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Morphodynamics of Spanish Cantabrian Rias

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ABSTRACT

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The *rías* are a characteristic feature of the Spanish coasts. Despite their important differences, all of them have some common problems such as those derived from infilling processes. Their littoral dynamics have been considered, with special attention to the Cantabrian coast, and a phenomenon particularly frequent in all indentated coasts has been observed: the reversion of the general direction of processes within the indented area; this phenomenon is essential to understanding the mechanisms of formation and evolution of the inlet shoals and emerged barriers of the *rías,* which separate their internal (sheltered) and external (open) zones; many different morphological observations have verifyed it (DIEZ, 1996 b). Current morphodynamics has been accurately approached in the *ría de Foz* (DIEZ, 1980–96) to get a morphodynamic model suiting the natural as well as the anthropic evolution. The balance of sediments used to verify the model (ESCOBAR *et al.,* 1991) is justified and summarized. Data about deposit volumes at different times had to be laboriously obtained to show total consistence with the morphodynamic model insider.

ADDITIONAL INDEX WORDS: *Eolian dynamics, littoral dynamics, fluvial currents, infilling, sediment budget.*

GEOMORPHOLOGICAL INTRODUCTION

The Galician-Cantabrian littoral has a territorial structure with difficult inland access and limited agricultural resources, what makes fishing a necessary activity. The coast is mostly beaten by the sea so that port activity has been relegated to the *rías,* as natural harbors; very few of them have become big harbors due in most cases to their small size (Figure 1) but also to their infilling processes (DIEZ, 1992); that is the paradigmatic case of the here frequently refered Gulf of Masma and *ría de Foz* (Figures 2 a, b, c). Differentely than "purely Atlantic" Galician, the Cantabrian littoral, while mainly "Atlantic", have a certain "Pacific" character, as a consequence of the converging phases between the Iberian and European plates that generated the Cantabrian mountains. Consequently Cantabrian rias are generally much smaller than those of the Atlantic front and much more infilled by sediments. Their immediate origin is evidently fluvial but they also have a remote tectonic genesis. The dredging system through faults and fractures usually allowed the widening of the fluvial outlets, although some exceptional estructural narrows can be found.

The alternating tectonic cycles of tension and compression over the Cantabrian coast, due to changes of direction in the relative movement of the Iberian and European plates, and their different inclination from east to west, have led to a great variety of *rías,* although all of them have common characteristics. The increasing settling towards the west (Figure 2 c), probably due to the Atlantic "graben", is evidenced to the west of Cape Vidio (*Asturias*). To the East of this cape, the settling seems to be more homogeneous or even appears to reverse itself in the *ría de Pravia.* Besides the transversal tensions, those parallel to the coast have also been uneven, causing fossae of different degrees of settling. The present depth at the entrance of the *ría de Pasajes* offer the example of an exceptional settling, without any apparent regularity. Over a structure of these characteristics, the ulterior eustatic episodes have led to different emerging and immersing cycles of varying amplitude, depending on the previous morphologic and structural characteristics of each *ría.* The estuarine environment of the Cantabrian *rías* is very peculiar, different from that of real estuaries and of fjords, although those of East Scotland (*firths*) are in a current similar situation (MCMANUS *et al.,* 1993), mainly in their infilling, albeit through a different evolution process. Nowadays every *ría* is subject to the following processes which require a continous maintenance and improvement of their harbours: natural infilling (anthropogenically acentuated very often) and urban and industrial growth, as in the *ría* of *Foz* (DIEZ, 1980–1996, a).

SUMMARY OF LITTORAL DYNAMICS

Different conditions of erosion, littoral and fluvial transports and previous morphology have led to different patterns of infilling in every *ría.* Following are the dynamic ocean effects (CEPYC, 1985, 1993; DIEZ, 1980–96):

The eolic dynamics is particularly significant due to the frequency and profundity of the subatlantic storms. Northwestern winds are dominant but northeastern winds are significant too. Breezes are less significant. The proximity of the mountains (ridges and horsts) reduces the continental pene-

