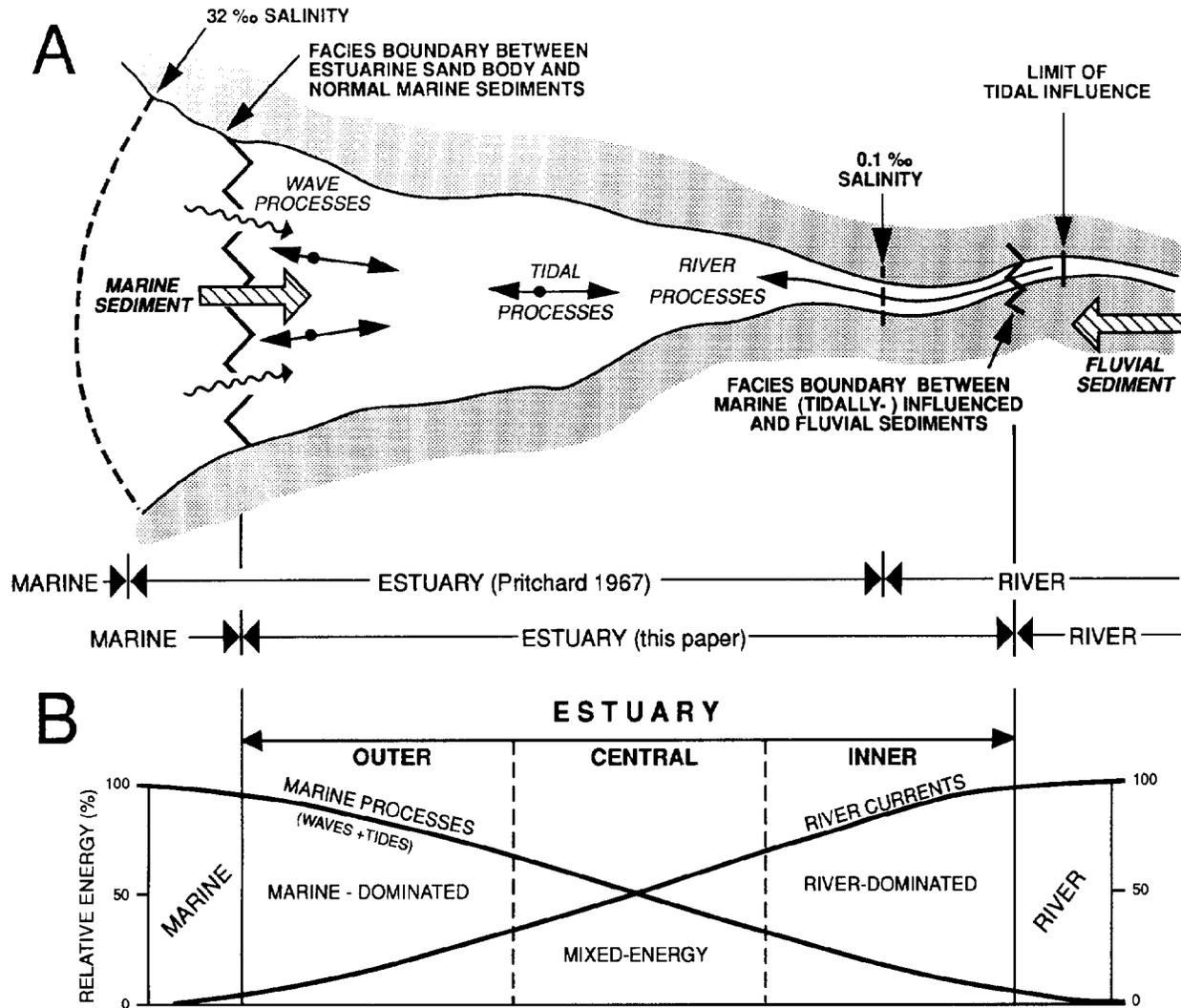


FIG. 1.—A) Schematic representation of the definitions of estuary according to Pritchard (1967) and this paper, and the generalized pattern of net, bed-material transport. The facies boundary marking the landward end of the estuary as defined here almost always lies landward of the 0.1‰ salinity value, but the facies boundary at the outer end may lie either landward (as shown here) or seaward of the limit of normal-marine salinities (~ 32‰). B) Schematic distribution of the physical processes operating within estuaries, and the resulting tripartite facies zonation.

ical and biological processes in the fluvial-marine transition, it is of limited use in the study of ancient deposits because the distribution of lithofacies, and particularly the sandy facies, is determined primarily by physical processes rather than salinity. For instance, tidal influence generally extends further landward than the limit of salt-water intrusion (Fig. 1; Rochford 1951; Nichols and Biggs 1985). Using Pritchard's definition, the fresh-water tidal zone, which may contain abundant tidal structures, would be placed in the fluvial environment. Geologically this seems inappropriate.

More recent discussions of estuaries explicitly recognize the importance of tides (Clifton 1982; Frey and Howard 1986). Fairbridge (1980, p. 7), for example, defines an estuary as "an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise". However, these definitions, if applied strictly, would (erroneously

in our opinion) classify many delta distributaries and back-barrier lagoons as estuaries. Thus, a new, geologically-oriented definition of estuary is needed in order to clarify what the facies models to be developed here must fit.

In arriving at such a definition, it is necessary to recognize that estuaries are widely regarded as occurring within river mouths which have been flooded by the sea (Curry 1969) and which are not currently building an open-coast delta. Indeed, in modern, drowned-river-mouth estuaries, sediment supply has not kept pace with the (local) sea-level rise, and the estuary acts as a sink for sediment of both terrestrial and marine origin (Guilcher 1967; Roy et al. 1980; Dalrymple et al. 1990). We would argue that the presence of a net landward movement of sediment derived from outside the estuary mouth (averaged over a period of several years) is one of the primary features that distinguishes estuaries from delta distribu-

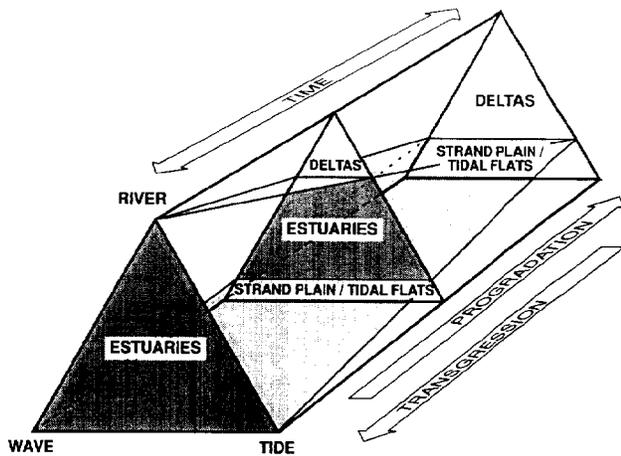


FIG. 2.— Evolutionary classification of coastal environments. The long axis of the three-dimensional prism represents relative time with reference to changes in relative sea level and sediment supply (i.e., transgression and progradation). The three edges of the prism correspond to conditions dominated by fluvial, wave and tidal processes. Deltas occupy the uppermost area; the intermediate, wedge-shaped space contains all estuaries; and the bottom wedge represents non-deltaic, prograding coasts. Transgressive, barrier-lagoon systems which form along coasts without incised valleys occupy part of the estuary field. During a sea-level cycle, a coastal area will track forward and backward through the prism at a rate, and by an amount, determined by the rate of sea-level change, the sedimentation rate and basin size.

taries where the net sediment transport is seaward. Furthermore, the definition should recognize that the estuary is a zone of interaction between river currents and a variety of marine processes, including tides and waves as well as salt-water intrusion.

Based on these considerations, we will define an estuary as *the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave 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* (Fig. 1; modified after Zaitlin and Shultz 1990). It is implicit in this definition that estuaries can only form in the presence of a relative sea-level rise (i.e., a transgression). They will begin to fill under slowly-rising or stable sea-level conditions or be submerged entirely if sea level continues to rise. Further implications of the definition are considered below.

