Rías and tidal-sea estuaries in: Knowledge for Sustainable Development, an insight into the Encyclopedia of Life Support Systems. UNESCO-EOLSS (ed.) vol 2, theme 11.6.3, 799-829. 2002

RÍAS AND TIDAL-SEA ESTUARIES

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Keywords: Rías, tidal-sea estuaries, sedimentology, morphology, sedimentary infilling

Summary

Coastal inlets such as estuaries, rías and bays occupy areas which are partially exposed to wave action and the hydrodynamic processes generated by tidal currents and fluvial discharges. These processes are often quite complex, and regulate many of the morphological and sedimentological characteristics occurring in this type of environment.

In aerial view, rías and estuaries are characterised by a funnel-shaped geometry and deep entrances, with a considerable reduction on both dimensions upstream. From a physiographical viewpoint, both types are classified as drowned river valleys as they were formed by sea flooding of Pleistocene-Holocene river valleys during the last transgression.

This chapter is a review of the main processes and attributes in rías and tidal-sea estuaries, initially focusing on the basic physical processes, morphology and sedimentology, with some examples highlighting the differences between both types which, historically, were considered as one. To document the Late Quaternary history of the Rías Baixas on the north-west Atlantic coast of Spain, a brief description of the sedimentary infilling is presented.

It is also intended to form a discussion of individual cases, and to the more specific characteristics given in other works in this volume, that were only briefly mentioned in the present article.

1. Introduction

The term "ría" originally dates back to the Middle Ages, as Méndez states in a recent publication. It is found in the 1495 edition of a Spanish-Latin vocabulary by Elio A. de Nebrija with the meaning of "river port, ostium fluminis". The same definition appears in diverse cartographic documents covering the old Kingdom of Galicia (NW Iberian Peninsula) from the sixteenth century. In 1780, the Royal Academy of the Spanish Language generalised its use to refer to a geographical area with a characteristic topography or morphology, defined as "the part of the river at the sea outlet". In the anonymous nineteenth century Dictionary of Spanish Geographical Terms, "ría" is described as "the lower part of a river, and near its outlet into the sea, to where the tide reaches and where fresh and salt water mix".

The term was introduced into the literature of Earth Sciences by the German geomorphologist Von Richthofen in 1886. He used the term for funnel-shaped or wedge shaped drowned valleys on coastal areas lying transverse to the regional structural direction of the land; in contrast to the Dalmatian coast of former Yugoslavia, which parallels the structural directions of the land. He took the Galician name used locally for the deep inlets that are so well developed in the region .

Once the term "ría" was introduced into the scientific literature, adapted from Von Richthofen's initial system, a relative, albeit still limited, knowledge of the same was achieved by comparing the ample literature with the numerous works on many estuaries found worldwide. Some of the most outstanding pioneering works include those by Schurtz, Scheu and Torre Enciso in the first half of the twentieth century; these focused on the origin of the term in geographical papers and interpretations of the existing cartography, as noted in Carlé on geomorphology and tectonics.

Nonn analysed topographic forms and established a classification for the rías on the Galician coastline, based on their most significant morphological features. More recent works such as those by Pannekoek in 1966 attributed rías to Hercyinian faults reactivated during the Tertiary .

The term "estuary" is derived from the Latin "aestus", meaning "of the tide". This means that the term is applied to any coastal environment where the tide is particularly important. A wide range of definitions exists, depending on the different disciplines concerned with the study of estuaries. Many are contradictory, due to the different types of knowledge in the hands of the researchers, or due to the specific characteristics of the estuary being studied.

In the latter half of the nineteenth century, the terms "ría" and "estuary" were considered synonyms and had the meaning which each individual scientist cared to give it, depending on the characteristics to be highlighted. Both cases were considered only as a part of the river mouth and the definitions given were variations which attempt to detail the definition given by Cameron and Pritchard (1967), adapted from a previous version given in 1952. This initial definition established that an estuary "involves a water body partially enclosed in a coastal area, with free connection to the sea and within which it is possible to measure the water diluted by the freshwater deriving from land drainage". It was not until the early 1950s when interest was aroused in estuaries, not only in terms of geomorphology, but increasingly in sedimentology, and their characteristic sediment transport.

From a geological viewpoint, it is no easy task to clarify many of the questions regarding estuaries. The systems proposed by Pritchard (1967) or Fairbridge (1980) establish solid bases for a more in-depth understanding of these coastal environments. Pritchard considers large scale processes, such as tectonics and eustatics, presenting different basic physiographic types of estuaries, establishing a physical limit demarked by the tidal influence. Fairbridge, in contrast, considers a dynamic system based on the affecting changes over a short period of time; seasonal changes caused by fluvial discharges, and at the same time as demarking chemical type limits in terms of the degree of dilution or concentration of salinity (see Figure 1). From the geological standpoint, Schubel in 1972 indicates that tectonic estuaries correspond to those that fill basins formed by faulting or other diastrophic movements. More recently, Hume and Herdendorf, in 1988, gave a classification based on the primary mechanism that shaped the basin prior to the possible modifications produced by Holocene processes. More recently Perillo (1995) gave a new morphogenetic classification of estuaries following the criteria given by Shepard in 1973 in his classification of shorelines. From the sedimentological viewpoint, the studies conducted by different researchers on the U.S. east coast and European Atlantic coasts, have shown that estuaries affected by high energy waves and tides exhibit characteristic morphological and facies patterns, which highlight the various refilling stages occurring in the basin, both in the axial and lateral direction of an estuary (see Figure 2).

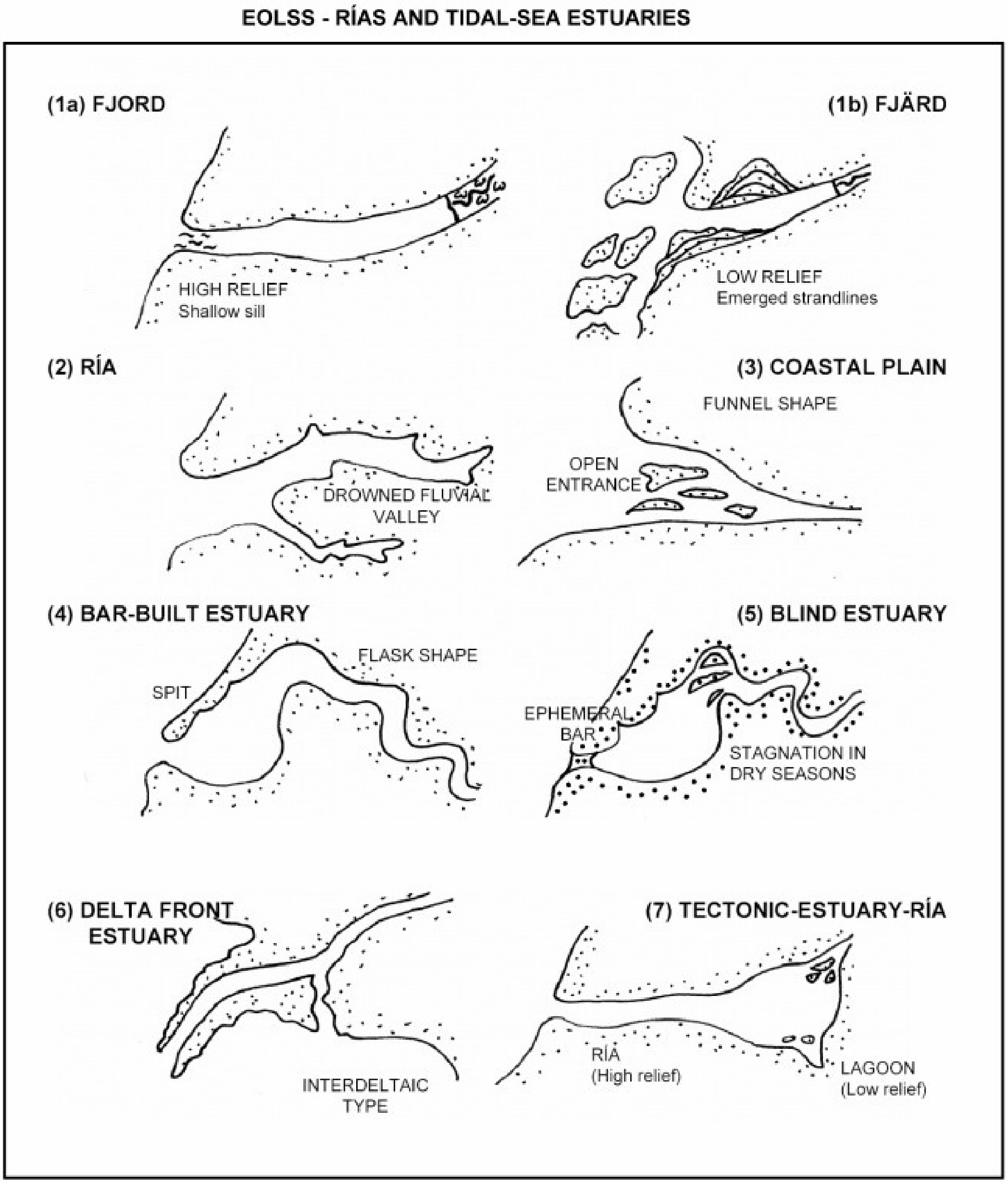

Figure 1. Physiographic types of estuaries based on the dynamic system over a short period of time (modified from Fairbridge, 1980).

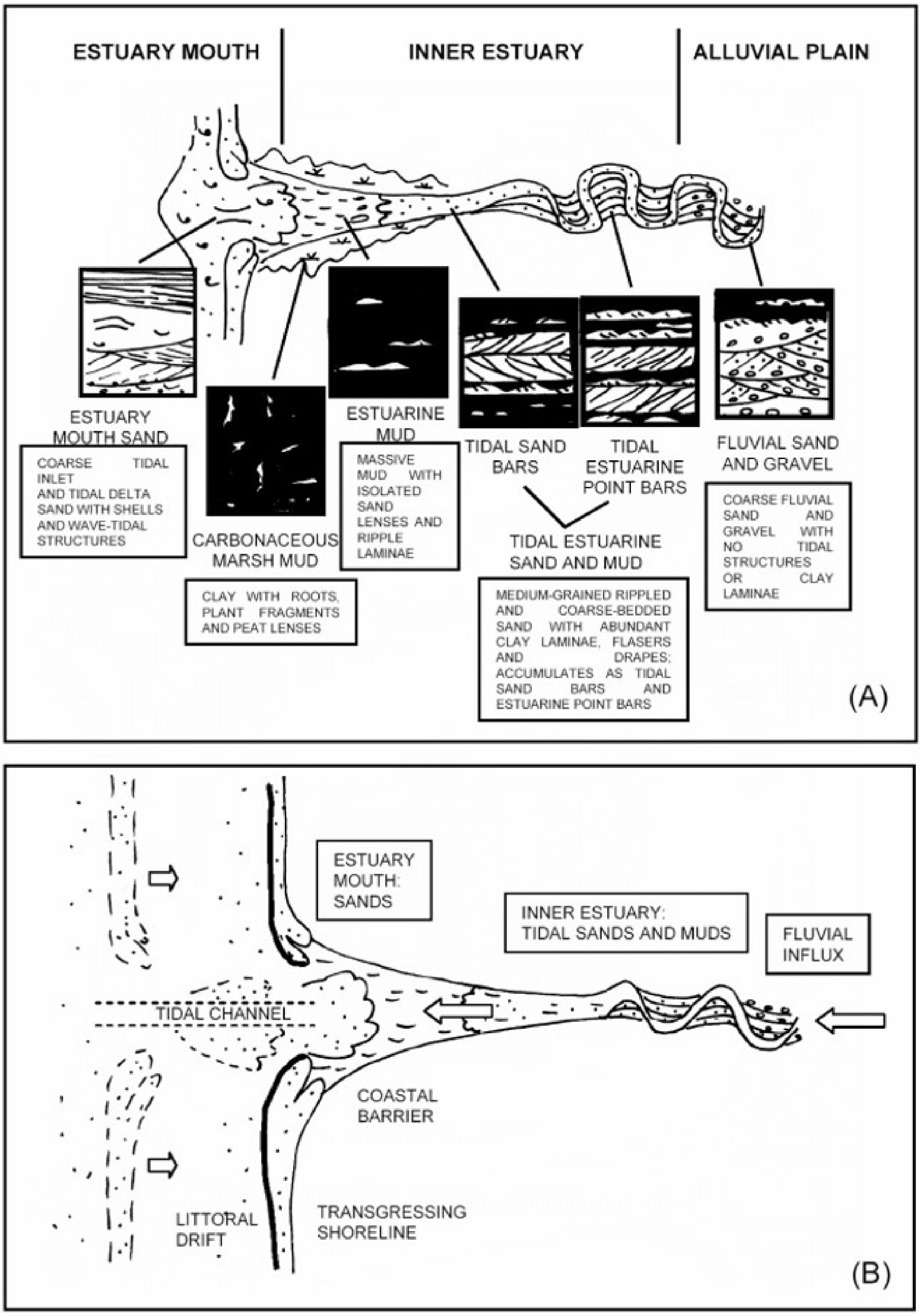

Figure 2. Morphological characteristics and facies patterns on the Gironde Estuary, showing different infilling stages in the basin (modified from Allen and Posamentier, 1994).

Pritchard (1967) clearly defined the oceanographer’s viewpoint when he defined an estuary as a semi-enclosed water body which has free connection with the open sea and within which sea water is measurably diluted by fresh water. The landward limit, according to the definition, is where the salinity falls below 0.1‰ (normal sea water has a salinity of 36‰). While this type of definition is highly valid in biological studies, this is not the case for studies of a geological nature, as it includes in some cases, and excludes others, areas which, due to their evolution, have formed as part of estuarine systems. Pritchard divided estuaries into three types, essentially based on the method of mixing of fresh and marine waters (Figure 3): A) Salt wedge estuary, B) Partially mixed estuary, and C) Vertically homogeneous estuary. There is a fourth type called a negative estuary, but this has not received as much attention as the others. Hayes (1975) classified estuaries into three main types based on their tidal range: macrotidal (>4 m tidal range), mesotidal (2 to 4 m) and microtidal (<2m). Dalrymple *et al.* (1992) consider that for an area to qualify for the term 'estuary' it must receive sediment from both fluvial and marine sources, as well as containing facies influenced by tides, waves and fluvial processes. According to this paper , the estuary, as in the case of rias, should be considered to extend from the limits of the coastal facies near its mouth and point of connection with the open sea, to the landward limit of tidal facies at its head. The latter is a point above the zone where sea and fresh water mix, and is merely an area where the sediments are affected by tides.

