Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Marine Systems 54 (2005) 261–276
JOURNAL OF MARINE SYSTEMS
www.elsevier.com/locate/jmarsys

Sediment distribution pattern in the Rias Baixas (NW Spain): main facies and hydrodynamic dependence

F. Vilas*, A.M. Bernabeu, G. Méndez

Departamento Geociencias Marinas y Ordenación del Territorio, Universidad de Vigo, 36200, Vigo, Spain

Received 12 January 2003; accepted 1 July 2004
Available online 21 September 2004

Abstract

The analysis of over seven hundred samples of sediments have made it possible to define a detailed distribution of seabed surface sediment properties like grain size, carbonate and organic matter content of the rías of Vigo, Pontevedra and Arousa (NW Spain). Furthermore, the comparison of these three rías allows establishing a general facies distribution pattern for a ría and interpreting the hydrodynamic processes, characterized the marine and fluvial prevalence.

In a simplified way, three main facies domains are characterized that delimit the area of influence of the different hydrodynamical phenomena: (a) siliciclastic sand with gravel, mainly associated with the river mouths, areas of important fluvial influence; (b) siliciclastic mud with high organic matter content, located in the inner and in the deeper areas of the rías, reflecting low wave action; and (c) biogenic sands with low organic matter content located at the margins of the external ría, where the presence of gravel may occasionally occur associated to the more wave exposed areas.

The wide range of wave energy conditions along the rías determines a distinct pattern distribution of facies. Moreover, the comparison of the granulometric characteristics between sediment samples of a ría and a estuary shows that the former is a more energetic sedimentary environment.

Keywords: Rías; Facies distribution; Surface sediment; Hydrodynamics

1. Introduction

The Rías Baixas are located in the western coast of Galicia (NW of the Iberian Península) (Fig. 1). There are four rías, from north to south: Muros-Noia, Arousa, Pontevedra and Vigo. Their characteristic morphology is that of a funnel in plan view, with its central axis lying in a SW–NE direction, and an approximate width of 8–12 km in their external part, and from 1–3 km in their inner part. Depth varies from approximately 50–60 m in the external part to 5–10 m at the mouth of the main river. All of the rías, with the exception of Muros (not included in this study), present rocky islands at their entrance, acting as a

* Corresponding author. Fax: +34 986812556.
E-mail address: fvilas@uvigo.es (F. Vilas).

0924-7963/$ - see front matter
doi:10.1016/j.jmarsys.2004.07.016

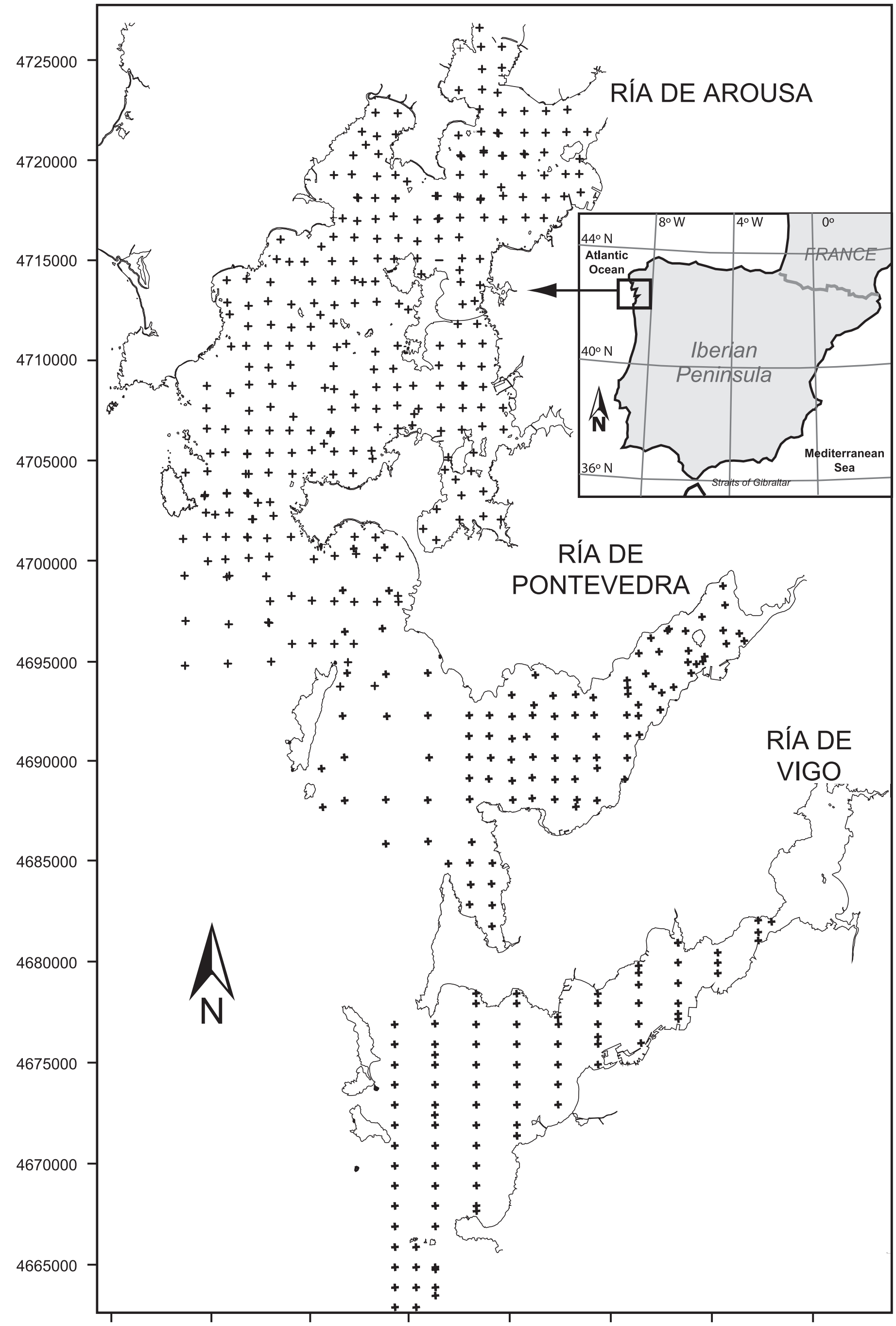

Fig. 1. Sketch of the study area and location of the samples.

shield against incident waves and giving rise to two entrances, the N and the S, each ría being with its own particular features. From a sedimentological viewpoint, Vilas (2002) established a distinction between estuarine and ría sedimentary environments, considering both the textural and compositional data of sediment, and the relative importance of the hydrodynamic phenomena acting on each. This author divides the rías into three clearly differentiated sectors from sea to land: the external and the internal zone and the estuarine area. In this work, based on a considerable number of sedimentary samples collected in the rías of Vigo, Pontevedra and Arousa, the surface distribution of facies is established and a first approximation to the hydrodynamic pattern is presented. Furthermore, the comparison of data on the rías of Vigo and Pontevedra with the data provided by Fleming (2000) for the Dyfi estuary makes it possible to gain a greater knowledge of the differences of the textural characteristics and sedimentary distribution between a ría and an estuary.