RELATIONSHIP OF ESTUARIES TO OTHER COASTAL SYSTEMS

In order to develop a framework for the classification of estuaries it is necessary to examine the relationship of estuaries to other coastal depositional systems from two perspectives: 1) the relative importance of the physical processes which are operating, and 2) the temporal changes which occur in response to sea-level changes. On the first point, numerous authors have shown that deltas and barrier coasts can be classified on the basis of the relative influence of river outflow, waves and tidal currents, because these processes control the morphology and facies

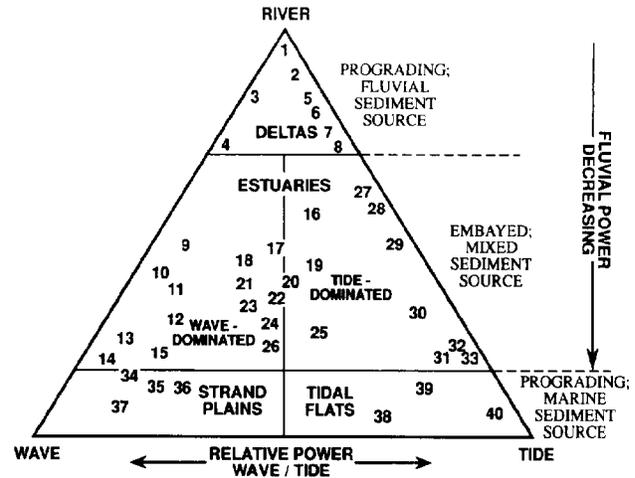


FIG. 3.— Vertical section through the coastal classification prism (Fig. 2) showing the position of representative modern systems (see Table 1, p. 1139, for key). Systems which are at different stages of infilling and are thus spread out along the length of the prism have been projected into the plane of the figure.

distribution (Coleman and Wright 1975; Galloway 1975; Hayes 1979). We believe that estuaries can be treated similarly. Estuaries are unlike other coastal systems, however, because they are geologically ephemeral: if the rate of sediment supply is sufficient (relative to the size of the valley), then estuaries become filled and cease to exist when the rate of sea-level rise slows. The site then becomes a delta, if the sediment is supplied directly by the river, or a straight prograding coast (beach-ridge or strand plain; open-coast tidal flats), if the sediment is delivered to the area by marine processes (waves or tides, respectively).

Figure 2 combines these process and temporal aspects to give an evolutionary classification of coastal systems. Following Coleman and Wright (1975) and Galloway (1975), the relative importance of river outflow, waves and tidal currents may be represented by a triangle (Figs. 2, 3) in which deltas are positioned at the fluvial apex because a fluvial sediment source dominates, while prograding, non-deltaic coasts (strand plains and tidal flats) are located along the opposite, wave-tide side because sediment is moved onshore by waves and/or tides. Estuaries occupy an intermediate position, because they have a mixed sediment source (Figs. 1, 3). The evolutionary aspect can be portrayed by adding a third dimension, relative time, to form a triangular prism (Fig. 2). In this context, relative time may also be expressed in terms of transgression and progradation (depositional regression; Curray 1964). Thus, changes which occur during progradation (estuary filling and their conversion into deltas or prograding beach-ridge plains or tidal flats) are shown by movement toward the back of the prism where estuaries no longer exist, whereas changes associated with transgression (flooding of river valleys and the creation of estuaries) are represented by movement toward the front face where all valleys have been converted into estuaries. These concepts are explored further by Boyd et al. (1991).

A vertical section through this prism can be used to classify coastal depositional systems (Fig. 3; Zaitlin and Shultz 1990). The upper triangle is equivalent to the delta triangle (Galloway 1975; Wright 1985), whereas the narrow band at the base is conceptually similar to the bivariate (wave/tide) classification of barrier coasts (Hayes 1979; Davis and Hayes 1984). The trapezoidal area in the center provides a framework for the classification of estuaries. Following the coastal classification of Hayes (1979) and Davis and Hayes (1984), we subdivide them into wave- and tide-dominated types, with the degree of river influence varying from weak to strong in each category. The addition of a fluvially-dominated category is unnecessary, because the relative influence of the river primarily determines the rate at which the estuary fills and does not alter the fundamental morphology of the system.

ESTUARINE DYNAMICS AND FACIES ZONATION: THE END-MEMBER MODELS

General Considerations

In order to construct a useful facies model, it is necessary to "distill away" all local variability and retain only the common features (Walker 1984). With regard to estuaries, we believe that the interaction between river and marine processes is the common "essence" (Roy et al. 1980; Nichols and Biggs 1985; Dalrymple and Zaitlin 1989) which provides the basis for a generalized facies model. Fluvial energy, as given by the energy flux per unit cross-sectional area or other suitable measure, typically decreases down an estuary (Fig. 1B), because the hydraulic gradient decreases as the river approaches the sea. Marine energy, by contrast, generally decreases headward, either because oceanic wave energy is dissipated by a wave-built barrier or tidal sand-bar complex, and/or because tidal current speeds decrease up the estuary as a result of frictional damping. Ideally, therefore, both wave- and tide-dominated estuaries can be divided into three zones (Fig. 1B): 1) an outer zone dominated by marine processes (waves and/or tidal currents); 2) a relatively low-energy central zone, where marine energy (generally tidal currents) is approximately balanced in the long term by river currents; and 3) an inner, river-dominated zone. This zonation is superficially similar to the three-fold subdivision proposed by Rochford (1951) and Fairbridge (1980) but is based on physical processes rather than salinity.

This tripartite zonation (Fig. 1) also corresponds with the general patterns of net bedload transport. Long-term (averaged over several years) transport of bedload is seaward in the river-dominated zone, whereas coarse sediment moves up estuary in the marine-dominated zone as a result of waves and/or flood-tidal currents (Guilcher 1967; Kulm and Byrne 1967; Roy et al. 1980; Dalrymple and Zaitlin 1989). Thus, the central zone is an area of net convergence and typically contains the finest-grained bedload sediment present in the estuary, regardless of

whether the estuary is wave- or tide-dominated. The movement of suspended sediment is largely independent of this zonation and is not considered here.

Wave-dominated Estuaries

Energy Distribution.—In a typical wave-dominated estuary, tidal influence is small and the mouth of the system experiences relatively high wave energy (Fig. 4A). These waves, in combination with any tidal currents, cause sediment to move alongshore (and onshore) into the mouth of the estuary where a subaerial barrier/spit or submerged bar is developed (Figs. 4–6). This barrier prevents most of the wave energy from entering the estuary (Fig. 4A); consequently, only internally-generated waves are present behind the barrier. In systems with a low tidal range and small tidal prism, tidal currents may not be able to maintain any breaches generated by storm surges and/or river floods, and they will close during fair weather, producing a "blind estuary" or coastal lake. Slightly higher tidal discharges will keep a small number of inlets open (Figs. 5, 6), but much of the tidal energy is dissipated by friction in the inlet, causing the back-barrier area to have a smaller tidal range than the open ocean and weak tidal currents (Fig. 4A; Roy et al. 1980; Honig and Boyd 1992). Estuaries in which this occurs are termed "hyposynchronous" (Salomon and Allen 1983; Nichols and Biggs 1985). Fluvial energy, by contrast, will decrease seaward because of the decreasing hydraulic gradient. The resulting profile of "total energy" for an ideal wave-dominated estuary shows two maxima, one at the mouth caused by wave energy and one at the head produced by river currents, which are separated by a pronounced energy minimum in the central portion of the estuary (Fig. 4A).

Morphology and Facies Distributions.—This distribution of total energy produces a clearly-defined, "tripartite" distribution of lithofacies (coarse-fine-coarse) within most wave-dominated estuaries (Figs. 4–6; Roy et al. 1980; Rahmani 1988; Zaitlin and Shultz 1990; Nichol 1991; Nichols et al. 1991). A marine sand body (the sand plug of subsurface examples) accumulates in the area of high wave energy at the mouth. It consists of a core of transgressive subtidal shoals and/or washover deposits on which is built a beach/shoreface barrier cut by one or more tidal inlets (Roy et al. 1980; Roy 1984). Headward-prograding, flood-tidal deltas are a major component of the sand body if there is moderate tidal influence (Hayes 1980; Honig and Boyd 1992).

Sand and/or gravel is also deposited at the head of the estuary by the river, forming a bay-head delta. In estuaries with a broad lagoon, this delta typically has a fluvially-dominated, birdsfoot morphology with straight, leveed distributaries and prominent inter-distributary bays (Fig. 5; Donaldson et al. 1970; Nichol 1991), but in more confined systems, this morphology is not able to develop (Fig. 6). It is also possible for bay-head deltas to adopt a wave- (Nichol 1991) or tide-dominated morphology (Allen 1991).

