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Shallow gas features in the Galician Rías Baixas (NW Spain)

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Abstract Areas with gas accumulations and gas escapes have been mapped in two rías from Galicia (Ría de Pontevedra and Arousa) and compared with already published data from the Rías de Vigo (García-Gil et al. 2002) and Muros-Noia (Magariños-Álvarez et al. accepted). Calculations indicate different areas of gas-bearing sediments for each ría. Quantitative data from acoustic plume studies and pockmark densities in the seepage areas were also obtained. In terms of the area of gas-bearing sediment and seeping activity, the Ría de Arousa is found to be the most important from a quantitative point of view. Comparison of the locations of the gas accumulations with grain size distributions of sediments reveals a spatial coincidence with finer surface sediments that are mainly muds.

Introduction

Shallow gas accumulations and gas escape features have been found along the Spanish coast in several environments, such as the Gulf of Cádiz slope (Baraza and Ercilla 1996; Díaz del Río et al. 2003; Pinheiro et al. 2003), the Ebro delta (Maestro et al. 2002) and the Balearic Promontory (Acosta et al. 2001). Some studies were also carried out in some coastal areas of Galicia (NW Spain), mainly in the so-called Rías Baixas region, such as Ría de Muros-Noia (Acosta 1984; Rey 1993; Magariños-Álvarez et al. 2002), Ría de Vigo (García-García et al. 1999; García-Gil et al. 2002), Ría de Pontevedra (Durán et al. 2001) and Ría de Arousa (Ferrín et al. 2001; Diez et al. 2003). These submarine-filled valleys have extensive areas of shallow gas accumulations and frequent occurrences of gas seepage.

Sonograms acquired from high-resolution seismic methods (Uniboom and 3.5 kHz profiler) as well as side-scan sonar and echosounder records were used to map gas-bearing sediment related features and seepage occurrence.

The aim of this paper is to characterize the different appearances of near shore shallow gas in the ría environments of the Rías Baixas region of Galicia.

A review of already published data from the Rías de Vigo and Muros-Noia together with the analysis of newly collected data from the other two rías (Arousa and Pontevedra) from the Rías Baixas region is presented and discussed here.

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The setting

The so-called 'Rías Baixas', located on the northwest coast of Galicia, are systems of river valleys initiated by the drowning of the continental shelf due to the combination of several processes: sea level changes, tectonics and preferential erosion and weathering along faults (Von Richtofen 1886; Pazos et al. 1994; García-Gil et al. 1999).

From north to south the Rías Baixas comprise: the Ría de Muros-Noia, the Ría de Arousa, the Ría de Pontevedra and the Ría de Vigo (Fig. 1).

The Ría de Muros-Noia is the smallest of the Rías Baixas, with an area of 125 km^2. In contrast, the Ría de Vigo, the Ría de Pontevedra and the Ría de Arousa are larger and cover 176.4, 219 and 258 km^2, respectively.

In plan view, they show a funnel-shaped geometry and deep entrances, with a considerable reduction on both dimensions upstream. The seabed topography is a remnant of a paleo-valley carved in the granite basement during the last glacial maximum (~18,000 ka). It was eroded when the sea level was at least 100 m below the present level (García-Gil et al. 1999).

Regarding the distribution of sediments on the seabed, Vilas et al. 1995, 1996, 1999, and FEUGA 2000

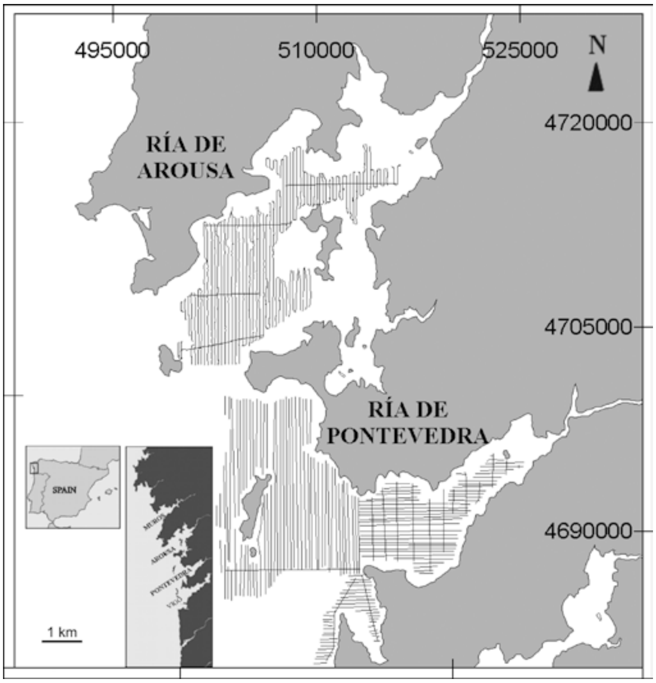

Fig. 1 Map (UTM coordinates) showing the location of the study area and position of high resolution seismic profiles. *Dark lines* represent the location of figures

