Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology 53
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Chapter 1

GEOMORPHOLOGY AND SEDIMENTOLOGY OF ESTUARIES: AN INTRODUCTION

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INTRODUCTION

Geomorphology is concerned with the study of earth-surface forms and with their evolution in time and space due to the physicochemical and biological factors acting on them. Most of the evolution is the product of a cyclic process based on erosion–transport–deposition of sediment particles. Added to this are the combinations that may occur from the meteorization of a hard rock until the particle is permanently buried and becomes part of a new sedimentary rock.

In particular, the coastal environments are subjected to the most energetic conditions on the earth surface. Modifications of geoforms and the characteristics of sediment distribution may occur in very short time periods. Nevertheless spatial and time scales may range from few seconds and centimeters to centuries and thousands of kilometers (Table 1-1). Estuaries are one of the most important coastal features subject to strong processes that fully cover the space–temporal scale. Geomorphologic and sedimentologic changes are continuously occurring within and around estuaries that effect their specific characteristics.

Normally estuaries occupy the areas of the coast least exposed to the marine action. In this way, wave activity is generally quite reduced, allowing the development of harbors, recreational facilities, or appropriate aquaculture initiatives. Nevertheless, within the estuaries the dynamical processes are rather strong and impose a remarkable stress over the biota, either permanent or temporary, the morphology and the civil works.

Some authors have indicated that "estuaries have been uncommon features during most of earth's history..." (Russell, 1967), simply because "estuarine deposits rarely can now be delimited unequivocally from other shallow water marine deposits in the geological record because of their limited areal extent, their ephemeral character and their lack of distinctive features" (Schubel and Hirschberg, 1978). Nevertheless, as

Table 1-1

Measurement units on the space-temporal scale (after Perillo and Codignotto, 1989)

	Megascale	Macroscale	Mesoscale	Microscale
Space	km	km	m	cm
Time	century	year/month	days/h	min/s

Table 1-2

Schematic sequences of sedimentary lithofacies in a transgressive estuarine environment for (a) axial and vertical trend, and (b) lateral and vertical trend (After Nichols and Biggs, 1985).

(a) Axial and vertical sequence in the estuarine environment		
River	Seaward	Sea
ESTUARINE FLUVIAL	ESTUARINE	ESTUARINE MARINE
		Coarse marine sands massive with abundant cross-bedding, tidal current ridges with low angle cross-bedding in fine sands with silt laminae
	Silt and clay with sandy lenses and laminae, massive silt and clay deposits	
Massive silt and clay with abundant plant and roots, sandy lenses, and laminations, grading downward into sand, gravel and cobble		
(b) Lateral and vertical sequence in lower estuary		
Shore		Mid-channel
SHORELINE DEPOSITS	SUBTIDAL FLATS	ESTUARINE MARINE
		Coarse marine sands massive or with abundant cross-bedding (as above)
	Laminated and massive muddy sands and sandy muds	
Sand, gravel, and shell with or without washover complex and muds with plant frangments and basal peat		

long as a river was present in any paleocoast being affected by tidal action inducing changes in salinity distribution within its valley, an estuary existed. By the time Russell (1967) proposed his opinion, there were few unifying models of estuarine deposition and geologist had difficulties to identify them from other shallow marine environments. However, Nichols and Biggs (1985) have provided axial and lateral sequences of estuarine lithofacies in transgressive conditions (Table 1-2). Figure 1-1 is a schematic representation of the evolution process due to high river-load discharge.

In the present time, estuaries are very common features in most world coasts. For instance, Emery (1967) estimated that 80–90% of the Atlantic and Gulf coasts and 10–20% of the Pacific coasts of United States are occupied by estuaries in the broad sense. The large variety of estuaries that exist depends on the local climatological, geographic, geological and hydrological characteristics. But also their