The low-energy central part of the estuary (the "central

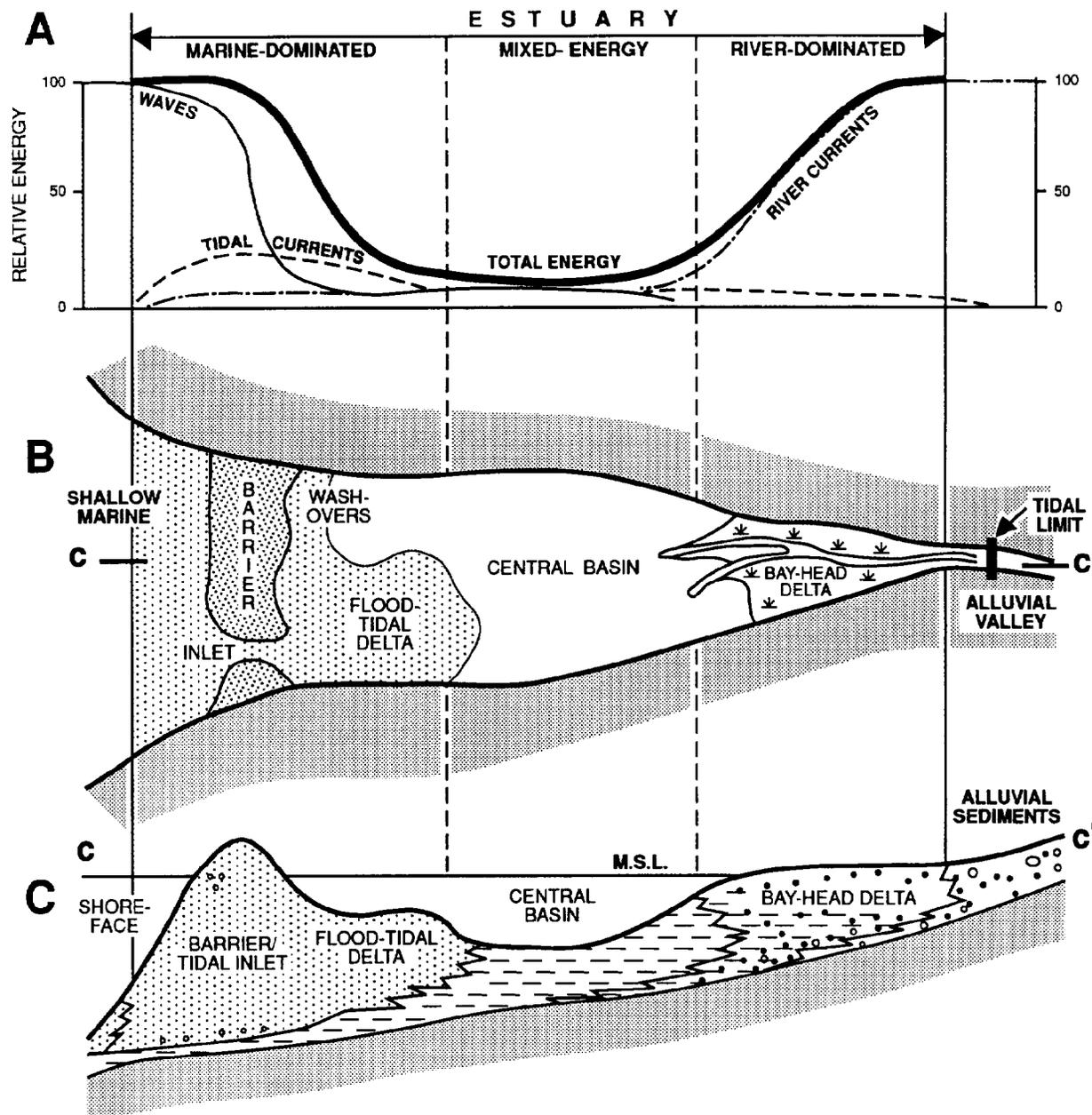


FIG. 4.—Distribution of A) energy types, B) morphological components in plan view, and C) sedimentary facies in longitudinal section within an idealized wave-dominated estuary. Note that the shape of the estuary is schematic. The barrier/sand plug is shown here as headland attached, but on low-gradient coasts it may not be connected to the local interfluvies and is separated from the mainland by a lagoon. The section in C represents the onset of estuary filling following a period of transgression.

basin”) acts as the prodelta region of the bay-head delta if there is an open-water lagoon, and fine-grained organic muds accumulate there (Biggs 1967; Donaldson et al. 1970). (Note that the central basin is a facies designation and thus is only partially equivalent to the geomorphic term “lagoon.”) The equivalent area of shallow (nearly filled) estuaries contains extensive salt marshes and is crossed by tidal channels which pass directly into the river channel(s) (Dörjes and Howard 1975; Clifton 1983).

Tide-dominated Estuaries

Energy Distribution.—Tide-dominated estuaries (Fig. 7) are less well known than their wave-dominated counterparts. Most of the best-known examples are macrotidal and include Cobequid Bay and the Salmon River (Fig. 8; Dalrymple and Zaitlin 1989; Dalrymple et al. 1990), the Severn River, England (Hamilton 1979; Harris and Collins 1985), and the South Alligator River, northern Aus-



FIG. 5. Aerial photograph of Wapengo Lagoon, Australia (Nichol 1991) showing the morphological elements which typify wave-dominated estuaries: a barrier spit/tidal inlet/flood-tidal delta complex on the right; a central basin; and a fluvially-dominated, bay-head delta on the left.

tralia (Fig. 9; Woodroffe et al. 1989). However, tidal dominance can also occur at much smaller tidal ranges if wave action is limited and/or the tidal prism is large (Hayes 1979; Davis and Hayes 1984). For example, in the Big Bend area of western Florida (R.A. Davis, Jr., personal communication 1991).

Tidal-current energy exceeds wave energy at the mouth of tide-dominated estuaries, and elongate sand bars are typically developed (Figs. 7, 8; Hayes 1975; Dalrymple et al. 1990). These bars dissipate the wave energy that does exist, causing it to decrease with distance up the estuary. On the other hand, the incoming flood tide is

progressively compressed into a smaller cross-sectional area because of the funnel-shaped geometry which characterizes these estuaries (Langbein in Myrick and Leopold 1963; Wright et al. 1973), and the speeds of the flood-tidal currents increase into the estuary (Fig. 7A). This tidal behaviour is termed "hypersynchronous" (Salomon and Allen 1983; Nichols and Biggs 1985). Beyond a certain distance, however, frictional dissipation exceeds the effects of amplification caused by convergence, and the tidal energy decreases, reaching zero at the tidal limit. Fluvial energy decreases seaward as in wave-dominated systems. Measurements in several estuaries (e.g., Cobequid Bay-Salmon River and Severn River) suggest that the location where flood-tidal and fluvial energy are equal lies landward of the tidal-energy maximum (Fig. 7A). As in wave-dominated systems, this "balance point" is the location of a minimum in the total-energy curve.

Morphology and Facies Distributions.— This total-energy minimum is not as pronounced as in wave-dominated estuaries, because tidal energy penetrates further headward than wave energy. Thus, the tripartite facies distribution is not as obvious, and sands occur in the tidal channels that run along the length of the estuary (Woodroffe et al. 1989; Dalrymple et al. 1990). Nevertheless, the energy minimum is the site of the finest channel sands. Muddy sediments accumulate primarily in tidal flats and marshes along the sides of the estuary.

In the extreme, end-member cases such as the Severn and Cobequid Bay-Salmon River estuaries, the marine sand body consists of two strongly contrasting facies. The best-known is the elongate tidal sand bar zone (Harris 1988; Dalrymple and Zaitlin 1989; Dalrymple et al. 1990), which is characterized by cross-bedded medium to coarse sand. These bars lie seaward of the tidal-energy maximum. The second facies, which coincides with the tidal-

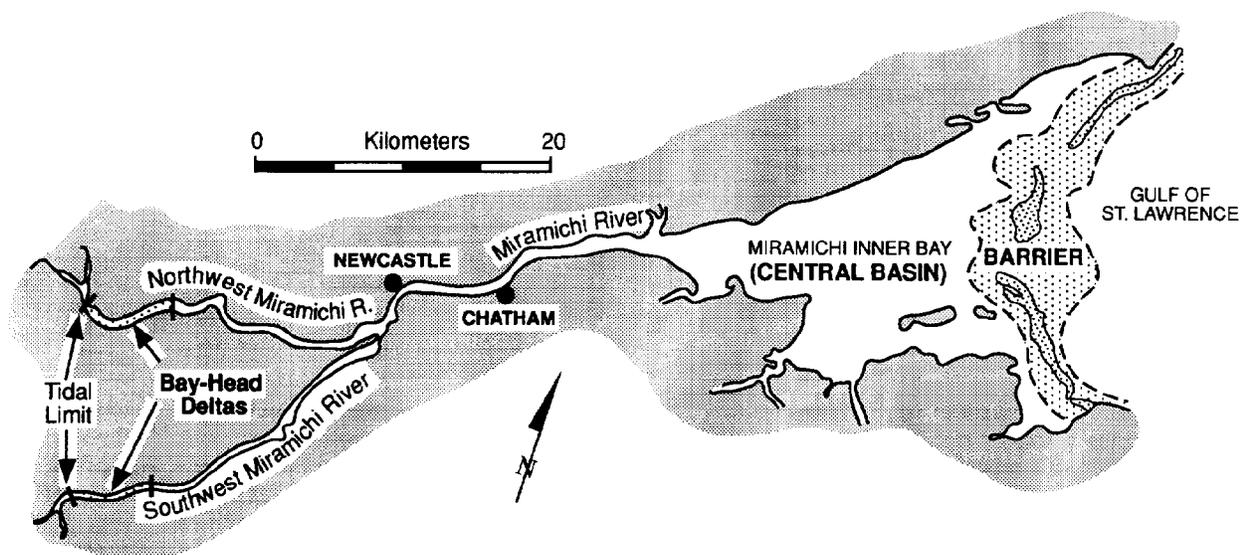


FIG. 6.— Facies map of the wave-dominated, Miramichi River estuary (12 in Fig. 3 and Table 1). Due to the large tidal prism, three tidal inlets dissect the barrier sand body. The bay-head deltas are small because of the low sediment yield. They do not show a birdsfoot morphology because the incised valleys are too narrow.