showed that the recent sediments are composed of both terrigenous and biogenic deposits with a major axial deposit of cohesive sediments relatively rich in organic matter. Towards the shoreline, and in the outer part of the ría, sediments become coarser and are mainly composed of mixed siliciclastic and skeletal sand or gravel. In the case of the Ría de Muros-Noia and the Ría de Pontevedra, the main deposit of finer sediments is located at the inner part of the ría, where marine currents are less energetic. In the Rías de Arousa and Vigo finer sediments are also deposited along its central axis.

From an oceanographic point of view, two very different zones can be distinguished in a ría: an internal area controlled by estuarine conditions, and an external area where marine processes are dominant. The water circulation within the rías is mainly characterized by the presence of seasonal upwelling (Fraga 1981).

The onland geology in the Rías Baixas consists mainly of post-Hercynian plutonic and Palaeozoic metamorphic rocks with N–S and NNE–SSW structural trends. Onshore faults show mainly NE–SW, NNW–SSE and N–S orientations.

Methodology

Geophysical data were acquired during a survey carried out in the summer of 1991 in the Ría de Pontevedra and Arousa (Fig. 1). The survey was conducted along a regular grid with lines spaced 250 m apart. Lines were oriented N–S in both rías, whilst in the inner part of the Ría de Pontevedra W–E oriented lines were also acquired. A total of 952 km of high-resolution seismic profiles were collected using both a high-resolution single-channel reflection profiler (EG&G Uniboom model 230 operating at 300 J), and an ORE 3.5 kHz sub-bottom profiler. In addition, a Klein 595 Side Scan Sonar operated at 100 kHz imaging 150 m on either side of the ship's track, and an Atlas Deso 20 echosounder were utilized. For navigation and positioning, a differential GPS Trimble 4000L System was used.

Results

Gas accumulations

We identified four types of gas accumulation in the Rías de Pontevedra and Arousa using acoustic techniques: acoustic blanket, acoustic curtain, acoustic column and acoustic turbidity. These correspond to the previously described accumulation types in the Ría de Vigo by García-Gil et al. (2002) and Muros-Noia by Magariños-Álvarez et al. (2002), using the nomenclature of Taylor (1992), Hovland and Judd (1988) and Karisiddaiah et al. (1993). The classification is based on seismic signature, geometry and dimensions.

As it has already been observed in the Rías de Vigo and Muros-Noia, acoustic blanket is the most frequent type of gas accumulation recognized in the new data, with a width ranging from 400–3,856 meters along the seismic profiles from the rías (Fig. 2).

Acoustic curtains are not very common seismic features within the Rías de Arousa, Pontevedra and Muros-Noia. This is in contrast with the Ría de Vigo, where acoustic curtains are more abundant. The few that have been identified on the high-resolution seismic records have an average lateral extension along the seismic profiles ranging from 50 to 400 m (Fig. 2).

Acoustic columns and acoustic turbidity are rare in the Rías Baixas. When these types of gas accumulation occur, it is usually close to the previously described types of gas accumulation (Fig. 2).

Analysis of the high-resolution seismic records (Uniboom and 3.5 kHz) from the Rías de Pontevedra and Arousa reveals the presence of areas where gas preferentially accumulates. We will refer to these areas as 'gas accumulation fields' (Fig. 3). Acoustic blankets are the main gas accumulation feature present in these fields, as they are also the most abundant in the records. The few acoustic curtains observed on the seismic records are located around the gas blankets whereas acoustic columns rarely occur outside the fields.

In the Ría de Pontevedra one main gas accumulation field was mapped (PF1) in its inner part (Fig. 3a). The surface area of PF1 is 4.54 km^2, which represents 2.6% of the whole ría area (Table 1).