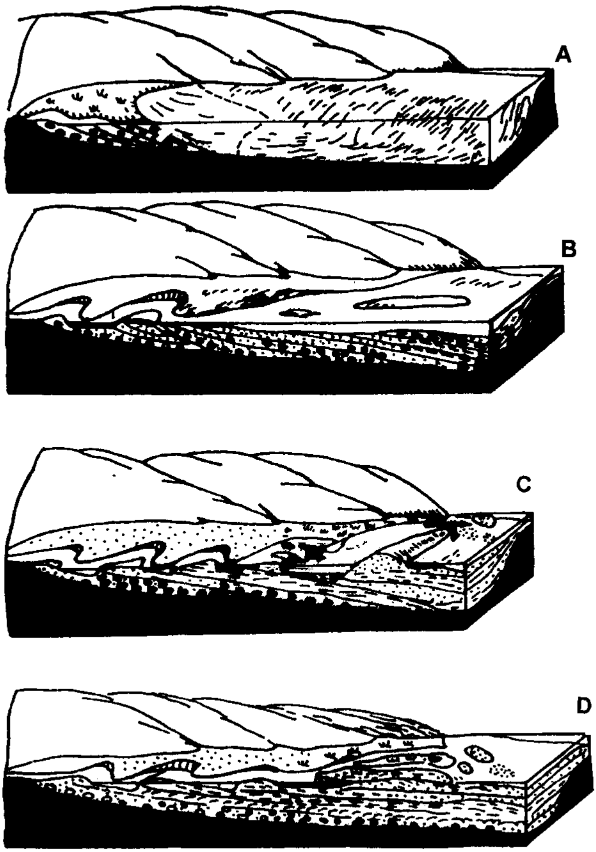

Fig. 1-1. Schematic evolutionary sequence of an estuary associated with a large ratio of river-load input to sea-level rise. A) Flooding by the sea of the fluvial valley; B) progradation of the coastal plain; C) developing of barriers by littoral transport, and D) developing of a river delta.

present position and future evolution largely relies on the variations in sea level, sediment supply and structural activity.

Therefore, the aim of the present chapter is to consider the basic geomorphologic and sedimentologic characteristics of estuaries in relation with its global distribution, factors that influence them and to provide some clues to identify estuaries in the geological record.

HISTORICAL BACKGROUND

Since river mouths have served as natural harbors from the beginning of civilizations, knowledge of the shallows and channels, tides and currents, and the extent of salt water penetration has been empirical for the first navigators, city founders and engineers. Nevertheless, the first morphological charts were introduced by W. Bourne

in 1578. He described the genesis and geomorphology of coasts, including the first indication of the presence of shoals at river and estuarine mouths.

As geomorphology was initiating in the last decades of the 19th century, much work was done in coastal environments and, specially, in rivers. They were made following the Davisian model associated to time evolution stages (youthful–mature–old) of landscape. However, estuaries were not regarded as a particular separated entity from the river. Actual interest in estuaries started at the beginning of the 50's, after a series of papers by Pritchard (1952), Stommel (1953) and Stommel and Farmer (1953) that followed the basic paper by Kuelegan (1949). However, most of these papers only considered the geomorphology of the estuaries in analyzing the constrains that the borders introduce in their circulation.

Pritchard (1952) introduced the first physiographic classification, modified by the same author in 1960 (see discussion by Perillo, this volume). His classification is still being considered as a good preliminary approach to the understanding of the general structure of these coastal bodies. Interest in the geomorphology, sedimentology, and sediment transport of estuaries has increased steadily since them. Classical papers like those produced by Postma (1961, 1967), Allen et al. (1980) and more recently Nichols and Biggs (1985) or books by Davis (1985) and Dyer (1986) stand out from a remarkable list.

Even though the extensive literature and the numerous experiments carried out in many estuaries in the world, precise knowledge of the actual processes that shape estuaries, distribute its sediments and control the fate of pollutants and biological species is still elusive. Integrated approaches has to be devised to understand individual estuaries or even some particular feature within an estuary.

OCCURRENCE AND DISTRIBUTION OF ESTUARIES

As long as freshwater is discharged into the sea in a channeled form, there is potential for the development of an estuarine environment. Figure 1-2 shows the distribution of the most important estuaries in the world associated to the tidal range and climatic zones (many of the estuaries mentioned in the following chapters have been included in the map). Most estuaries developed in former river valleys are located on subtropical and temperate regions and associated with mesotidal conditions. Those related to previous glacial valleys have formed in polar and subpolar climates. Pure coastal plain estuaries appear in areas where sediment load provided by the rivers are relatively small when compared with the dynamic forces that redistribute the material. Deltas, on the contrary, are found in places where these conditions are reversed. Although delta tributaries may behave as estuaries themselves.

On the other hand, fjords are concentrated in high latitudes and mostly on rocky shores, meanwhile the few existing fjards are observed on low-lying coasts of northern Sweden. Rias are detected in rocky or cliffy shores where alpine glaciation did not reach into the inundated valley or its modifications cannot be revealed from the river influence. Structural estuaries cannot be related to any climatic or tidal range criteria, but to areas presently active like the western boundary of the American continent.