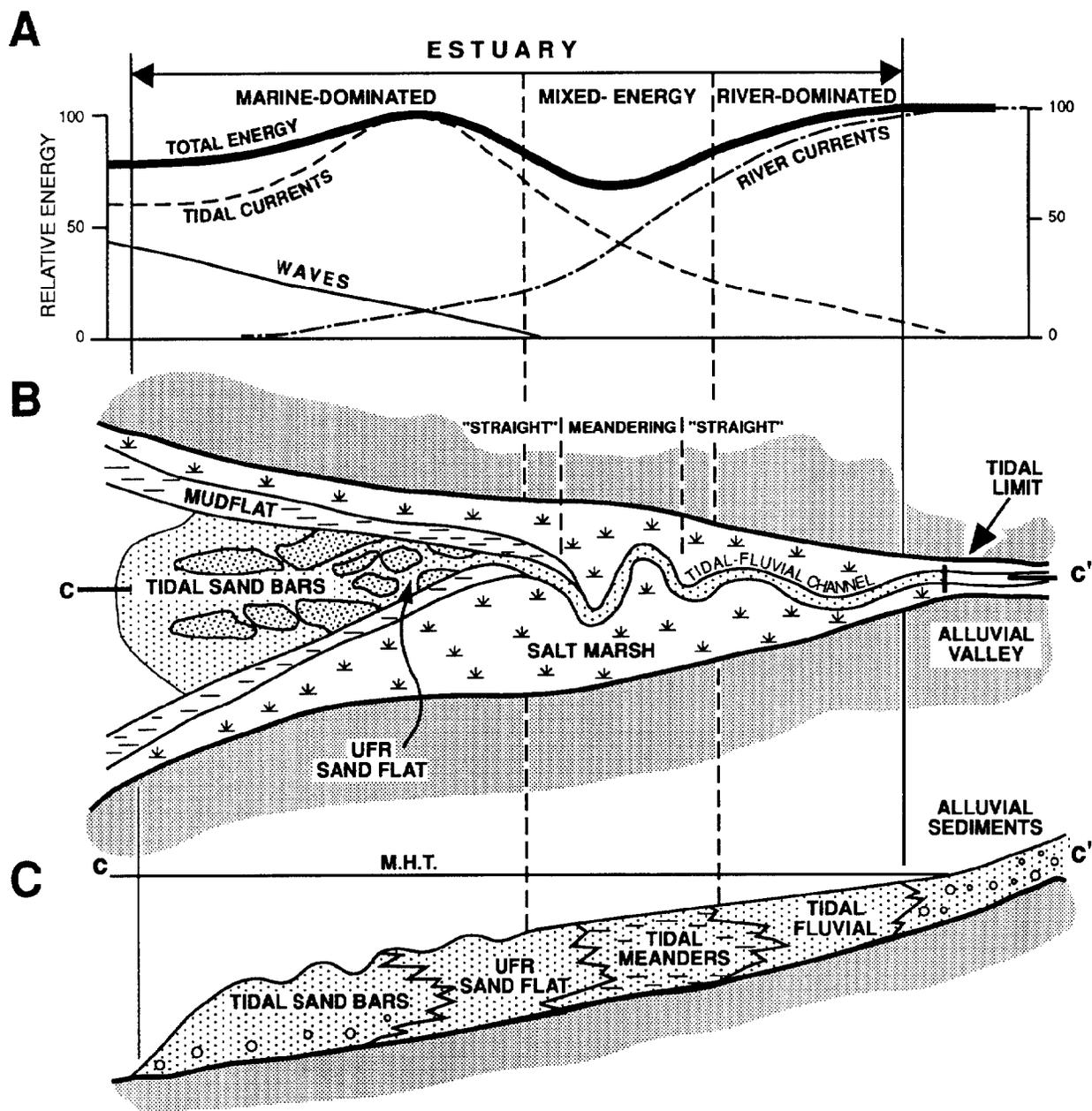


FIG. 7.—Distribution of A) energy types, B) morphological elements in plan view, and C) sedimentary facies in longitudinal section within an idealized tide-dominated estuary. URF = upper flow regime; M.H.T. = mean high tide. The section in C is taken along the axis of the channel and does not show the marginal mudflat and salt marsh facies; it illustrates the onset of progradation following transgression, the full extent of which is not shown.

energy maximum, consists of upper-flow-regime (UFR) sand flats which display a braided channel pattern where the estuary is broad but become confined to a single channel further headward (Figs. 7–9; Hamilton 1979; Lambiasi 1980; Dalrymple et al. 1990). The deposits of this facies, which may not be present in tide-dominated estuaries with smaller tidal ranges, consist of parallel-laminated fine sand.

In the central, low-energy zone of systems in which the

main channel is unconfined, this channel consistently displays a regular progression of sinuosities (Ashley and Renwick 1983; Dalrymple and Zaitlin 1989; Woodroffe et al. 1989) which we term “straight-meandering-straight” (Figs. 7–9). The outer straight reach in these estuaries is tidally dominated, and the net sediment transport is headward due to strong flood-tidal currents (e.g., Dalrymple et al. 1990). The channel contains alternate, bank-attached bars (Fig. 8B) and some mid-channel bars. The

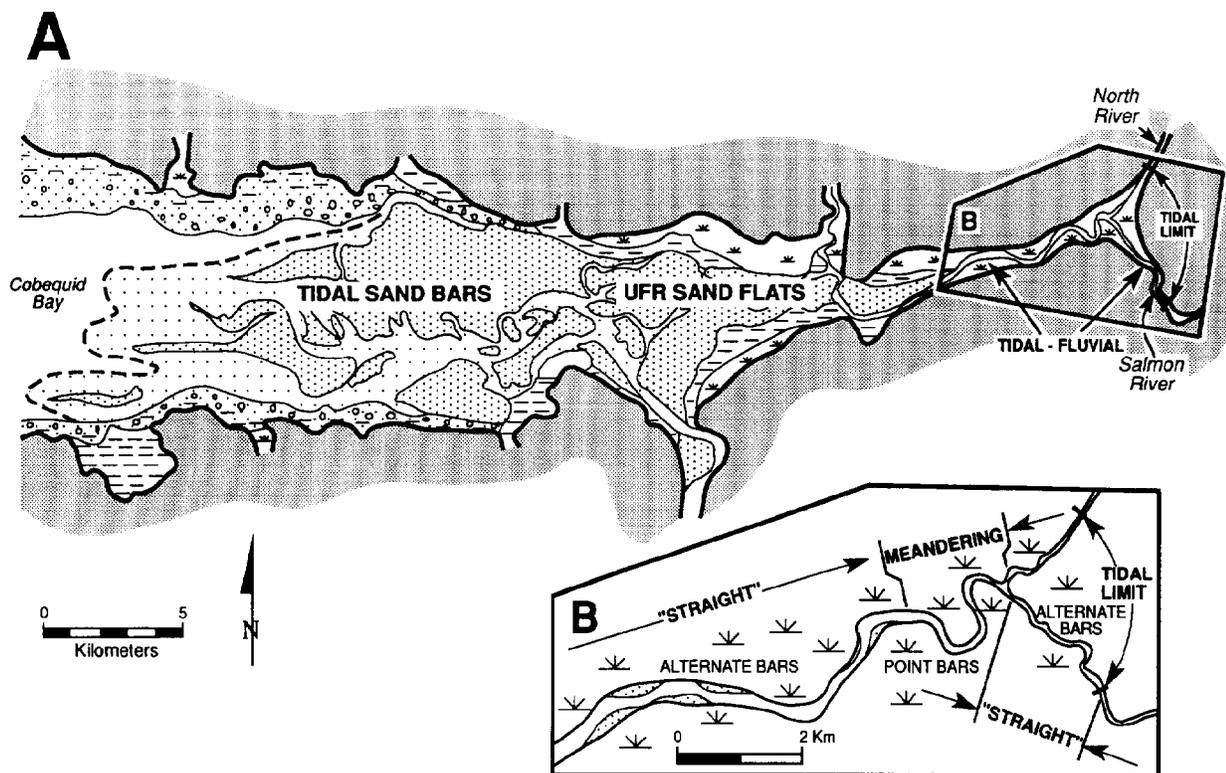


FIG. 8. — **A**) Facies zonation in the tide-dominated, Cobequid Bay-Salmon River estuary (33; Dalrymple et al. 1990). The dashed line in Cobequid Bay marks the outer limit of the estuarine sand body. **B**) Enlargement of the inner portion of the estuary showing the longitudinal changes in channel morphology and bar type.

inner straight reach also contains similar bar types, but here the net sediment transport is downstream due to the long-term dominance of river flow over tidal currents. The region between the two straight reaches contains tight meanders (Figs. 8, 9) which commonly exhibit symmetrical point bars. This meandering zone is the lowest-energy portion of the system and is the position of net bed-load convergence. Grain sizes in the channel become finer toward this area from both directions (Dalrymple and Zaitlin 1989). The cause of this channel pattern is not known but may be due to changes in the hydraulic gradient which mimic the distribution of total energy (Fig. 7A). Schumm and Khan (1972) have shown, for instance, that the sinuosity decreases as slope increases in the transition from meandering to braided.

