PERGAMON

Continental Shelf Research 22 (2002) 2303–2315

CONTINENTAL SHELF
RESEARCH

www.elsevier.com/locate/csr

Shallow gas features in incised-valley fills (Ría de Vigo, NW Spain): a case study

S. Garcia-Gil*, F. Vilas, A. Garcia-Garcia

Dpto. Geociencias Marinas y Ordenación del Territorio, Facultad de Ciencias de Vigo, Universidad de Vigo, 36200 Vigo, Spain

Received 1 December 1998; received in revised form 1 July 1999; accepted 1 September 1999

Abstract

Areas with gas accumulations and gas seeps, where gas escapes from the seabed to the water column have been mapped in the fill of a submarine incised valley, the Ría de Vigo. The various gas features have been classified into four types according to their specific seismic signatures: (1) acoustic blanket, (2) acoustic curtains, (3) acoustic columns, and (4) acoustic turbidity. At the same time, three types of gas escapes features have been distinguished: (1) acoustic plumes, (2) cloudy turbidity, and (3) pockmarks. Calculations indicate mean densities of 1.7 acoustic plumes km^{-2} and 1.6 pockmarks km^{-2}. Estimations of the gas fluxes towards the atmosphere range from 144.37 to 4134.9 $\mathrm{t\,yr}^{-1}$. It is concluded that sedimentary facies is the main factor determining whether gas accumulates or seeps, and also determines the specific type of accumulation or seep at each location.

Keywords: Acoustic records; Shallow gas accumulations; Gas seeps; Ría de Vigo

1. Introduction

The presence of shallow gas within seafloor sediments has been recognized as a feature of seafloor sediments for a long time. Since the 1950s, different anomalies on echo sounder and side-scan sonar records have been interpreted as being indicative of gas escaping from the seabed. The incorporation of seismic sub-bottom profiling surveys has provided conclusive evidence for gas accumulations within the shallow seafloor sediments.

Schüller (1952) was the first to relate the masking effect on echosounder records to free gas in shallow marine sediments. He named it the “basin effect” (*Beckeneffekt*).

Since the earliest report of gases in marine sediments (Emery and Hoggan, 1958), different authors have reported concentrations of methane and other gases in near-surface marine sediments (Fader, 1991; Fader and Buckley, 1995; Hovland and Judd, 1988; Davis, 1992; Karisiddaiah and Veerayya, 1996; Solheim and Larson, 1987; Veerayya et al., 1998; Wever and Fiedler, 1995). There are also many papers which consider the appearance of gas in coastal areas such as bays or estuaries (Acosta, 1984; Fader, 1991; Hempel et al., 1994; Hovland and Judd, 1988; Karisiddaiah et al., 1993; Kelley et al., 1994; Pickrill, 1993; Taylor,

---

*Corresponding author. Tel.: +34-986812651; fax: +34-986812556.

E-mail address: sgil@uvigo.es (S. Garcia-Gil).

PII: S0278-4343(02)00057-2

1992). Along the Spanish coast, shallow gas accumulations have been found in several environments, Golfo de Cádiz slope (Baraza and Ercilla, 1996), Ría de Muros y Noia (Acosta, 1984) and Ria de Vigo (Garcia-Gil et al., 1997, 1998).

Seabed pockmarks were first reported by King and McLean (1970) from the continental shelf off Nova Scotia, Canada. Subsequent reports from many other areas around the world have demonstrated that pockmarks are more than mere geological curiosities of only academic interest. Not only does the venting of gas from the seabed represent a significant erosional process (Driscoll and Uchupi, 1997), thus affecting the emplacement of structures on the seabed, but it also plays a role in biological productivity. Dando et al. (1994a) studied the effects of methane gas seepage at an intertidal/shallow subtidal area on the Kattegat coast of Denmark and found that epifauna was more abundant in the seep zone.

Quantitative data on gas flux rates from seabed seepages has been forthcoming from only a few authors (Hovland and Sommerville, 1985; Dando et al., 1994a, b; Judd et al., 1997; Gaedicke et al., 1997; Dimitrov, 1998; Garcia-Garcia et al., 1998).

Worldwide concern for the warming of the planet through the "Greenhouse effect" has highlighted the possibility that gas venting from the sediments beneath the oceans may be making a significant, yet not very well known, contribution to atmospheric methane and CO_2 concentrations.

The aim of this paper is to characterize the different appearances of nearshore shallow gas in an incised valley fill, taking as an example the Ría de Vigo. This submarine filled valley has extensive areas of shallow gas accumulations and frequent occurrences of gas seepage.

2. The setting

The Ría de Vigo (Fig. 1) is located on the passive Atlantic margin of south western Galicia (NW Spain). The Ría physiography shows a distinctive funnel shape in plan view. The Ría de Vigo is one of the Rías Bajas which trend at nearly right angles to the region's Paleozoic basement structure. The basement is composed of Palaeozoic metamorphic and granitic rocks cut by NE–SW, NW–SE and N–S trending faults. It is possible that the Rías are related to the post Pyrenean extensional phase, during both the Oligocene and Miocene. The sediment fill in Pontevedra indicates that deposition along the eroded fault zone began during the emplacement (Garcia-Gil et al., 1999).