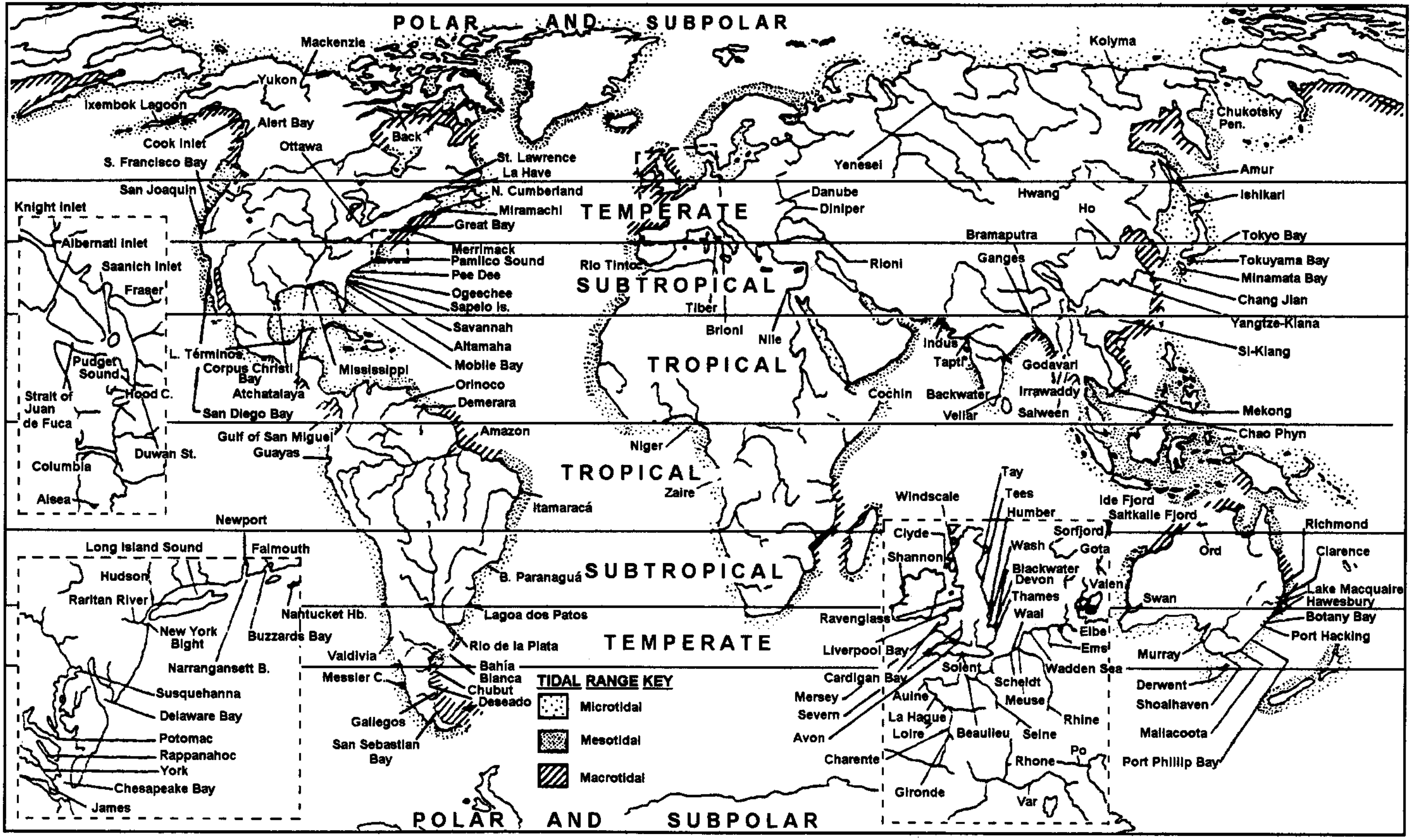

Fig. 1-2. Distribution of major estuaries in the world related to tidal range and climatic zones (modified from Olausson and Cato, 1980).

Table 1-3

Factors controlling the formation of estuaries.

Climate	Polar and subpolar Temperate Tropical and subtropical
Type of coasts	Trailing edge Collision Marginal sea
Coastal lithology	Hard-rock Soft-rock (sedimentites)
Tidal range	Macrotidal Mesotidal Microtidal
Coastal stability	Submerging Emerging Stable
Neotectonism	Present Absent
River discharge and sediment load	High Low
Marine diffusive forces (waves, littoral currents, tidal currents, etc.)	High Low
Atmospheric influence (winds, temperature, humidity, etc.)	High Low

Finally, coastal lagoons present a complete different criteria. They are the product of marine action that totally cleared the original valley by providing its particular morphology. In general, coastal lagoons are associated with micro and mesotidal coasts where littoral processes are presently, and/or in the near past, dominant. According to Emery (1967) these features are characteristic of coastal plains where minor sea level increases may inundate large surfaces.