The Ría de Arousa has six main fields of gas accumulation (Fig. 3b), which is in contrast with the Rías de Pontevedra and Muros-Noia, in which there is only a single field. The biggest mapped field AF1, of 19.1 km^2

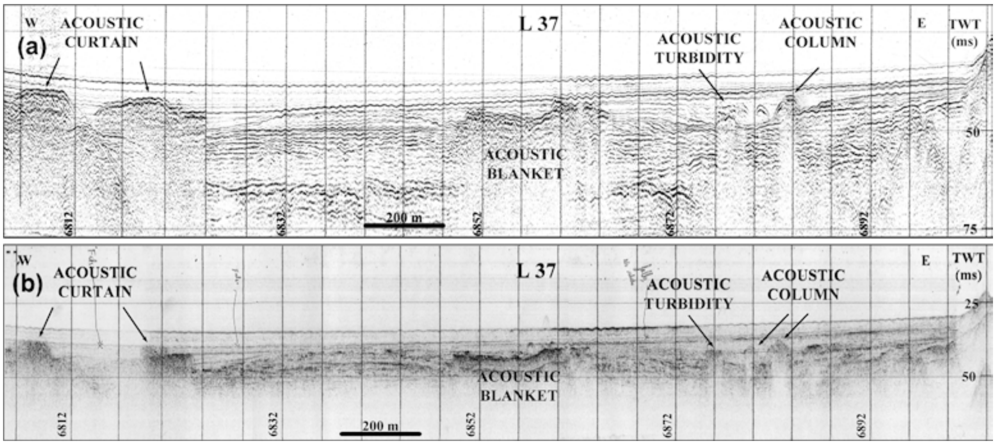

Fig. 2a,b High-resolution seismic record, 3.5 kHz and Uniboom, showing different types of gas accumulation identified in the Ría de Pontevedra: acoustic blanket, acoustic curtains, acoustic columns, and acoustic turbidity

in area, is located in the inner part of the ría, whilst five smaller fields (AF2, AF3, AF4, AF5 and AF6) of 0.17, 1.81, 0.73, 3.26 and 0.19 km^2, respectively, are present at the middle-outer part of the ría central axis. The total surface of these six fields (25.29 km^2) represents 9.8 % of the total area of this ría.

High-resolution seismic records (Uniboom and 3.5 kHz profiler) have been used for depth determination of the upper boundary of the gas accumulations (Table 1). In the Ría de Pontevedra depth ranges from 0 to 12 ms (TWT) and in the Ría de Arousa it ranges from 0 to 8.4 ms (TWT).

Types of gas escapes

There are many indirect indications of gas escape on the different acoustic records. Echosounder, 3.5 kHz profiler, and side-scan sonar have proven to be the best tools for recognizing gas escape features in the rías.

The different acoustic signatures of the sediment surface and the water column are grouped as follows:

Acoustic plumes

High-resolution seismic profiles (3.5 kHz profiler) and echosounder records show the presence of plumes of acoustic turbidity within the water column rising up from the seafloor up to a particular height (Fig. 4). These plumes can appear either as isolated features or in groups forming plume fields. The plumes are often spatially related to gas accumulations (acoustic blankets, acoustic turbidity, etc.) beneath the seabed.

To quantify the gas seeps rising from the seafloor in the rías, we have used the 3.5-kHz profiler sonographs as well as the echosounder records. We have been very