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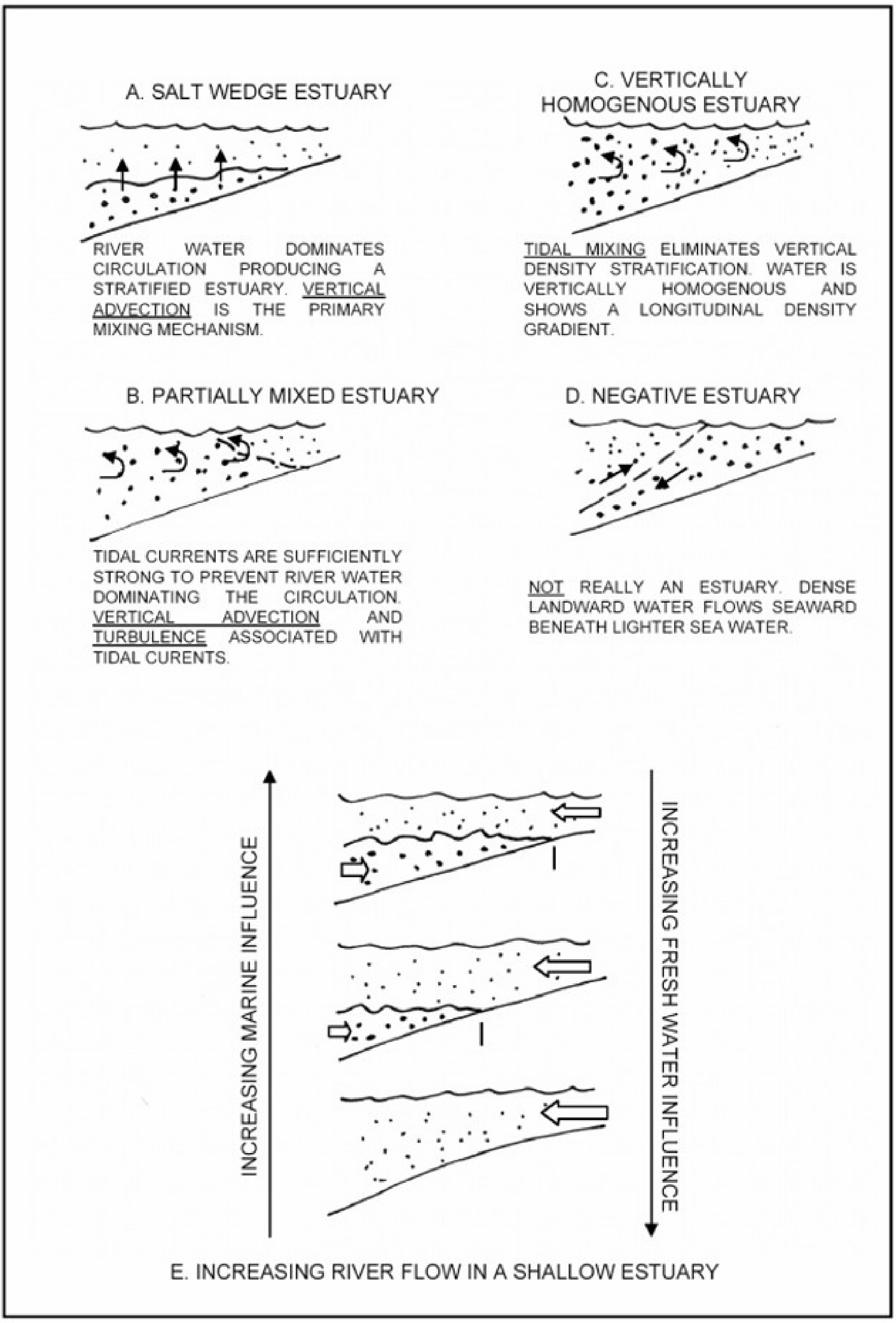


Figure 3. Classification of estuaries based on mixing of fresh and marine waters as proposed by Pritchard (1967), redrawn after Evans (1995).

Based on geomorphological criteria, and not on hydrodynamics and sedimentology, Perillo distinguished between Coastal Plain Estuaries and Rías. According to their coastal relief, the first type occupies low relief coasts mainly produced by sedimentary infilling of the river, whilst rías are former river valleys which have developed into high relief coasts. Most regional studies on rías show hydrodynamic processes similar to those identified in most estuaries. However, considering the sedimentary characteristics and sediment distribution of so-called Rías Baixas, located on the north west coast of Spain, (Vilas et al., 1995 to 1999), there are differences if we compare them to the facies model established for a mixed energy tide and wave-dominated estuary.

Following the distribution given by Olausson and Cato of major estuaries in the world related to tidal ranges and climatic zones, the majority of the estuaries developed in former river valleys, such as Coastal Plain estuaries (low relief coasts) and Rías (rocky shores in high relief coasts), are located in subtropical and temperate regions. Those developed in former glacial valleys are given other terms (Fjords and Fjards in Scandinavia, Firth in Scotland, Loch in Ireland), and correspond to cold climate areas. Those known as structural estuaries, however, cannot be related to any climatic or tidal range criteria, but rather to neotectonic processes such as faulting and vulcanism, from the Pleistocene to the present. Based on these considerations, diverse factors are in play (type of coast, lithology, wave-tide energy, river discharge), which control and determine the very nature of a given estuary or ría.

According to Castaing and Guilcher (in Perillo, 1995), the term "ría" should be restricted to the Iberian Peninsula and to some other areas with high relief coasts, such as those in Brittany (France), Devon and Cornwall (UK), Korea, and some parts of the Chinese and Argentine coasts. Summarizing the information given by these authors for the aforementioned regions, all are flooded valleys surrounded by hills, some of them with very shallow entrances filled by small grain size sediments where sand barriers, mud flats and saltmarshes are developed behind them (e.g. in the northern Spanish coast and Brittany). Some others present deeper mouths ranging from 30 to 50 m, progressively decreasing upstream to fall between 10 and 5 m (north-western Spain, Korea, south-east China, and southern Patagonia (Argentina).

2. General Processes

The processes involved in coastal entrances such as estuaries or rías, are of a highly complex nature; dynamic, chemical and biological factors are clearly related to sedimentation mechanisms. There are a large number of well-known papers on sedimentation mechanisms on estuaries, but few and scarcely known works exist on rías. In view of the extent of current knowledge, and in general terms, it can be understood that they have similar characteristics.

These mechanisms are determined by the dissipation of energy from fluvial flows, density gradients, tide, waves and meteorological forces. As energy is dissipated, sediments are transported, mixed, interchanged or accumulated and the bottom geometry is altered. Despite the complex action involved in these different processes, it is possible to identify the predominant ones and their relationship to the resulting sedimentary characteristics. The processes of erosion, transport, deposition and consolidation depend on the dynamics of the fluid and on the properties of the particles, their size, shape, density and composition. In cohesive sediments, the hydrodynamic forces act in a very different manner to how they behave in non-cohesive sediments, such as sand grains. Whereas in the former, particles measuring less than 25 µ increase their degree of cohesion with the organic content, such as particles from mucous secretions or biogenic pelletizations, the non-cohesive sediments depend on the weight of the particle on the bottom as its main stabilising force. Ample literature is available on the movement of non-cohesive sediments, and also there are recent books about movement of cohesive sediments in estuaries, such as the one published by Dyer in 1986. Small and large-scale processes are considered in the behaviours of sediments in suspension. The small-scale processes such as those of gravitational nature, operate on the individual particles and, following Stokes' Law: fall velocity of particles in a fluid will depend on the difference between the force of gravity acting on the particle and the flotation capacity in the liquid. Also, the suspension of particles is determined by the local hydraulic conditions and characteristics of particles, i.e. velocity of the current and particle size.

The large-scale processes are considered as properties of a local medium, and may be altered and exert an influence on the above-mentioned mechanisms: processes such as the differences in density between water masses and the velocities of the current. The differences in density between masses of fresh and salt water cause them to separate: the denser saline waters below the fresh waters. In the absence of strong current velocities, the mixture of two water masses would be limited to diffusion processes between both. Conversely, with the presence of strong currents, the mixing processes are more effective. Pritchards (1967) classified estuarine circulation systems in terms of the importance of these processes acting on the water masses (see Figure 3).

There is ample literature about all the different processes in an estuary that affect the build-up of sediments; the differences in density between the water masses modify the settling of particles in suspension. Conversely, Whitehouse in 1960 and Gibbs in 1983 state that saline water is also involved in the velocities of different clay minerals by physico-chemical flocculation processes. Other processes may be physical, i.e. those which explain how, in terms of the growth and decay of tidal currents, the particles in suspension begin to be deposited before the turn of the tide, as reported by Postma in 1967. For this reason, accumulations of fine sediments in an estuary are related to the variations in the maximum tidal reach and the degree of fluvial discharge. Laterally, these shift from sectors dominated by fluvial processes in one direction to others dominated by marine processes .

The limit of the fluvial sector is marked by the fresh/salt water transition. Dynamically, this is characterised by an input of fresh water, which supplies significant amounts of sediments to the estuary. These inputs maintain the longitudinal and transversal salinity gradients. The flushing capacity of fresh water in an estuary is quantifiable in terms of its outlet velocity. This parameter is obtained by dividing the annual average fluvial discharge by the transversal section of the area at the transition point of fresh and saline water. The outlet velocity demarks the landward limit of the intrusion of saline water and the transition segment of the sedimentary sub-environments and dispersion routes in the fluvial sector of the estuary. In exceptional cases, rivers may produce substantial discharges with important sedimentological consequences. The morphological changes within the estuary, however, are relatively small, except when the discharge reaches the estuary mouth and cuts the sand bars and spits which close it.

The morphology of this sector responds to that typical of fluvial waterways: meanders with "point bars" and sandy bars, influenced by tides, and "levées" which protect bogs and marshes . The surface distribution of sediments varies depending on the existing relationship between the morphology of the bottom, the type of sediments and the dynamic forces prevailing (see Figure 4). Basically, sediments comprise silt and clays with intercalated sandy bottoms and sandy bars dissected by secondary channels which laterally become muddy sands on intertidal flats. The action of tidal currents increases in importance downstream, although when a high flow occurs in the river, fluvial action may predominate; with retention of sediments, and the formation and migration of the different configurations of sandy bottoms is very closely linked to the decrease in tidal amplitude and the velocities of currents upstream in the estuary.

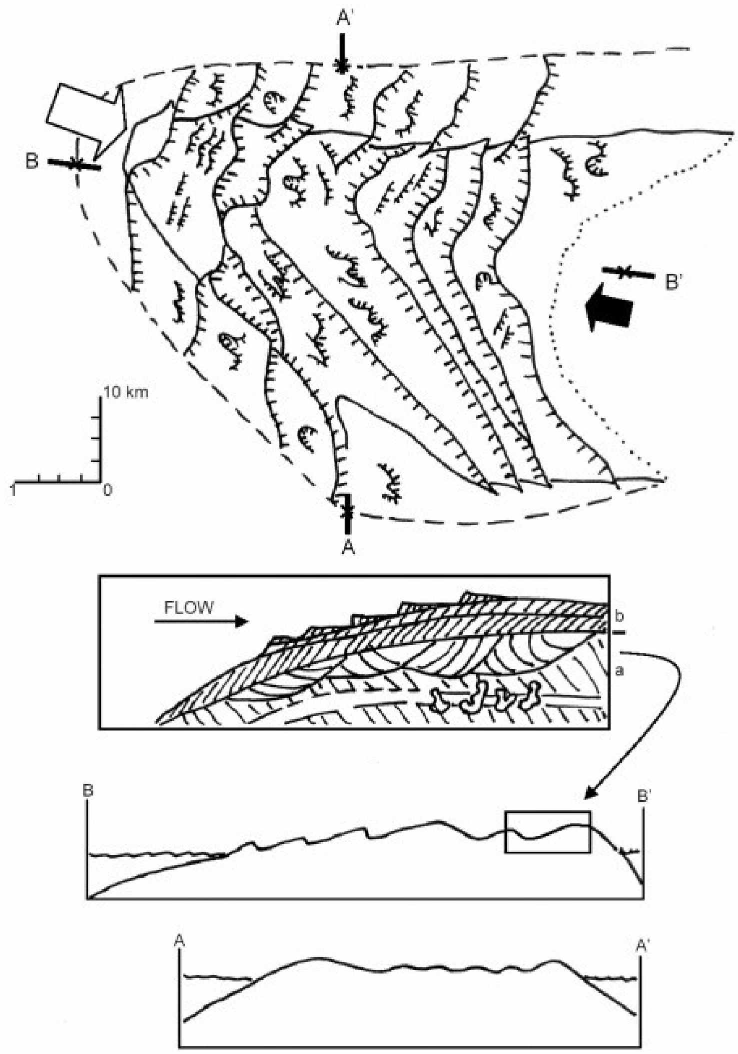


Figure 4. I) Diagram of a flood sand bar with development of ripples on surface. Longitudinal profile B-B´ and transversal A-A´. Solid and white (single) arrows indicate flood and ebb directions respectively.
II) Diagram drawn up from a lacquer peel, showing internal structures: a) lamination and cross stratification during flood, with traces of bioturbation originated during slack waters.
b) Reverse lamination produced by ebb conditions with ripples on top. Estuarine sand bar in the estuarine sector of the Ría of Vigo, estudied by Nombela and others in 1985.

When tides propagate in estuaries, they are altered and increase the transport of sediments landward and seaward. Soloman and Allen differentiate between three types of processes: 1) by friction on the bottom; 2) by convergence or constriction in the channel, and 3) reflection on sandbanks.

Generally, any effect of friction tends to reduce tidal amplitude upstream, reducing current velocity. Fine sediments are finally deposited upstream of the estuary. Nevertheless, although the effect of friction reduces tidal amplitude, a decrease in the section of the channel may give rise to a concentration of energy and therefore an increase in amplitude. In this case, if the opposite effect to friction is added, Le Floch (1961) differentiates between three types of models (see Figure 5):

A. If the convergence exceeds dissipation by friction, tidal amplitude increases upstream before reducing towards the river. It tends to characterise a hypersynchronic estuary.
B. If the convergence is equal to the friction, tidal amplitude is maintained throughout the estuary before reducing towards the river. It tends to characterise a synchronic estuary.
C. If the convergence is less than the friction, tidal amplitude is reduced upstream from the estuary mouth. It tends to characterise a hyposynchronic estuary.