In summary, there are several criteria that control the presence or absence of estuaries and, in the former case, their type. Some of the most important are presented in Table 1-3. The listing is not complete and it has not been ordered in any specific manner. Evidently adequate combinations of these factors will produce characteristic types of estuaries which in themselves have particular circulation patterns. Although most factors have been quantified, there is still no clear correlation between any combination of these parameters and the resulting estuary.

EVOLUTION OF ESTUARIES IN THE GEOLOGICAL TIME SCALE

Being coastal features, the position of estuaries depends on the location of the shoreline, which itself is conditioned by sea level oscillations, tectonism, isostasy, etc.

A stable coast is the product of the balance between forces that tend to move it either landward or seaward. If the delicate balance becomes modified, the result is a transgression or a regression of the sea. Bowen (1978) suggests that sea level may change due to one or several of the following processes: long-term tectonism, glacial isostasy, hydro-isostasy, geoidal modifications and glaciation.

General falling of the sea level during the Tertiary period can be related to worldwide tectonism and orogeny. Uplift implied deepening of ocean basins since ocean floor material must have been used to fill up the elevations. Although the tectonic effect on sea level is important in itself, a consequence of the formation of high mountain ranges is the major changes that occurred on the climatic pattern of the Earth. Notably is the formation of the Antarctic ice cap 5 Myr ago. As suggested by Tanner (1968), the mid-Cretaceous sea level was some 130 m higher than at present. The sea level reduction occurred in two steps: about 50 m were reduced in 70 Myr due to the tectonism during the late-Cretaceous–earlier Tertiary. The second step spreaded for another 25 Myr with a 75 m sea level drop that may have been produced also in another two processes. These were, first an isostatic rebound due to erosion of the mountain ranges, and second, and more important for our purposes, was the growth of the Antarctic and Greenland ice sheets. If the latter process did not occur, sea level should be about 68 m higher than it is now. This is coincident with Russell (1964) observation that melting of the Antarctic and Greenland ice caps would produce a rise of sea level between 60 and 75 m.

There is general agreement that four major glaciation periods occurred during the Pleistocene (since 2.8 Myr BP). Fairbridge (1961) scheme (Fig. 1-3) considers that sea level was reduced from a maximum of about +80 m during the Aftoninan interglacial to −100 m (Kraft and Chrzastowski, 1985) during the Wisconsin, some 15–18,000 yr ago. Although some authors (i.e., Emery, 1967) place the lowermost sea level stand at −130 m. The passage from glacial to interglacial periods and back was marked by numerous oscillations. Employing oxygen isotopes analysis, Shackleton and Opdyke (1973) found out nine glacial and ten interglacial events within the last 700,000 yr, while Beard et al. (1982) proved the occurrence of eight interglacial and the same

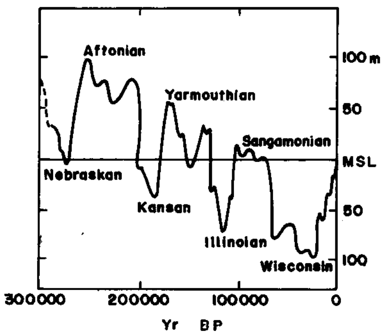

Fig. 1-3. Mean sea level variations within the Pleistocene due to the different glacial and interglacial periods. Note the general sea level trend that clearly shows a marked long-term reduction. (Modified from Fairbridge, 1961.)

number of glacial events for the whole Pleistocene. Anyway, the largest glaciation and the one that concerns us the most is the previously mentioned Wisconsin (Würm, as it is named in Europe).

Glaciations occur when the water that normally flows to the sea is retained on the continent as ice. The lack of runoff and the associated strong evaporation on the sea, product of dry atmospheric conditions that tend to accompany glaciations, lower the sea level. Although ice sheets developed around the poles, this simple process affected the world ocean on each glacial period. This is specially true during the Wisconsin which apparently covered the largest surface than any previous glaciation.