Several studies are available about the origin and geology of the Galician Rías (Carlé, 1947; Torre Enciso, 1958; Vidal Romaní, 1984; García-Gil et al., 1999; cfr. Méndez and Rey, 2000). Few studies, however, focus on the knowledge of materials located on their bottoms (Nonn, 1966; Koldijk, 1968; I.N.I., 1979; Rey Salgado, 1993a,b). Nonn (1966) drew up a map based on information on the quality of the bottom recorded on nautical charts at a scale of 1:400,000. The result was a map with four classes (mud, sand, gravel and "rocks"), with no numerical limit among them since these textural classes were established de visu by the hydrographical service. Koldijk (1968) conducted an exhaustive study, exclusively restricted to the ría of Arousa, the larger of the four Rías Baixas, but also perhaps the most different, both physiographical and in terms of its genesis (Nonn, 1966; Pannekoek, 1966a,b). Furthermore, in this study the textural classification by Folk (1954) was modified, reducing the number of classes. Other studies, drawn up by the I.N.I. (1979), I.G.M.E. (1977), Ministerio de Industria y Energía (1976), evaluated the mining potential of the rías of Pontevedra and Vigo, providing information on surface sediments. More recently, Rey Salgado (1993a,b) established the distribution of surface sediments into only three classes: sand, gravel and mud, for the ría of Arousa and in less detail, for the other Rías Baixas and the adjacent continental shelf. Vilas et al. (1995, 1996, 1999) developed an extensive work involving surface sampling and analysis of the same, which concluded with a detailed cartography of the bottom of the rías of Vigo, Pontevedra and Arousa, information used as a basis for this study.

The importance of knowledge of the sedimentary bottoms of the rías is of interest for applied research inasmuch as the Rías Baixas are extremely highly productive areas, where the extensive and intensive exploitation of different species of bivalves are developed. The distribution and evolution of the different types of bottom is a conditioning factor when exploiting this basic resource in the local economy. The intense occupation of the rías by mussels' rafts, whose faecal deposits contribute large amounts of mud to the bottoms, calls for knowledge of their influence on the environment in order to estimate their impact on benthonic species. Also, alterations induced by man along the coastline have led to changes in the sedimentary dynamics, with substantial losses of sediment on some beaches. Therefore, knowledge of the sandy banks available in the rías has been shown to be essential for the adequate development of a beach regeneration policy. In view of the above, cartography of ría sediments is also shown to be useful when developing coastal and marine planning. In terms of basic research, distribution studies on facies make it possible to approach the genesis, evolution and the present and past processes in the rías.

2. Methodology

Studies aimed at gaining knowledge and cartography of the sedimentary bottoms in the rías of Vigo, Pontevedra and Arousa began in 1990. Samples of bottom sediment in these three rías were obtained in the course of three main oceanographic cruises conducted in July 1990, 1991 and 1996, respectively. Seven hundred samples in all were collected and positioned by GPS and echo sounder (Fig. 1). All samples were obtained with Van-Veen grab sampler and box and gravity corers. This study exclusively analyzes surface samples.

Grain size distribution of the samples was determined by standard dry sieving procedure for the fraction of over 63 μm and with a sedigraph (Micromeritics, Sedigraph 5100) for the fine fraction. The results of the granulometric analyses were classified into the groups established by Folk (1954). Carbonate content was determined by gasometrical evaluation using the Bernard calcimeter, comparing with pattern samples of pure calcium carbonate (Guitián and Carballas, 1976). In order to determine organic matter content, the content of organic carbon in the total sample was measured, using the Sawerlandt method modified by Guitián and Carballas (1976). This method lies in the digestion of the powdered sample, with an excess of potassium dichromate in a strongly acidic medium. Then, the dichromate, which had not reacted, is evaluated with Mohr salt, using sulphuric diphenylamine as a marker. The total organic matter was later calculated by multiplying the value of the carbon by the factor 1.724 (Guitián and Carballas, 1976).

3. Results

Grain size analysis of the samples collected in the rías of Vigo, Pontevedra and Arousa made it possible to determine the proportion of gravel, sand and mud in each of them (Vilas et al., 2001). Fig. 2 shows the ternary diagrams of grain size for each of the rías studied. Taking into account the different proportions of each fraction present in the samples, 15 textural classes were defined (Folk, 1954). The class limit values for the gravel fraction were 1%, 5% 30% and 80%. For mud and sand fractions, the ratios shown in Fig. 2a were considered: 1:9, 1:1 and 9:1. Table 1 describes each of these classes. This textural description makes it possible to draw up a detailed distribution map of surface sediments for each ría studied. Comparison of the three sedimentary maps shows a repetitive distribution pattern.

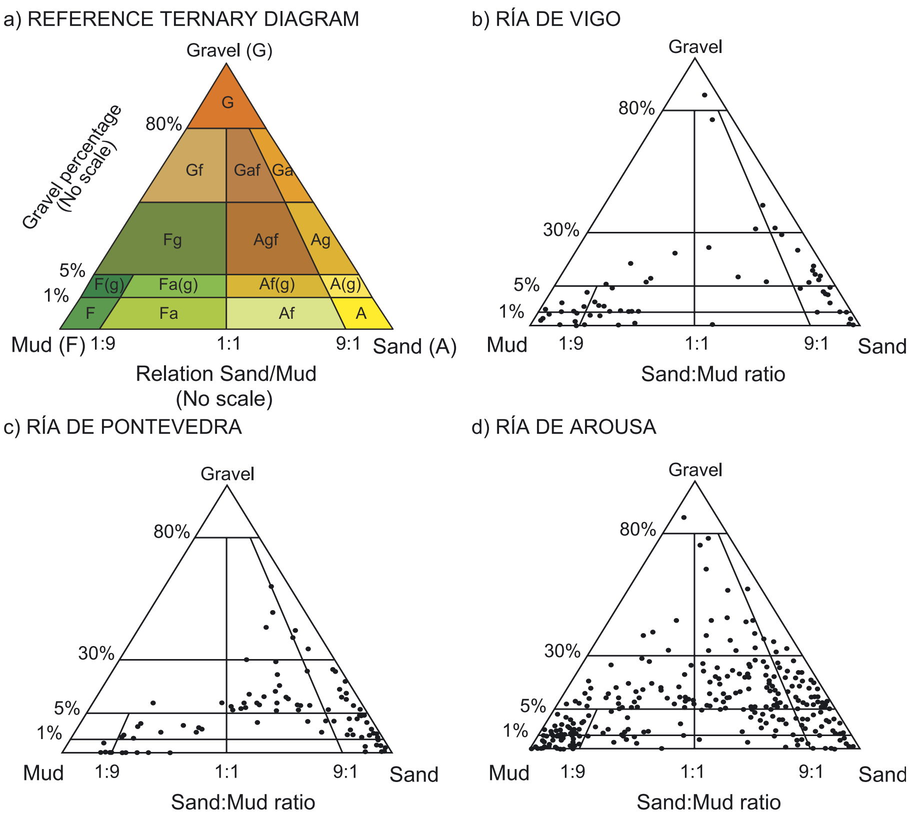

Fig. 2. Ternary diagrams: (a) reference diagram representing the 15 lithological domains considered, (b) characterization diagram of the Ría de Vigo, (c) characterization diagram of the Ría de Pontevedra and (d) characterization diagram of the Ría de Arousa.

Table 1
Textural description of the domains defined

G	gravel
Gf	gravel with mud
Gaf	gravel with sand and mud
Ga	gravel with sand
Fg	mud with gravel
Agf	sand with gravel and mud
Ag	sand with gravel
F(g)	mud with scarce gravel
Fa(g)	mud with sand and scarce gravel
Af(g)	sand with mud and scarce gravel
A(g)	sand with scarce gravel
F	mud
Af	sand with mud
Fa	mud with sand
A	sand

3.1. Ría of Vigo

The sedimentary cover in this ría is characterized by 14 of the 15 classes described, the only type lacking being Gf (gravel with mud) (Figs. 2b and 3a). The classes mainly comprising mud (F, Fa, Fa(g) and F(g)) are located along the central axis of the ría in a lengthwise direction (NE–SW). This type of sediment extends from the innermost and shallowest part of the ría (San Simón inlet) to the internal part, where it occupies the central zone and south side of the ría, and the external area of the ría where its presence restricts on the deepest areas (20–40 m). The Fa (g) domain is the most abundant, occupying the entire central axis of the ría, whereas the other mud domains (F, Fa and F(g)) appear in located areas. A band comprising mud and gravel in variable proportions, between 5% and 30%, lies parallel to the central axis towards the north. This band demarcates the transition to coarser materials, which lay out the north side in the most exterior areas of the ría. I.N.I. (1979) presented a sediment distribution demarcating an ample build-up of mud, coinciding with the more detailed distribution of the mud fields described in this work.