A bay-head delta is not present in the river-dominated portion of tide-dominated estuaries. Instead the fluvially-dominated straight reach passes directly into the river channel above the tidal limit.

ESTUARINE VARIABILITY

Although the two facies models developed above (Figs. 4, 7) correspond closely to the essential features of most estuaries, many show some deviation from the model "norms", as is to be expected, because of local factors (Walker 1984). Here we will examine the effects of some of these, in order to show that the variations can be ac-

commodated within the models. The numbers in parentheses following examples refer to locations cited in Table 1 and Figure 3.

The Wave to Tide Transition

The models developed above are for the end-member cases of wave or tide dominance. In this section, we examine the nature of the changes which occur in intermediate cases. The changes discussed do not refer to the evolution of a single estuary but rather to differences between estuaries.

As the tidal energy increases relative to wave energy, the barrier system of wave-dominated estuaries becomes progressively more dissected by tidal inlets, and elongate sand bars develop in the locations previously occupied by barrier segments and the channel-margin linear bars of ebb-tidal deltas (Hayes 1975). Dramatic changes also occur within the estuary as energy levels increase in the central, mixed-energy zone. Marine-derived sand is transported greater distances up estuary, and the generally muddy central basin is replaced by sandy tidal channels flanked by marshes, as in the Ogeechee River (21) and Oosterschelde estuary (25). If the main tidal channel is linked directly with the river channel, it will display the straight-meandering-straight morphology that typifies tide-dominated systems. For example, the Raritan River (18; Ashley and Renwick 1983) demonstrates such a

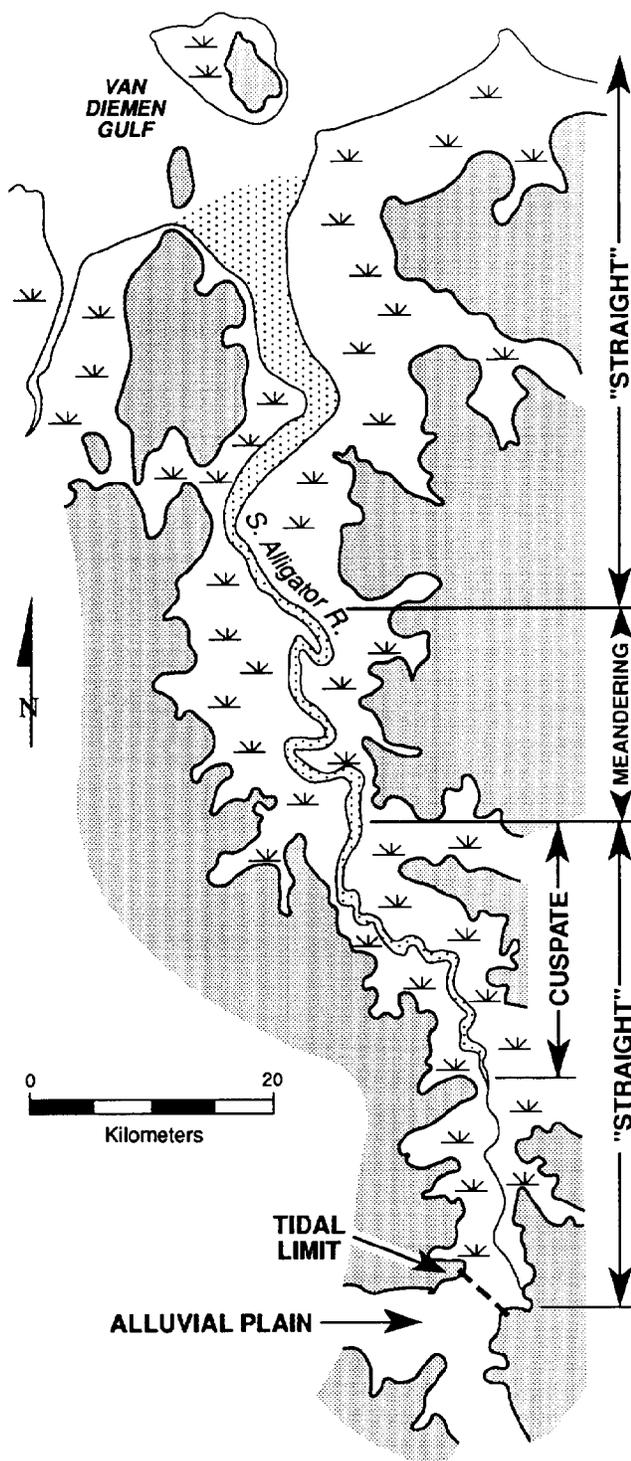


FIG. 9.—Map of the inner part of the South Alligator River estuary (29; after Woodroffe et al. 1989) showing the straight-meandering-straight channel pattern. The cusped reach was formerly meandering, but the meanders have moved seaward as a result of estuary filling and progradation. Note that the relative length of the fluvially-dominated straight reach is much greater than in the Cobequid Bay-Salmon River estuary (Fig. 8).

channel pattern in the inner part of what is, on the whole, a wave-dominated estuary. An increase in the tidal influence within a wave-dominated system may cause the bay-head delta to change from a fluvially-dominated morphology to a tide-dominated morphology (Coleman and Wright 1975). The Gironde estuary (17; Fig. 10) illustrates the latter case (Rahmani 1988; Allen 1991). The tidal bars in the Gironde clearly differ from the estuary-mouth bars of truly tide-dominated systems (Figs. 7, 8) with respect to their location within the estuary (they lie landward of a muddy central basin) and their sediment source (landward versus seaward).

Length of Estuarine Zones: The Estuarine "Accordion"

Because the inner end of an estuary is defined here as the limit of geologically-detectable tidal influence, coastal-zone gradient and tidal range together determine the length of an estuary by controlling the extent of tidal penetration. Thus, estuaries become longer as the coastal gradient decreases and/or as the tidal range increases.

The relative lengths of the marine- and river-dominated zones may also vary, in response to differences in the strengths of the flood-tidal and river currents. For example, in the South Alligator River (spring tidal range 6 m; maximum river discharge $1500\text{--}2000\text{ m}^3\text{ s}^{-1}$; Woodroffe et al. 1989), the marine and fluvial zones are of approximately equal length (Fig. 9), whereas in the Cobequid Bay-Salmon River estuary (mean spring range 12 m; maximum river discharge $55\text{--}60\text{ m}^3\text{ s}^{-1}$) the tidally-dominated reach is nearly 10 times longer than the fluvial zone (Fig. 8). The opposite situation would exist if the magnitudes of the tidal and river discharges were reversed.

The size of the marine and fluvial sand bodies is also determined by sediment availability. If the river supplies little sediment, the bay-head delta will be small or absent (Fig. 6; Honig and Boyd 1992), whereas a large sediment input leads to rapid seaward progradation of the fluvial zone, as in the Shoalhaven River (35; Roy et al. 1980). Similarly, the size of the marine sand body (wave or tide dominated) depends on the amount of sand supplied by marine reworking. Thus, tidal sand bars are poorly developed in Cumberland Basin, Bay of Fundy (32; Amos et al. 1991) but extensively developed in Cobequid Bay (Dalrymple et al. 1990), solely because of differences in marine sediment supply.