The increment in the atmospheric temperature produced the melting of the ice, originating thus a rise in sea level. Most authors agree that sea level raise was very rapid during the first 12–15,000 yr until about 3,000 yr BP (Fig. 1-4). Since then, the rate of change of sea level has diminished significantly reaching in the present rates on the order of, for instance, 2 mm/yr in the eastern coast of US (Hicks, 1980) and 1.6 mm/yr in the Argentine coast (Lanfredi et al., 1988).

Further evidence presented by Fairbridge (1961) suggested that the rising process was also marked by strong oscillations. Some of them that occurred within the last 7,000 yr moved the sea level above the present stage. As an example, Gonzalez (1989) has displayed a series of four transgressive episodes that occurred between

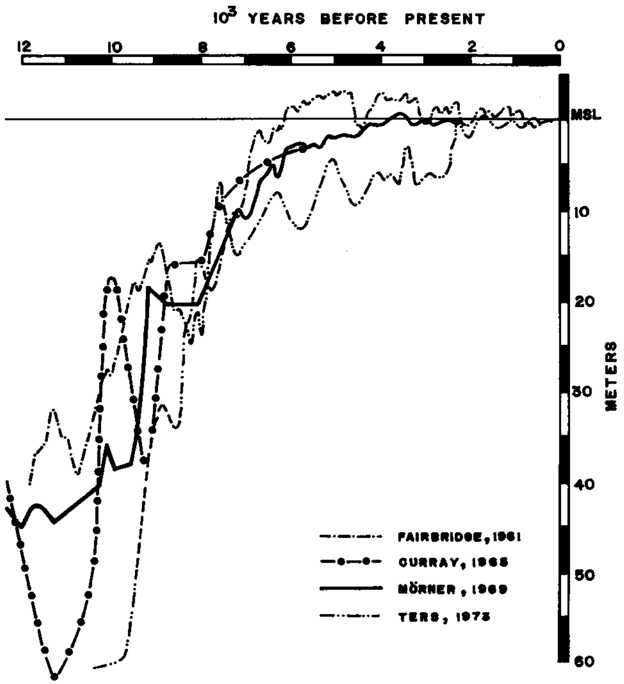

Fig. 1-4. Mean sea level curves from various authors for the last 12,000 year. Fairbridge (1961) curve shows several fluctuations above the present mean sea level which later was confirmed for the Southern Hemisphere (see Figs. 1-5 and 1-6).

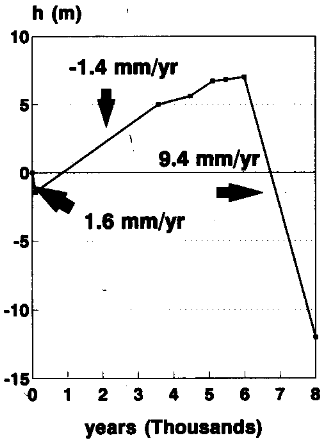

Fig. 1-5. Estimated mean sea level curve for the Bahía Blanca Estuary (Argentina) showing a very high (up to 7 m) sea level stand above the present condition (modified from Gómez and Perillo, 1994).

5,990 and 3,560 yr BP in the Bahía Blanca estuary (Argentina). The maximum and oldest transgression left beach and tidal flats deposits at about 7 m above the present sea level. Aliotta and Perillo (1985, 1990) have described a series of wave-cut terraces between 13 and 16 m below datum level near the mouth of the same estuary which were formed during a lower still stand 8,000 yr BP. Gómez and Perillo (1992, 1994) have described similar terraces at depths of 15 m outcropping from beneath shoreface-connected linear shoals.

Based on the information provided by Aliotta and Perillo (1985,1990), Gómez and Perillo (1992) and Gonzalez (1989), Gómez and Perillo (1994) developed a minimum sea level variation curve. The curve shows the different rates of sea level evolution during the last 8,000 yr for the Bahía Blanca Estuary (Fig. 1-5). It was made by using the minimum depth at which the macroterraces were found and assigned them an age of 8,000 yr, and the lowest level of occurrence of each transgressive stage mentioned by Gonzalez (1989) giving to each of them their probable geological age.

The resulting composite curve shows a sharp increase, roughly 1 cm/yr in the first 2,000 yr; having about the same rate assumed by most authors for the period 15,000 to 6,000 yr BP (Schubel and Hirschberg, 1978). The Late Pleistocene–Early Holocene delta complex of the Desguadero–Colorado rivers (Perillo, 1989) was rapidly covered by the sea; becoming for over at least 4,000 yr a shallow inner shelf zone. The calculated rate of 1.4 mm/yr considers as if the sea level dropped continuously until 90 yr ago, giving a minimum rate, from which we used Lanfredi et al. (1988) estimate. Obviously this rate may be much larger if we consider that upward movement of the sea level must be occurring for at least 400–500 yr as has been recently proposed by Gonzalez and Weiler (1994), but there is no enough evidence to support this. The curve given here compares quite well with the general structure of the curves given by Isla (1989) (Fig. 1-6) for different sites on the Southern Hemisphere and specially along the Argentina coast where sea level above the present has been repeatedly recorded.