Sand classes (A, A(g), Ag, Af, Af(g) and Agf) prevail on both margins of the ría. On the north side, this field extends in a continuous band, occupying the internal and external area of the ría (Fig. 3a). This field comprises the coarser domains, mainly Agf (sand with a percentage of gravel from 5% to 30% and mud from 10% to 50%). On the south side, the sand class only appears in the more exposed areas of the ría, forming equal sized patches with no lateral continuity. The sand domains with a finer grain size, Af(g) and Af, are associated with the shielding area created by the Islands of Cies. Local build-ups of coarse sand are also found (Ag, Agf) close to the mouth of the river Oitavén-Verdugo. The fields of gravel also appear associated with the river mouth, inside the San Simón inlet and locally in the more protected areas of the north margin of the ría.

Fig. 4a shows the correlation between carbonate content and the grain size of the samples from the ría of Vigo, in line with the descriptions of other areas (Flor, 1980; Macías and Calvo de Anta, 1988; Rubio et al., 1996; López-Galindo et al., 1999). The calcium carbonate content present in the samples is of biogenic origin, deriving from the shells of benthonic organisms and calcareous algae, which develop in this area. The samples mainly comprising mud (in a percentage of over 70%) contain less than 30% carbonate. Their content increases as the percentage of sand and gravel increases in the sample, attaining values of over 90%. This ratio between carbonate content and the grain size is reflected in the carbonate distribution map of the ría (Fig. 5a). The general trend shows a decrease in the percentage from the entrance to the ría towards the estuarine area, coinciding with the distribution pattern for sands and gravels. In the San Simón inlet, the average percentage of carbonates is less than 3%, with a maximum of 36.3%, related to the areas of intense exploitation of bivalves. Towards the internal area of the ría, carbonate content increases from the south side, with less than 10%, towards the north side, where values locally rise from 90% to 100%. In the more exterior part, the central axis presents the lowest carbonate contents, coinciding with mud accumulations. From the axis, the percentage increases radially seawards. The maximum values in this area are found located in the north (60–70%) and south (80–90%) mouth of the ría. This distribution of carbonates and its ratio with grain size makes it possible to describe two prevailing facies in the ría of Vigo: siliciclastic mud and sand with bioclastic gravels.

The ratio between organic matter content and grain size is indicated in Fig. 6a. An inverse behaviour is noted to that of carbonate content, organic matter increasing as the percentage of sand and gravel decreases. This ratio between organic matter and

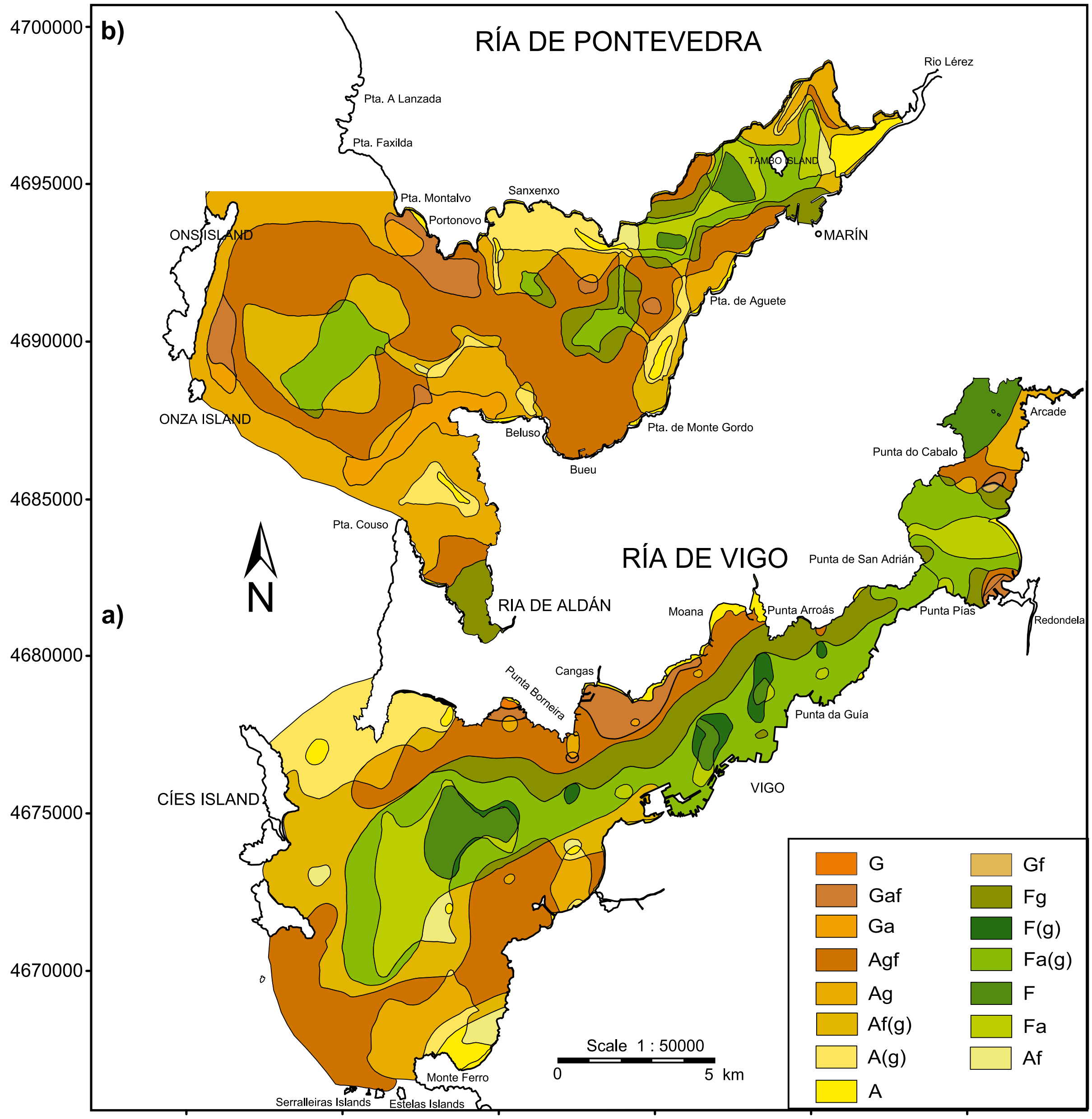

Fig. 3. Surficial seabed sediment distribution map with the 15 textural domains: (a) Ría de Vigo and (b) Ría de Pontevedra.

mud size has already been established (Macías and Calvo de Anta, 1988; Rubio et al., 2000). The distribution map (Fig. 7a) shows an increase in content in two directions, longitudinally towards the estuarine part and from both sides towards the centre of the ría. The maximum values are located in the central axis and in the internal ría, linked to important build-ups of muddy sediment. In this zone, organic matter follows an inverse pattern to that of carbonate content, with maximum values on the south side and a decrease towards the north side. In the more exposed part of the ría, the central axis presents a maximum