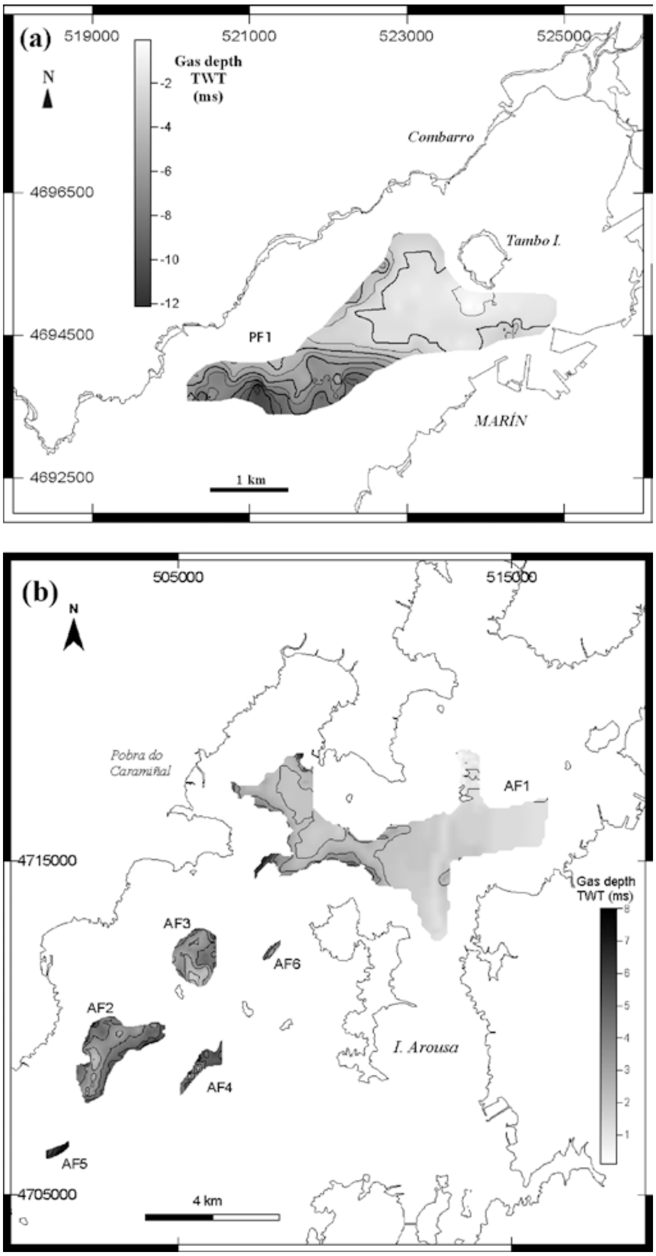

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Fig. 3 Isopach maps from **a** Ría de Pontevedra and **b** Arousa, showing the gas field identified in the sedimentary infill of the rías. *Grey scale* represents depth of the gas upper boundary from the seafloor in milliseconds

Table 1 Quantitative data from the four Rías Baixas of gas accumulations, seeps and pockmarks

	RÍAS	VIGO *(García-García* et al. *1999, García-Gil* et al. *2002)*	PONTEVEDRA	AROUSA	MUROS *(Magariños-Álvarez* et al. *2002, accepted)*
GAS FIELD	**Ría area**	176.4 km^2	219 km^2	258 km^2	125 km^2
	Gas area	12.60 km^2	4.54 km^2	25.29 km^2 (19.1+0.17+1.81+ 0.73+3.26+0.19)	11.5 km^2
	% of the ría area	7 %	2.6 %	9.8 %	9.2 %
	Depth to top of the gas (ms, twt)	0-10 ms	0-12 ms	0-8.4 ms	0-4 ms
SEEPS	**Number identified**	165 seeps	36 seeps	337 seeps	59 seeps
	Mean density in seeping area	1.72 s/km^2	15.7 s/km^2	5.62 s/km^2	7.37 s/km^2
	Mean density in ría area	0.93 s/km^2	0.14 s/km^2	1.31 s/km^2	0.47 s/km^2
	Type	Individual & fields	Individual	Individual & fields	Individual & fields
POCKMARKS	**Number identified**	158 pocks	248 pocks	915 pocks	1940 pocks
	Mean density in seeping area	1.65 p/km^2	14.5 p/km^2	17.6 p/km^2	97 p/km^2
	Mean density in ría area	0.89 p/km^2	1.13 p/km^2	3.97 p/km^2	15.52 p/km^2
	Dimensions diameter-long & small axes	Elliptical: 6.8 4.6 m	Circular: 1.6-4.8 Elliptical: 3.2-8 2.4-6.9	Circular: 3-50 m	Elliptical: 5.9-8.2 0.6-1.0

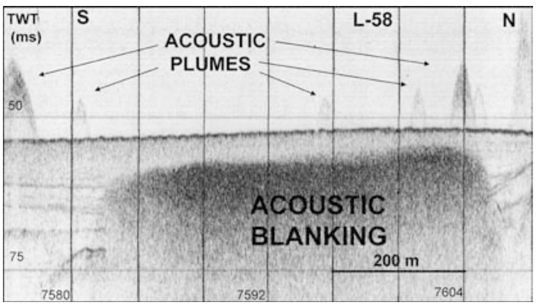

Fig. 4 High-resolution seismic record, 3.5 kHz, from the outer part of the Ría de Arousa. It shows some gas seeps surrounding an acoustic blanket. Seeps are clearly detected in the record as *acoustic plumes* in the water column

conservative in resolving these gas targets, counting only those seeps recognized by both methods.