Influence of Valley Shape

The shape of the valley system being flooded also has a significant control on the nature of the facies developed in an estuary, particularly in the early stage of infilling, before deposition has modified the inherited geometry. Tidal-wave amplification is unlikely to occur in irregularly-shaped valleys, and they tend to be hyposynchronous (Salomon and Allen 1983; Nichols and Biggs 1985). This situation favors the development of wave-domi-

TABLE 1.— Summary of depositional systems shown in Figure 3. 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; unpublished 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 Latoche 1981; Allen 1991
18	Raritan River, USA	Low-Mod	Low-Mod	Mod	Ashley and Renwick 1983
19	Humber River, GB	Mod-High	Mod	Mod	unpublished observations
20	James River, USA	Mod	Low-Mod	Mod	Nichols et al. 1991
21	Ogeechee River, USA	Mod	Mod	Mod	Dörjes and Howard 1975; Greer 1975
22	Chesapeake Bay, USA	Low-Mod	Low-Mod	Low-Mod	Biggs 1967; Colman et al. 1988
23	Delaware Bay, USA	Low-Mod	Low-Mod	Low-Mod	Knebel et al. 1988
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	unpublished 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, 1985; Coleman and Wright 1978
29	South Alligator, Daily and Adelaide Rivers, Australia	High	Low	Mod	Woodroffe et al. 1989
30	Severn River, GB	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
Prograding Strand Plains					
34	Senegal "Delta"	Low	High	Low-Mod	Coleman and Wright 1975; Wright 1985
35	Shoalhaven River, Australia	Low	High	Low	Roy et al. 1980; Wright 1985
36	Yaquina Bay, USA	Low-Mod	High	Low	Kulm and Byrne 1967
37	Nayarit, Mexico	Low	High	Low	Curry et al. 1969
Prograding Tidal Flats					
38	Mont St. Michel Bay, France	High	Mod	Low	Larsonneur 1988
39	Head of the German Bight	High	Low-Mod	Low-Mod	Reineck and Singh 1980
40	East coast, Taiwan	High	Low	Low	Reineck and Cheng 1978

* Before human interference.

nated estuaries and the formation of a barrier bar at a local constriction (Boyd et al. 1987). Chesapeake Bay, with its extensive network of tributary valleys, is an example of this. On the other hand, estuaries which either

initially have or subsequently develop a funnel-shaped geometry are more likely to be hypersynchronous and tide dominated. The tide-dominated inner portion of the Gironde estuary is an example (Salomon and Allen 1983).

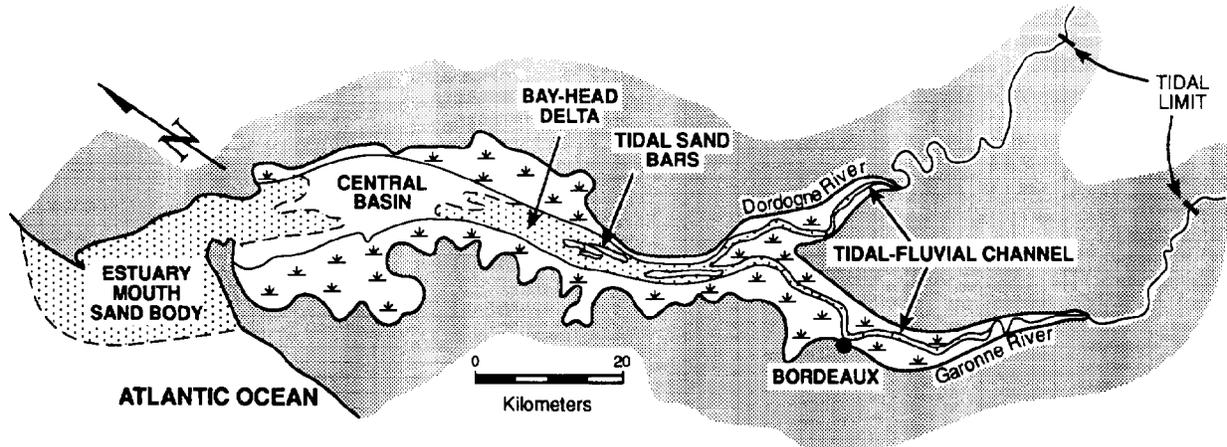


FIG. 10.—Map of the Gironde estuary (17; Allen 1991), a mixed-energy system. Note the tide-dominated nature of the bay-head delta.

Estuary Evolution

Estuaries are initially formed at the beginning of a transgression and migrate landward as transgression proceeds. As far as is known, relatively little morphological change occurs during this process, as long as the external process variables remain constant and the facies zones simply translate landward. Morphological changes which cause deviations from the end-member models begin to occur, however, once the rate of sediment supply exceeds the rate of relative sea-level rise and the estuary starts to fill.

The morphological evolution of wave-dominated systems as they fill is summarized by Roy et al. (1980) and Nichol (1991). As the bay-head delta progrades seaward and the flood-tidal delta extends progressively further up the estuary, the central basin shrinks and ultimately ceases to exist. At this point, the tidal channels in the flood-tidal delta merge with the river channel, thereby allowing tidal energy to penetrate into the inner estuary more easily (Fig. 11). Because of this, wave-dominated estuaries may develop the straight-meandering-straight channel pattern of a tide-dominated estuary at this time. The Ogeechee River (21; Dörjes and Howard 1975; Greer 1975) and Willapa Bay (24; Clifton 1983) may be at this stage.

In tide-dominated estuaries, tidal currents readily redistribute the sediment supplied by both river and marine sources. As a result, there is rapid infilling of the deeper and wider parts and development of the classic funnel-shaped geometry and facies distribution (Fig. 12). Once this situation exists, further sediment input should cause the facies zones to prograde seaward, with the relative distribution of facies remaining essentially constant. The stages in the growth of the sand-bar facies have been discussed by Harris (1988), who shows that the bars become broader as the estuary fills. The seaward movement of the zones in the inner estuary is best shown by the South Alligator River estuary in which the inner end of the meandering reach has migrated seaward more than 20 km since the end of the Holocene transgression (Fig. 9; Woodroffe et al. 1989).

Both wave- and tide-dominated estuaries evolve into deltas if there is sufficient, direct river influence (Fig. 2). However, the morphological distinction between estuaries and deltas (“a seaward protrusion of the coastline of fluvial origin”) is far from clear in wave-dominated systems which are near the point of transition (i.e., the central basin is no longer present but there is no coastal bulge) and in tide-dominated systems located in embayments where designation of the average coastal trend is not possible. As discussed above, we suggest that the direction of transport of bed material is the most fundamental difference between estuaries and deltas. Morphologically, this distinction may be made using the straight-meandering-straight channel morphology which is present in tide-dominated estuaries throughout their life and is commonly developed in wave-dominated systems after the central basin fills. The presence of the tight meanders indicates that the net bedload transport is landward in the region seaward of the meanders and that the system is an estuary. The absence of the meandering zone indicates that the net bedload transport is seaward throughout and that the system is a delta (Figs. 11C, 12C). Indeed, the active distributaries of all deltas are relatively straight right to their mouth (Coleman and Wright 1975; Wright 1985), whereas abandoned distributaries and tidal channels in interdistributary areas show the straight-meandering-straight pattern typical of estuaries (e.g., the Mahakam delta; Allen et al. 1979). On this basis, the Shoalhaven River (35; Roy et al. 1980; Wright 1985) is no longer an estuary, whereas the Ogeechee (21; Dörjes and Howard 1975) and Ord Rivers (28; Wright et al. 1973) are still estuaries (Fig. 3).

STRATIGRAPHIC IMPLICATIONS

General Aspects

Despite the complex assemblage of river-, wave- and tide-dominated facies which occur in estuaries, the models indicate that these facies have a predictable spatial distribution. Consequently, it is possible to predict the

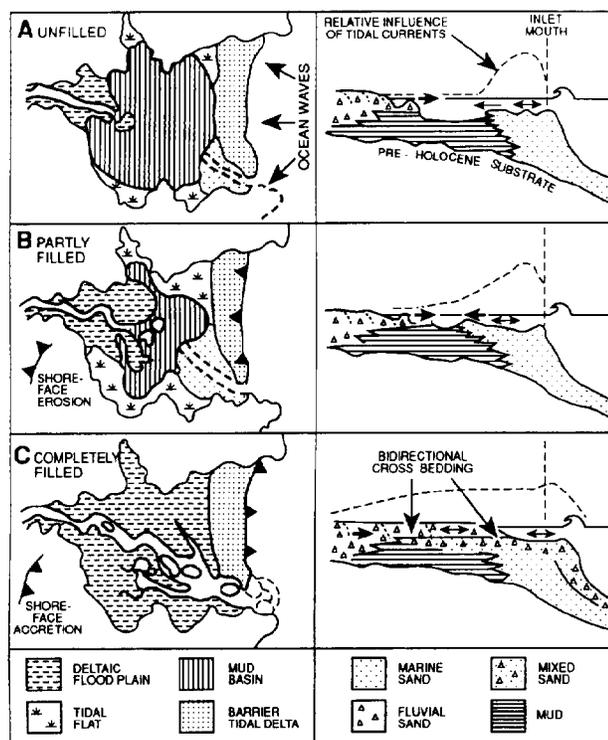


FIG. 11.—Stages in the filling of a wave-dominated estuary (after Roy et al. 1980). Note that the relative influence of tidal currents increases as the estuary fills. The mud basin is equivalent to the central basin described in this paper. Stage C is considered here to be a delta because fluvial sediment is accumulating on the shoreface.

general nature of the stratigraphic succession produced by an estuary as sea level rises from a lowstand and subsequently stabilizes at a highstand.