The water depths within the Ría de Vigo range from 7 m in its inner part, up to 53 m at the outer (southwest) entrance to the sea. The grain-size distribution at the present seafloor of the Ría consists of mixed siliciclastic and skeletal gravels in both the outer area and the edges of the Ría. The central and inner parts of the Ría are dominated by clay and silt which have up to 10% organic matter content (Vilas et al., 1995).

3. Data acquisition

A total of 640 km of seismic lines were acquired and interpreted in detail in order to detect gas accumulation signatures (Garcia-Gil et al., 1997, 1998). The survey was performed as a rectangular grid with lines spaced 66–550 m apart (Fig. 1). The data were acquired using high-resolution single channel reflection profilers (E.G. and G. Uniboom Catamaran Model 230 operating at 300 J, and an ORE 3.5 kHz subbottom profiler). An Atlas Deso 20 echosounder and a side-scan sonar (Klein Model 595 operating at 100 kHz on three channels with a 150 m scan on each channel) were also employed. Navigation and position fixing were performed using a Trimble 4000 RL Differential GPS station combined with a transponder unit. X-ray photographs of a gravity core (Fig. 2) has also been used as direct evidence of the presence of gassy sediments.

4. Types of gas accumulations

The gas accumulations in the Ría de Vigo have been classified into several types, mainly taking into account their seismic signatures, geometry

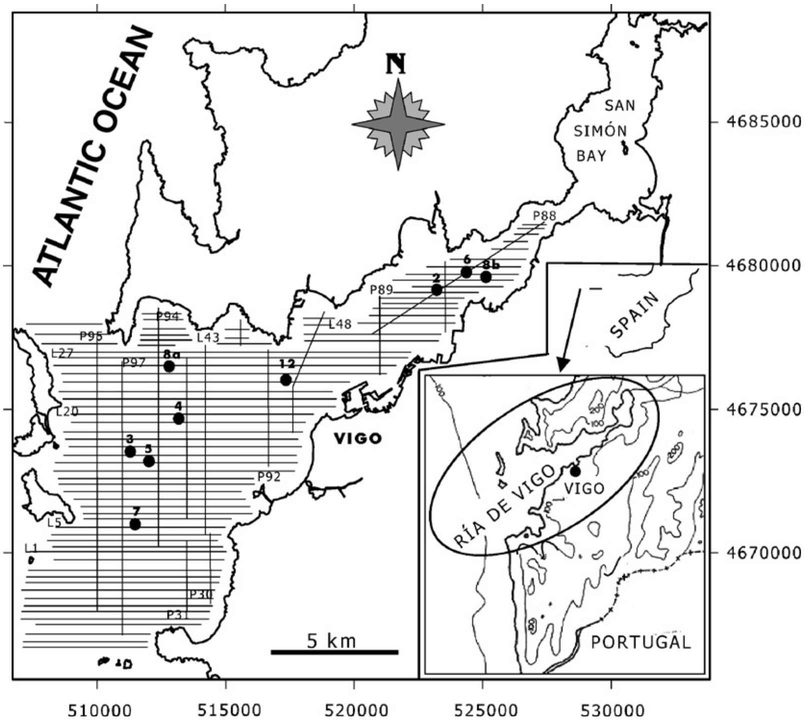

Fig. 1. Ría de Vigo showing survey lines and core location.

and dimensions. The following gas accumulation types have been distinguished:

4.1. Acoustic blankets

This type of gas accumulation is the most frequent in the Ría de Vigo (Fig. 3). It is identified by an upper strong coherent or broken reflection (enhanced reflection) over a complete masking of the underlying seismic record, with no possibility of establishing a connection to a source of gas.

The upper boundary of this type of gas accumulation is denoted by broken reflections with a 2D flat (or gently sloping) geometry. In some cases (Fig. 3) there are evidences that reflections are not flat, but tend to follow one or two bedding planes. The accumulations are typically 224–2560 m wide along seismic profiles with very sharp edges. This seismic signature is comparable to the *blankets* described in Taylor (1992) and to the *acoustic blanking* or *acoustic masking* in Hovland and Judd (1988).

4.2. Acoustic curtains

In *acoustic curtains* there is also a complete masking of the underlying seismic record, and again no possibility of determining a connection with a gas source. These are common seismic features in the Ría de Vigo (Fig. 4). These gas features show a characteristic convex or chevron-shaped upper boundary, which appears as a strong phase-reversed reflector. The average lateral extension along seismic profiles ranges from 32 to 400 m. Another noticeable characteristic of *acoustic curtains* accumulations is that the gas-bearing zone can display strong dipping coherent reflections (pull-downs) to the curtain sides due to the reduction of acoustic velocity in the gas charged sediments (Fader, 1997).

This type of accumulation is very similar in both, shape and dimensions, to the *curtains* of Taylor (1992) or to the *mushroom type* of Karisiddaiah et al. (1993).