For density calculations, we have divided each ría into cells, each one with an area of 1 km^2. By assigning every seep into the geographically appropriate cell, we obtained the representative density of gas seeps per km^2 affecting the water column.

Acoustic plumes in the Ría de Pontevedra are located in the inner part of the ría (Fig. 5a), surrounding the gas accumulation field area (PF1). From 3.5-kHz profiles and echosounder records, a total of 36 gas seeps have been identified (Table 1). This represents a density of 15.7 acoustic plumes/km^2 in the seeping area (2.3 km^2). Considering the total ría area (219 km^2), density would

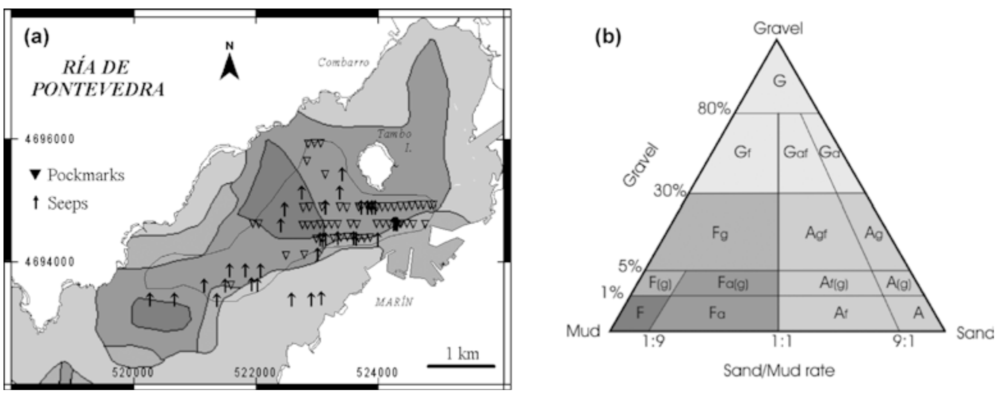

Fig. 5 a Map showing the location of pockmarks and seeps in the Ría de Pontevedra. *Solid line* represents the contour of the shallow gas field and the *grey scale*, the depth in ms of the gas field top. **b** Legend of sedimentary distribution at the seabed

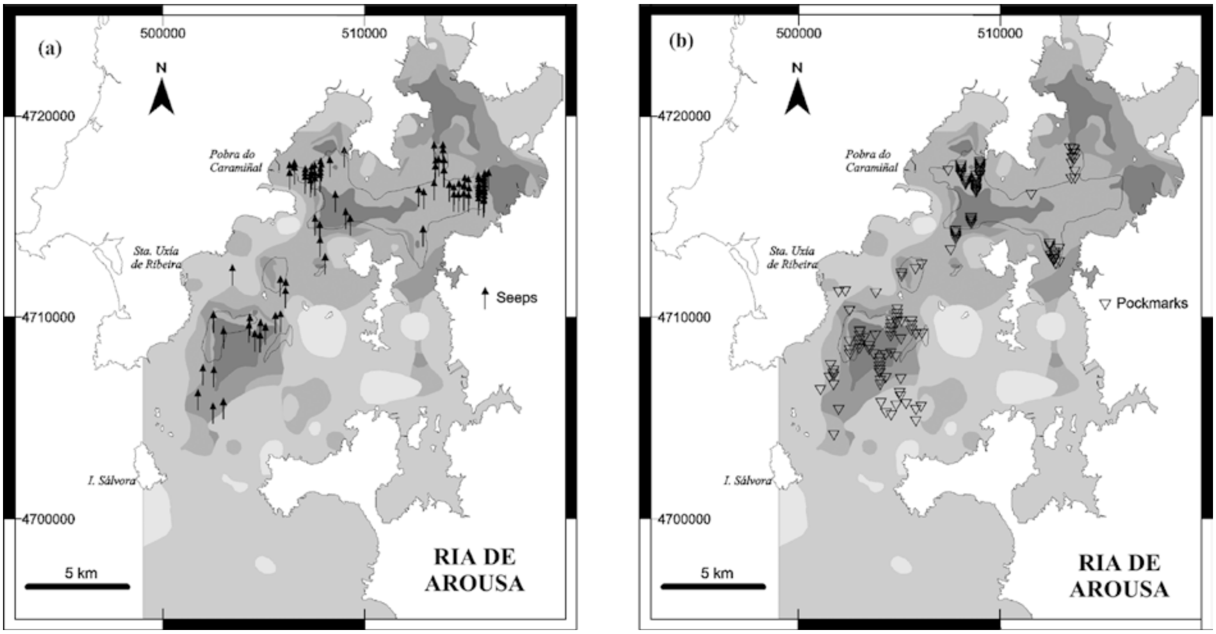

Fig. 6 Sedimentary distribution maps (legend in Fig. 5b) of the Ría de Arousa where it has been included the location of seeps in the water column (**a**) and pockmarks (**b**)

be 0.146 acoustic plumes/km^2. Gas seeps appear here as individual features rising several meters into the water column.