The base of the paleovalley is marked by an erosional unconformity formed by fluvial erosion during the lowstand (Weimer 1984; Van Wagoner et al. 1990). In the most complete, transgressive succession, this surface is overlain by fluvial deposits, which are in turn overlain by estuarine sediments. The contact between them is a flooding surface (Figs. 13, 14). As the estuary continues to translate landward, the upper portion of the transgressive succession is generally removed by shoreface or tidal channel erosion, depending on whether the estuary is wave- or tide-dominated. The amount of section removed will vary among examples, depending on the relationship among the rate of sea-level rise, sediment input and the depth of the paleovalley (Davis and Clifton 1987; Demarest and Kraft 1987). Partial transgressive successions, in which the basal fluvial and fluvial-estuarine facies have the highest preservation potential, should occur along the transgressed portion of the paleovalley, seaward of the highstand shoreline (Figs. 13, 14).

At the point of maximum transgression, the shoreline stabilizes and the estuary will fill *in situ*, if the highstand is of sufficient duration. At this location, the transgressive succession will be overlain by a progradational estuarine deposit (Figs. 13, 14), the length of which will be equal

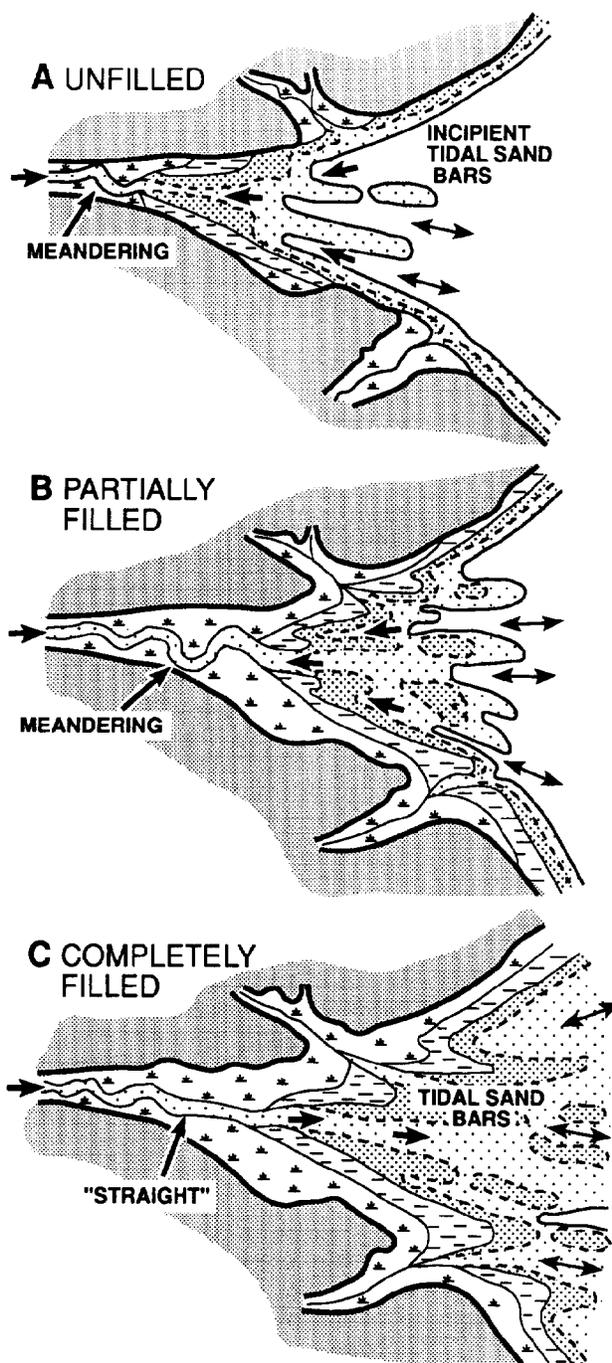


FIG. 12.—Stages in the filling of a tide-dominated estuary (based partially on Harris 1988), showing the expansion and shallowing of the sand bars, and the seaward movement of the meandering zone. When the meandering zone disappears (C), the system is considered to be a delta.

to that of the highstand estuary. Progradation beyond the seaward end of the estuary will occur either as a delta, a beach-ridge plain or open-coast tidal flats (Fig. 2). If sea level falls before the valley is full, the transgressive to highstand estuarine deposits will be dissected during the following lowstand and overlain by a second valley-fill

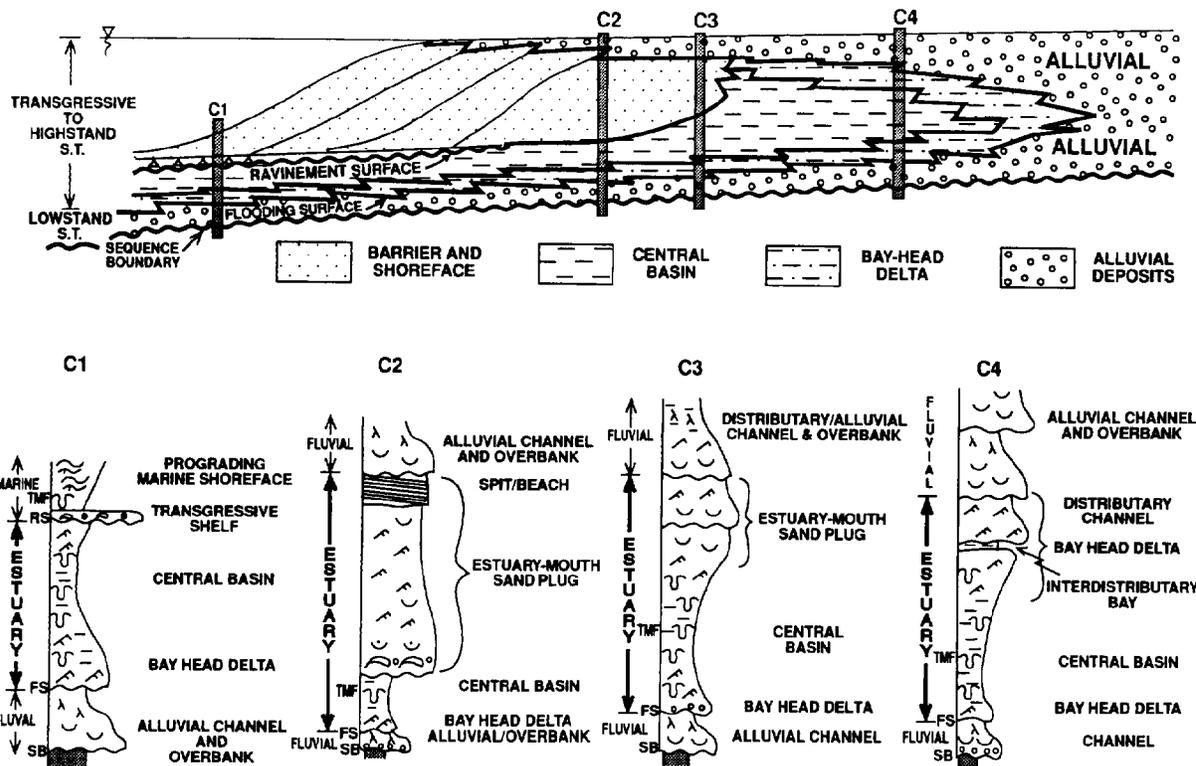


FIG. 13.—Schematic section along the axis of a wave-dominated estuary, showing the distribution of lithofacies resulting from transgression of the estuary, followed by estuary filling and shoreface progradation. The amount of the transgressive succession preserved depends on the relative rates of sea-level rise and headward translation of the shoreface. See Figure 14 for legend.

succession (e.g., Chesapeake Bay; Colman and Mixon 1988).

From the foregoing it is clear that incised-valley estuarine deposits will occur in the transgressive and early part of the highstand system tracts. Because sediment is supplied to the estuary by both fluvial and marine sources, the estuarine deposits may contain two petrographically different sands of the same age.