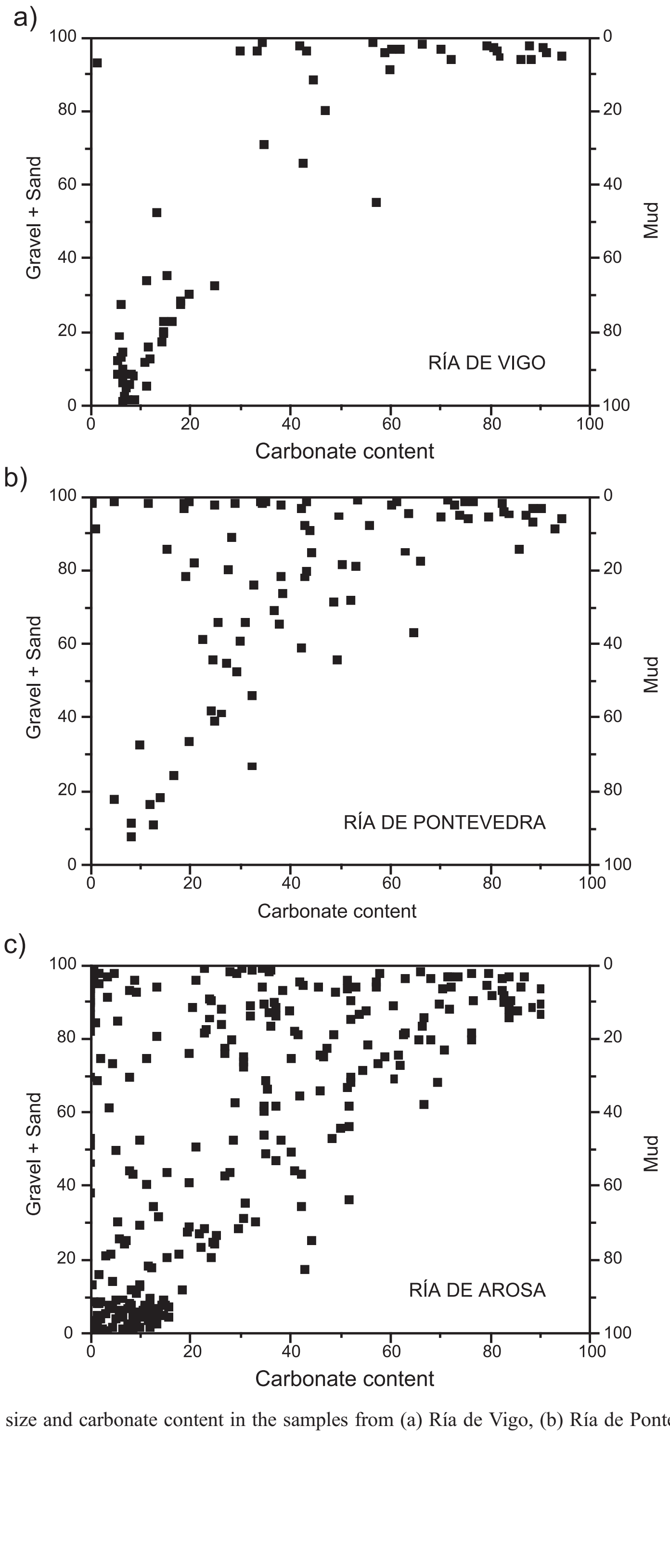

Fig. 4. Relation between grain size and carbonate content in the samples from (a) Ría de Vigo, (b) Ría de Pontevedra and (c) Ría de Arousa.

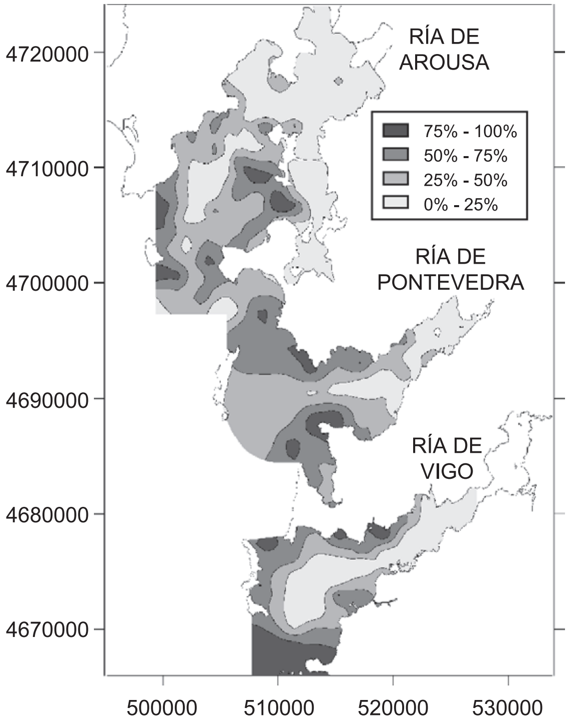

Fig. 5. Carbonate content distribution map in the rías of Vigo, Pontevedra and Arousa.

level of organic matter, decreasing towards both sides and towards the exterior.

3.2. Ría of Pontevedra

This ría presents the most sandy cover among the three studied, where mud content never exceeds 90% of the total of the sample. Classes G, Gf, F(g) and Af, out of the 15 initially defined, do not appear in the samples analyzed (Fig. 2c).

The muddy classes are less abundant than in the ría of Vigo. These fields appear dispersed in discontinuous patches, along the central axis in the internal and estuarine areas of the ría, surrounding the Isle of Tambo, and in the inner part of the Ría of Aldán (Fig. 3b). Coinciding with the study conducted by I.N.I. (1979), a mud patch is located in the shadow of the Isle of Ons. The depth of these areas varies from 5 m near the Isle of Tambo to 50 m at the most exterior point of the muddy domain.

Sandy classes prevail in the surface distribution of sediment in this ría (Fig. 3b). In the estuarine area, the fields A, Ag and Af(g) appear to be associated with the mouth of the Lérez River, and class Agf is located in two bands on both sides of the central muddy axis. This textural class is the most abundant in the internal ría, extending from the central axis to the south margin, with the presence of some muddy build-ups. As occurred in the ría of Vigo, on the north side of this area, Sanxenxo bay mainly comprises by the class A(g). In the external ría, the sediment is arranged in concentric strips. In the centre, a field of muds is located (Fa(g)) surrounded by domains of coarser grain size towards the exterior: Af(g), Agf and Ag, respectively. The domains of gravel occur in localized areas. The most important classes (Ga and Gaf) are situated on the north margin of the external ría, parallel to the coast from Montalbo point to Portonovo.

In the Ría of Pontevedra, the highest content of carbonate appears to be linked to the coarser fractions (Fig. 4b). In contrast with the ría of Vigo, there are some samples with a high content in sand and gravel (>90%) present a low percentage of carbonates (<30%). These samples define a facies of sand with siliciclastic gravel associated with the mouth of the Lérez River at the head of the ría. In spite of that, the Ría of Pontevedra presents the highest content in carbonate out of the three rías, which is related to the greater presence of sandy sediments. The distribution pattern describes a decrease in content towards the estuarine part of the ría in a longitudinal direction, and an increase from the central axis towards the north and south sides (Fig. 5b). In the estuarine area of the ría, near the Isle of Tambo, the percentage of carbonate is less than 10%, associated with a considerable build-up of mud and siliciclastic sand of fluvial origin. The maximum values (75–100%) appear in the more exposed area of the ría, at the south mouth and, occasionally, on the north margin of the internal and external part of the ría.