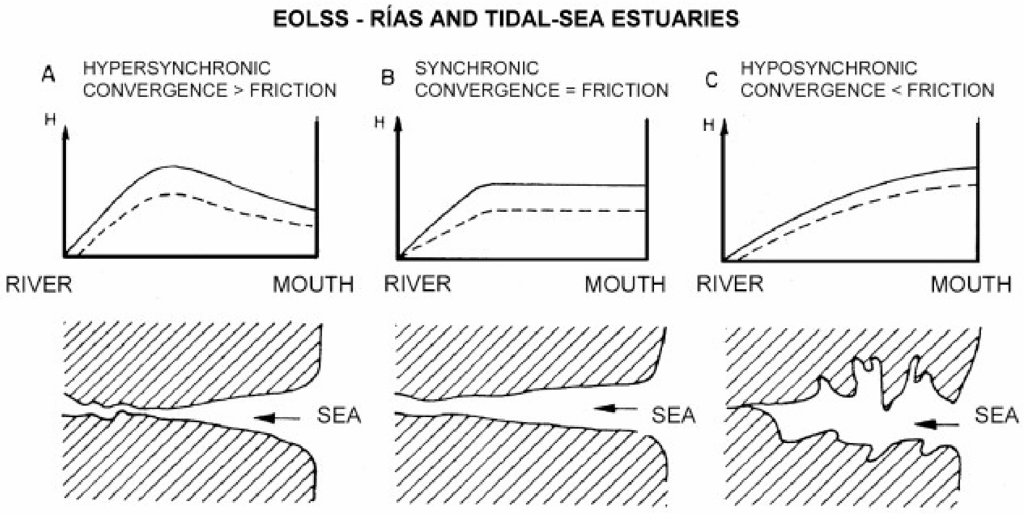


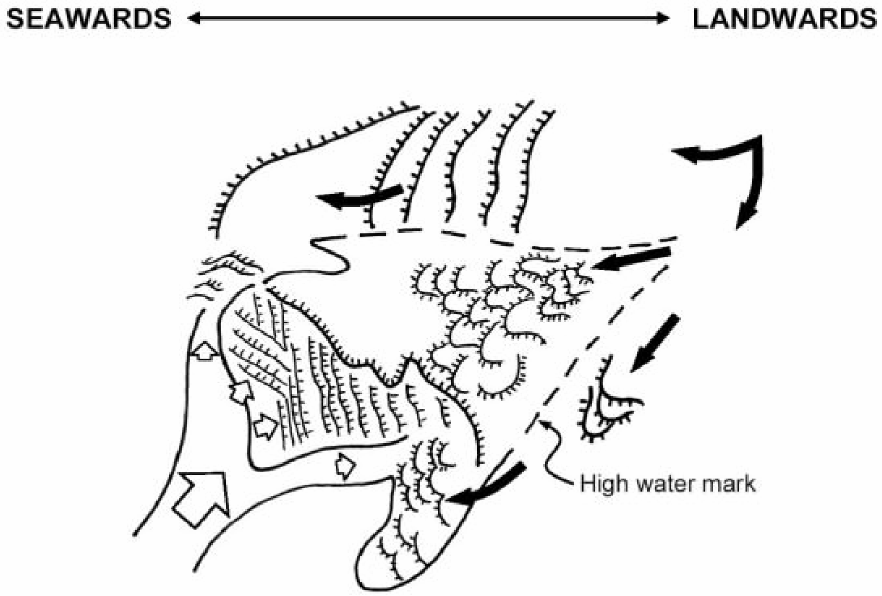
Figure 5. Models of tide propagation in estuaries (modified from Le Floch, 1961).

Most estuaries are hypersynchronic and tidal currents attain their maximum strength in the central or upper part of the estuary. Reflection of the tidal wave on sandbanks or banks of the estuary may equally increase amplitude.

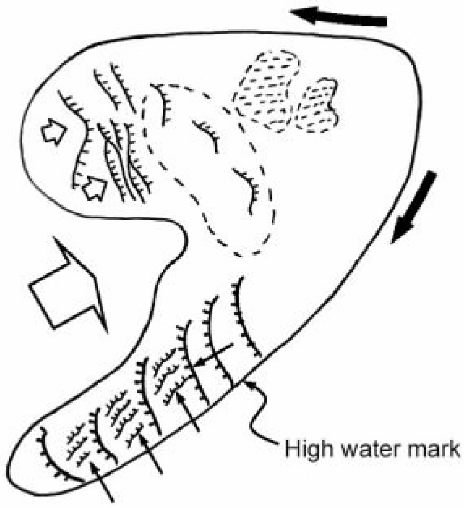
Fluctuations in tidal currents and their cyclical nature generate residual currents which, although they may be relatively small in a tidal cycle, following many tidal cycles may produce a significant residual shift with important consequences in the transport of sediments in suspension. Generally, concentrations of sediments in suspension are less when the tide halts after high tide than after low tide. This is due, as states by Postma in 1980, to the longer sedimentation time, which fosters a landward shift in sediment giving rise to accumulation of fine sediments. Several authors such as Van Straaten and Kuenen in 1958 and Postma in 1967 explain this transport phenomenon in intertidal flats, in terms of the time taken by a particle to reach the bed after a decrease in tidal velocity.

Finally, at the marine entrance to estuaries and rías, wave action is dominant, causing both depositional and erosive effects. As oceanic waves invade shallow water areas, friction at the bottom occurs and sand transport commences. The morphology of estuary inlets exerts an important influence on the transport routes of sandy sediments; in areas with sandy bottoms, waves are dissipated, whereas in deep channels they may continue advancing. This gives rise to a distribution of textures which may serve as a reliable indicator of variations in energy.

Morphologically, this sector is characterised by large deposits of sandy bodies modelled by tidal currents and the wave system (Figure 6). In tidal-sea estuaries, and depending on tidal range, these deposits are generated in areas adjacent to tidal entrances in the shape of flood and ebb tidal deltas, depending on their occupying an internal or external position in terms of the tidal entrance. Further inside the entrance, meandrous channels predominate where intertidal sandy bodies appear.



A. SPRING TIDE SITUATION



B. NEAP TIDE SITUATION

Figure 6. Different morphology presented by a sand bar in spring (A) and neap (B) situations in the Miño Estuary, at the NW coast of Spain, by Vilas and Somoza, 1983. The influence of tidal currents modify the shape of the sedimentary body and generate a variety of superimposed sedimentary structures. White and solid arrows represent flood and ebb directions respectively.

3. Morphology and Sedimentology

In aerial view, rías and estuaries are characterised by a funnel-shaped geometry and deep entrances, with a considerable reduction on both dimensions upstream. From a physiographical viewpoint, both types are classified within the group defined by Pritchard in 1967 as drowned river valleys as they were formed by the flooding of Pleistocene-Holocene river valleys during the last transgression. The V-shaped geometry of these valleys is very-well defined on those formed on rocky or hilly coasts such as the rías (Figure 7), if compared with those developed in coastal plain areas.

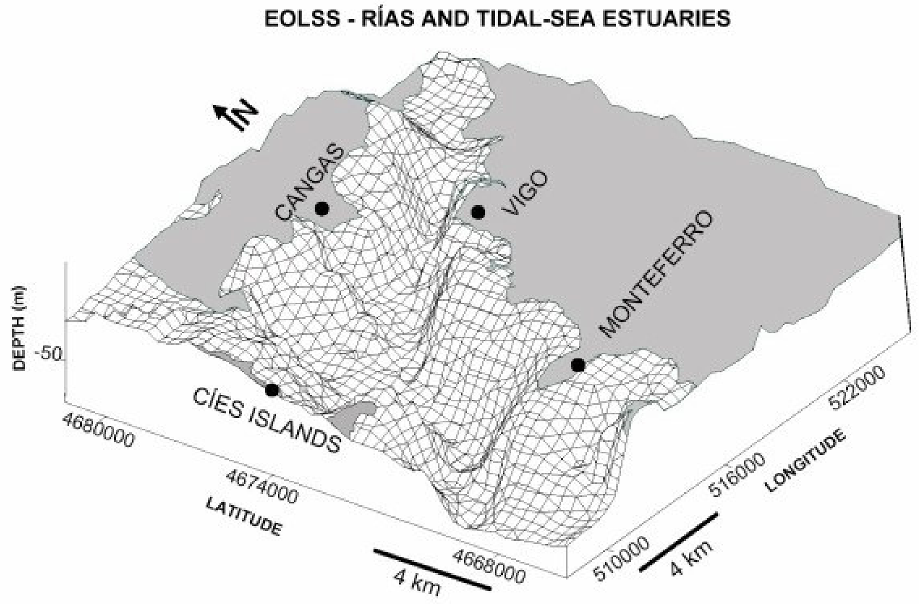


Figure 7. 3-D reconstruction of the Ría of Vigo valley, showing the V-shaped geometry.

Tidal currents determine an appreciable upstream transport particularly in macrotidal shores, where littoral processes appear as dominant in the local environment as occurs in certain estuaries very well described by different authors around the world, such as the Gironde Estuary in France, the Severn Estuary in UK, Cobequid Bay in Canada, and the Fly Estuary in New Guinea. In all of them, even in estuaries where tide dominance is low or moderate (micro or mesotidal), the transport of sediments may occur, particularly in the absence of an active wave system interfering in the hydrodynamic system. These circumstances, apart from the influence of fluvial discharge, determine the distribution of the main morphological components which characterise this type of environment. In any case, sediments are received from both the river and the shelf (Figure 8), but those deriving from the river are halted and deposited by the tidal currents, particularly in the case of strong tidal currents, destroying vertical stratification and producing bidirectional currents, and depositing sediments as elongated sand bodies (Dalrymple *et al*., 1992). Conversely, in wave-dominated estuaries, sediments tend to be distributed in the three typical facies which characterise a wave-dominated or microtidal estuary: sand barrier-inlet at the marine zone, muddy central basin in the estuarine zone, and bay-head delta in the fluvial-tidal zone (Figure 9). However, between the two extreme cases, there are coastal embayments with low river discharge, moderate tidal currents, and very small wave influence in the central basin, due to the protection of the surrounding hills, as is the case of certain rías. Distribution of major morphological components and sedimentary facies presented in such cases, is rather different from those described previously (see Fig. 11 in comparison with Fig. 15).

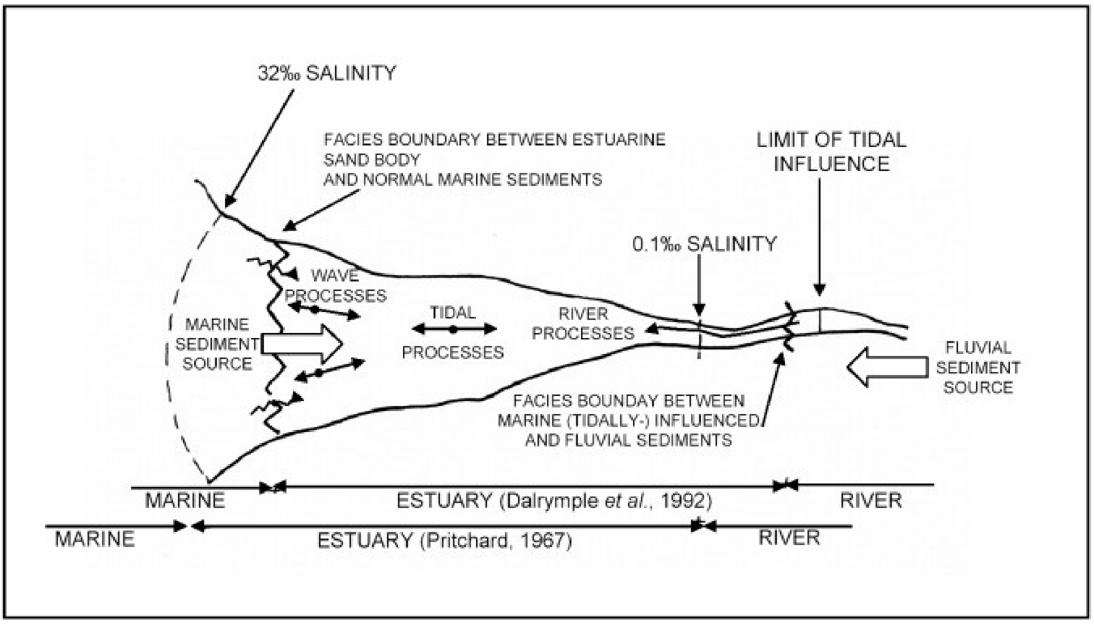


Figure 8. Main processes and domains of an estuary (Modified from Dalrymple et al., 1992). The estuarine extension differs in the sense of Pritchard (1967) or in the sense of Dalrymple an others (1992).