The acoustic location of the plumes in the Ría de Arousa matches with that of the gas accumulation fields (Fig. 6a). In the inner part of this ría, acoustic plumes occur basically on both sides of the gas accumulation field (AF1), some of them at the outermost parts of it. At the middle-outer zone of the ría they appear in between the gas accumulation fields (AF2, AF3 and AF4), sometimes overlapping them.

A total of 337 gas seeps have been identified in the Ría de Arousa, which implies a density in the seeping area (97 km^2) of 5.62 seeps/km^2, and 1.31 seeps/km^2 in the whole ría area (258 km^2).

Acoustic plumes have been recognized at the middle-outer part of the ría as individual features whilst at the inner part they appear to form high-density seep fields.

Pockmarks

Pockmarks represent morphological evidence of fluid escape from the seafloor. On side-scan sonar records pockmarks appear as dark spots called *eyed-pockmarks* by Hovland (1989). Pockmarks can either be rounded or elliptical, with different diameters for each ría. The echosounder and 3.5-kHz profiler records, show v-shaped features of 0.4–1.3 m deep on the seabed surface (Fig. 7). We keep the original term *pockmark* (King and MacLean 1970) due to its worldwide use. Hovland and Judd (1988) confirmed the theory that these depressions originate because of fluids escaping from the seabed, adding that in most cases the escaping fluid is gas. For calculation of the density of the pockmarks, we have applied the same method already used for density calculations of seeps (Table 1). In the study rías, pockmark locations coincide with the area where the acoustic plumes appear.

A total of 248 pockmarks have been identified on Side Scan Sonar records from the Ría de Pontevedra

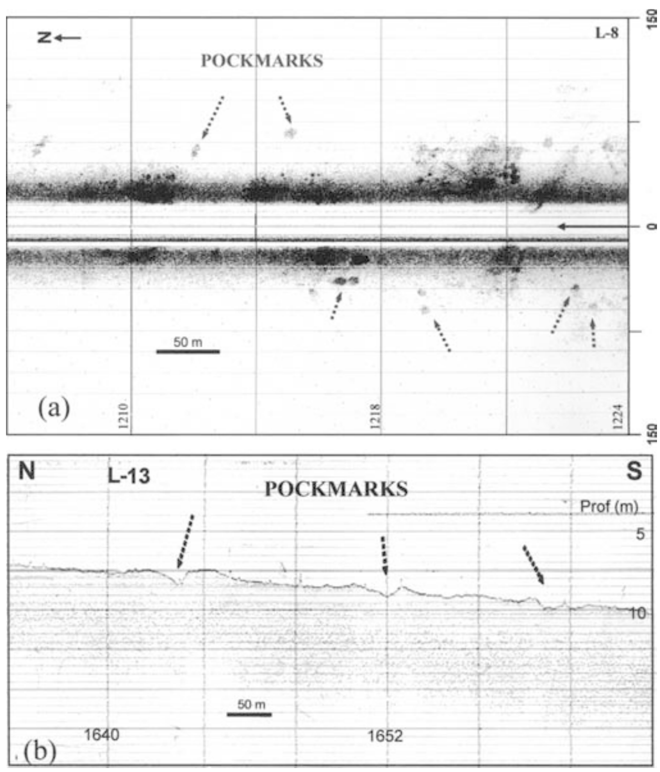

Fig. 7 Pockmarks in the Ría de Arousa in two different reocrds: **a** Side scan sonar, and **b** Echo sounder

(Fig. 5a), showing a density of 14.5 pockmarks/km^2 in the seepage area, and 1.13 pockmarks/km^2 when considering the whole ría area. The pockmark shape as interpreted on Side Scan Sonar records can be either circular (with diameters from 1.6 to 4.8 m) or elliptical (with a long axis from 3.2 to 8 m and a small axis from 2.4 to 6.9 m).