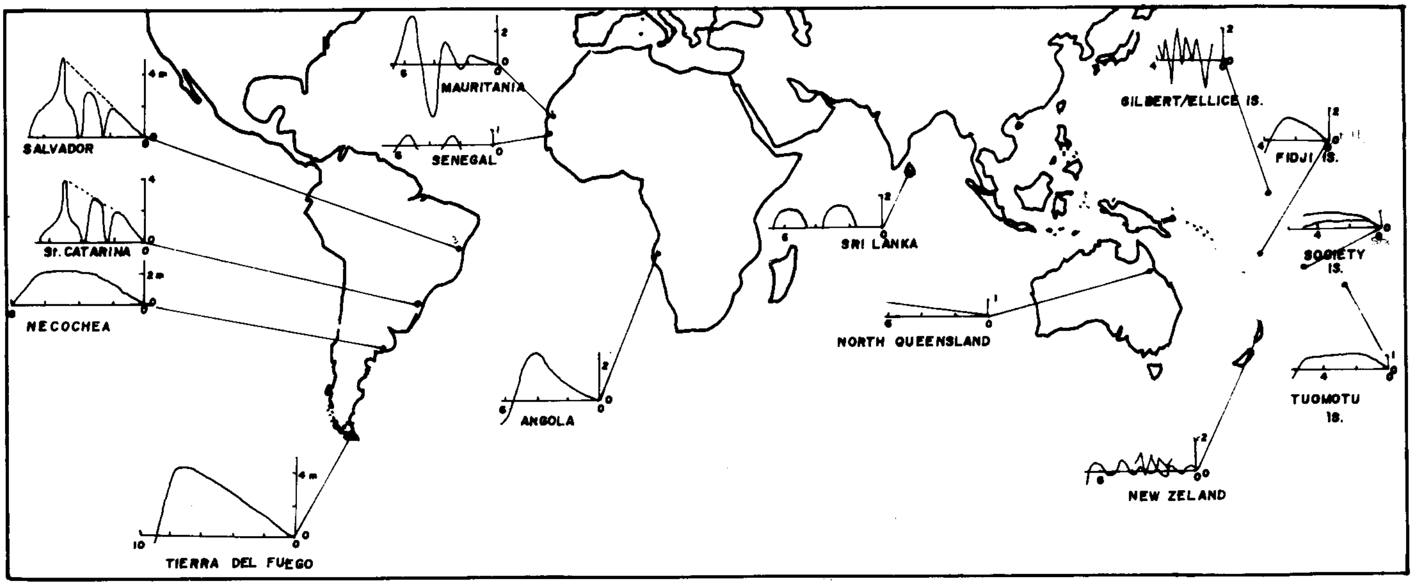

Fig. 1-6. Examples of mean sea level curves from the Southern Hemisphere exhibiting in all cases estimates above the present mean sea level (modified from Isla, 1989).

As the sea level stood at its minimum position, most of the world continental shelves were converted in extensive plains. As estimated by Emery (1967), the average shelf break (−130 m) is at or near the predicted values for the lowest sea level. During almost all the Tertiary and Pleistocene, rivers were restricted to the present day hinterland. Then during the glaciation period, they found their way through the continental shelves driven by a lower base level. Both, the rivers and glaciers that occupied previous river valleys in high latitudes, cut down more definite and deeper valleys on the continental shelves. In many cases, they reached the shelf break where they originated submarine canyons (i.e., Hudson, Baltimore). To the present, there has not been found any evidence of a connection between the very few submarine canyons existing on the continental slope of the Argentine shelf and present day rivers. It is considered that during the last glaciation and even up today, the Patagonian climate was dry. Therefore, rivers had relatively low discharges that prevented them from reaching the shelf break that is over 200 km up to 850 km away.