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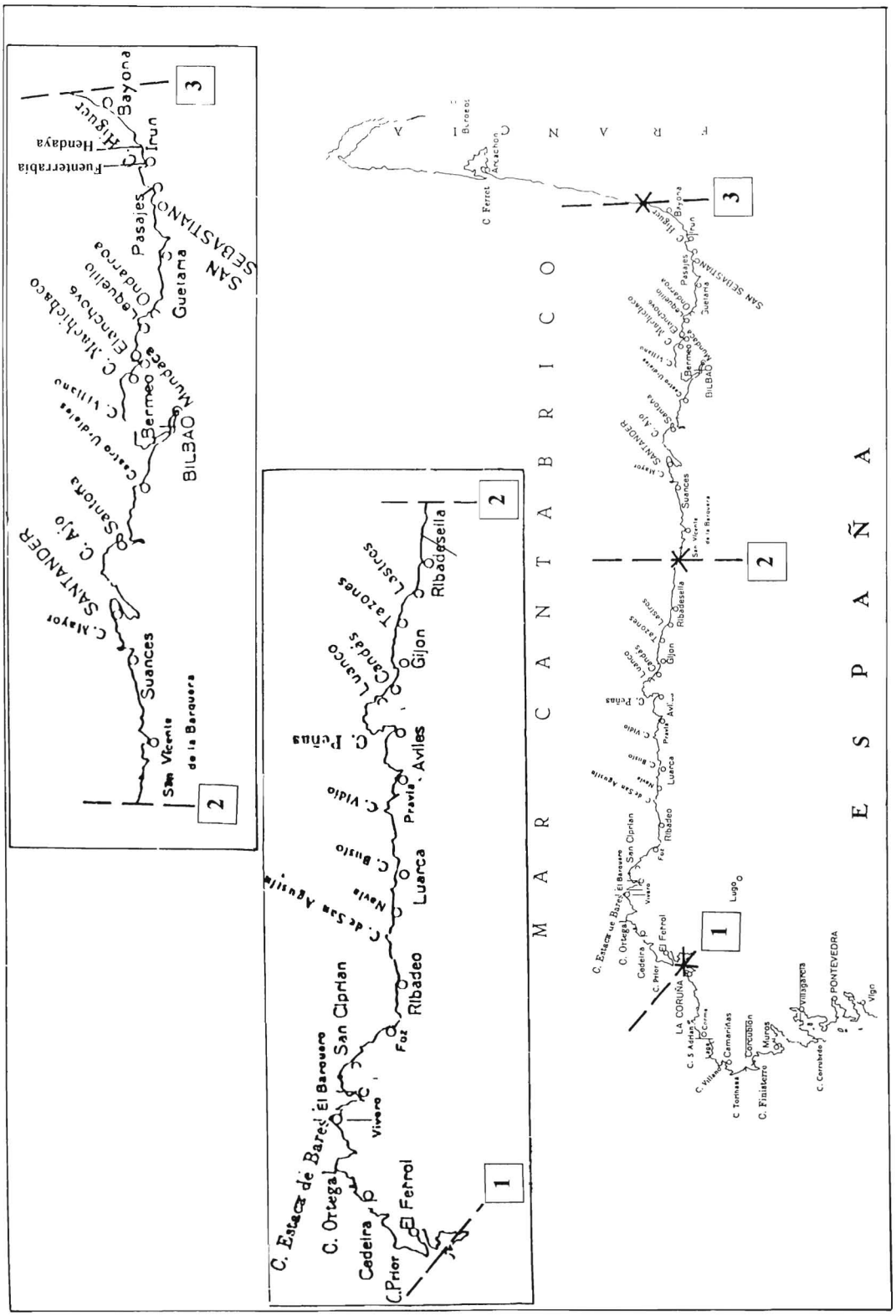
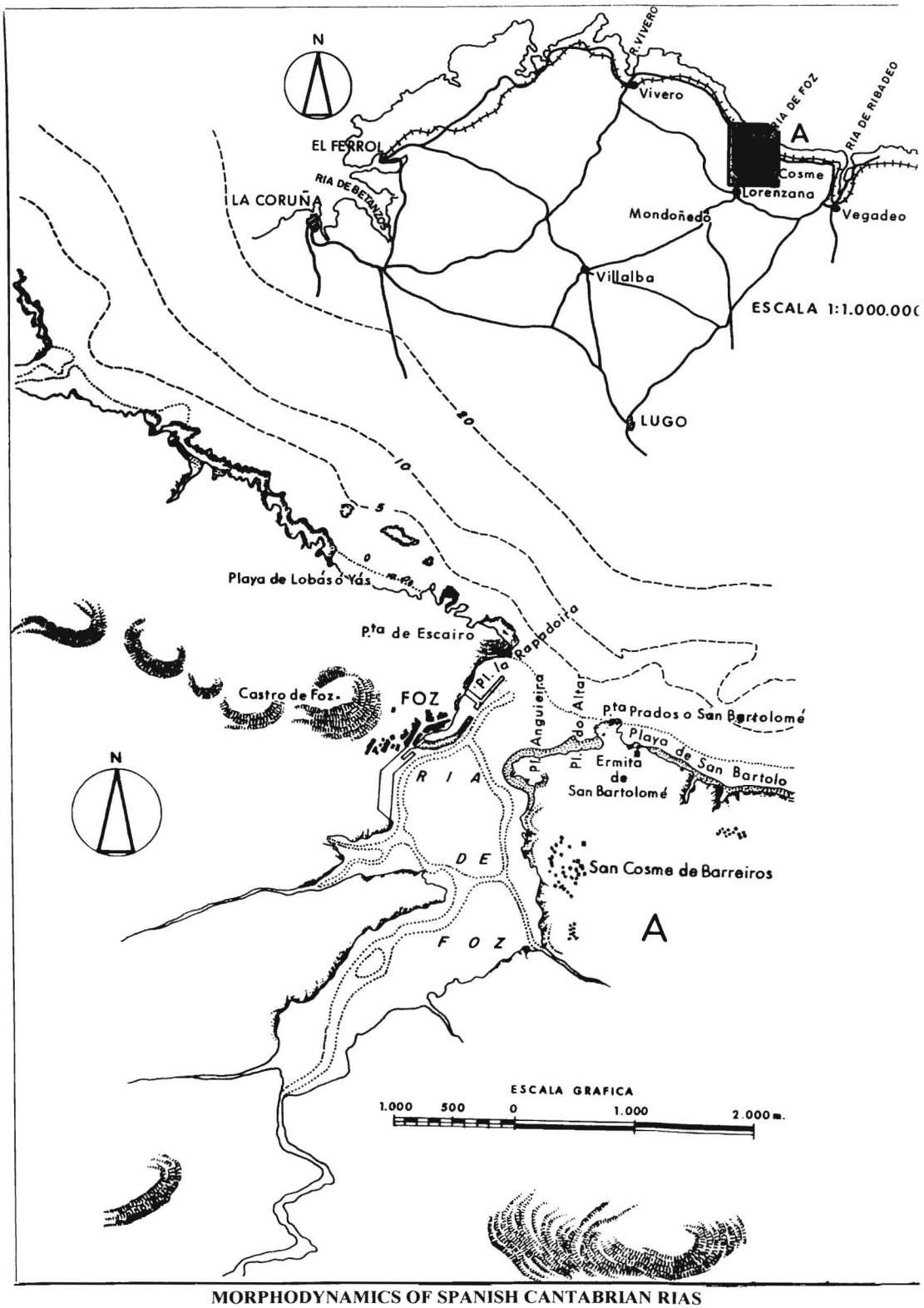


Figure 1. Spanish Cantabrian coast and rias.



MORPHODYNAMICS OF SPANISH CANTABRIAN RIAS

Figure 2a. Gulf of Masma at the end of the Cantabrian coast.