In the Ría de Arousa 915 pockmarks have been identified (Fig. 6b), giving a density of 17.6 pockmarks/km^2 in the seepage area (52 km^2) and 3.97 pockmarks/km^2 across the whole ría area. Pockmarks from the Ría de Arousa have a circular shape, and their diameter is variable. Those from the inner part of the ría are the largest, reaching a maximum diameter of 50 m (Fig. 7). Pockmarks found in the middle outer area are smaller, with a diameter ranging from 3 to 10 m.

As it was found in the case of the gas accumulations, the comparison of gas escape related features location with grain size distributions of surface sediments in the study rías reveals a spatial coincidence with finer surface sediments, mainly mud (Vilas et al. 1995, 1996 and 1999; FEUGA 2000), but in this case small percentages of sand and gravel are also present.

Discussion

For a quantitative and qualitative comparison of the different appearances of near shore shallow gas in the Rías Baixas region of Galicia, new results from the Rías de Arousa and Pontevedra are discussed with previously published data from the Rías de Vigo and Muros-Noia.

Four types of gas accumulations have been identified and characterized in the study area. These types coincide with those found in the Ría de Vigo by García-Gil et al. (2002) and Ría de Muros-Noia by Magariños-Álvarez et al. (2002). García-Gil et al. (2002) suggested that the porosity of the facies where gas accumulates and the seal facies determines the type of gas accumulation and escape feature.

Mapping of the distribution of these features has enabled the recognition of different main gas accumulation fields. The presence of an inner gas field is a common characteristic in the four rías. Additionally, five smaller fields (AF2, AF3, AF4, AF5, and AF6) are present in the Ría de Arousa at its middle-outer part (Fig. 3b), and one further field is located at the central axis of the Ría de Vigo.

The data show that Ría de Arousa presents the largest area of gas-bearing sediments (22.26 km^2), followed by Ría de Vigo (12.6 km^2), Ría de Muros-Noia (11.5 km^2) and Ría de Pontevedra (4.54 km^2) (Table 1). Considering the entire surface of each studied ría, gas-bearing sediments area represents similar percentages in the Ría de Muros-Noia and in the Ría de Arousa (9.8 and 9.2%, respectively). In the Ría de Vigo it represents 7% and in the Ría de Pontevedra only 2.6%.

Gas accumulations are spatially coincident with present fine-grain sea-bottom sediments, mainly mud (Vilas et al. 1995, 1996 and 1999; FEUGA 2000). This mud corresponds to the youngest Holocene seismic unit (García-Gil et al. 2000) and constitutes the seal for the gas accumulations (Figs. 5, 6). Fine-grain sediments are preferentially concentrated at the inner part of the four rías. Additionally, the Rías de Arousa and Vigo accumulate mud also along their central axes. This sediment distribution pattern explains the presence of a main inner accumulation field in all the rías, but also the extra gas accumulation fields occurring in the central axis of the Rías de Vigo and Arousa.

In the Ría de Muros-Noia gas accumulations occur at shallower levels than in the other rías (Magariños-Álvarez et al. 2002); (Table 1). This can possibly be due to a facies control (permeability, organic matter content).

Direct gas analyses were not available until recently. New data from the Ría de Vigo (García-Gil, this volume) demonstrates the presence of methane in the gas. Bacterial degradation of organic matter in shallow sediments is considered the most likely source for the gas. This conclusion is strengthened by Acosta (1984), who suggested that 7% of organic matter in the sediment would be enough to generate sufficient gas to produce acoustic masking.

Analysis of high-resolution seismic records (3.5-kHz profiler) and echosounder records has allowed us to map areas where gas escapes from the seafloor in the study rías (Figs. 5, 6). Data show that acoustic plumes are located in close association with gas accumulation fields, generally at the outermost parts of them. The gas accumulations are found to be the source of the escaping gas, as it is shown in the high-resolution seismic records (Fig. 4). In these areas the porosity of the overlying facies would not be low enough to constitute an efficient seal, allowing the gas to be released in different ways (i.e. pockmarks and acoustic plumes).

Quantitative data from the four rías reveal that acoustic plumes are up to ten times more frequent in the Ría de Arousa water column than in the other rías (Table 1). This can be explained by the fact that Ría de Arousa is also where gassy sediments are more abundant. It is also noticeable that, where acoustic plumes were mapped, muddy sediments are present on the seabed, but with a small percentage of sand and gravel. The presence of these coarser size sediments might be responsible for the decreasing efficiency of the seal, thus allowing gas release as seeps.