The relationship between organic matter and grain size shows the same trend as noted before (Fig. 6b). The distribution of organic matter shows an increase towards the internal ría and from the sides towards the central axis (Fig. 7b). The maximum values are located around the Isle of Tambo, where mud is in a majority. Significantly, the sand with siliciclastic gravel present content in organic matter lower than

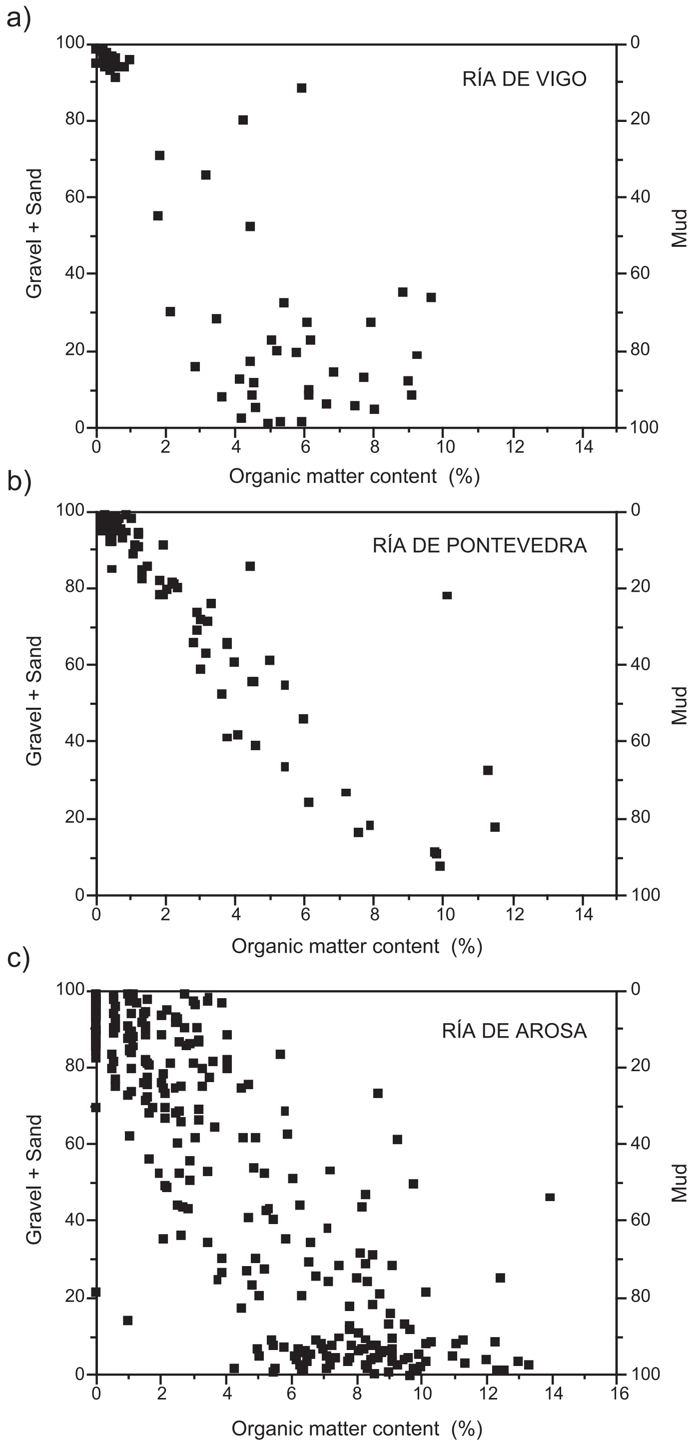

Fig. 6. Relation between grain-size, and organic matter content in samples from: (a) Ría de Vigo, (b) Ría de Pontevedra and (c) Ría de Arousa.

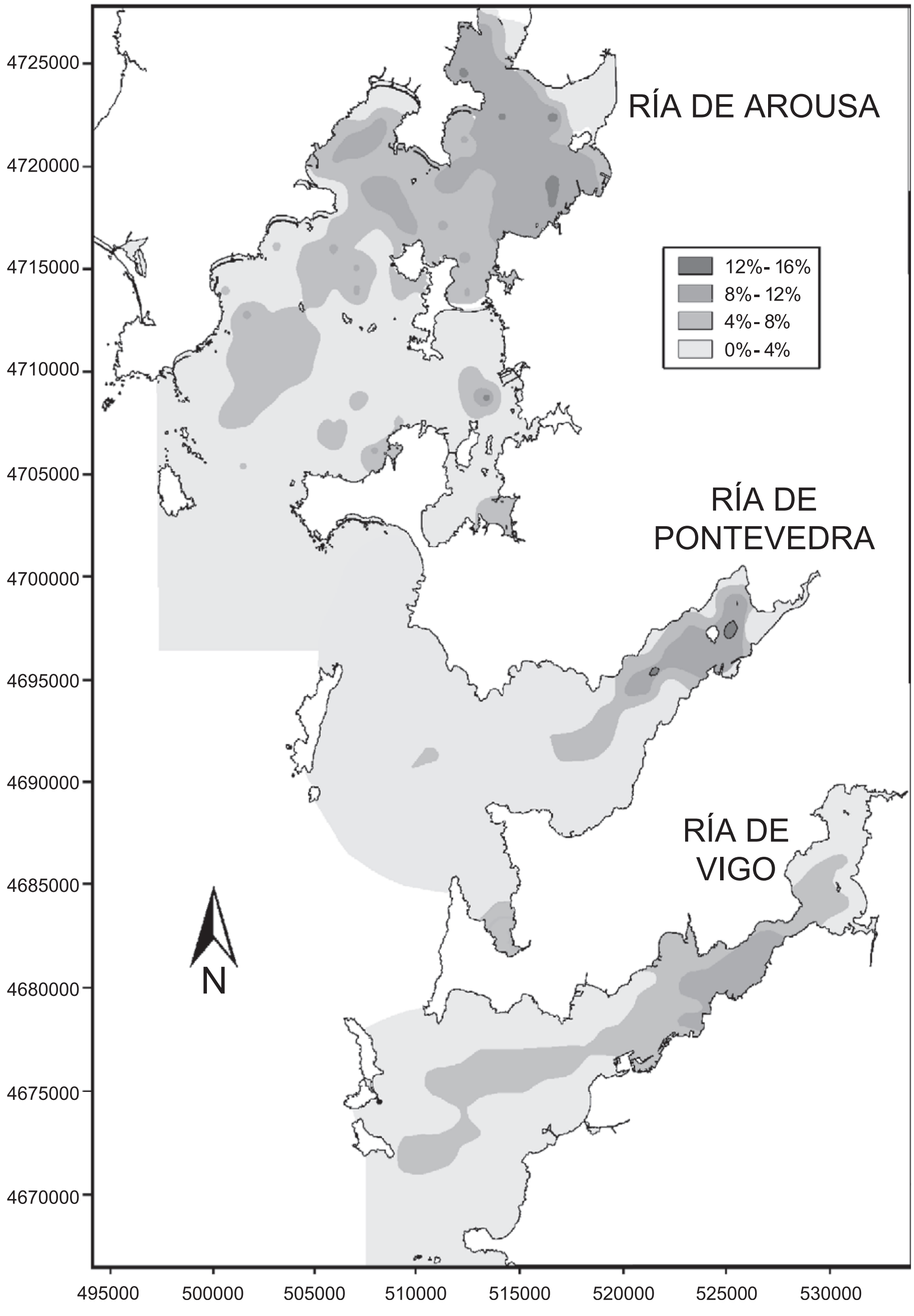

Fig. 7. Distribution map of the organic matter content in the rías of Vigo, Pontevedra and Arousa.

2%, far removed from the maximum values (14–16%) attained at neighbouring points. In the internal and external areas of the rías, the percentage of organic matter does not exceed 6%.