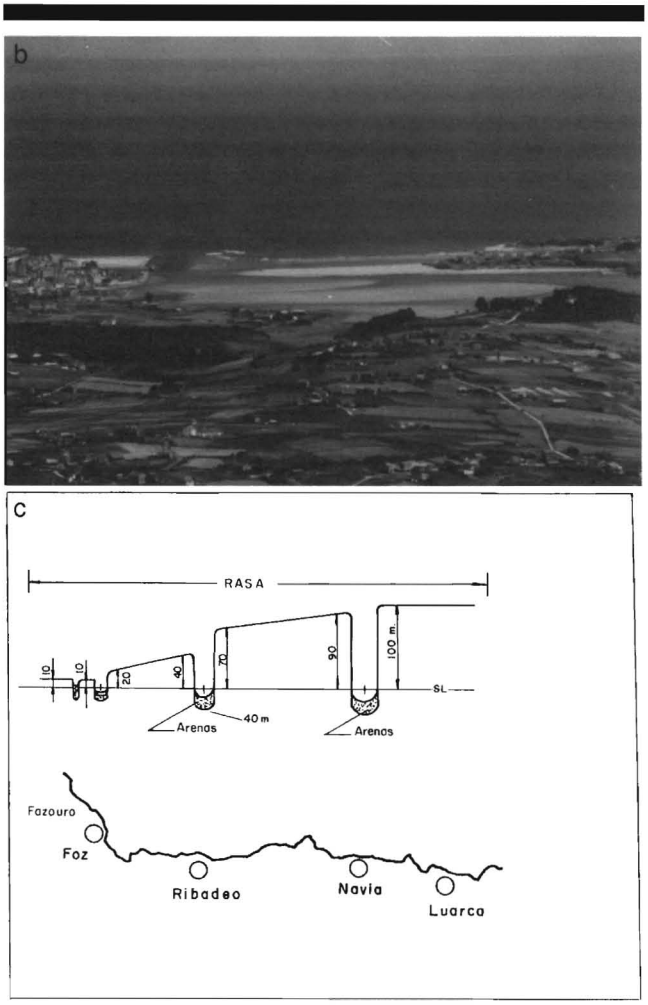


Figure 2. Continued.

trability of winds but eolic processes are very noticeable in the sandy littoral systems. Their role in the infilling processes in the rias should not be underestimated.

The littoral dynamics due to the waves undoubtedly decreases from West to East (although the potential net transport towards the East increases again in the eastern part) but the transport capacity is huge in both directions in all the Cantabrian littoral. However, actual littoral drift is very inferior to the potential transport in all points of the Cantabrian littoral, since the availability of materials is, by far, lower than the transport capacity. Therefore, the differences between gross and net transports and from some *rías* to others are smaller, even relatively, in real terms than they might be potentially. Although there are noticeable differences from one *ría* to another, depending on the rate of erosion and fracturation of the cliffs, the fluvial contributions to the littoral currents are negligeable at the present moment, but during prior periods that contribution made up deposits in combination with marine sediments which can now be dragged by the littoral current, as it is the case of those in front of *Fazouro* ("Gold mouth").

The tides, semidiurnal with a strong half-monthly modulation, can be considered very homogenous along the Cantabrian and Galician littorals with differences of no more than 10% of the tidal range and of the high and low tide levels. This homogeneity is extended to the variability out the tidal range in the monthly and annual cycles. And, except for the lowest values of the monthly cycles (affecting a maximum of two or three days) the tidal ranges (up to 4–4,5 m, depending on latitude) are of much greater influence than the parallel transport. This statement depends on the corresponding values of the respective tidal prisms, normally small due to the dimensions of the *ría,* but their restrictive effect is, by far, less significant than that previously mentioned, in reference to the solid parallel transport.

The storm surges do not stand out particularly, although they can be significant. Unpublished investigations in the *ría de Foz* (Figure 3) have detected values of up to +60 cm, usually coinciding with the NE phase of the winds, immediately after the passage of a storm, and of up to −40 cm, with strong south winds, prior to the passage of that storm. This situation can be extended to several low and high tides.

The tidal currents are then predominant over the real parallel transport, and that, added to the asymmetry derived from the perpendicular action of the waves (DIEZ, 1979, 1980) favors the infilling process of the *rías* with materials coming from the littoral areas (ASENSIO, 1979). The fluvial currents on the other hand, although important for the length and form of the currents, have less importance in the shaping of the river mouth, even in minor *rías,* with exception of some small *rías* almost completely infilled, as that of the *Ouro* (Gold) river. At present, these currents do not deposit a significant amount of solid beach materials, because of the low rate of erosion of the river beds, protected by abundant vegetation, although the frequent forest fires of past years and already controlled could change the situation. The materials are mainly deposited within the swamps of the estuarine bed of the *rías,* collaborating to enlarge them (ASENSIO, 1984).

All the dynamic factors mentioned above, besides leading to the natural infilling of the *rías,* also allow the generation of sandy barriers (DIEZ, 1980; DIEZ *et al.,* 1988) whereby the mechanism that accomplish the "mass action law" is set up, reducing the rate of infilling of the *rías* to a minimum. The dynamic response factors which constitute the littoral morphodynamics should be studied here. For this study the main factor to be considered is the formation, development and stability of the gorge spit-barrier (BRUUN *et al.,* 1958; BRUUN, 1973; WILLIAMS *et al.,* 1982).

A discussion of the results of different sediment studies in the *ría de Foz* and of many other approachs to different *rías* has verifyed that data accurately agree with the "local" littoral dynamics (DIEZ, 1980–96b; MCMANUS *et al.,* 1993; DUCK *et al.,* 1995). Current (last forty years) morphodynamics have been approached in Foz in order to understand harbor operations and to establish the condition of use (function of the *ría*) and the condition of recourse (regime of the outlet). Once the hydrodynamic circumstances (actions) and the geomorphologic and sedimentary conditions (reactions) have been established, the impacts of such actions and the necessity of possible corrections could be studied, applying the au-