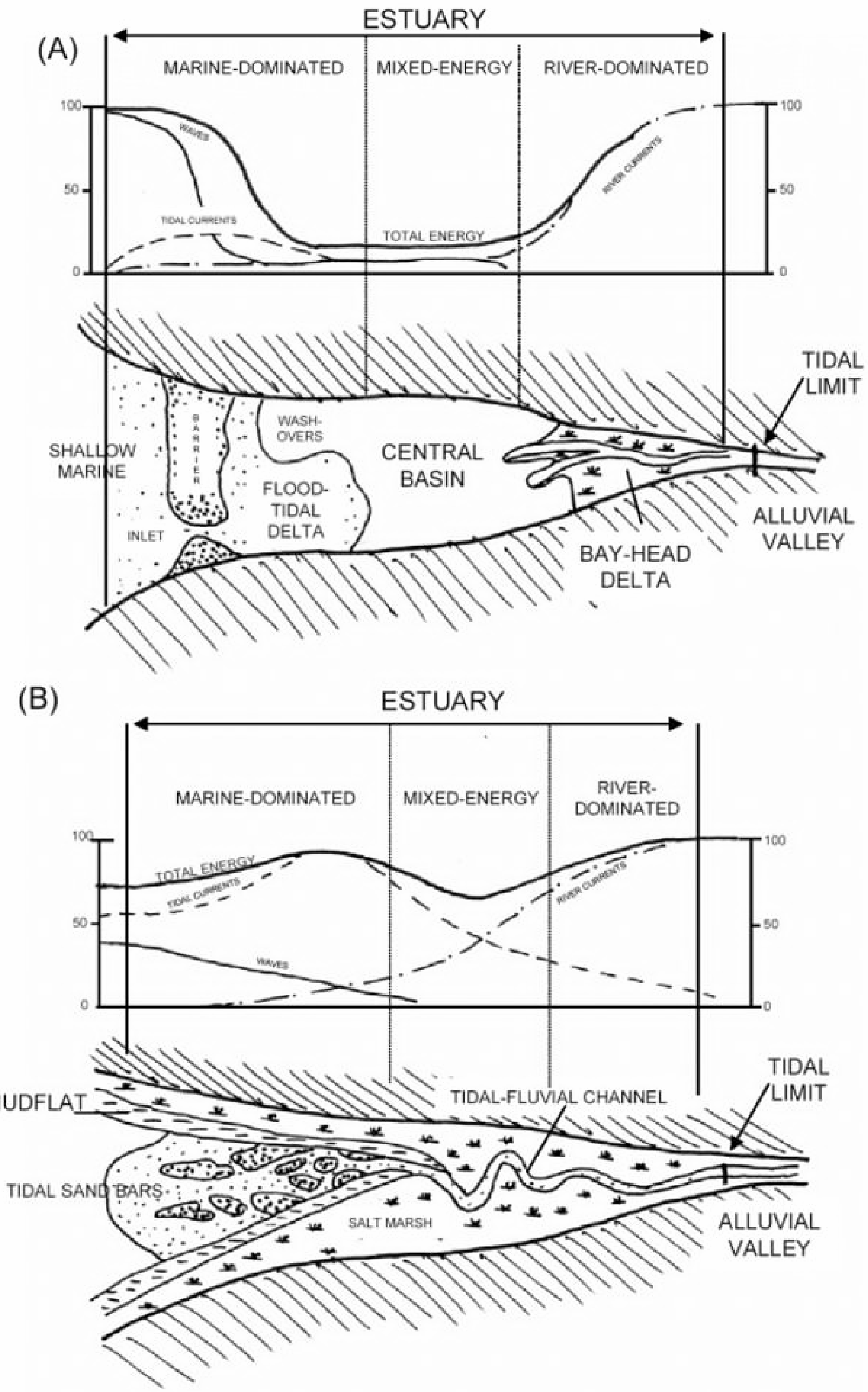


Figure 9. Dynamic processes and major morphological components along the estuary. A) Wave-dominated estuaries, B) Tide-dominated estuaries. (Modified from Dalrymple et al., 1992).

3.1. The Ría **environment**

The environment of rías, such as those on the NW coast of Spain (Figure 10), is characterized by seasonal upwelling and sharply contrasting boundary conditions at their seaward and landward margins (upwelling and estuarine, respectively) meaning that they incorporate processes normally associated to both continental margin and coastal boundary zones. Two very clearly differentiated zones are noted (Fig. 11 & Table 1) considering salinity values, tidal currents recorded in the area and sediment distribution (Vilas *et al.,* 1995-99). The main sector, occupying about 80% of the total surface, has a marine control and depth decreases from 40 m at its mouth to 15 m inlands. The second zone belongs to the most internal area and has a typical estuarine control. It is a very shallow area, of less than 5 m depth which rapidly shoals landwards.

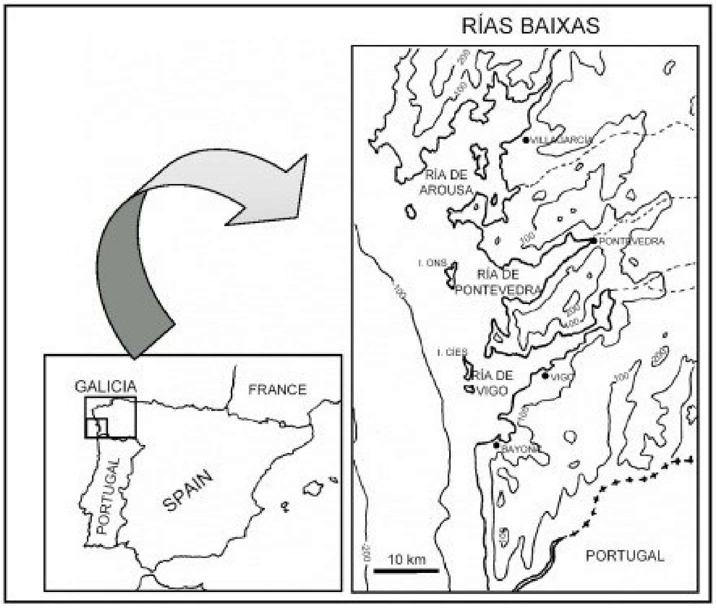


Figure 10. Location of the Rías Baixas, showing three of them : Vigo, Pontevedra, and Arousa rías. Galicia (N.W. Spain).

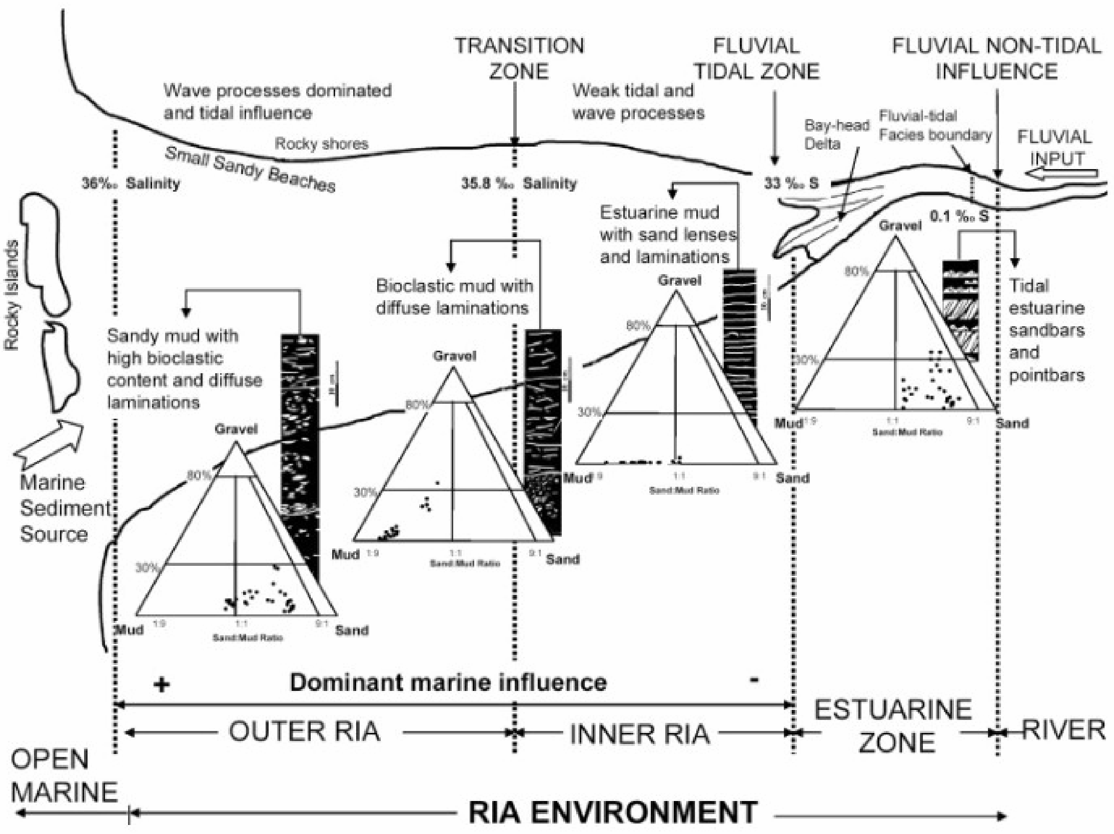
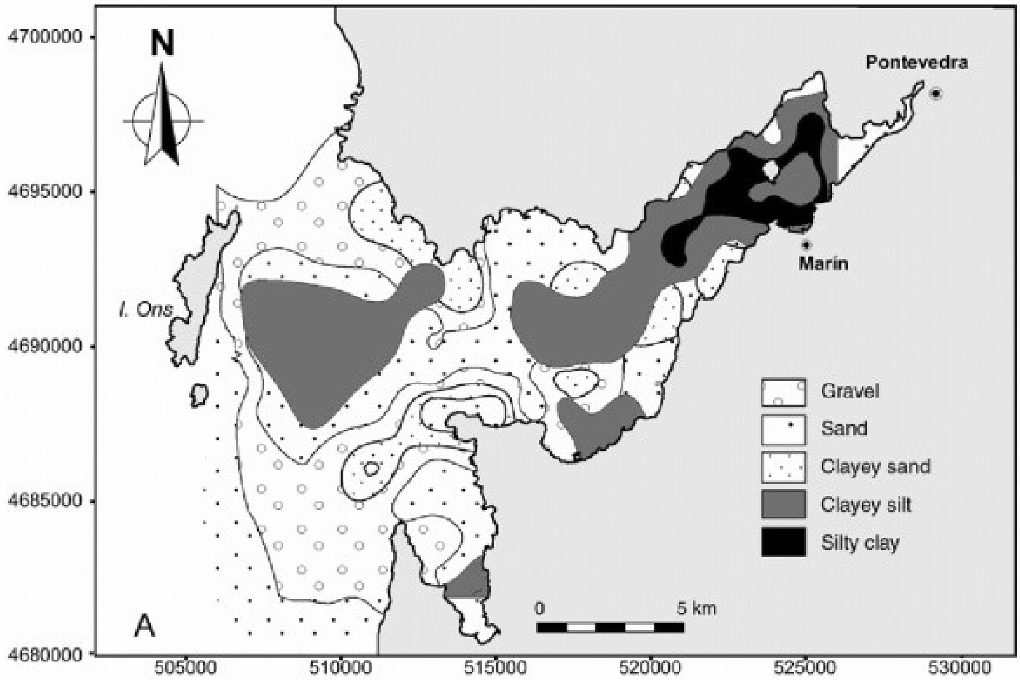


Figure 11. Diagram showing the distribution of main domains, processes and sedimentary facies along a ría environment included in this paper. Two sectors with different morphological components and sedimentary facies are distinguished: Outer and Inner Ría, and the estuarine zone.

Table 1: Synthesis of the main characteristics and domains of ría environments, in terms of morphology, sedimentary facies and dynamics.

			CONTROL	**MORPHOLOGY**	**SEDIMENTARY FACIES**	**DYNAMICS**
RIA ENVIRONMENT	**ESTUARY DOMAIN**		Fluvial	Meandering channel, sandy levees, muddy sand flats and crevasse-splay deposits, roots, plant fragments	Coarse fluvial sand and gravel with no tidal structures and silty-clay lenses	Unidirectional water movement. Fluvial sediment source
			Tidal	Tidal estuarine sand bars and point bars, intertidal mud flats and salt marshes. Estuarine muds with isolated sand bodies	Channels with medium-grained ripples and cross-bedded sand. Masive muds with sand lenses and clay laminae	Intermitent dominance of fluvial-tidal influence and changing water velocities. Sand movement in the fluvial-tidal zone. Bidirectional water and sand movement in the estuarine zone
	MARINE DOMAIN	**INNER RIA**	Tidal influence	Low regime flat beds at the bottom. Small salt marshes and intertidal sandy-mud-flats, and sandy beaches to the flanks	Dominance of muds and fine sands. Low content in carbonates and high content in organic matter	Tide influence and weak waves. Bidirectional water movement. Local fluvial inputs. Low tidal velocities for sand movements
		OUTER RIA	Wave dominated and tidal influence	Low regime flat beds and low relief sand bars at the bottom. Sandy beaches and small beach-barriers at the banks	Bottom: mixed siliciclastic and skeletal gravels with sandy or muddy component. Shoreline: coarser sands grading into clean skeletal carbonates sands. Low content in organic matter	Bidirectional water movement. Wave dominated and tidal influence. Upwelling influence and local fluvial inputs

A brief synthesis of the recent sediments and sedimentary distribution covering the floor of the rías (Vilas et al.,1995-99), shows that the main sector entails a heterogeneous distribution of both terrigenous and biogenic deposits with a major axial deposit of cohesive sediments relatively rich in organic matter (Figure 12). The outer part is covered with mixed siliciclastic and skeletal gravels (with a sandy or muddy component) which, along of the main axis pass landward into fine sands, clayely silts and mud-grade sediment (with admixtures of skeletal gravel and sand), as stated Nombela and others in several works on ría sedimentation. Towards the shoreline the sediments become coarser, grading to various intermediate sediment types: clean carbonate skeletal sands or mixed siliciclastics sands. The organic matter content, particularly in the inner and axial parts, reaches values up to 9% associated to fine grained sediments. Calcium carbonate content, and contrary to organic matter, is highest in the outer parts of the ría, and can receive more than 94%.



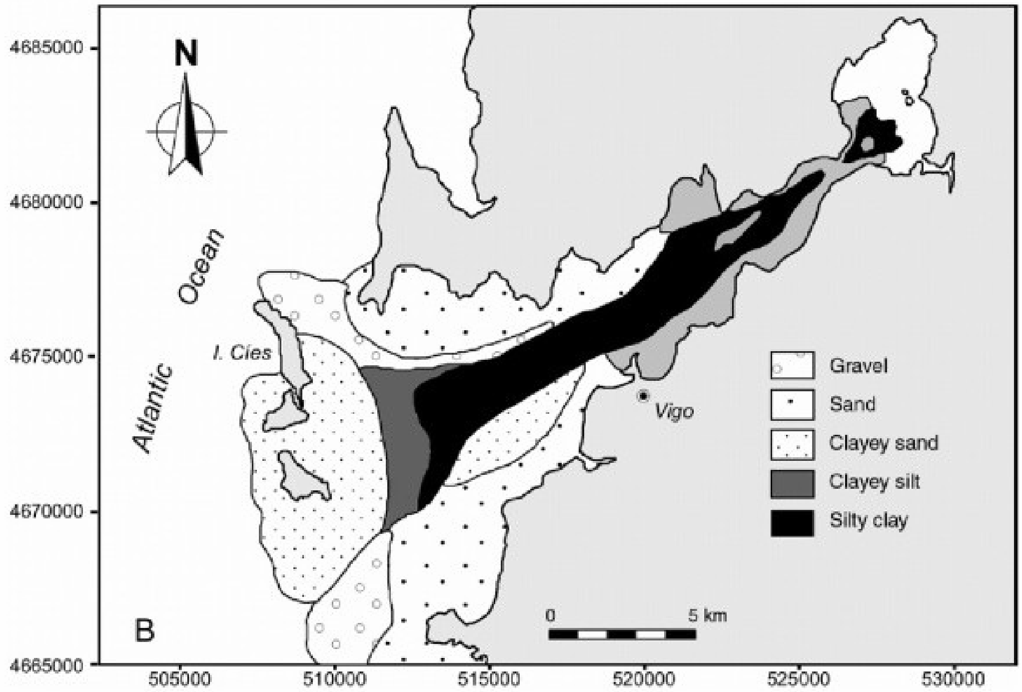


Figure 12. Distribution of bottom sediments in A) the Ría of Pontevedra and B) the Ría of Vigo. (Modified from Vilas et al., 1995, 1996). They incorporate processes associated to seasonal upwelling affecting to the Outer and Inner Ría, and estuarine at the landward margin.