3.3. Ría of Arosa

This is the most heterogeneous of all the rías studied, presenting the highest variability in sedimentary contents, comprising the 15 classes initially defined (Fig. 2d). Koldijk (1968) presented cartography for surface sediment, considering 10 grain size classes. In this work, a greater differentiation between the classes of mud makes it possible to obtain a more detailed cartography. The classes of mud (F, F(g), Fg and Fa(g)) cover the shallower internal area of the ría (Fig. 8). The more abundant domains are F and F(g), attaining approximately 75% of the total surface in this zone. These domains are related to the presence of floating mussel rafts, a type of intensive mussel culture typical of the Galician coast. In the deeper internal area of the ría, the muddy sediments are located coinciding with the main channel in the ría,

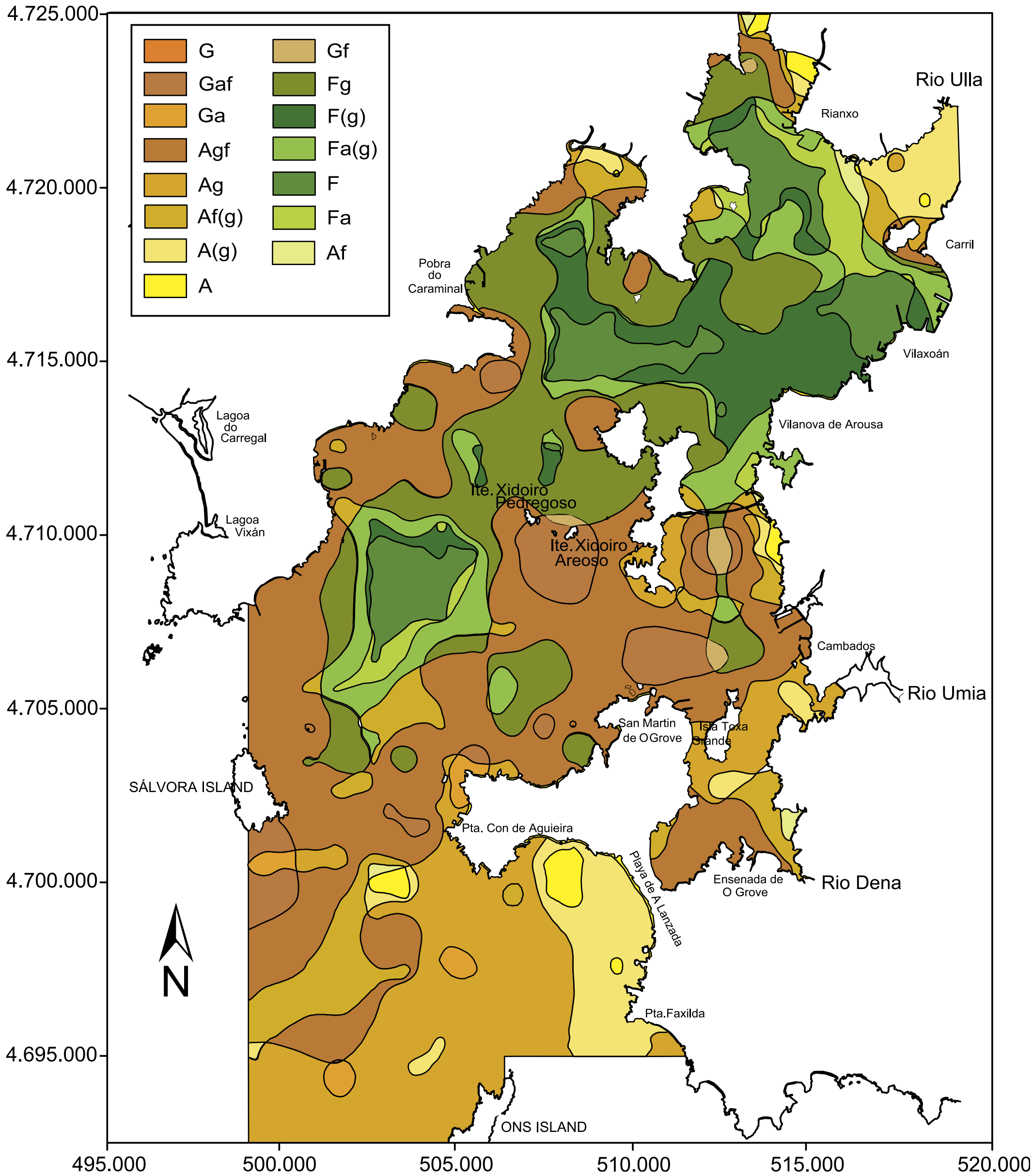

Fig. 8. Map showing the surficial distribution of the 15 textural domains in the Ría de Arousa.

which is slightly displaced northward. The depth, in which muddy domains are found, ranges between 5 m in the innermost part and 50 m in the central part of the muddy fields.

The sandy domains are present in the estuarine area, directly related to the Ulla River (Fig. 8). In the internal sector, the Agf facies occupies the greater part of the extension to both sides (north and south) of the muddy fields. Build-ups of sand in the O Grove bay are associated with the mouth of the Dena and Umia rivers. The inner platform linking the external part of the rías of Arousa and Pontevedra is covered with coarser classes of sand (A, A(g), Ag and Agf) with an increase in grain size from the coast (A Lanzada beach) seawards. The gravel classes (Ga, Gaf and Gf) are mainly present in the internal area of the ría. These are located in shallow areas near the north and south margins or are associated with small rocky isles (Xidoiro Pedregoso and Xidoiro Areoso).

As far as carbonate content is concerned, the estuarine and shallower internal area presents values of less than 10%, with the exception of local maxima rising to values of 50% (Fig. 5c). These peaks are related to the presence of floating mussel rafts. Towards the external area, the range of values is broad, varying from 10% to 90%. Minimum values are concentrated on the central axis of the ría, with maximum depths and high concentrations of mud, and on the south margin, associated with fluvial contributions from continental sands. Occasional peaks are noted of over 90% carbonate content, located south of the isles of Arousa, Xidoiro Pedregoso and Xidoiro Areoso, between the two strips with minimum values, and associated with the north mouth of the ría. In the external area, carbonate content varies from 1 to 84%. The highest concentrations are located south of the Isle of Sálvora and north of the Isle of Ons, which partially seals off the north mouth of Ría of Pontevedra. This distribution shows a correlation between content in carbonates and grain size, as illustrated in Fig. 4c.

The distribution pattern of organic matter defines a decrease in content from the internal towards the external part of the ría, as occurred in the rías of Vigo and Pontevedra. Consequently, in the innermost area the maximum values (13.92%) are found, although the average value is about 10% (Fig. 7c). Towards the exterior area, the maximum value is 12.42%, and is located off the town of Cambados in the most sheltered part of the ría. The average value in this area is 7%, less than the percentage for the innermost areas. Finally, in the external sector, the extreme values do not exceed 4% and the average values 1%. In the Ría of Arousa, the relationship between organic matter and mud obtained for samples in the rías of Vigo and Pontevedra is maintained (Fig. 6c). Content in organic matter in the samples, however, with a different sand-gravel percentage, is more variable. Samples with more than 90% sand and gravel contain up to 4% of organic matter.

3.4. Hydrodynamic implications

The textural trend of the rías of Vigo and Pontevedra are represented on a ternary diagram on the basis of sand/silt/clay ratios (Fig. 9), for samples with a mud contain up to 5%. The major difference between the samples from both rías is caused by their different sand content, because the textural composition of the mud fraction is virtually the same in both cases. This higher percentage of sand in the ría of Pontevedra is related to the location of Ons and Onza islands, at a greater distance from the mouth of the ría, this results in a more intense exposure of the southern part of the ría.

In the same figure, the previous results are compared with data of a different sedimentary environment, in this case the Dyfi estuary (Fleming, 2000). Taking into account the hydrodinamyc models of Pejrup (1988) and Fleming (2000), the location of data within the ternary diagram reflects specific hydrodynamic energy conditions. The closer to the silt endmember, the higher the energy level. Consequently, the difference between the rías and the estuary results in different depositional conditions. This information highlights the presence of finer materials in the estuary (clay content up to 60%), reflecting a less energy-charged hydrodynamic system with a balanced fluvial and tidal contribution.