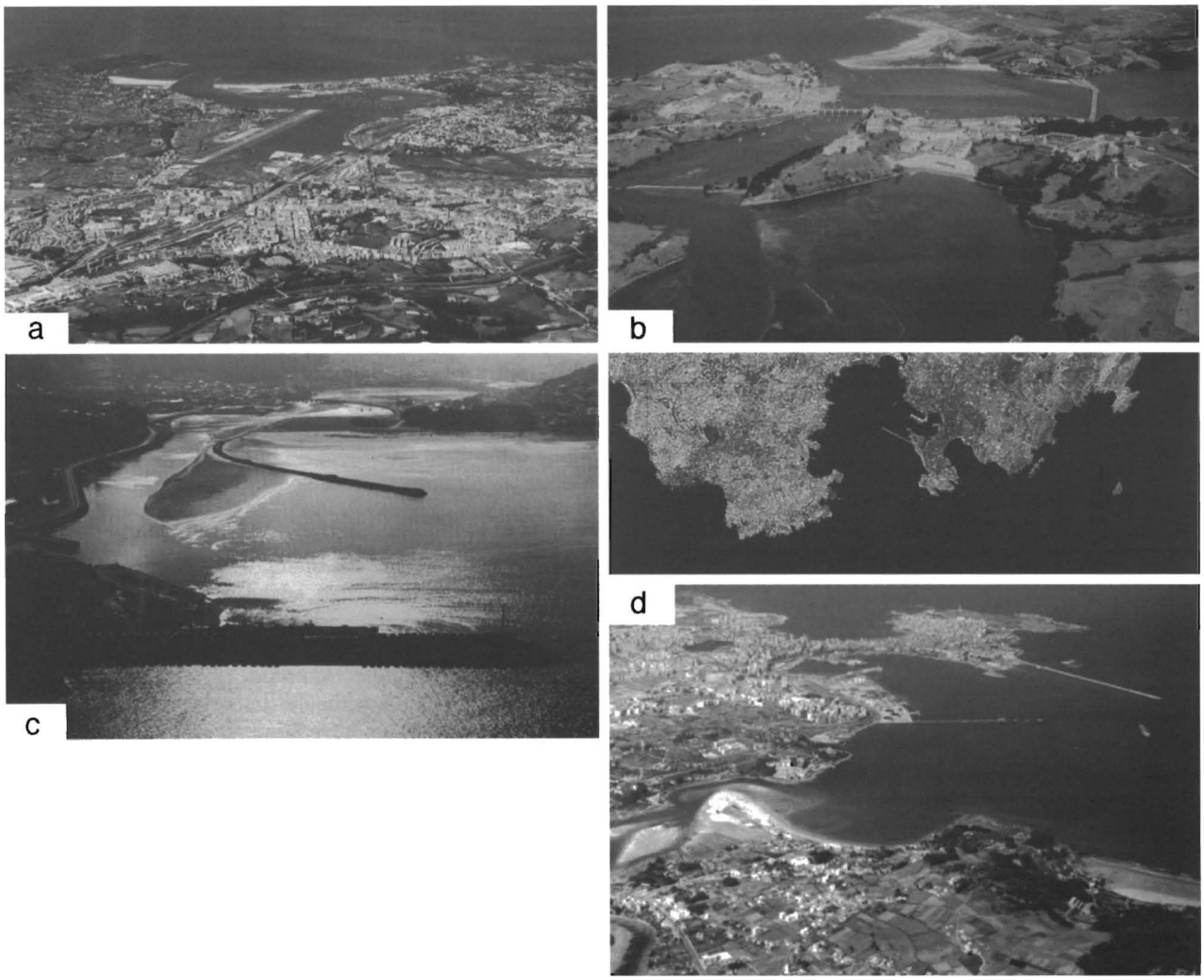


Figure 3. (a,b) Cantabrian rias; (c,d) Galician rias

thor's experience. As a conclusion, a morphodynamic model is developed, suiting the natural evolution as well as the modifications introduced into the environment by human actions.

The Anthropogenic Consequences

Problems of infilling can be natural or anthropogenically induced. The natural evolution of the coast areas leads to a regularization of the shoreline tending to lessen the littoral processes; this is part of a wider process in which the action and reaction forces keep in balance the geodynamic cycle of the planet. While the conditions for a geological future of new coast irregularities are being created, the cliffs are being eroded and indented areas infilled. In this process, new humid and shallow-water areas are developing while others become infilled, although with unequal balances on different coasts. The infilling of the *rías* inexorably leads to the draining of humid areas. But for the first time men have the capability of modifying these natural processes in all or in part of the affected areas.

The problems generated by anthropogenic actions are much more complex and the especificity of the *rías* makes the application of experiences elsewhere difficult. First, we will look at the cases in which these actions accelerate the problems due to natural processes like the sudden increases in the infilling of the *rías* (for instance in *Foz*). Actions aimed at stopping or diminishing these problems, either for environmental or economic reasons, should obviously be considered very urgent. Delays in their application should not lead to their being rejected as useless and counterproductive. Rather, they will require complementary measures in order to lessen unwanted secondary effects. From this point of view, some dredging in the interior of certain *rías* can be considered appropriate, even synergetic, with a policy of regeneration and creation of beaches in their vicinity.

Ancient settlements in areas close to the *rías* were few and their impact were insignificant during many centuries. Only harbor development and related industrial and urban growth led to an essential transformation of some few *rías,* the *rías*

of a particular tectonic type, in which the necessary draughts for harbor development were assured. The processes of infilling in these cases were attenuated by human action, which on the other hand increased contamination with dumping of all kinds. In the rest of the *rías* the development of harbor facilities corresponded to the natural growth of population and fishing arts. There also were some commercial and industrial activities, but always limited by the dimensions and characteristiques of each *ría* and its communications with the interior of the peninsula. For some time the *rías,* even the smallest and shallowest Cantabrian ones, have had a certain capacity of self-maintenance. But this capacity is being lost even by the *rías* of the Atlantic front, which are much deeper and larger. The relative economic underdevelopment of a great part of the Galician and Cantabrian littorals has helped to maintain the fonctionality of some rías. Posterior economic development had however a differed detrimental impact on the environment. In other cases the same natural infilling processes have acted in the opposite direction.

The present infilling processes of the *rías* probably began as a consecquence of the deforestation and the almost continuous amelioration of the climate since the XVII century. Even though the significance of the climate changes (owing to the concomitant tectonic movements) at sea level in the Cantabrian coast is not clear, it is obvious that, from the moment in which the CO_2 levels started to rise in the atmosphere (XIX century), the capacity of erosion of the sea also grew, mainly in the carbonated steep rocks, due to the increased weathering capacity of the air on all kinds of rocks and to the increased CO_2 concentration in the sea water. This last factor makes easier the dissolution of carbonates, the proliferation of organisms with shells and, finally, the availability of the calcareous fraction in the littoral sediments. However it is during this century that the infilling processes have certainly increased, linked to the channeling and sheltering constructions which made possible the continued use of traditional inner harbors. The problems began when the size of the small fishing vessels started to become incompatible with the tidal channels that had always served as access ways; their stabilization by means of either one jetty alone or two insufficiently anchored jetties led to sudden erosive processes in the gorge barrier (BRUUN and GARRITSEN, 1959) to the widening of the entrance to the *ría* and to the increase of the infilling rate, once the barrier imposed by the "mass action law" had been eliminated. The Cantabrian cases of *Fuenterrabía-Hendaye* (Figure 3 a) and *San Vicente de la Barquera* (Figure 3 b) as that of *Covas-Vivero* (Figure 3 c) and *Santa Cristina-La Coruña* (Figure 3 d) in the Gallician corner, among many others, join the case of Foz.