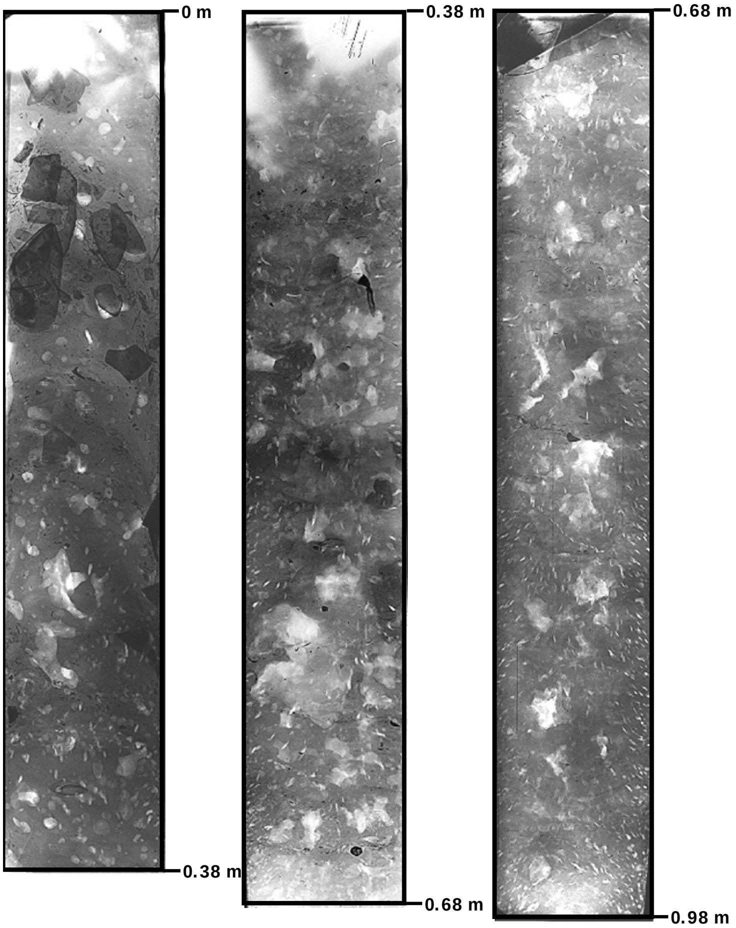

Fig. 2. 0.98 m compacted gravity core (1.37 m with a 40% decompaction). Originally gas-filled pores can be distinguished as white elongated spots with higher deformation at the edges of the core. Within the upper 0.40 m, the bioclastic facies shows higher porosity allowing the gas escape (see Fig. 1 for core location).

4.3. Acoustic columns

These are identified as vertical smearing features; occasionally they appear as transparent zones (Fig. 5). The upper limit presents a strong reflection with phase reversal. In this case, the connection with the gas source level can be distinguished. These features are frequently located close to the previously described types of gas accumulation acoustic blankets and curtains.

Hovland and Judd (1988) described similar seismic signatures as transparent columnar perturbations originated by the upward migration of fluids, probably gas.

4.4. Acoustic turbidity

This type of gas accumulation consists of a variable degree of disturbance on the seismic record (Fig. 4), occasionally it is possible to follow the reflectors through the disturbance. The origin of this type of accumulation is explained by the reflection and scattering of the acoustic energy by myriads of in situ gas bubbles, provoking a dark smearing on the seismic records. This effect can be