During the lowest sea level, estuaries occupied the border of the continental shelves. They were, in general, scarce and limited in their areal distribution. In effect, estuaries were mostly restricted to valleys bordered by abrupt walls. The most immediate effect of the thawing of continental ice was felt by river discharges which also raised substantially the sediment load input to the sea. Due to the high gradient valleys in the canyons, sediment was not deposited in them. Bypassed sediments formed abyssal cones and partially contributed to the building of the continental rise. Similar situations are observed today with the abyssal cones formed by, for instance, the Ganges (India) and Mississippi (USA) rivers.

There is little evidence of estuarine deposits in the proper canyons. If there are, many deposits originated during this period may be easily confused with those formed by fluvial action. Why? As a general approximation, we can infer that the tides against the Wisconsin coasts were small as it occurs near present-day ocean islands having steep accesses. Also, based on the water equivalent ice volume estimated by Flint (1961), average salinity must have been about 1‰ higher than present. Therefore, the circulation on the mouth of the estuaries that occupied the "canyon" valleys must have been of the salt wedge type. However, tidal effect in the inner part must have been important. It is expected that because of the strong convergence and relatively low friction, these estuaries were of the hypersynchronous type resulting in a continuous increment in tidal height and tidal current headward. Consequently, we may estimate that mixing of water masses occurred only at the mouth and sedimentation within the "canyon" may appear as fully fluvial although affected by tidal influence.

High river runoff resulted in a sea level rise. After surpassing the shelf break, the transgression front found the extensive, low gradient (on average 7′ slope) shelf plains. Therefore, the channeled river valleys were replaced by the development of quite ephemeral coastal lagoons (Fig. 1-7), tidal flats and salt marshes similar to those presently observed on the east coast of USA and northern Europe. Only those places where rivers have cut down a deep valley across the shelf may have retained the classical estuarine type.

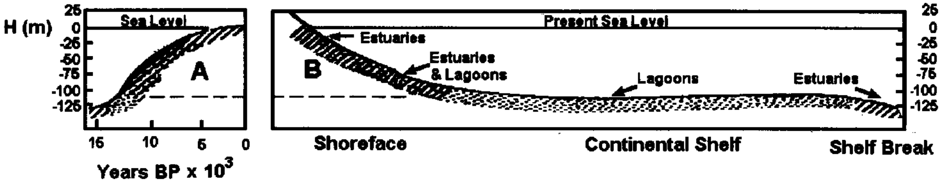

Fig. 1-7. Estimated relationship between continental shelf slope and type of estuary resulting from a sea level rise: A) general trend of sea level rise in the last 15,000 years, and B) scheme of a continental shelf. (Modified from Emery, 1967; Nichols and Biggs, 1985.)

Due to the low relief, minor elevations of the sea level should have produced large inundations on the continental shelves; therefore, the lagoon type deposits cannot be too thick. Emery (1967) suggests that many sand ridges found presently on the continental shelves as described by Swift et al. (1978) have trends, shapes and sizes analogous to the sand bars and barrier islands that close present day lagoons. Field and Duane (1976) also indicated that barrier islands occurred in many places of the continental shelves and that they migrated continuously in time but discontinuously in space toward the present coastline. The dynamical conditions acting on these estuaries were probably similar to those observed on the present microtidal estuaries, specially concerning wave and littoral sediment transport. However, general tidal range must have been higher than before the sea level passed over the shelf break, and average salinity values were reducing slowly due to major input of fresh water.

Further sea level raise allowed the transgression to reach the inner shelves which gradients (about 17′) are larger than those of the middle and outer shelf. Here the presence of valleys, now formed by river, glacial and (in a lower number) neotectonic activity, lead to the appearance of some classical estuaries but mixed with lagoons (Fig. 1-7). Their areal distribution was dependent upon the local shoreface gradient.

Allowing for the fluctuations mentioned earlier in this section, there is general agreement that sea level reached about the present position 3,000 yr BP. Today estuaries have then reached their present position. From then on estuaries have adapted to the particular conditions of each coast, river and climate in which they have developed. The search is now toward an equilibrium that most probably will never attain.

Here is where we can introduce the idea of the ephemeral conditions of estuaries from the geological time scale standpoint. Considering the cyclicity of the Pleistocene glaciations, many authors agree that we are in an interglacial period. Schubel and Hirschberg (1978) even stress that interglacial periods occurred only during 8% of the time in the last million years; each lasting $10,000 \pm 2,000$ yr. Then it should be only a matter of time before the return of the glaciers. However, the present situation differs from that during the Sangamon or earlier interglacials because of the presence of the "industrial man." Through the combustion of fossil fuels, man is changing the CO_2 cycle and thus intensifying a greenhouse effect with an associated artificial

rise of Earth's temperature. Prediction as to the behaviour of the temperature for the next few thousands years based on what happened in the last one and half centuries seems uncertain. However, if the present trend is firm, ice caps will be slowly retreating and consequently coastal areas will be invaded by the sea. Hoffman (1984) predicts an increase in mean sea level of the order of 1 m within the next 60–150 yr. More recent estimates indicate that value will not be larger than 0.3–0.5 m (Carter et al., 1992).