"Normal" and "Abnormal" Spit-Barriers of the Cantabrian *Rías*

Since the littoral dynamics of the fourth quadrant are dominant in the Cantabrian coast, and since this coast has a general East-West orientation, we must expect that the average annual resultant of the waves at the mouth of the *rías* (as in the rest of the river mouths), at indefinite depths, had a slope situated in the fourth quadrant, relative to the shore line. That means that, if this average resultant is not modified by the river bed, the net littoral transport will be toward the Gulf of *Gascuña*. Around the river mouths, this has a particular meaning due to their geometrical discontinuities and the capacity of these mouths to be infilled. When the external outlet, due to its depth and slope, allows the formation of shoals, these are typically built in the shape of a spit progressing toward the East. Conversely, when the conditions for the formation of these shoals do not exist or if other shoals are built in a more internal mouth of the *ría,* the latter are governed by transformed waves whose average annual resultant has shifted to the first quadrant, and which causes them to progress in the shape of a spit toward the West. We have assumed that the littoral dynamics parallel to the coast predominates over the tidal dynamics, which is normally the case in the Cantabrian river mouths.

Being a coast with a dominant eastward littoral transport, the pressence of many westward progressing spits have driven engineers and scientists to consider all or most of them as bars/barriers, *i.e.* barriers generated from emerging bars under the dominant action of the transversal component of the wind waves, undervalueing the effectiveness of the longshore component. And therefore they even were called "bars" in Spain though permanentely being both emerged as barriers and connected, always to the same side, as spits. But, as our research has showed in the case of *Foz,* they are true typical spits formed in response to the inverted dynamics at the shelter mouth of the *ría.* (DIEZ, 1980–96). The same misunderstanding is shown in many references (WILLIAM and BUILDING, 1982) in other coastal zones in which that kind of local inversion of the longshore littoral component is produced; in fact the number of barrier islands proceeding from original long spits in some flat coasts is greater than it is considered. This could be the origin of the idea of the existence of "updrift migrating" inlets and/or barriers, when migration is, necessarily, downdrift. Local inversion of the drift caused by local reffraction and/or diffraction could have led to this misunderstanding. In Figure 3 d, showing the *Ria de La Coruña,* these effects on the spit accentuated by the breackwater are perfectly evident.

THE MORPHODYNAMIC MODEL

After the analysis of the littoral processes on the *ría de Foz* and its environment, a synthesis of the resultant morphodynamic model was proposed, and it can be generalized to the other rias taking into account the "normal or inversed dominant longshore littoral transport"; this model has been contrasted with the sediment budget based on the different sand deposits in the ria (ESCOBAR *et al.,* 1991; DIEZ, 1995). The following interconnected phenomena have been shown:

(1) The littoral dynamics, very powerful on the whole Cantabrian coast, leads to a great transport capacity in both directions although predominantly towards the east. The absence of significant sediment supplies makes the actual transport much less abundant and certainly more balanced. Nevertheless, the situation changes in the interior of the *rías* where the direction of the transport is many times reversed. In the *ría de Foz,* for example, the reversion is total and the

gorge barrier that separates the internal (sheltered) and external zones of the *ría* becomes a real spit growing westward.

(2) River and tidal currents may be significant, but the latter are always dominant. The net balance of drift is always towards the interior of the *rías* which act as traps for the sediments. It is a consequence of the asymmetric action of waves, always coming landwards. River currents however might sporadically open new channels in the gorge area of the *ría,* although the net transport is inwards, the movements in both directions are significant and both have to be taken into account.

(3) There is a "normal" eastwards littoral transport along the open shore, but in most rias the transport is reversed in their mouths westwards. Part of the dragged materials remains in the *rías,* keeping a balance between these deposited materials and those eroded from cliffs and dunes. The formation of spits reduces the infilling of the *rías* and makes the transport more homogeneous.

(4) Because the presence of the spit, the amount of transport through the channel is reduced due to the lower rate of infilling. The natural spit had an optimum efficiency and its situation, morphology and orientation depends on the environment whose characteristics were affected by certain modifying actions.

(5) The variability of the channels in the inner zone is reduced when the rate of infilling increases. However, when the river flooding is significant, the ebb currents can open new channels. Wind activity causes circulation of sediments and mobilization of dunes too, possitively affecting general stability.

(6) The chain of impacts does not end with the beaches close to the *ría*. The littoral balance is dynamic and the dominant eastward transport is effective in the open coast stretches, so that, when far beaches exist they can suffer a subsequent erosion. In the particular case of the *ría de Foz,* the coastal stretch between *Foz* and *Rinlo* (*Ribadeo*) suffered the differed regression of all the present several beaches until the dominance of the cliffs (*Benquerencia, San Miguel, La Devesa,. . .*).

Extension of the Model

In the Cantabrian coast there are a lot of westward spits, *Foz, Hendaya, San Vicente de la Barquera, Navia* and *Area de Vicedo* among others. The hypothesis of considering bars as their origins leads to evident erroneous actions. It implies that the narrowing of the channel at its gorge must lead to a shortening of the bar by the erosion of its end. The spit hypothesis, however implies that the continuous supply of sediments to that end from the barrier leads to a weakening of this barrier and to its destruction when there is a favorable combination of waves and tides. In the Cantabrian sea, this might occur around equinoxes, almost every year. The destruction of *Punta de Hendaya* (*ría del Bidasoa*) in the forties was obviously caused by the channeling jetty of *Fuenterrabía* (similar to that of *La Rapadoira* in *Foz*); the jetty that was built subsequently on the French side was aimed at reducing the unrestrained impacts. The jetty of support of the spit of *Punta Arena* (*ría deSan Vicente de la Barquera*) built in the fifties was a consequence of that previous experience and the reasons why the same experience was not taken into account in *Foz* in the seventies are unknown.