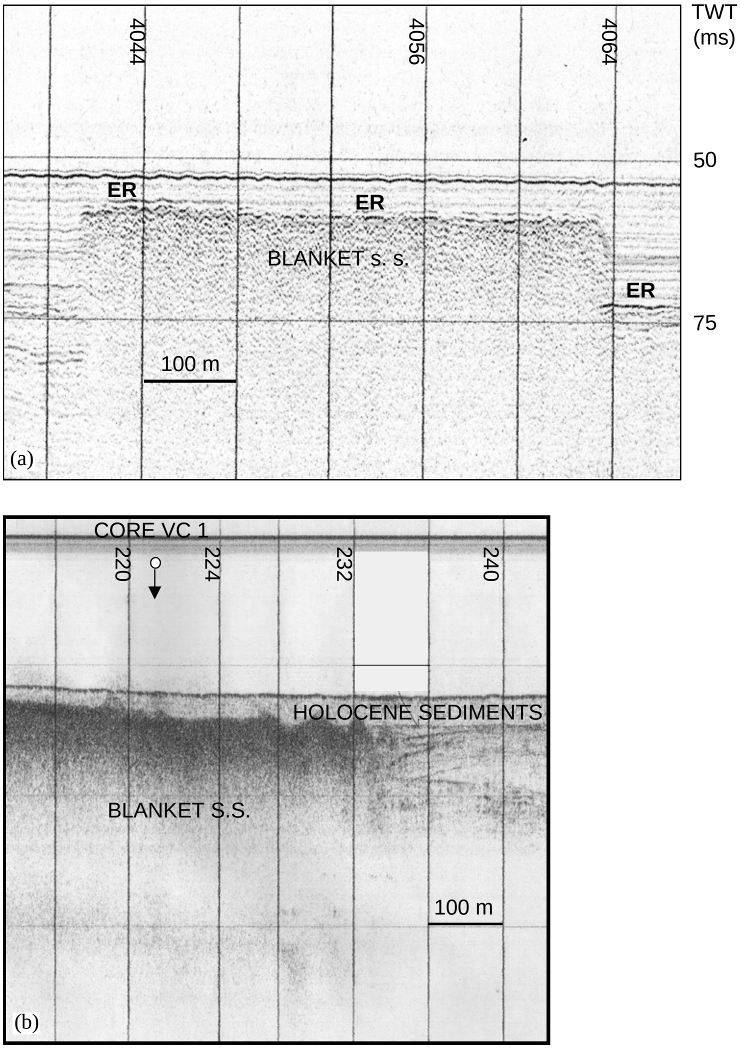

Fig. 3. (a) Uniboom seismic record (profile L-14) showing a gas accumulation blanket Type; and (b) 3.5 kHz record (profile L-56) with gas blanket and core location (see Fig. 1 for profile location).

produced with only 1% by volume of gas in the sediment (Fannin, 1980).

5. Quantitative data

Gas accumulations occur mainly along the central axis of the Ría (Fig. 9). Two main gas fields can be identified: the east and west fields. The east field (EF) covers an area of 7.6 km^2, whilst the west field (WF) has an area of 5 km^2. Together these areas represent 12.6 km^2 containing gas accumulations. Considering the 176.4 km^2 entire surface area of the Ría de Vigo and excluding from this the 40 km^2 corresponding to the inner San Simón Bay (Fig. 1) where seismic profiles are not available, gassy sediments in the 136.4 km^2 surveyed area represent 9.24% of the whole area (Table 1). Differences in the depths of the gas accumulation between the fields (EF and WF) are commented in the discussion of this paper.

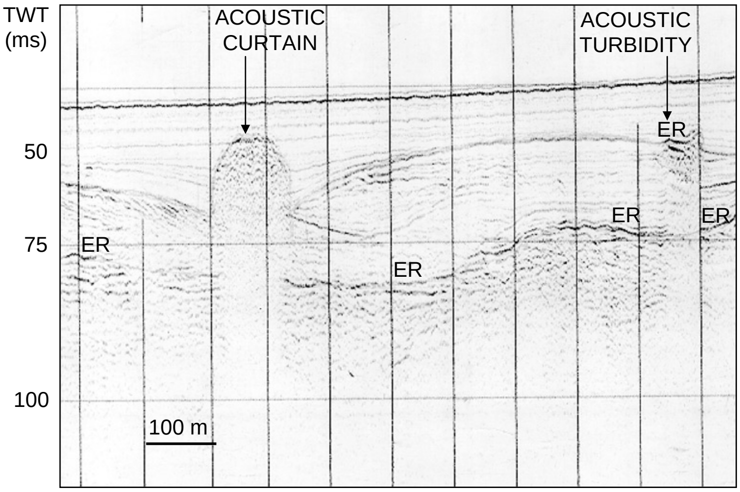

Fig. 4. Uniboom seismic record (profile L-18) showing acoustic accumulations of the acoustic curtain and acoustic turbidity types (see Fig. 1 for profile location).

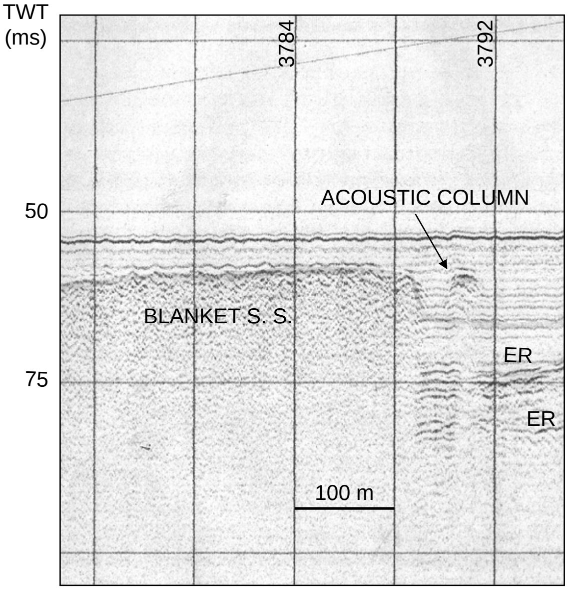

Fig. 5. Uniboom seismic record (profile L-13) showing an acoustic column (see Fig. 1 for profile location).