The data sets corresponding to both rías make clear that a ría is a more energetic environment and presents a facies zonation related to this differentiate depositional conditions. Considering the ría of Vigo data, the samples with a sand content up to 30% correspond to samples located in both margins of the ría. For samples with a sand content less than 30%, the

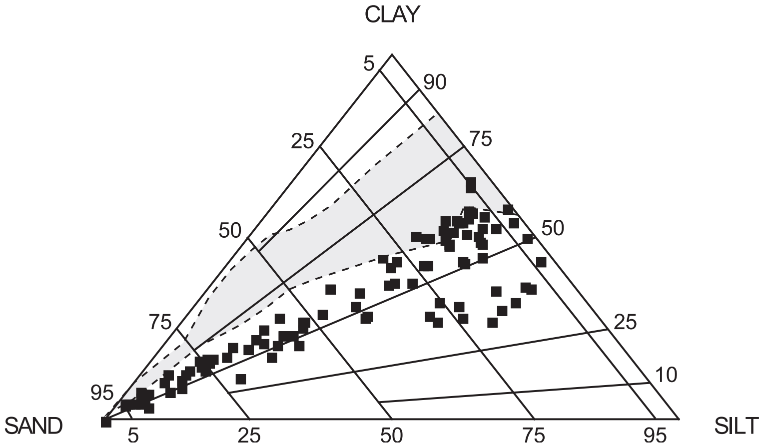

Fig. 9. Ternary diagram proposed by Fleming (2000). The grey band represents the Dyfi's estuary presented. The dots correspond to samples of Ría de Vigo and Pontevedra.

dispersion of the data reflects this energetic zonation. The samples with clay content varying between 25% and 45% correspond to the axial external ría zone; the increasing clay content (45–50%) correspond the samples located in the internal ría and when the clay content goes beyond to 50%, the samples are located in the most internal and protected areas of the ría. As Fleming (2000) proposed, this gradation of the mud textural composition reflects the depositional energy conditions varying along the ría.

4. General facies distribution pattern in a ría system

Surface distribution of grain size follows a common pattern for the three rías studied. The greater concentration of fine materials (silt and clay), with percentages of over 50%, is invariably located in the sheltered, estuarine area where waters are shallower, and on the central axis of the ría with a NW–SE orientation, where depths of up to 50 m are attained. The sandy fractions with higher carbonate contents are distributed on both sides of the build-up of mud, bordering the north and south margins of the rías, in the internal and external sectors. The siliciclastic sandy fractions are presented in the estuarine areas, locally associated with river mouth. This facies distribution is related to a marked energy-depositional conditions variation inside a ría.

The characteristic ría geomorphology determines the marine influence is mainly associated with wave motion which spatially predominates over tidal and fluvial action. The principal wave action is the distribution of bottom sediment both from fluvial contributions (siliciclastic materials) and biogenic origin sediments and the resuspension of the finer sediments (Rey et al., in press). Some previous studies conducted on this area have noted the relationship between waves and the processes of sediment transport and distribution. Thus, García-Gil et al. (2000) and Durán et al. (2001) identified the relationship between wave climate and the genesis of a field of ripples, lying north of the Island of Ons, corresponding to the external sector of the Ría of Arousa. In a further study conducted in the area, Manso et al. (2001) and Rey et al. (2002) established the influence of waves in the distribution and formation of heavy minerals placers in the sub-tidal area of Corrubedo beach, located at the north mouth of the Ría of Arousa.

The spatial extension of wave-action inside the rías is conditioned by two important factors: depth, which varies from values greater than 50 m at the central axis of the external areas to values of 5–10 m in the innermost zones; and the effect of shielding exerted by the islands at the entrance to the rías. The base level of the most frequent wave motions on this coast, from 8 to 10 s period, lies between 50 and 75 m (Rodríguez et al., 2001), this being a depth rarely exceeded in the rías. Therefore, the most frequent waves condition is able to interact with sedimentary bottom of the rías, increasing its influence as depth decreases in the more exposed areas. Thus, in the deeper areas, the milder wave-bottom interaction facilitates decantation of the finer sediments (Rey et al., in press). This situation is favoured by the sheltering effect of the islands at the mouth of the ría, as they attenuate wave motion behind themselves. So in the case of the Ría of Pontevedra, the location of Ons and Onza islands leaves a wide entrance southward across it the waves penetrate more distance landward inside the ría. As a result, this ría has the lowest percentage of fine sediments, its main component being the fraction of medium-fine sized sand. In the rías of Vigo and Arousa, the islands of Cíes and Sálvora, respectively, lie near the mouth of the ría with narrower entrances to the north and south, which exert a great control on waves inside the ría. This situation promotes a higher deposition of fine fractions in the external and internal sectors. The area of influence of wave motion in the rías is defined by the distribution of the coarser textural classes (gravel and sand).

Tidal influence is restricted to the innermost and shallower areas, with the development of tidal channels; and in the narrowing points of the ría that contribute to the tidal current intensification. In the latter case, this effect is also reflected in the intertidal deposits. Queralt et al. (2002, 2003) established a good correlation between sedimentary parameters, beach morphology and hydrodynamic processes, discriminating between the external wave-exposed and the internal tidal-controlled beaches.

Fluvial influence is limited to the areas close to the mouth of rivers. In these cases, the coarser fractions of the transported material are deposited in the vicinity and there is no sufficiently energetic process able to re-distribute this material. The presence of this siliciclastic sand, with low carbonate content, demarcates the area of fluvial influence. Spatial distribution and the importance of these facies vary between rías, depending on the flow rate and drainage basin of the rivers (Figs. 3a,b and 8). Consequently, the Ría of Arousa presents the highest spatial distribution of siliciclastic sand, related to two important rivers: the Ulla and the Umia with drainage basins of 2803 and 440 km^2 and with mean flow rates of 79.3 and 16.3 m^3/s (Río and Rodríguez, 1996), respectively. In the rías of Pontevedra and Vigo, the main rivers, the Lérez and the Oitavén-Verdugo, respectively, have lesser drainage basins (450 and 334 km^2) and mean flow rates (21 and 17 m^3/s) that is reflected in the smaller spatial area of siliciclastic sand facies.

5. Conclusions

Fifteen sedimentary classes have been described to establish a detailed distribution of sub-tidal sediments in the rías of Vigo, Pontevedra and Arousa. Samples analysis has also made it possible to establish the distribution of carbonate and organic matter. The comparison of the results for the three rías allows defining a general sedimentary distribution pattern in a ría. Furthermore, the description of these parameters (grain size, carbonate and organic matter content) makes it possible to differentiate between three demarcated facies in the rías: a siliciclastic muddy facies, a sandy facies with siliciclastic gravels and, finally, a sandy facies with bioclastic gravels. Their bottom distribution delimits the influence zone and the interaction between fluvial and marine action. The main differences between the three rías analyzed are basically associated with variations in these areas of influence. So in the Ría of Arousa, with a higher fluvial contribution, the spatial presence of siliciclastic sands associated with the mouth of the rivers is greater. Whereas in the Ría of Pontevedra, where the shielding effect generated by the island of Ons is less pronounced, bottom sediments present a higher content in sands where, generally, the sediment is coarser than in the other two rías.

The use of the ternary diagram proposed by Fleming (2000) for sampling the rías of Vigo and Pontevedra, has made it possible to not only differentiate between different sedimentary environment, but also define the energetic gradation inside the ría, in terms of their specific hydrodynamic conditions, which are reflected in the facies on the bottom.

Acknowledgements

We would like to thank the Dpto. Geociencias Marinas at the University of Vigo, since this paper comprises information compiled over the last decade. Also many thanks to Dr. Serra, Dr. Morales and Dr. Guillén for their constructive comments. Paper no. 303 of the Marine Geology Group (XM2) of the University of Vigo. Contribution to the projects: REN2003-2822MAR, REN2003-03233, VEM2003-20093-C03-03 (MCYT) and PGIDITT3RMA30101PR (Xunta de Galicia).

References

Carlé, W., 1947. Die westgalischen Meeresbuchten. Natur und Volk 77, 5–14.

Durán, R., Manso, F., Bernabeu, A.M., García-Gil, S., Vilas, F., 2001. Estudio de la dinámica sedimentaria de la plataforma interna gallega: La Lanzada (NO España). Geotemas 3 (1), 145–148.