In the Ría de Arousa, acoustic plumes appear both as high-density seepage areas (seep fields), and as individual features. Seep fields mainly occur in the inner part of the ría, representing high-activity seeping areas.

In the Ría de Pontevedra, acoustic plumes appear only as individual features and in a small area, indicating that gas seeping processes are more intense in this ría than in the other two. This fact is also in direct relationship with the smaller gassy sediment surface that occurs in Ría de Pontevedra.

Side Scan Sonar, echosounder, and the 3.5-kHz profiler were used to recognize and map pockmarks in the study rías (Figs. 5, 6). Pockmarks occur at the same areas as the acoustic plumes, and show a similar distribution. These pockmarks were formed in the areas where cohesion of the overlying facies would not be enough to constitute an efficient seal, allowing the gas to be released. But this cohesion would be higher than in the facies where seeps occur and no pockmarks appear. This fact would provoke sediment collapse after the explosive release of gas with subsequent pockmark formation.

The inner part of the Ría de Arousa is characterized by large pockmarks (ranging from 25 to 50 m; Fig. 6b) whilst it is in the Ría de Muros-Noia where the greatest density of pockmarks has been found (Magariños-Álvarez et al. 2002). The pockmarks described in the Ría de Arousa have not been recognized at any of the other rías, which implies that gas seeping in this ría can be quantitatively more important. A higher gas pressure in this area plus an increase in the sediment cohesion would be responsible for the formation of these big pockmarks.

Conclusions

Areas with gas accumulations and gas escapes have been mapped in two rías in Galicia (Rías de Pontevedra and Arousa). These new data have been compared to previous data from Ría de Vigo (García-Gil et al. 2002) and Ría de Muros-Noia (Magariños-Álvarez et al. 2002).

Gas accumulation types coincide with those found in the Ría de Vigo (García-Gil et al. 2002) and Muros-Noia (Magariños-Álvarez et al., accepted): (1) Acoustic blanket (2) acoustic curtains (3) acoustic columns, and (4) acoustic turbidity. Acoustic blanket is the most frequent type of gas accumulation identified in the four rías.

Calculations indicate that the extent of gassy sediments is more important in Ría de Arousa (25.29 km^2) than in the other Rías Baixas (Ría de Pontevedra: 4.54 km^2, Ría de Muros-Noia: 15.5 km^2 and Ría de Vigo 12.60 km^2).

Quantitative data about acoustic plumes in the seepage area of the Rías de Pontevedra and Arousa show densities of 15.7 and 5.62 seeps/km^2, respectively. These values are in contrast with previous data from the Ría de Vigo and Muros-Noia, where the densities are 1.72 and 7.37 seeps/km^2, respectively.

Seeping activity is more important in the Ría de Arousa, where 337 seeps where found. Nevertheless, it is in the Ría de Pontevedra where seeps are more concentrated within the seepage area.

Densities of pockmarks in the seepage area of the rías and previous data from Rías de Vigo and Muros-Noia reveal that the Ría de Muros-Noia concentrates the highest density of pockmarks, with 97 pockmarks/ km^2, about six times greater than the others (Magariños-Álvarez et al. 2002).

From all these data, the Ría de Arousa is found to be, in quantitative terms of gassy sediments surface and actual seeping activity, the most important. The Ría de Muros-Noia is where pockmarks are most abundant.

Comparison of the locations of the gas accumulations and gas escape related features with grain size distributions of sediments reveals a spatial coincidence between both gas fields and finer surface sediments, consisting mainly of muds. This mud corresponds to the youngest Holocene seismic unit (García-Gil et al. 2002) and constitutes the seal for the gas accumulations. Nevertheless, pockmarks and seeps could be associated with the presence of small percentages of coarser sediments with the mud. Their presence would increase seal permeability, allowing the gas to be released. The appearance of seeps or pockmarks will depend on small differences in the sediment cohesivity as well as on the quantity of gas diffusing up.

All these new data evidences from the Rías de Pontevedra and Arousa together with the pre-existing data from the Ría de Vigo and Muros-Noia reveals that the Rías Baixas as a whole present similar behavior with respect to gas accumulation types and the presence of gas related features. Nevertheless, there are quantitative differences between the rías. These can be explained in terms of variations in the sedimentary distribution patterns within the Rías Baixas, as a result of differing marine dynamics and physiography.

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