6. Types of gas escapes

Direct evidence of the existence in the Ría de Vigo of gas seeps, gas bubbles rising through the water column, has been reported by fishermen as "*boiling water*". Indirect evidence comes from various acoustic methods. Echo sounder, 3.5 kHz profiler and side-scan sonar have proved to be the best for recognizing gas escapes. The different acoustic signatures of the sediment surface and the water column are grouped as follows:

Table 1
Quantitative data from gas accumulations

Gas fields	Gas area (km^2)	Depth to top gas (m)	% of the surveyed Ría de Vigo area
East field	7.60	0–7	5.57
West field	5.00	4–11	3.67
Total	12.60		9.24

6.1. Acoustic plumes

High-resolution seismic profiles (3.5 kHz) and echo sounder records have proved to be the best methods for the detection of this type of seeps in the Ría. Acoustic records of both techniques show the presence of a plume of acoustic turbidity rising up to 15 m from the seafloor within the water column. These plumes appear as isolated features and in groups forming plume fields (Fig. 6). Frequently the plumes are associated with gas

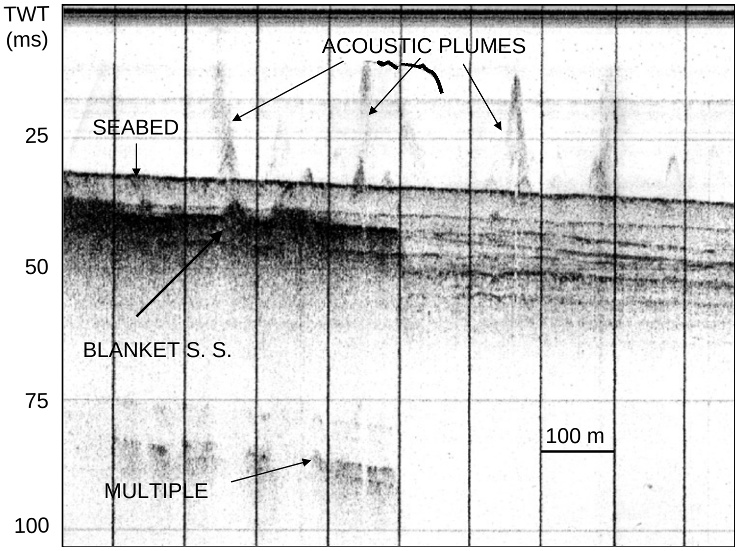

Fig. 6. 3.5 kHz seismic record (profile P-88) showing blanket type accumulation and the acoustic plumes gas escapes (see Fig. 1 for profile location).

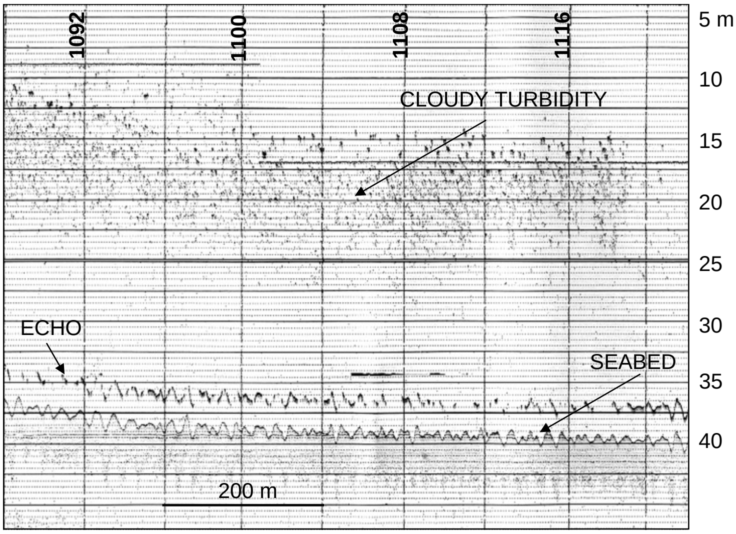

Fig. 7. Echosounder record (profile L-5) showing cloudy turbidity within the water column (see Fig. 1 for profile location).

accumulations (acoustic blankets, acoustic turbidity, etc.) beneath the seabed, these being the source of the escaping gas (Fig. 6).

Taylor (1992) described the plumes as an accumulation feature consisting of a series of high-amplitude, parabolic reflections with a frequency of occurrence along the seismic line of typically one every 100–200 m. It is noticeable that the author used the term *plume* for a type of gas accumulation that has not been found in this area. We use the term *plume* for the gas escape feature described above.

6.2. Cloudy turbidity

This type of gas escape can be detected with both Uniboom (300J) and echo sounder (Fig. 7). On the echo sounder records it appears within the water column as a stain-like feature, without any characteristic geometry as a layer of reflections and scatters, but always related to areas with underlying gas accumulation. It is thought that this type of feature is caused by the resuspension of seafloor sediments by escaping gas or organisms that occupy this inferred enriched zone of energy or nourishment.

6.3. Pockmarks

Pockmarks represent morphological evidence of fluid escape from the seafloor. On side-scan sonar records pockmarks appear as dark spots (Fig. 8a) named *eyed-pockmarks* by Hovland (1989). The Ría de Vigo pockmarks have 6.8 × 4.6 m as a typical side in plane view. The echo sounder and 3.5 kHz profiler records, show v-shaped features of 2–3 m deep on the seabed surface (Fig. 8b). This geometry also appears on the Uniboom records, where besides the v-shaped features there are similar features affecting some sub-seabed reflectors; these probably correspond to ancient pockmarks.