Fleming, B.W., 2000. A revised textural classification of gravel-free muddy sediments on the basis of ternary diagrams. Continental Shelf Research 20, 1125–1137.

Flor, G., 1980. Los carbonatos biogénicos de la zona intermareal de playa en relación con la dinámica y morfología costeras en Asturias y Cantabria. Boletín de la Real Sociedad Española de Historia Natural 78, 275–289.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. Journal of Geology 62, 344–359.

García-Gil, S., Vilas-Martín, F., Muñoz, A., Acosta, J., Uchupi, E., 1999. Quaternary Sedimentation in the Ría de Pontevedra (Galicia), Northwest Spain. Journal of Coastal Research 15 (4), 1083–1090.

García-Gil, S., Durán, R., Vilas, F., 2000. Side scan sonar image and geologic interpretation of the Ría de Pontevedra seafloor (Galicia, NW Spain). Scientia Marina 64 (4), 393–402.

Guitián, F., Carballas, T., 1976. In: Sacro, Pico (Ed.), Técnicas de análisis de suelos, Santiago de Compostela.

I.G.M.E., 1977. Investigación minera preliminar de la plataforma continental submarina de la costa gallega. Plan Nacional de la Minería. Ministerio de Industria y Energía. Inédito. 55 pp.

I.N.I. [Instituto Nacional de Industria], 1979. Investigación minera de detalle en los fondos submarinos de la zona de las rías de Pontevedra y Vigo (Gali-Rías). Unpublished, 83 pp.

Koldijk, W.S., 1968. Bottom sediments of the ría de Arosa (Galicia, NW Spain). Leidse Geologische Mededelingen 37, 77–134.

López-Galindo, A., Rodero, J., Maldonado, A., 1999. Surface facies and sedimentary dispersal patterns: southeastern Gulf of Cádiz, Spanish continental margin. Marine Geology 155, 83–98.

Macías, F., Calvo de Anta, R., 1988. Arcillas y limos de sedimentos actuales de las rías de Galicia, Consideraciones genéticas. Geociencias 3, 179–187.

Manso, F., Bernabeu, A., Rey, D., Vilas, F., Gago, L., 2001. A genetic model for coastal heavy mineral placers in restricted areas. The case of Corrubedo bay (NW Spain). Abstracts of European Geophysical Society. XXVI General Assembly, Nice, France.

Méndez, G., Rey, D., 2000. Perspectiva histórica del conocimiento geológico de las rías gallegas. Journal of Iberian Geology 26, 21–44.

Ministerio de Industria y Energía, 1976. Investigación minera preliminar de la plataforma continental submarina del área sur de Pontevedra. Inédito. 242 pp.

Nonn, H., 1966. Les régions cotières de la Galice (Espagne). Étude géomorphologique. Publications de la Faculté des Lettres de l'Université de Strasbourg, Paris. 592 pp.

Pannekoek, A.J., 1966. The geomorphology of the surroundings of the Ría de Arosa (Galicia, NW Spain). Leidse Geologische Mededelingen 37, 7–32.

Pannekoek, A.J., 1966. The Ria problem: the role of antecedence, deep wathering, and Pleistocene slope-wash. Tijdschrift van het Koninklijk Nederlandsch Aardrijkskundig Genootschap 83, 289–297.

Pejrup, M., 1988. The triangular diagram used for classification of estuarine sediemtns: a new approach. In: de Boer, P.L., van Gelder, A., Nio, S.D. (Eds.), Tide-Influenced Sedimentary Environments and Facies. Reidel, Dordrecht, pp. 289–300.

Queralt, S., Rodríguez-Fernández, N., Bernabeu, A.M., Rey, D.y, Vilas, F., 2002. Características morfosedimentarias de las playas de la Ría de Vigo: influencia de las condiciones hidrodinámicas. Geogaceta 32, 211–214.

Queralt, S., Rodríguez-Fernández, N., Álvarez-Vázquez, R., Bernabeu, A.M., Rey, D.y, Vilas, F., 2003. Differential beach behaviour in the Ría de Vigo (NW Spain): hydrodynamic influence. Abstracts of European Geophysical Society, XXVIII General Assembly.

Rey, D., Manso, F., Bernabeu, A.M., Vilas, F., Gago-Duport, L., Queralt, S., 2002. Hydrodynamic modelling of heavy mineral placers formation in subtidal conditions. The case of Corrubedo Bay (NW SPAIN). Abstracts of the European Geophysical Society, XXVII General Assembly.

Rey, D., Mohamed, K., Rubio, B., Bernabeu, A.M., Vilas, F., in press. Early diagenesis of magnetic minerals in marine transitional environments: the interaction of primary production, wave climate and water depth. Cuaderni de Geofisica, 26.

Rey Salgado, J., 1993a. Mapa fisiográfico de la ría de Arosa E. 1:50000. Instituto Español de Oceanografía. Publicaciones Especiales, no 15, Madrid.

Rey Salgado, J., 1993b. Relación morfosedimentaria entre la plataforma continental de Galicia y las Rías Bajas y su evolución durante el Cuaternario. Publicaciones Especiales vol. 17. Instituto Español de Oceanografía, Madrid.

Río, F., Rodríguez, F., 1996. Os ríos. As augas de Galicia. Ponencia de Patrimonio Natural. Consello da Cultura Galega, Santiago. 611 pp.

Rodríguez, N., Bernabeu, A.M., Ulla, A., Vilas, F., 2001. Efecto del oleaje sobre el transporte en suspensión en el litoral de la Ría de Vigo. Resúmenes de comunicaciones del Taller de Oceanografía, p. 41. Universidade de Vigo.

Rubio, B., Gago, L., Vilas, F., Nombela, M.A., García-Gil, S., Alejo, I., Pazos, O., 1996. Interpretación de tendencias históricas de contaminación por metales pesados en testigos de sedimentos de la ría de Pontevedra. Thalassas 12, 137–152.

Rubio, B., Nombela, M.A., Vilas, F., 2000. Geochemistry of major and trace elements in sediments of the Ría de Vigo (NW Spain): an assessment of metal pollution. Marine Pollution Bulletin 40 (11), 968–980.

Torre Enciso, E., 1958. Estado actual del conocimiento de las rías gallegas. In: Galaxia, V. (Ed.), Homaxe a R. Otero Pedrayo, pp. 237–250.

Vidal Romaní, J.R., 1984. A orixe das Rías Galegas. Estado da cuestión (1886-1983). Cuadernos da Área de Ciencias Mariñas. Seminario de Estudos Galegos 1, 13–25.

Vilas, F., 2002. Rías and tidal-sea stuaries. Encyclopedia of Life Support Systems. UNESCO-EOLSS (Coastal Zone and Estuaries: Estuarine Systems, 2.6.3.1.). UNESCO, Paris.

Vilas, F., Nombela, M.A., García-Gil, E., García-Gil, S., Alejo, I., Rubio, B., Pazos, O., 1995. Cartografía de Sedimentos Submarinos. La Ría de Vigo. Escala 1:50.000 (Memoria y Mapa). Xunta de Galicia. 40 pp.

Vilas, F., García-Gil, E., García-Gil, S., Nombela, M.A., Alejo, I., Rubio, B., Pazos, O., 1996. Cartografía de Sedimentos Submarinos. La Ría de Pontevedra. Escala 1:50.000 (Memoria y Mapa). Xunta de Galicia. 40 pp.

Vilas, F., García-Gil, E., García-Gil, S., Nombela, M.A., Alejo, I., Francés, G., Méndez, G., 1999. Ría de Arousa. Cartografía de sedimentos submarinos. Escala 1:50000 (Memoria y Mapas). Xunta de Galicia. [Santiago]. 32 pp.

Vilas, F., Méndez, G., Bernabeu, A.M., 2001. Cartografía de los sedimentos de las Rías Baixas gallegas (NW Spain). Abstracts of Taller de Oceanografía, 7.