In the "bar" hypothesis, the spit destruction does not necessarily imply great aftermath problems, while in the "spit" hypothesis this destruction is followed by a process of quick erosion of the eastern beaches, primary source of materials: in the case of *Foz,* the beaches of *Anguieira* and *Altar*; in the case of the *Bidasoa,* the long beach of *Hendaya,* etc. The erosion in the beach of *Hendaya* could not be easyly predicted but in the eighties, the erosion of the beaches of the *ría de Foz* were predicted in advance (DIEZ, 1980). In fact, the prediction may be immediate, as long as the spit origin of the barrier is accepted: the annexe beaches, the natural source of sediments for the spit, will continue being eroded. The physical evidence of this phenomenon is delayed in the case of beaches initially stable or hyperstable, with a complete profile. At first, the slopes of the transversal profiles in the intratidal or submerged beach sections increase, and this implies a lapse of time between the beginning of the process of erosion and its most evident consequence: the backwards motion of the dry beach line at high tides.

In the particular case of Foz the section of the coast between *Foz* and *Rinlo* (Figure 4) can be considered as a quasi-continuous cliff-beach although its transversal profile is not complete (dry beach, strand and submerged beach) at any place. Some sections, as the beautiful beaches of *Los Castros* and *Las Catedrales,* do not have a permanent dry supratidal beach. Some others, usually close to some bay creeks, have a hypercomplete profile with even dunes, as at *Benquerencia* and *Reinante.* And in some beaches the submerged profile is broken by rocky outcrops, as on the beach of *San Miguel de Reinante.* So, the chain of impacts extends to all these beaches. Their continuity and the sedimentological research show the existence of a real eastward net littoral drift, difficult to estimate but much smaller than the transport capacity. When beaches exist, there is an equilibrium between deposited and eroded materials. This general equilibrium however can coexist with punctual deposits or erosions lasting for variable periods of time and in a more or less permanent way. In any case the real problem is to determine whether these cliff beaches have suffered, or can suffer in the future, any impacts consequence of the previous ones. The regression of several beaches (*Benquerencia, San Miguel, La Devesa*) was very noticeable in some stretches, probably accentuated by the typical hyperannual variability of the transversal profile; but as a mater of fact only a few of them had showed a permanent regression. At present, however, there are enough indications of the existence of a widespread regression. Due to the particular nature of the dynamic equilibrium, the length of the beaches, the small intertidal slope of some sections and the presence of some dunes of unpredictable evolution, the total evidence of this fact is obscured by the attenuation and redistribution of the erosive phenomena along over ten kilometers. The signs however are unmistakable, especially in *San Miguel de Reinante.* A regression of this type should be expected if the *ría* has been a drain for large amounts of sediments during the years without the barrier spit as it has happened.

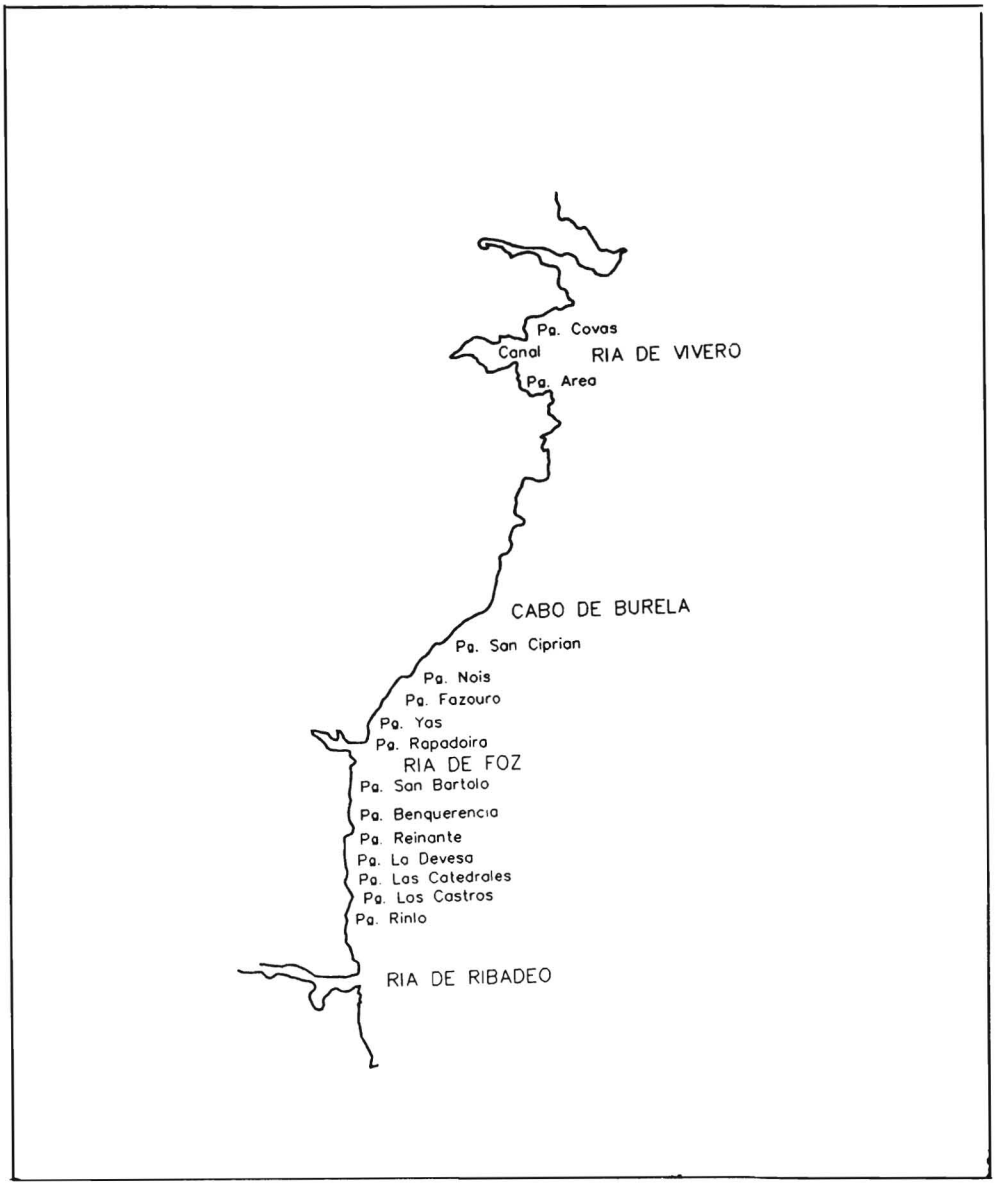


Figure 4. Gulf of Masna and ria of Viver.

Checking Sediment Budget

A singular sediment budget was done in the *ría de Foz,* initially to check the volumes of dredgings and nourishement (ESCOBAR *et al.,* 1991), but it also permited to verify the mentioned morphodynamic model.