Wave-dominated Estuaries

The marine sand body in these estuaries is a composite feature which may contain several discrete facies. In transgressive successions, some or all of the barrier-bar complex is likely to be eroded during shoreface retreat and overlain by a ravinement surface (Fig. 13-C1). If any remains, it will consist of the deeper facies, including erosionally-based tidal-inlet deposits and the landward-directed cross bedding of washovers and flood-tidal deltas which may interfinger with the underlying central-basin muds (Honig and Boyd 1992). By contrast, the marine sand body may be preserved more or less intact in progradational situations, with shoreface and beach sediments overlying a core of washover, flood-tidal delta and tidal inlet deposits (Fig. 13-C2, C3; Zaitlin and Shultz 1990; Ricketts 1991).

In vertical profile, fine-grained central basin sediments ideally exhibit a symmetrical grain-size trend. The basal

upward fining represents the passage from transgressive, fluvial and bay-head delta deposits through progressively more distal prodelta sediments. The finest sediments represent the center of the central basin. This will be overlain in turn by an upward coarsening into either flood-tidal delta/washover sediments (Fig. 13-C1, C2, C3) or bay-head delta deposits (Fig. 13-C4), depending on where in the estuary the section is located.

The bay-head delta facies are distinguished from true fluvial sediments by the presence of tidal structures and/or a brackish-water fauna. Bay-head delta sediments are likely to be common at the base of transgressive successions and will occur at the head of the progradational estuary where they will exhibit an upward-coarsening succession (Fig. 13-C4; Reinson et al. 1988). Meandering tidal channels containing inclined heterolithic strata (Thomas et al. 1987) are likely to be most abundant in the late stage of estuary filling when the bay-head delta merges with the flood-tidal delta (Smith 1987; Nichol 1991). Such channels may erode some or all of the underlying central-basin succession and might scour down to the basal unconformity.

Tide-dominated Estuaries

During transgression, the marine sand body is likely to be erosionally truncated or completely removed (Fig. 14-C1) by the headward migration of the tidal channels which

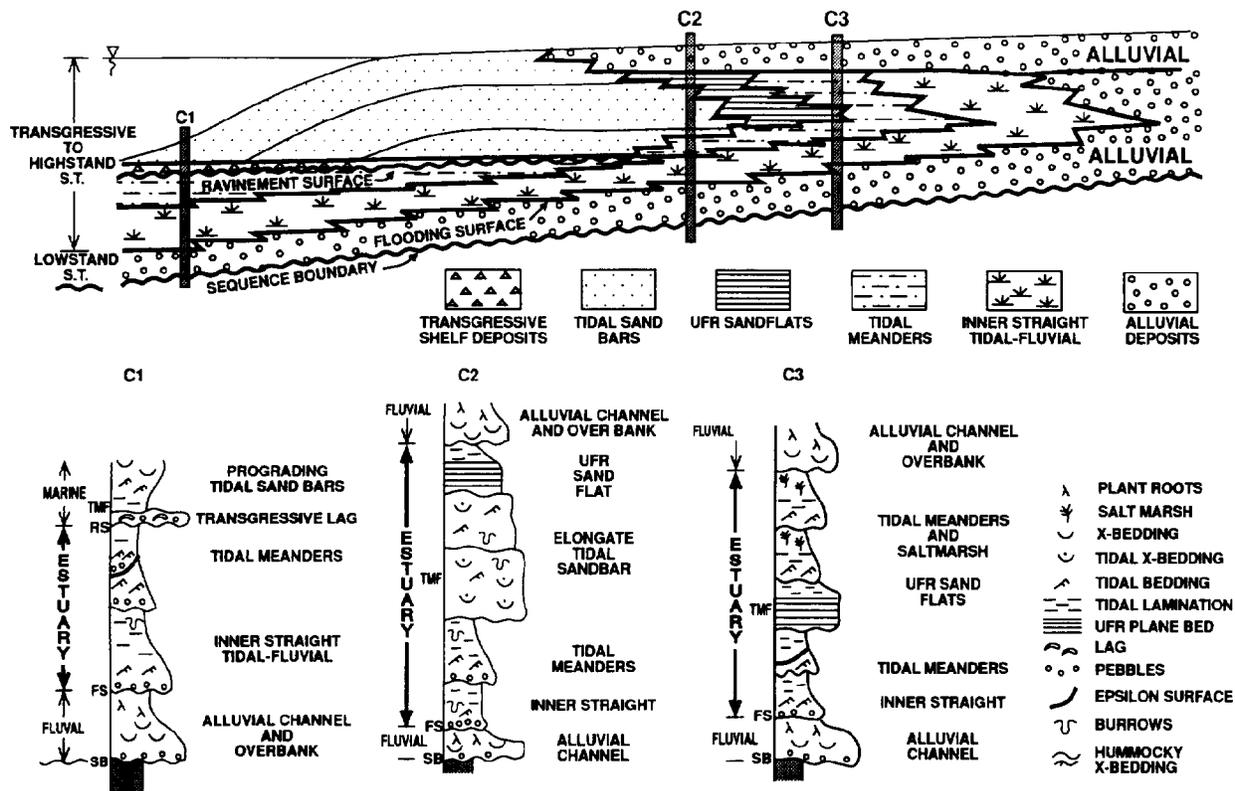


FIG. 14.—Schematic section along the axis of a tide-dominated estuary, showing the distribution of lithofacies resulting from transgression of the estuary, followed by estuary filling and progradation of sand bars or tidal flats. The amount of the transgressive succession preserved depends on the relative rates of sea-level rise and headward translation of the thalweg or the tidal channels.

separate the sand bars. The amalgamation of these channel scours produces the equivalent of a ravinement surface. Erosion by the channels during transgression also causes the cross-bedded sands of the sand bars, or the parallel-laminated, UFR sand-flat deposits, to overlie (Fig. 14-C2) or abut erosionally against mudflat and salt marsh sediments along the margins of the estuary. If the transgressive succession contains both sandy facies, they will produce an upward-coarsening trend. The contact may be either erosional or gradual. In progradational situations, the marine sand body will be thicker and have an overall upward-fining trend (Fig. 14-C2; Dalrymple et al. 1990).

The central, mixed-energy (meandering) and inner, river-dominated portions of the estuary are characterized by tidal channel deposits that are flanked by vertically-accreted, salt-, brackish- and fresh-water marsh sediments. In both transgressive and regressive successions, the point-bar sediments of the meandering zone will be over- and underlain by the deposits of straighter channels (Fig. 14) that display opposite paleocurrent directions, unless the last channel to cross the area erosionally removes the older deposits. UFR parallel lamination predominates in the outer (tide-dominated) straight reach (situated above the point bars in transgressive settings and below in regressive situations; Fig. 14), whereas ripples and/or dunes

are likely to be more abundant in the meandering and inner straight reaches. The channel sediments are finest, and the mixing of fluviably- and tidally-supplied sediment is most pronounced, in the meandering zone. The contacts between facies zones are likely to coincide with erosional channel bases. The channel bank sediments consist of tidally-bedded sands and muds that occur either as erosionally-bounded wedges of flat-lying strata (Dalrymple et al. 1991), or as inclined heterolithic strata. The latter will be most prevalent in the meandering reach.

SUMMARY

Estuaries, which are defined here as the marine-influenced, seaward portion of drowned valleys (Fig. 1), are depositively complex because of the interaction of river and marine (tidal and/or wave) processes. Despite this, a high degree of organization occurs because the predictable, longitudinal variation in the relative intensity of fluvial and marine processes develops a tripartite estuarine zonation (Figs. 1, 4, 7). Coarse sediment supplied by marine and river processes accumulates in the outer, marine-dominated and inner, river-dominated portions of the estuary, respectively, while finer sediment is present in the central zone. The nature of the facies within each of the zones depends on the relative influence of waves

and tides; thus, estuaries can be divided into wave- and tide-dominated types (Fig. 3).

In the ideal wave-dominated estuary, the tripartite facies distribution is clearly expressed (Fig. 4): a marine sand body that consists of barrier-related deposits including flood-tidal delta sediments; a typically muddy central basin; and a bay-head delta formed by river discharge. An analogous three-fold subdivision is also present in tide-dominated estuaries but is not as clearly developed because tidal currents penetrate into the inner estuary more effectively than waves. The marine sand body consists of elongate sand bars and broad sand flats. Headward of this, the channel narrows and shows a straight to meandering to straight progression of sinuities. The meandering reach contains the finest channel sediments and is the location of bedload convergence. It is dynamically equivalent to the central basin of wave-dominated systems.

Most modern estuaries deviate in some way from these idealized models, due to such secondary factors as the mixed influence of waves and tides, differences in the amount of coarse sediment supplied by marine and fluvial processes, the size and shape of the valley being flooded, and the evolutionary stage of the estuary. We believe, however, that the two idealized models (Figs. 4, 7) describe the most basic attributes of estuaries and fulfil the four criteria set out by Walker (1984) for facies models. Most importantly, they allow predictions to be made of the facies characteristics and stratigraphic organization of estuarine deposits within a sequence stratigraphic context (Figs. 13, 14). We await tests of these predictions.

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