Core sediment samples from the estuarine, inner and outer areas of the rías (Figure 13) reflect the presence of two main grain size populations. One population is dominated by silt and clay, derived mainly from terrestrial sources, and the other by fine sand to coarse silt which is derived mainly from the continental shelf or the ría mouth. In a very recent publication by Rubio and others, mineralogical analysis shows the presence of several diagenetic minerals (Figure 14); iron sulphides in the inner ría and iron silicates and oxyhydroxides in the outer part.

EOLSS - RÍAS AND TIDAL-SEA ESTUARIES

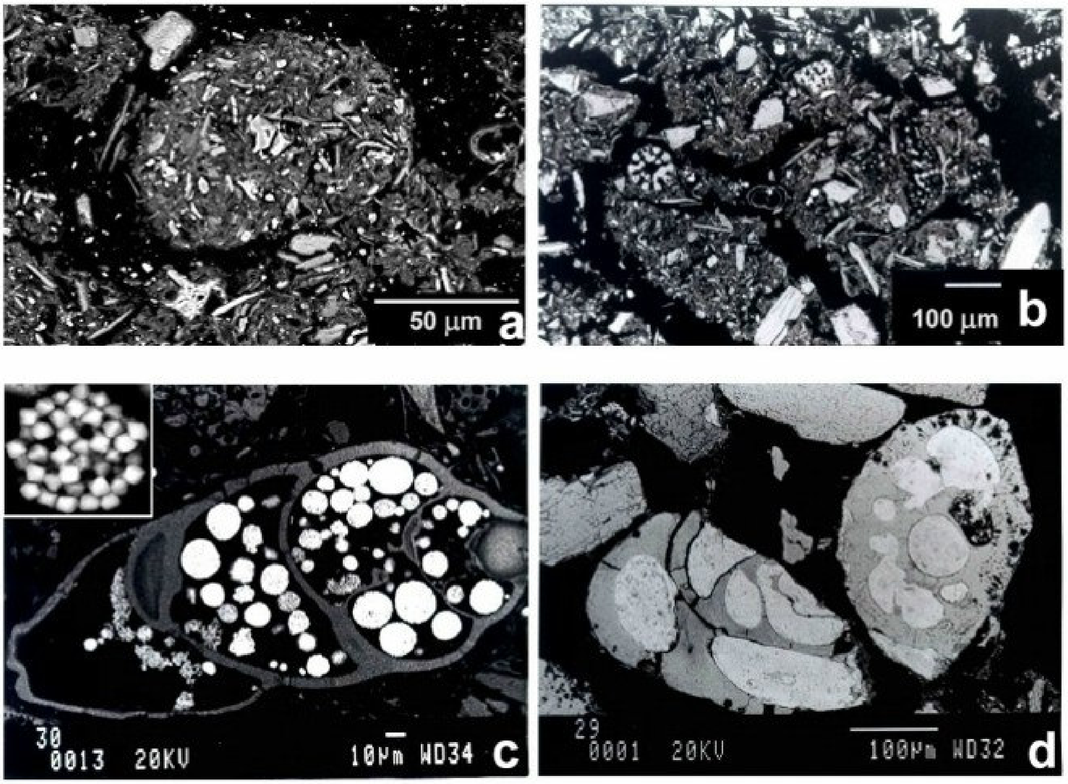


Figure 14. Backscatter scanning electron microscopy (BSE) images, of core sediment samples studied by Rubio and others (2001) in the Ría the Pontevedra. a) Fecal pellet with sulphides (bright dots), produced by biological activity in the Inner Ría sector. b) Fragmented fecal pellet in the transition Inner to Outer Ría sector. Note the presence of more abundant bioclasts than in image (a). c) Framboidal pyrite in a foraminifera chambers from the Outer Ría sector. Amplified detail in the upper margin. d) Iron-rich aluminosilicate replacement (light grey) in rounded carbonate clasts (dark grey) in the Outer Ría sector.

Main dynamic processes at the outer part have a SW wave component during winter, producing both resuspension of fine sediments and littoral sand transport to the north into the inner basins where beaches accumulate at the foot of cliffs. No barrier-spits exist which fully or partially close the mouth. In the seaward parts of the region, broad beaches backed by dunes infill the bays extended between low cliffs. Occasionally, small estuaries are sometimes found, with sandy spits enclosing backbarrier marshes. In contrast, in the inner parts, beaches become narrower and cliffs are more common. In some cases, however, submerged sandy bars appear occupying outer and inner sectors which are mainly locally incorporated from sediments derived from the terrestrial sources and not due to transport by currents. The average current velocities in the rías, range from 33 cm/s in the mouth to 18 cm/s at the headlands, and they are considered very low to transport sand fraction inlands. The circulation pattern indicates that tidal currents incorporate sand along the southern coast from colluvium deposits and small fan deltas. The sand waves reflect this transport direction. Reversal currents are weaker and circulate seawards by the north side of the rías. However, currents are strong enough to allow a tide induced turbidity maximum similar to those described by Allen, which produce layers of laminated and frequently very bioturbated muds, which is one of the most representative sedimentary structure in this sector.

At the head of the rías, terrigenous sediments are supplied by rivers. These rivers are relatively small with low input of freshwater and do not carry large loads of suspended sediment. This sector, where the river enter the area to form a tide-dominated estuary, is usually fringed by a narrow muddy and sandy intertidal area at the landward extremity. The intertidal zone is dominated by an estuarine channel bordered by sandy levées, muddy sand flats and crevasse-splay deposits colonized by *Zostera nana* and scattered *Salicornia* sp. which pass seawards into sand flats often fashioned by the flood tide into a series of landward facing meter-scale sand bars. Both, estuarine channel systems and sand flats pass seawards into subtidal mud sediments.

Measurement of low-field magnetic susceptibility within the sediments have been recently used by Rey and others (2000) as a proxy parameter to asses the marine influence and diagenetic evolution of this type of environment, in an attempt to find a comprehensive but simple descriptor of their compositional and textural diversity. Surficial seabed sediments of the Rías Baixas of Galicia, particularly in Vigo and Pontevedra rías, showed a significant increase in susceptibility towards the open sea and away from continental influenced areas that correlate well with the textural characteristics of the sediments. This is ultimately controlled by the interaction of wave energy and subsequent organic matter evolution. In this sense, the diagentic evolution during the early stages of burial is controlled by the upwelling induced abundance of organic matter accumulating in low energy areas that controls the redox potential in the sediment column. Bacteria mediated decomposition of organic-rich sediments generates significant amounts of gas that gradually accumulates in the sediment during burial, until they are episodically released into the water column (generally in a catastrophic manner). Pock-marks, acoustic plumes and other evidence of gas escapes described in recent publications by García-Gil and others, Vilas and others, García-García and others, are a common present day features of the rías seabed.

3.2. Tidal-sea estuary

Bottom morphology in tide–dominated estuaries comprises a wide variety of bedforms at different scales, ranging from centimetres to kilometres as explained by numerous authors (Figure 15). Linear sand banks, also termed as subtidal sand bars or sand ridges, are distributed within the estuarine zone, clearly reflecting the transport route for sediments. Sand ridges during strong tidal currents are oriented parallel to the main axis of the flow. Bedforms can reverse their direction of migration under alternating ebb and flood currents. The intensity of these reversals depends on several factors such as bedform scale, subordinate currents, lithology and sediment texture. The inner part of the estuary consists of a pattern of sinuous channels with an intense meandering in the zone near the landward limit of tidal influence (Dalrymple *et al.*, 1992). In cross section, a macrotidal estuary shows tidal flats and associated wetlands usually flanking a wide strip bordering the estuary, as opposed to the situation dominated by low tidal range. In the middle of the basin, sand banks that can be exposed above mean sea level and colonised by vegetation may form linear islands.

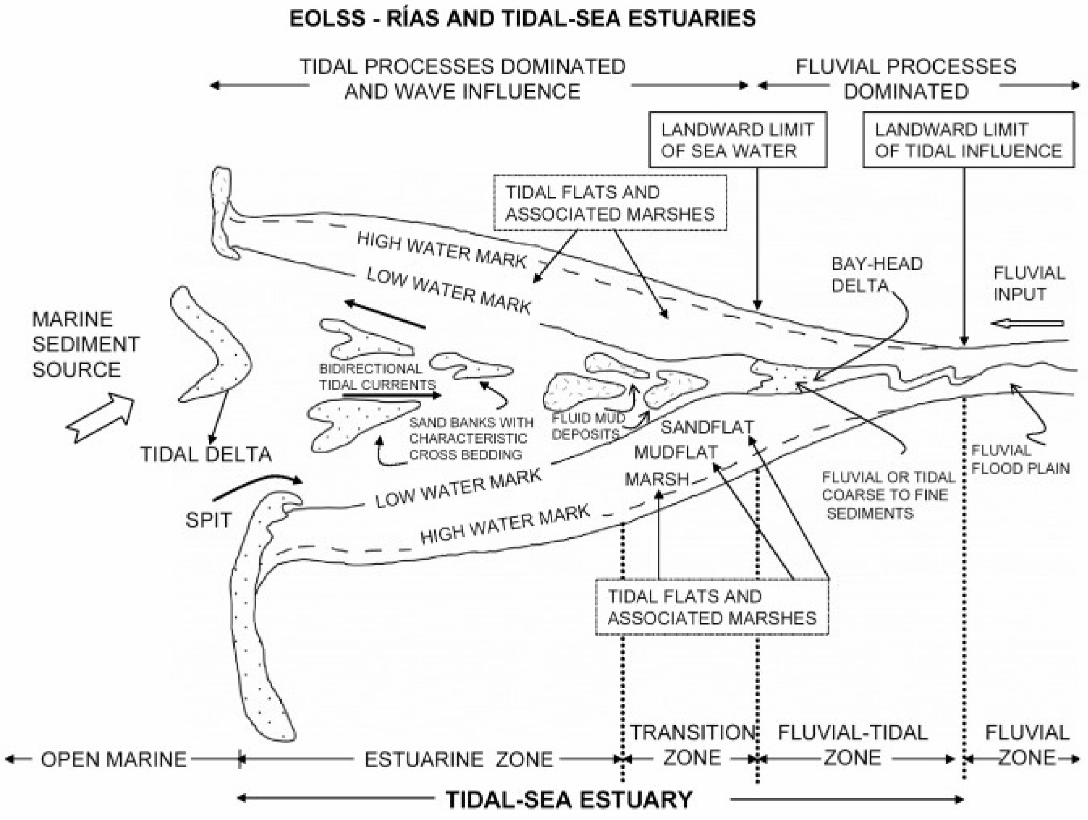


Figure 15. Diagram based on Terwindt and others (1963) showing main domains, processes and morphological features of a typical tidal-sea estuary.

The deposits in these estuaries present a wide variety of structures. Cross bedding channel sands, ripple lamination, reactivation surfaces, herringbone, flaser, wavy, and lenticular bedding, as defined by different authors often entail criteria to diagnose not only the type of medium in the fossil record, but also the dynamics of sedimentary transport.

The dominant-channel facies are formed by medium sands, and are thicker towards the mouth and also to the estuary head. Variations of the force of the current in the channels and their lateral shifting, give coarsening upward sequences over the sand bar crests. Extensive sand flats are formed landward of tidal sand bars in the region with enhanced tidal flow. An important characteristic which differentiates strong-dominant from those considered as low-dominant estuaries (Figure 16) is the absence, at least partially, of muddy lagoonal facies. Muds are present in estuaries, and according to their characteristics, Parker in 1983 and Allen in 1990 explain that can form settled mud deposits of their own in the mud beds of tidal flats, and stationary and mobile mud suspensions, which constitute semi-permanent or permanent moving fluid muds along the spring-neap tidal cycle as it has been described by Allen in 1977 or by Kirby and Parker in 1983. Mud deposits which eventually resist resuspension and remain deposited on the bottom throughout the entire tide cycle, may become a part of the sedimentary record. Tidal current reversals and neap-spring variations originate sedimentary cross-bedding structures defined by Boersma in 1969 as tidal bundles, where mud drapes identify slack-water periods and subordinate currents over neap-spring cycles.