The *Ría de Foz* (Figures 2, 4 & 5) is located in the west part of the Cantabrian littoral. It has a south-southwest–north-northeast orientation, with an inflection due to Punta Frondal which gives a sigmoid aspect to the *ría.* The entry mouth to the *ría* is open to the Northeast, with an approximate length of 1000 meters from *Punta de El Escairo* to *Punta de San Bartolomé.* There are two external beaches: *Rapadoira* beach on the left side and *Altar* beach on the right. *Punta Anguieira* tightens the mouth towards the interior of the *ría,* and the sandy spit which supports *Anguieira* beach, of variable size and position, makes even narrower the entrance to the *ría.*

Punta Anguieira shelters the inner beach. In the middle part of the *ría,* there are two leveled geographical features: the *Ensenada de Vilaxoane* and *Punta Frondal.* The inner part of the *ría* goes from this *Punta Frondal* to *La Espiñeira* bridge. Toward the middle of it the bridge and rockfill of the *Ferrol-Gijon* railroad mark the inner limit of the area under study. This 600 meter long construction closes part of the bed of the *ría,* markedly affecting its configuration since the immobilization of the sediments allows the growth of typical

swamp vegetation which is very developed toward *La Espiñeira* bridge.

From *La Espiñeira* bridge to *El Escairo* point the distance is about 3800 meters and from here to the railroad bridge some 2600 meters. The size of the entire *ría* is nearly 2,8 square kilometers. The following cartographic and photographic information (CEPYC, 1985; DIEZ, 1989, 1995) has been taken into account:

(1) Bathymetries.
   a) Relative to the "0" (Datum) of the harbor: Spring 85, August 85, September 86, March 87, September 87, August 88 and February 89.
   b) Relative to the "0" (Datum) of Alicante: the first of September and the fifteenth of November of 1985.
   c) Unknown Datum (probably, that from the La Coruña harbor) and season: 1962–63 and 1970.
(2) Transversal Profiles along 1987–89 on the beaches of *Barreiros, A Rapadoira, Yas* and *San Pedro de Benquerencia.*
(3) General and historical cartography.
(4) Aerial photographies (several types and dates).

The sediment budget in the zone of the *ría* between *Punta del Escairo* and *Punta deSan Bartolomé* was isolatedly considered. It was later extended to the rest of the beaches east of the *ría,* as far as *Rinlo.* The whole *ría* was initially reduced to its main body with its three partial "deposits", while taking into account the flows between them. A fourth deposit would be that of the beach of *La Rapadoira* but it was separatedly considered because of its semi-isolated condition: able to receive material from the other deposits but unable to create a flow towards them until having been replenished. And the area lying beyond *Punta del Frondal* up to the marsh and estuary limits was not included here because it can be considered stable in relation to this problem, given that the materials they have received have been insignificant.

The main body of the *ría* was finally divided in two zones separated by the line defined by the lighthouse, the gorge and the exterior shoreline of the spit and beaches. The indetermination for changes in the natural spit and respect to the present barrier has been solved subdividing the interior zone into two deposits, the "internal" and the "intermediate" (Figure 5). The latter would be the spit, either the natural (before) or the artificial (nowadays). The spit could also be defined by means of the bathimetry, with the isobath of height (+2) as a reference.

Problems for the Balance

In order to make this balance, information about flow and deposit volumes is needed, so that the unknown data may be determined by means of the correspondent equations. As the flows were unknown and no equations could be used for their precise determination, the only way to obtain them was from data about deposit volumes at different times. The bathimetries used for this determination had significant differences among them and among their "datums". An investigation was made in order to determine what level of reference had been used. The application of experimental results to the volumetric estimations, establishing successive upper and lower limits to certain magnitudes, so as to determinate mutually compatible flow values. These values were consistent with those of the morphodynamic model.

A remark must be made, regarding the collected data for this and many other cases: the *0* (Datum) of any harbor is a height below the lowest equinoctial low tide, considering meteorological variations. At present the *0* of *Foz* corresponds to the height (−1.65 m) from Datum of *Alicante,* while the *0* of *La Coruña* is (−1.8183 cm) lower than the *0* of *Alicante.* The harbors of the Cantabrian coast make their bathimetries in relation to the height *0* of the emblematic harbor of each zone: that of *Foz* used to be *La Coruña.* The Spanish "Plan de Costas" however has tried to use a more general system of reference: the *0* of *Alicante* for vertical coordinates and the U.T.M. horizontal coordinates. Due to the simultaneous use of both systems, some discrepancies may have been made in the measurements we have considered.

Besides some apparent contradictions can appear; the two different bathimetries (of all considered) made by the local harbor authorities in 1962–63 and in 1970, for example, must have used the same Datum, (possibly of La Coruña), although it was impossible to know which one. Comparing them however, an erosion in the *ría* and in every section of it is observed, which is in contradiction with the experimental observations; nevertheless it could be explained by the possible differences in the reference level due to athmosferical causes, since meteorological variations of up to 60 cm were recorded, during those years. Differences of up to 30 cm can be compatible with acceptable sea conditions in the interior of the *ría.*

Taking into account this kind of elements for the analysis it was possible to close a good double balance with the following final results which verify all the points of the model.

—Rate of net accretion in the inner zone: 4.000 m3ly. during the existence of the natural spit-barrier (before 1978); 114.000 m3ly. while the spit remained erosioned (1978–86); and 9.000 m^3/year after the artificial regeneration of the spit (1987–91).
—Rate of net accretion/erosion in the external zone: 14.000 m^3/year with the presence of the spit (1987–91 and before 1978); and 100.000 m3ly. in the absence of the spit (1978–86).
—Rate of eolic transport over the present spit: 1000 m^3/year.

And the consequences on the farest eastward beaches (*Benquerencia, San Miguel, La Devesa,. . .*):

—Eastern beaches induced erosion (1978–86): 910.000 (1.400.000 in 1978–93).
—Total volume of accretion at *La Rapadoira* from 1965: 350.000 m^3.