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.

7. Quantitative data

For the estimation of the quantity of gas escaping in the Ría we have used the 3.5 kHz profiles sonographs, and the echo sounder records (Fig. 9). Gas venting appears as acoustic plumes rising upwards into the water column. We have been very conservative in resolving these gas targets, counting only the seeps recognized in both methods. Following the methodology applied by Judd et al. (1997) and Dimitrov (1998), we have divided the Ría into 35 cells, 1′ latitude (1.85 km) and 2′ longitude (2.72 km) in dimension. Assigning every seep into the geographically appropriate cell,

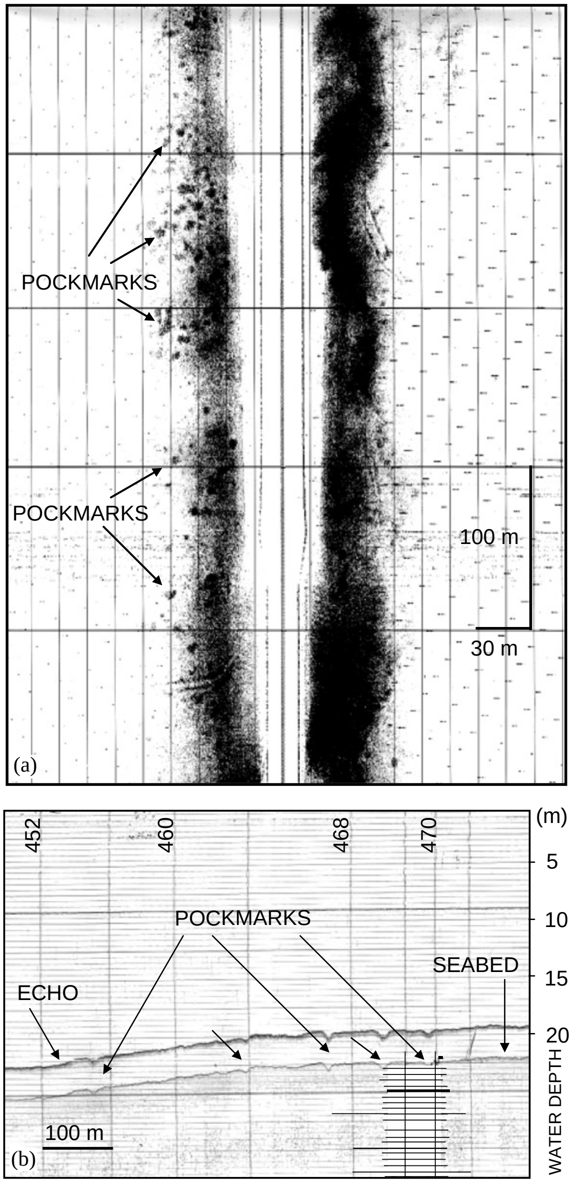

Fig. 8. (a) Side-scan sonar record (profile L-2) showing pockmarks on the seabed. The average dimensions are 6.83 m × 4.62 m. (see Fig. 1 for profile location); and (b) echosounder record (profile L-58) showing v-shaped depressions corresponding to pockmarks (see Fig. 1 for profile location).

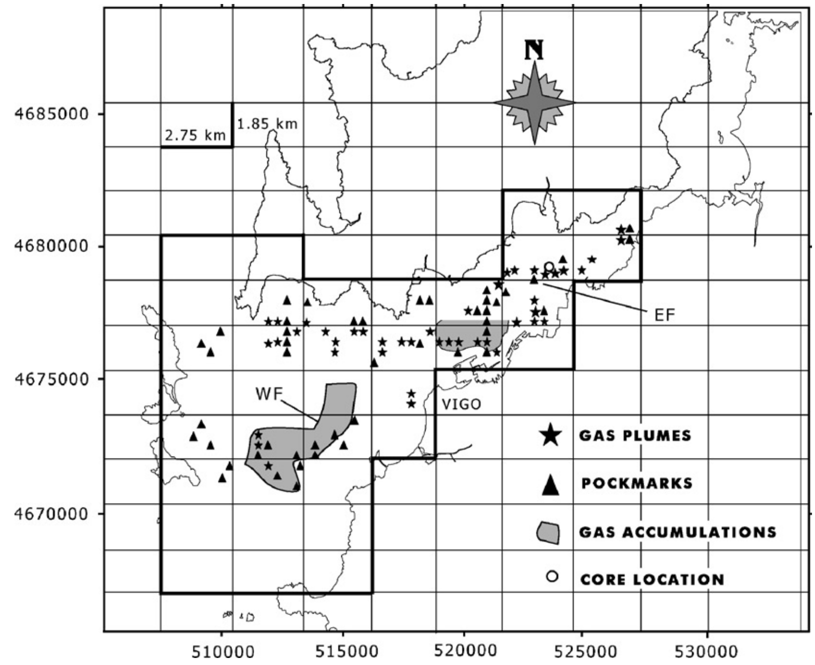

Fig. 9. Distribution of gas escapes (acoustic plumes and pockmarks) and gas accumulations.