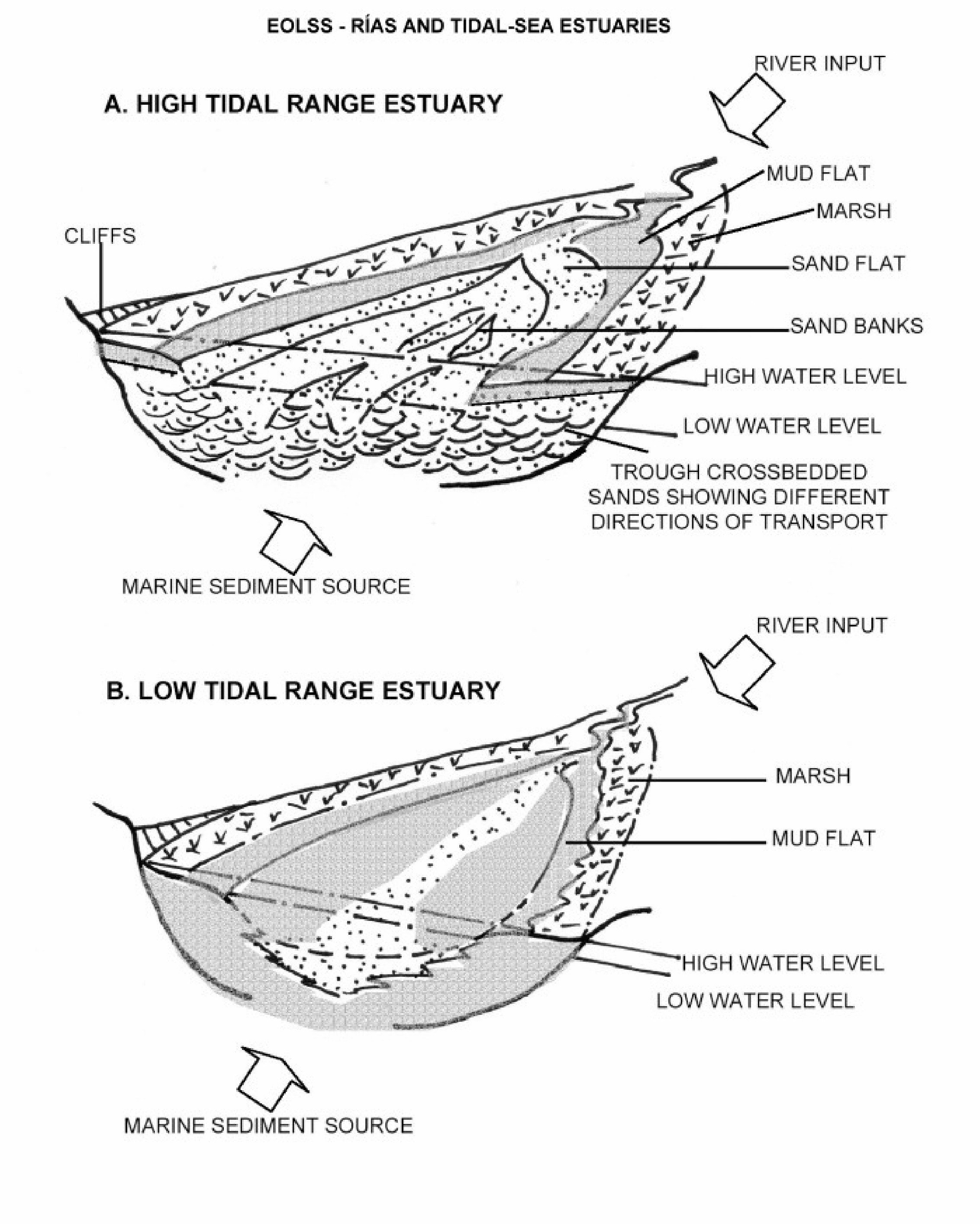


Figure 16. Block-diagram redrawn after Evans (1995) showing the internal structure of an estuary in two different situations: A) High tidal range and B) Low tidal range.

Many of these major characteristics described for tide dominant-estuaries are absent in the sector with dominant marine influence of a ría, but the same bedforms patterns and equivalent sedimentary features can appears in the estuarine controlled area.

4. Sedimentary Infilling

As a result of the geological evolution of an area at the interphase between land and sea, as estuaries or rías, erosion during low sea level and deposition during high sea level can alternate over time. Due to this, numerous parameters are involved in stablishing a single type of infilling model. Nevertheless, for each of the classical types of estuaries described in the published literature, there may be characteristics as common as the infilling processes.

During falling sea level, fluvial degradation erodes channels into the substrate conveyance water and sediment onto the new coastline. During the subsequent sea-level rise, the surface sediment on the fluvial plain is reworked by waves and tides, and according to the works by Walker in 1992, up to 5-15 m (typical depth of the wave base) may be removed by marine erosion during sea-level rise. As the sea transgresses over the shelf and coastal plain, topographic lows are backfilled by sediments deposited in different coastal environments. Environments of deposition range from shore-parallel, wave-dominated barrier island and lagoonal complexes to shore-normal environments such as river valleys. Coastal deposits include intertidal peat, abundance of mud, a faunal record reflecting less-than-normal salinity and numerous sedimentary structures reflecting both landward and seaward paleocurrent indicators.

Throughout the coasts, all the possible states of evolution of estuaries and rías may be noted. According to Roy (1984), sandy banks located on an open coast may affect the tidal flow at the mouth of estuaries, so that the following distinctions are made: rías with deep and wide entrances, with a complete tidal interchange; estuaries with inlets comprising channels where tides are attenuated, and finally, mature estuaries with fully or partially closed entrances, which may be classified as coastal lagoons. These types arise from two primary controls which act in a hierarchical manner: coastal topography and fluvial-tidal energy. The former controls the sedimentation of marine sands in submerged coastal valleys; rías with deep, open entrances where sedimentation forms submerged tidal deltas prior to the stabilisation of the marine level, in response to a decrease in wave energy within the protected part. The later controls the sedimentation in shallow depth estuaries where sediments form sand bars or emerged sand barriers in the inner reaches, depending on tidal energy and fluvial discharge (Figure 17).

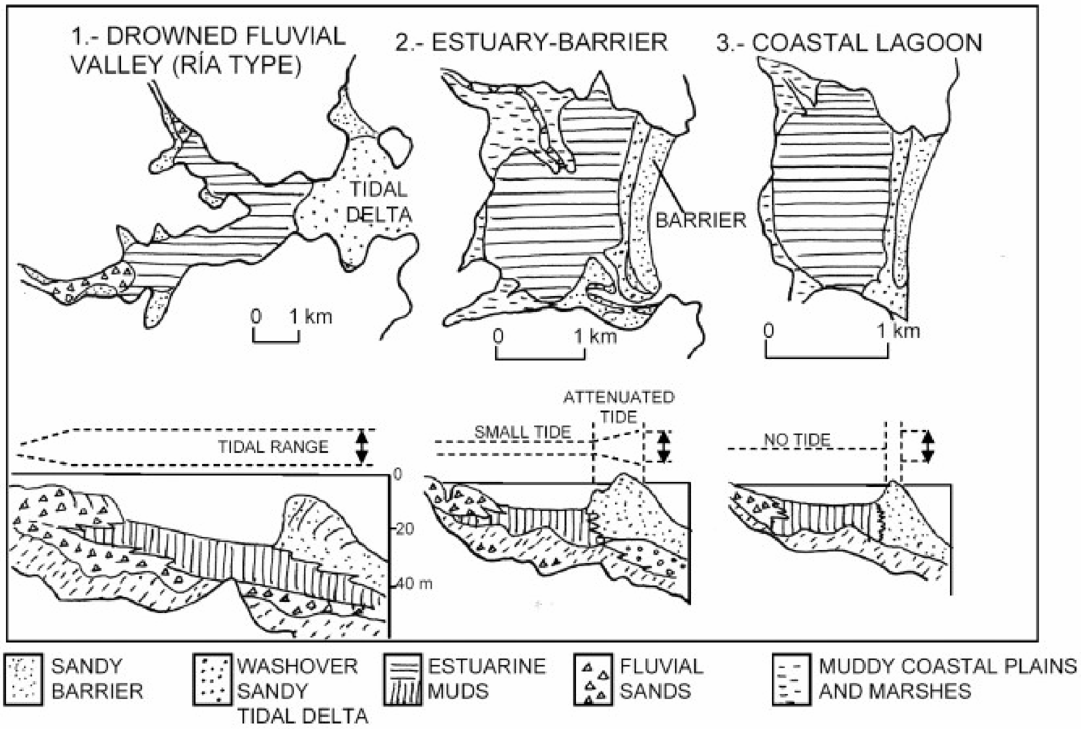


Figure 17. Three types of estuaries depending on the tide entrance conditions. (Modified from Roy, 1984).

Although the majority of tidal-sea estuaries have attributes in common with infilling processes, the examples described for Holocene tidal sea dominated estuaries, such as the cases of the Bristol Channel (U.K.), the Gironde Estuary (France), the Cobequid Bay-Salmon River Estuary (Canada), present differing infilling phenomena, due to their own variations in aspects such as the type of sediment, degree of subsidence, local variations in sea level history and intensity of transport processes. In the case of the Gironde Estuary, one of the most thoroughly studied examples, sedimentary facies showing a transgressive axial-vertical sequence (Figure 18), makes it possible to note the tidal sea influence: estuary-fluvial facies at the base, changing to a marine-estuary at the top.

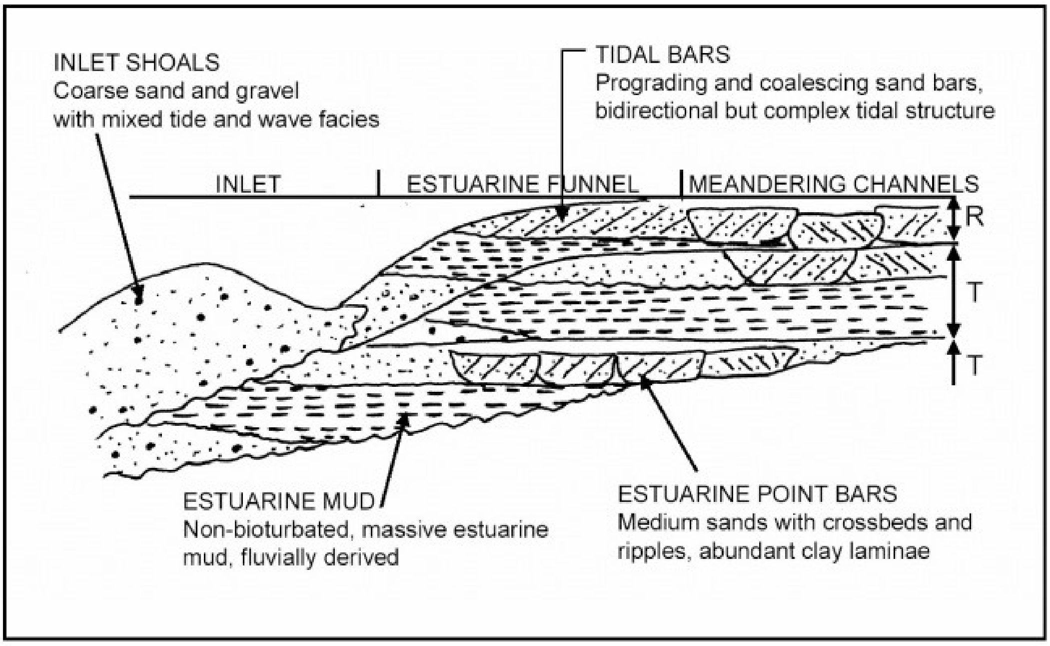


Figure 18. Stratigraphic section of the Gironde Estuary (France) showing the sedimentary facies in a trangressive (T) and regressive (R) axial-vertical sequence. (Modified from Allen, 1991).

In the fossil record, few examples of facies associations are found. In one of the cases described from the Pleistocene of Holland by De Raaf and Boersma in 1971, the intermittent migration of bedforms has been interpreted as a response to tidal fluctuations, presenting "flaser" and "lenticular" structures as bimodal palaeocurrents. The formation of the Fall River in the Lower Cretacean in Wyoming (USA) and some parts of the Lower Tertiary in the Bagshot layers in south eastern England have also been interpreted as estuary sequences.

5. The Rías Baixas **infilling: a case study**

The area of the Rías Baixas is located at the Northwest Atlantic Coast of Spain, and is part of a passive continental margin that tipically have a low rate of subsidence, low sediment supply, mixed wave and tidal energy, and moderate to high (300 m) topographic relief. Sedimentary infilling in rías still remains largely unknown, so that no clearly defined model exists. Nevertheless, mainly based on a synthesis of high-resolution seismic data, and sedimentological an paleoceanographical information given by sedimentary cores from several sites of the rías, it is possible to give an overall view of their evolution.

Developed since the last glacial episode (Würm, approximately 18,000 years BP), the continental shelf which had remained emerged, suffered rapid flooding, and the coastline, which was located near the area of the current slope, shifted towards areas inside the rías which started to become flooded (Figure 19). This increase in the sea level was interrupted at approximately 11,000 years B.P. with the cold event known as Younger Dryas. In the last 6,000 years the marine level has only undergone relatively small variations due fundamentally to tectonic processes (sinking and raising)

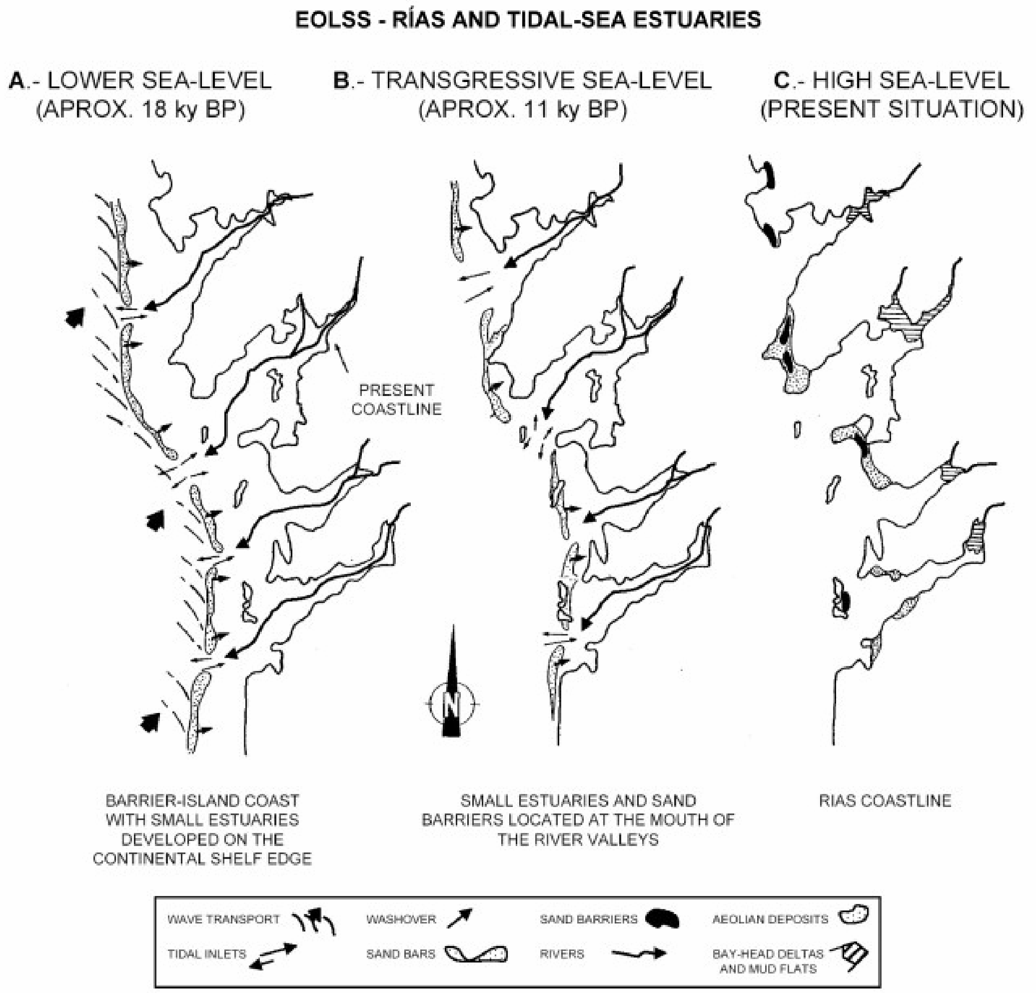


Figure 19. Diagram showing the theoretical evolution of the Rías Baixas coastline since the last sea-level transgression. The coastline shifted towards areas inside the rías which started to become flooded.