Nevertheless, any increase in sea level will move estuaries further inland. Transgression over trailing edge coasts that have extensive plains may result in developments of coastal lagoons and tidal flats rather than typical estuaries. Meanwhile, collision or subduction coasts will produce very short estuaries of the ria type.

However, eustatic modifications are not the only way in which estuaries evolve. Once they are formed, estuaries become sediment traps (Nichols and Biggs, 1985). First, let us imagine that a coast is stable, that is, there is no coastal migration and no eustatic changes occur. Therefore, the interplay is between the sediment introduced and the estuarine circulation that should export it to the continental shelf. The circulation within the estuaries is restricted due to the reversing nature of the tidal currents. Only the residual fluxes, which are strongly dependent on the density structure and tidal asymmetry, drive the sediment within the estuary and the material is not always exported. As a consequence, residence time of the sediment particles may increase exponentially to infinity (ultimate deposition) from the values in the river. In a stable coast, this process results in the filling of the estuary and, later on, the river bypassing it and discharging directly into the shelf.

If the coast is affected by subsidence, filling up of the estuary will then depend on the balance between sediment supply and rate of subsidence, either due to isostasy or eustasy. If supply is larger than subsidence, we have the same result as described in the previous paragraph (i.e., formation of deltas). When subsidence is equal to or larger than supply, we have the "eternal" estuary since it will never be filled up as long as the general conditions do not change.

FACTORS INFLUENCING THE GEOMORPHOLOGY AND SEDIMENT DISTRIBUTION

A detailed description of the dynamic factors that influence the geomorphology and sediment distribution of estuaries is beyond the scope of the present chapter. There is a large bibliography that provides deep insight on these factors, for instance, the books by Dyer (1973, 1986) and Officer (1976). Specific influences related to particular types of estuaries and major environments commonly found in them are included in the respective chapters of the book. Dyer (this volume) describes the sediment transport process occurring in estuaries. Nevertheless, it is important to mention here the most significant factors that induce the formation of estuaries or act on their evolution.

As prime responsible of the estuarine characteristics are the hydrodynamic factors, namely tides, river inflow, estuarine circulation, waves and atmospheric forcing. The resulting estuary is primarily a consequence of the combination of these factors

acting over all the estuary or in specific parts of it. Interactions between the different factors with the borders are complex; mostly non linear. Evidences of them are the geomorphologic changes that occur in the estuary associated with the sediment transport processes.

The general sedimentology of a specific estuary is the consequence of many conditions. One of the most important is the sediment source, which may be from the river, the adjacent shelf, transported by littoral currents and introduced into the estuary by tidal action or littoral drift. Erosion of inner estuary rocks or pre-estuary sediments and biogenic material is also significant in relation with the particular geological setting of the estuary or the climatic situation of the region. Furthermore, within the estuary proper, sediment distribution is extremely variable reflecting the hydrodynamic conditions and the particular transport processes dominant on each portion of it. All these aspects are treated in detail on the corresponding chapters of the book.

SUMMARY

Normally estuaries occupy the areas of the coast least exposed to the marine action. In this way, wave activity is generally quite reduced, allowing the development of harbours, recreational facilities, or appropriate aquaculture initiatives. Nevertheless, within the estuaries the dynamical processes are rather strong and impose a remarkable stress over the biota, either permanent or temporary, the morphology and the civil works.

Although the number of examples of estuaries observed in the geological record is small yet, there are increasing evidences that they were a common feature of the planet. It is only a matter of common sense to accept this concept, since river and sea have interacted from the Precambrian period to the present. Still, their cast is difficult to find due to the fact of their little regional span and the variety of facies that can be confused with other environments.

The interplay of elements like climate and type of setting may define the basic structure of the estuary during its formation. However, once formed, further evolution depends on many factors that act at different scales in time and space. The most important are the physical parameters and the input of sediment. The former will act to modify the original shape to attain an equilibrium form, while the latter is either deposited within the basin or exported to the shelf. Whichever prevails, the estuary disappears or becomes a permanent feature in the coast as long as the sea level does not change dramatically.

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