Table 2
Quantitative data from gas escapes

Type of gas escapes	Number identified	Mean single dimensions	Cell occurrence	Mean density in seeping area (target km^{-2})	Mean density in Ría area (target km^{-2})
Pockmarks	158	2–4 m relief 31.55 m^2 area	19	1.65	0.89
Gas plumes	165	Up to 20 m high	19	1.72	0.93
Total	323				

only 19 of the total 35 cells show evidence of seeps. This means that the seafloor area affected by seeps is about 54% (i.e., 96 km^2) of the whole Ría de Vigo area.

A total of 165 seeps (plumes) were identified in the seep area (96 km^2) of the Ría de Vigo. This indicates a seepage density of 1.72 targets km^{-2}, a value very close to the density reported by Judd et al. (1997) for the UK. If we make the assumption that all the gas in the sediments is pure methane, with a density of 0.7167 g l^{-1}, and take into account the suggestion made by Judd et al. (1997) that the flux rates would range from 1.25 t yr^{-1} minimum to 35.80 t yr^{-1} maximum, respectively, a total methane flux estimation for the Ría de Vigo to the water column would range between 206.25 (0.000206 Tg yr^{-1}) and 5907 t yr^{-1} (0.005907 Tg yr^{-1}). If we assume that 70% reaches the atmosphere (Dimitrov, pers. com.), it can be estimated that the total methane flux to the atmosphere in the Ría is within the range 145–4135 t yr^{-1}.

Following the same methodology we have found 158 pockmarks in the seep area, which suggests a mean density of 1.65 pockmarks km^{-2} (see Table 2).

8. Discussion and results

Four different types of gas accumulations have been identified and characterized. Mapping of the distribution of these features has enabled two main fields to be recognized. The EF and the WF are located at the mid-inner and outer parts of the Ría de Vigo, respectively (Fig. 10). Comparison of the locations of the gas accumulations with grain size distributions of sediments (Fig. 11) reveals a

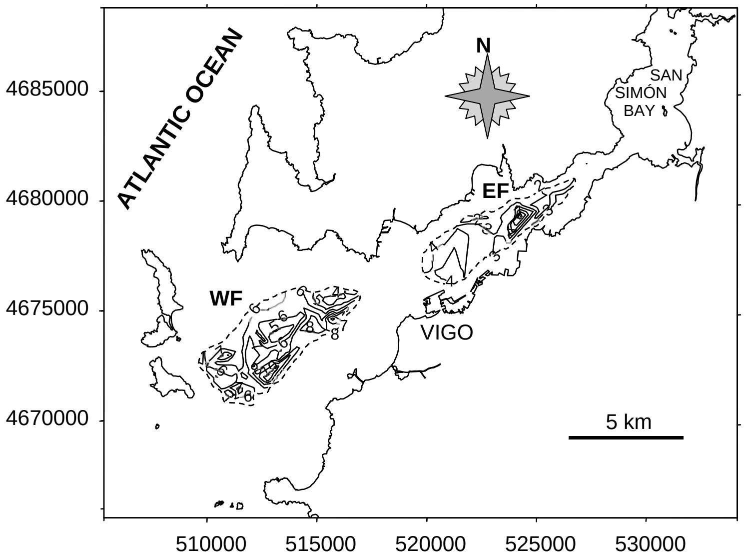

Fig. 10. Contours show the depths below sea bed of the top of the gas accumulation (in meters). In the west field gas accumulates deeper (4–11 m) than in the east field (0–7 m).

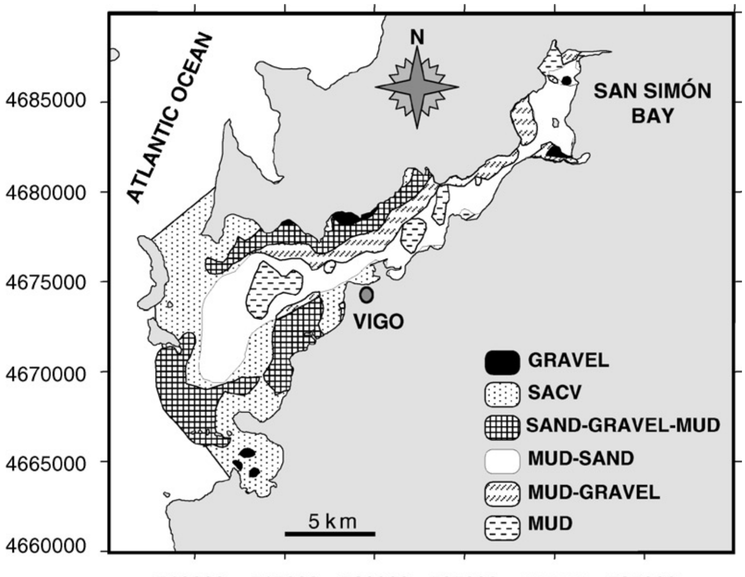

Fig. 11. Map showing the superficial sediments distribution in the Ría de Vigo seafloor (modified from Vilas et al., 1995).

spatial coincidence between both gas fields and finer surface sediments, mainly muds (Vilas et al., 1995). These muds correspond to the youngest Holocene seismic unit (Garcia-Gil et al., 1999) and constitutes the seal for the gas accumulations.