According to very recent works by García-Gil and others (in press), and based on high-resolution seismic data, an average thickness of 50 meters has been calculated for the Holocene sediments and taken as a whole, from the Palaeozoic basement, comprising metamorphic (shales and gneiss) and igneous rocks (granites), three sedimentary sequences (S_1, S_2 & S_3), which represent the depositional record of sea-level change, separated by two prominent stratigraphic discontinuity surfaces (L_2 & L_3) were identified (Figure 20). Both uncomformities represent the limits of each of the sequences, in other words, reflects subaerial exposure and erosion by surface processes during sea-level lows. The lower limit (L_2) corresponds to the top of a marked palaeorelief affecting both the Palaeozoic rocks of the basement as the materials in the top of the lower sedimentary sequence (S_1). The upper limit (L_3), which is also erosive, presents a milder palaeorelief and develops on top of the sequence (S_2), representing the base of the most recent package of sediments (S_3).

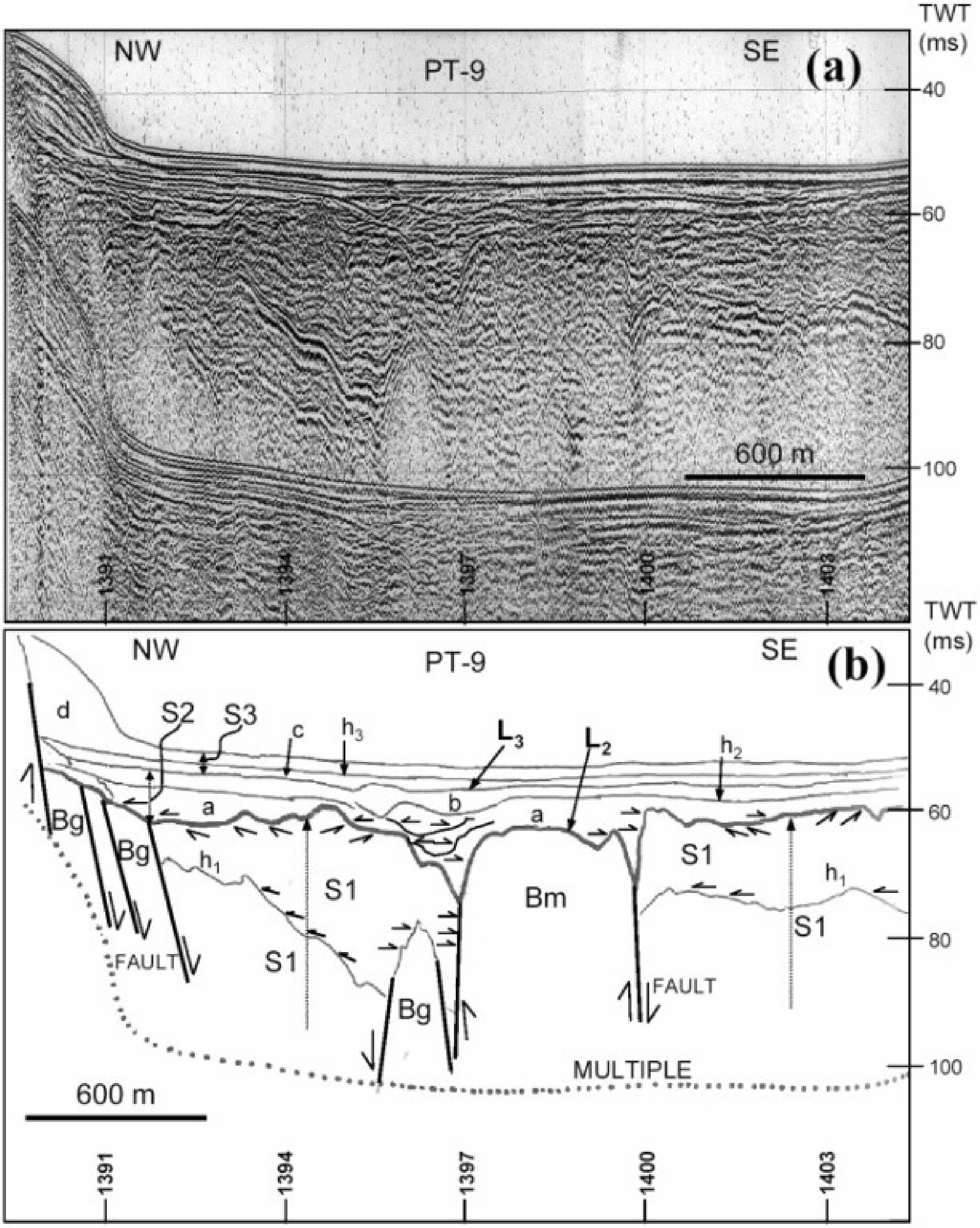


Figure 20. (a) Non-interpreted seismic reflection profile (line PT-9, Ría of Pontevedra). (b) Seismic interpretation showing: sequence boundaries (L2 & L3) and hiatus (h1, h2 & h3), sedimentary sequences (S1, S2, & S3), seismic units (a, b, c & d), lateral terminations of reflectors (<) granitic basement unit (Bg) and metamorphic basement (Bm). Numbers at the lower part of all figures correspond to the shot points. (García-Gil et al., in press).

The lower sequence (S_1) is the oldest and the deepest, and is characterised by the continuity of the seismic reflectors, which occasionally appear folded over. This being indicative of the fact that they have undergone deformation immediately to the deposition . The discontinuity (L_2) which separates the two sequences (S_1 of S_2) has been tentatively considered as corresponding to the marine regression during the Würm glacial period (18,000 years ago). For that period, a drop in sea level of the order of 100-150 m is recorded throughout the world. This means that at that moment, the rías did not exist (Figure 19, A), as they would be emerged areas forming valleys where the river cross them. Sediments would be deposited beyond the limits of the current rías, since the coastline and, therefore, the mouths of these rivers, would be located at the edge of the continental shelf, as could be interpreted by the results obtained by Bao and others in 1993 after a preliminar study of diatoms from core samples. Thus, the areas occupied by the rías would be areas subjected to erosion, restricting sedimentation to the areas of the fluvial palaeochannels mentioned.

Transgressive sea level drowned the small incised valleys developed on the continental shelf during low stands (Figure 19, B) and may have outplaced estuarine deposition or estuarine deposits may have been removed by transgressive reworking, producing sand plugs (beach ridges or barriers) at the headlands of the coastline. Deposition at the ría basin starts to take place and originate sequence (S_2) (see Figure 20). This sedimentary sequence (S_2), comprises two sedimentary units (a) and (b), which in turn are separated by marked stratigraphic surfaces, some of which represent uncoformities. These units became increasingly more extensive over time. Unit (a) has a limited extension and only appears infilling the depressions and irregularities of the palaeorelief developed on top of the first sequence (S_1). Unit (b) is considerably more extensive and marks a broadening of the areas covered by water in the rías. Its main characteristic was the presence of palaeochannels. The top of this unit, (discontinuity surface L_3) has been correlated with the relative decrease in the sea level during the Younger Dryas event (11,000 years ago), when the sea level fell some 50 m.

As the Holocene transgression continued to flood the incised fluvio-ría valleys, the modern ría coastline formed (Figure 19,C). Each ría basin became a depocenter of sediments, forming the youngest Holocene sedimentary sequence (S3). This last sequence comprises two units (c) and (d). Unit (c) has a slightly erosive base particularly towards the edges of the rías, showing the presence of channel incisions with subsequent refilling. It is more extensive than the previous units (a) and (b), covering previously emerged basement areas. The top is marked by a non-erosive hiatus surface (h3) which separates unit (c) from (d). Unit (d) is more recent and is the most extensive with geometries of typical deltaic fan profiles (Figure 21). These sedimentary bodies (conical in three dimensions), located at the mouths of the rías, and particularly between the rocky islands, have been generated during periods of strong storms in which large waves transported enormous amounts of sediments from the shelf to the outer marine-dominated zone where they are trapped, as it was recently interpreted by García-Gil and others. In this unit (d), lobule geometries are indicating alluvial fan sediments formed on the lateral edges of rías which was recently described by Hernández-Molina as an infralitoral prograding wedge. The different depths, ranging from 15 to 30 m, at which these bodies are found, are documenting the various positions of sea level during the Holocene.

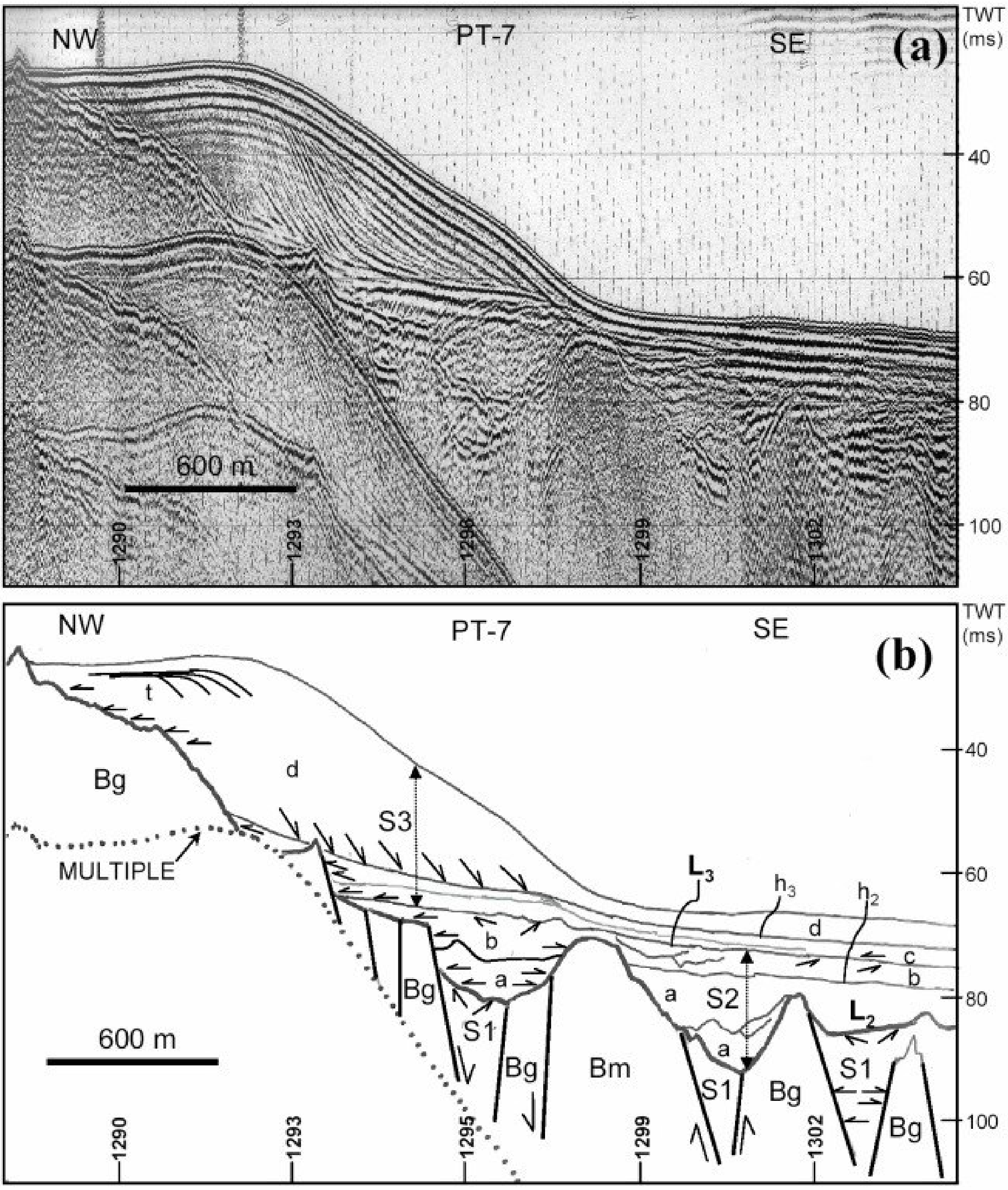


Figure 21. (a) Non-interpreted seismic reflection profile (line PT-9, Ría of Pontevedra). (b) Seismic interpretation showing: palaeochannels in S1, prograding sedimentary body in unit "d", with lateral terminations in onlap, downlap and toplap "t" (respectively to the edges, towards the basin, and in the top). (García-Gil et al., in press).

6. Environmental features in rías and estuaries

Many studies on life in estuaries and rías show that the distribution and abundance of animals and plants is less than the number of species in either the sea or fresh waters. Among others, turbidity due to suspended sediments is of ecological importance as it limits the penetration of light required by plants for photosynthesis; the larger seaweeds may be restricted to a depth of as little as 0.5 or 1 m below water, although in clear seas they extend 60 m or so below this level. Pathogenic bacteria discharged in untreated sewage are rapidly killed by sunlight, while some toxic chemicals are absorbed and thus concentrated on suspended particles, so their typically high turbidity also makes estuarine waters less suitable to receive such waste. A high rate of deposition or erosion may make it difficult or impossible for animals to colonize on sand or mud banks, while their nature (especially the particle size) will determine the abundance and variety of this fauna. Intertidally, few animals live on the surface of soft sediments. Those which move about at high tide dig in or retire to a prepared hiding-place when the water leaves the banks, while the majority occupy some sort of burrow throughout their adult lives. With the exception of coarser sediments at the top of the shore, sand and muds retain water, so there is no danger of desiccation.