CONCLUSIONS

The Cantabrian *rías* are in a natural process of infilling what makes more and more difficult the accomplishement of their traditional harbor function. This difficulty increased abruptly in the middle of this century due to the new size and characteristics of fishing ships. Granulometries and min-

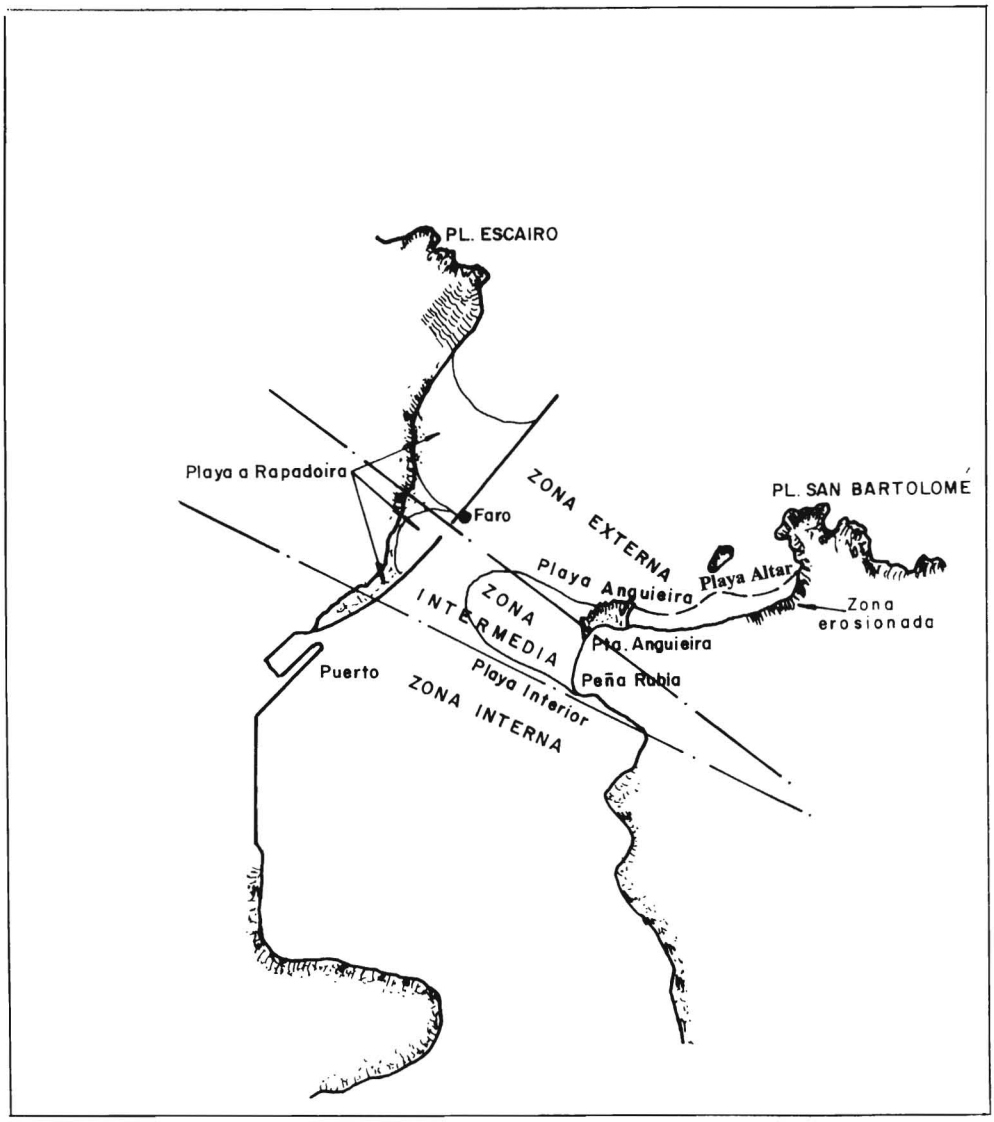


Figure 5. Ria of Foz.

eral composition show the external origin of the sandy sediments, the littoral continuity (with the exception of *Fazouro* mouth and canyon) and the stability of sediment banks in the interior of the *ría*. The supply of materials by the littoral transport, responsible for the infilling processes, is however much lower than the potential one due to the limited availability of sediments and to the structure of the coastal platform.

Harbor actions and navigation infrastructures usually cause impacts on the infilling process. These problems must be solved considering the territorial function of the *rías* and taking into account the natural processes of their modification and the anthropic actions able to improve, transform or destroy them. Morphodynamics are the main aspect to be considered due to their close relation to the environmental circumstances and infilling processes. A difficulty in the investigation usually is the lack of clear references about the Datum of previous bathymetries.

Paradoxical as it is, some actions aimed at improving harbor facilities in the Cantabrian *rías* led to a loss of effectiveness in them. The main reason for this failure is the misinterpretation of the natural formation and evolution of the spit-barriers of the *rías*. In particular, the assumption that a "bar" (formation due to the transversal equilibrium imposed by the waves) is the origin of the gorge barriers of the *rías* must have been the erroneous criterion for projects in the past, as in *Fuenterrabía* in the forties. Nevertheless the awareness of this mistake, deduced from the destruction of Hendaye spit after the works in *Fuenterrabía* could serve for both the posterior defense of the beach of *Hendaya,* and the

project for the harbor and *ría* of *San Vicente de la Barquera*. The hypothesis of a "spit" as the origin of the aforementioned gorge barriers has not yet been assumed however in any project except in the *ría de Foz* (DIEZ, 1986).

A second but simultaneous impact is the destruction of the gorge barrier itself and the ulterior process of erosion of the beaches outside of the *ría,* on the other side of the mouth. The direction of longshore transport in many *rías* (on the shore of the gorge spit-barrier) is westwards, despite the fact that the dominant direction along the open coast and in front of the *ría* is eastwards. This phenomenon is essential to understanding the mechanisms of formation and evolution of the gorge barriers of the *rías,* which separate their internal (sheltered) and external zones; and it occurs in a lot of cantabrian *rías* as well as in many other bays, firths, estuaries and interbarrier inlets. On the other side, the chain of impacts does not end on the beaches close to the *rías*.

The previous conclusions do not imply that harbor actions in a *ría* are incompatible with its natural evolution. They only show that any action in a *ría* must be taken after a careful study of its natural morphology and the dynamic conditions of the littoral, so as to improve navigation without modifying natural processes. These situations, on the other hand are not exclusive of Spanish Cantabrian *rías*. They are also frequent in other kinds of estuaries and bays as in the barrier island-tidal inlet systems of the eastern coast of USA.

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