Animals are obviously subject to salinity changes. Those which cannot tolerate low levels, may nevertheless penetrate far up the estuary if they are able to obtain sufficient food in a short time; amongst bivalves, for example, deposit-feeders such as *Scrobicularia* can usually take in food more rapidly than the suspension-feeding cockles. The horizontal distribution of the epifauna (animals living on the surface of either soft or hard shores) between the mouth and head of the estuary is, in contrast, determined more by salinity than any other factor. The vertical distribution of sedentary plants and animals, particularly on shores or hard artificial surfaces, is largely determined by tidal level, as on the open coast; but the pattern is confused by changes in salinity at any given point on the shore resulting from tidal movements of water up or down the estuary. We cannot overemphasize the important presence in significantly populated estuaries of what are often termed as secondary consumers, notable examples of which are birds and fish. Birds mostly feed on the rich intertidal populations of annelids, crustaceans and molluscs, which are exposed by the tide. Fish populations in estuaries can be abundant with a wide diversity of species; much of the abundance is seasonal, as mainly fish move into the estuary to breed, and having used the estuary as a nursery, the young fish grow and move out to sea again. Only a few species live in the estuary throughout the year.

6.1. Biological characteristics in the Rías Baixas

The predominant fauna in the rías is largely of marine origin. Only in the innermost areas, which are influenced by river contributions, is it possible to detect the presence of different communities than those found in saline waters. The influence of marine waters combined with contributions from the rivers, and the complex topography and bathymetry, determine the presence of a great sedimentary and environmental variability which has important biological consequences. Within a ría, we may find practically the whole range of coastal sediments, both within the intertidal and the subtidal zone.

In the intertidal mud flats areas, communities of species with a greater or lesser resistance to variations in salinity are abundant. These species are frequently sustained by the presence of marine phanerogams (*Zostera marina* and *Z. Noltii*), involving a highly interesting environment as they are particularly favourable zones for numerous infauna and epifauna species, spawning areas, juvenile refuges, sources of oxygen and organic matter. The *Zostera* platforms are one of the areas with the highest biological productivity within the estuarine systems

Mud bottoms appearing in the inner areas and central channels of the rias are occupied by species which may also be found in wide sectors of the continental shelf. These involve communities fundamentally dominated by surface and subsurface deposit feeder species. The predominating groups are polychaeta, crustacea and molluscs. The most abundant families among the polychaeta are the Capitellidae (*Notomastus, Heteromastus*), the Maldanidae (*Euclymene*), the Nephtydae (*Nephtys hombergii*), the Spionidae (*Polydora, Spio, Aonides*), the Ampharetidae (*Melinna palmata*), the Chaetopteridae (*Spiochaetopterus solitarius*), the Polynoinae (*Harmothoe, Sigalion*), and a large number of Sabellidae equipped with filtering combs (*Sabella pavonina*).

Molluscs are a further dominant group within the muddy subtidal area, with an important presence of bivalves (*Nucula turgida, Abra alba, Pandora albida, Thysira flexuosa*, etc.).

Small-sized crustaceans are also particularly numerous, in almost all cases, the Amphipoda (*Ampelisca, Gammarous*) or Thainadaceae (*Apsweudes latreilli*).

Sandy bottoms are also densely populated, both in the subtidal and intertidal environments. The type of community depends on the type of sands on which they settle: fine, medium or coarse grained although as a general rule, the three types are dominated by polychaetae, molluscs, crustaceans and echinoderms, with important presences of filter feeder species and surface deposits feeders. Although a large number of the especies cited for silty bottoms may be present in sandy areas (particularly where this is coarse-grained), certain species, which may be cited as characteristic of muddy bottoms appear, such as molluscs of the family Cardiaceae (*Cerastoderma edule, Acanthocardia spp*, etc) Veneraceae (*Venus striatula, Venerupis spp*) and Tellinacea (*Tellina tenuis, T. fabula*).

Among the polychatea, the presence of a large number of omnivorous species is important, although these have a predatory tendency, particularly the families Eunicidae (*Lumbriners spp., Diopatra neapolitana, Hyalinoecia bilineata*, etc), Nereidae (*Nereis spp.*) and Nephtydae (*Nephtys cirrosa*).

The echinoderms frequently become a highly interesting group in the sandy areas of rias, not only for their abundance, but also for the high degree of biomass contributed by these species, particularly due to the presence of Ophiurae (*Ophiothrix fragilis, Amphiura filiformis* and *A. chiajei*).

Coarse sediments comprise shell remains, although occasionally, patches of calcareous algae of the genus Lithothamnion are detected. These areas have special biological interest for the great diversity of fauna found on them. In the Ría of Vigo, as many as 120 different species have been gathered, measuring over 2 mm, in a surface area of 30x30 cm These are small sized species which find an ideal environment for spawning, refuge and feeding.

6.2. Special uses

Since time immemorial, the coasts of rías and estuaries have been places for human settlement. Over time, this has meant that they have introduced numerous changes in the natural processes involved in these systems. The presence of water pollutants, both chemical or physical, retaining waters by dams, which also tend to reduce the amount of sediments supplied by rivers, and many others such as trade, manufacturing industry, fisheries, leisure pursuits, are often in conflict, since the effects of one may be disadvantageous to another. At present, one of the major activities determining the shape and position of the land-water boundary is the behaviour of man, particularly in his roles as a reclaimer of land and protector of coastlines.

Estuaries in general, and the Rías Baixas in particular, are regarded as amongst the most fertile natural areas in the world. One of the greatest important commercial values is bivalve molluscs. Among them, mussel culture has now become very common in the deep rías of Galicia in north-western Spain. In this region, mussel production is one of the major economic sectors, producing as much as 40% of world productivity. Contrary to the normal custom in other parts of the world, in the Galician rías mussels are cultivated by attaching them with strong threads to solid ropes, hanging vertically from a raft platform. Each raft supports hundreds of long ropes; the young mussels attached to these ropes can utilize the full depth of water. In the last 50 years, the proliferation of mussel culture platforms and related activities, such as maintenance, cleaning and marketing, have given rise to importnt modifications to the sedimentary beds; it is estimated that 190 kg in dry weight of biodeposits per day and per platform means a total of 240,000 tonnes per year of biodeposits for the Rías Baixas. In these areas, the fine sediments present a high concentration of contaminants in the form of heavy metals, a product of the interaction between waters from urban and industrial waste. (Figure 22).

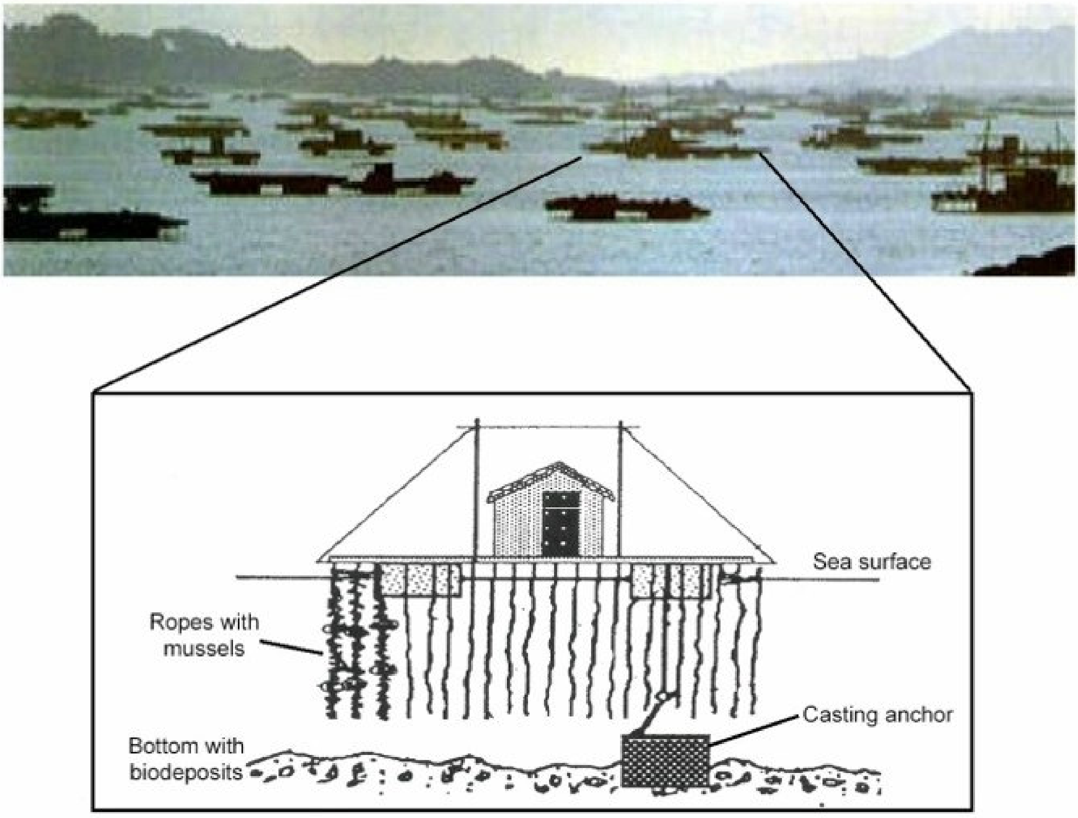


Figure 22. General view of the mussel rafts in one of the Rías Baixas (N.W. Spain)

Finally, these environments have a great value for geological and biological teaching and research. For the geologist, they provide exposures and processes characterized by their length and continuity, in contrast to the much smaller outcrops and more intermittent processes inland. For the biologist, they are no less important due to the combined effect of many factors, which broaden the spectrum of environmental diversity and ensure that different communities of organisms are present.

7. Conclusion

This chapter gives an overview of the main geological characteristics studied in rías and tidal-sea estuaries. The term "ría" has historically been considered as a type of estuary. Its inclusion in the classification of estuaries is based on geomorphological studies conducted besides data obtained from the oceanographers viewpoint. Nevertheless, in the few sedimentary studies made on rías, great differences are noted in terms of the classical modes of estuaries described. The question which now arises is if the term may be used as a sedimentological term in the sense of there being any distinguishing characteristic allowing it to be used as a criteria for identifying rías sedimentary sequences in the fossil record

From another point of view, based on research conducted on estuaries and, more especially on rías, other fields of research applied in issues associated with the human impact on the environment as well as on global climatic change are highly relevant.

In the first place, due to the special characteristics of rías, they induce sediment retention rather than dispersion to the continental shelf, making them efficient catch-basins for sediments. This consideration also makes them susceptible to retain polluted substances present in the water column, particularly in areas where upwellings generate a high rate of build up of organic matter, in addition to that deriving from urban and/or industrial areas. In the second place, the sequences generated in the course of the sedimentary infilling of ría basins, contain evidence of the relative Holocene variations in sea level and of the climatic changes which occurred during the Pleistocene .

Acknowledgements

Over the last few years, the Marine Geology group of the Dept. of Marine Geosciences at the University of Vigo has contributed, from several angles of the Earth Sciences, to the understanding of the ría environment. This paper reflects and synthesises information derived from the work conducted in different Spanish research projects funded by the M.E.C. (Mar 95-1953, Mar 97-0626, REN 2000-1102).

I would like to thank B. Rubio, A. García, R. Duran, S. García, D. Rey, L. Gago and I. Isla, for their useful comments, and particularly to same of them for their invaluable help in drawing up the graphics for this paper. My thanks also to I. Emmett for the English translation.

Glossary

Alluvial fan: an outspread mass of alluvium deposited by flowing water where it debouches from a steep, narrow canyon onto a plain or valley floor.
Bar: any of various types of submerged or emergent elongated sand or gravel mass built by waves or currents.
Barrier island: elongated coastal island representing a sand ridge rising above high-tide level and lying roughly parallel to the coast but separated from it by a marsh or a lagoon.
Bedding: layered feature of sedimentary rock characterized by differences in composition, texture or structure.
Coarsening upward: sand composed of grains getting coarser upwards, and easily visible to the naked eye.
Colluvium: unconsolidated material at the bottom of a cliff or slope, generally moved by gravity alone.
Continental margin: the totality of the various divisions between the shoreline and abyssal ocean floor. It includes the continental shelf, continental rise and continental slope.
Crevasse splay: a break or breach in a river bank, such as a natural levée.
Cross-bedding: sedimentary layering within a bed that is inclined at an angle to the main beeding plane.
Diagenetic: the sum of all changes, physical, chemical and biological, to which a sediment is subjected after deposition.
Diatom: any of numerous microscopic unicellular marine or freswater algae having siliceous cell walls.
Fan-delta: alluvial fan or fan-shaped mass of alluvium.
Flaser bedding: discontinuous curved lenses of finer sediment (mud or silt) deposited in the troughs or draped over ripples in cross-laminated sands.
Flocculation: the process of forming aggregates or compound masses of particles.
Herringbone: cross-bedding in which some cosets the foresets within adjacent sets dip in opposite directions. Are produced where there are reversals of the current directions
Hiatus: gap or interruption in stratigraphic record, as represented by the absence of rocks that would normally be part of a sequence, but were never deposited or were eroded away prior to the deposition of beds immediately overlying the break.
Natural levée: an embankment of silt and sand built up by a stream along both its sides.
Palaeocurrent: currents of water or wind, active in the geological past, whose direction can be inferred from sedimentary structures such a cross-bedding, ripple marks and others.

Ripple marks: mall-scale ridges and troughs formed by the flow of wind or water over loose sand-grade sediment.

Sedimentary facies: an areally confined part of a assigned stratigraphic unit that shows characteristics clearly distinct from those of other parts of the unit.

Seismic discontinuity: boundary between rocks of differing density and/or different elastic properties, at which the velocities of seismic waves change abruptly.

Siliciclastic: pertaining to a sediment composed chiefly of fragments derived from pre-existing rocks or minerals, containig a high percentage of silica.

Stratigraphy: the branch of geology concerned with all characteristics and attributes of rocks as they are in strata, and the interpretation of strata in terms of derivation and geological background.

Terrigenous deposits: land-derived marine sediments that are carried down the continental shelf by gravity and geostrophic currents.

Tidal delta: a sedimentary deposit of sand formed at the estuary inlet. The form and size depend upon the hydrologic regime of the river, and the local waves and tides.

Tidal flat: a broad, flat, marshy or barren tract of land that is alternately uncovered and covered by the tide.

Transgression: the incursion of the sea over land areas, or a change that coverts initially shallow-water conditions to deep-water conditions.

Turbidity maximum: suspended load of sediments concentrated at the salt intrusion boundary of an estuary.

Wave ripple mark: an oscillation ripple mark, produced by the oscillating or lapping movement of water.

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(The references provided in the text only scrape the surface of the voluminous literature covered in this article. The intention has been to cite the key references which are important to consult for some of the original work on a subject and indicate where further information can be found).

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