Direct gas analyses are not available at present but the limited thickness of sediments (less than 100 m) and the shallow water depth (less than 50 m) excludes a thermogenic gas origin, and the presence of gas hydrates. The required pressures and temperatures would not be reached in this area. Thus, bacterial degradation of organic matter in shallow sediments is considered the most likely source for the gas in the Ría de Vigo. Acosta (1984) suggested that 7% of organic matter is the minimum for generating sufficient gas to produce acoustic masking. As methane is the only gas found in significant quantities in marine sediments (Floodgate and Judd, 1992), it is considered likely that the gas here is principally methane.

The EF covers an area of 7.6 km^2 and gas accumulates at depths of 0–7 m below the present seabed. The WF extends over a 5 km^2 surface area, and gas appears to occur between 4 and 11 m below seabed. The WF therefore lies within deeper horizons in the sedimentary record than the EF (Fig. 10).

Within both fields, EF and WF, a zoning of the different types of gas accumulations can be observed. Acoustic blanking occurs in the central parts of each field, surrounded by acoustic curtains, whilst acoustic columns and turbidity occur outside the fields.

The spatial distribution of the different gas accumulation types in the Ría de Vigo is interpreted as evidence of control by the sedimentary facies, porosity and quantity of gas within them (Fig. 2). It is suggested that the porosity in both the facies in which gas accumulates and the seal facies are the main controls which determine the type of gas accumulation. When there is a high porosity contrast between the seal facies and gas-bearing sediments then the accumulation takes the form of acoustic blanking. However, if the porosity of the seal facies is only a little higher, the upper gas boundary will be less sharp and the accumulation would be an acoustic curtain. Apart from porosity, lower percentages of gas in the sediments would cause the formation of acoustic columns and acoustic turbidity.

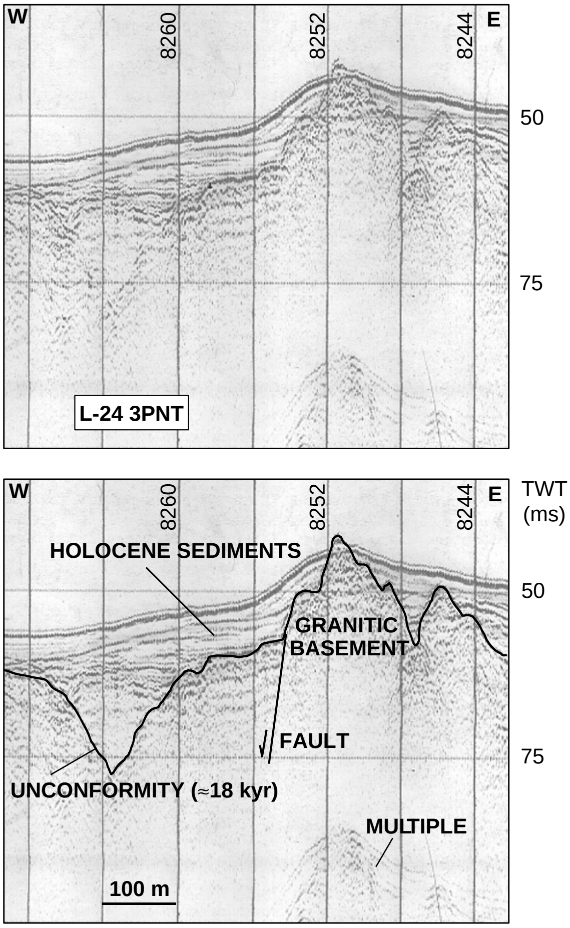

Fig. 12. Uniboom seismic record (L-24) showing both seismic lines (a) uninterpreted; and (b) interpreted. See Fig. 1 for profile location.

Mapping of areas of gas escapes (Fig. 9) shows that these are located in the outermost zones of the gas accumulation fields. In these areas the porosity of the overlying facies would not be enough to constitute an efficient seal, allowing the gas to be released in different ways (pockmarks, acoustic plumes or cloudy turbidity).

Analysis of the high-resolution seismic stratigraphy of the Ría de Vigo shows two sedimentary sequences, separated by an unconformity. The lower sequence is found in the deepest parts of the Ría, and its distribution is controlled by faults.

The upper sequence is divided into four seismic units corresponding to periods of low, transgressive and high sea level. The basal unconformity (Fig. 12) has been interpreted as due to a drop in the sea level during the Würm Glaciation (Garcia-Gil et al., 1999).

This indicates that the seismic units of this sequence are of Holocene age. The gas apparently originates from organic matter that accumulated in sediments deposited during the periods of low sea level and transgression. Bacterial degradation of the organic matter generated the gas. Subsequently, this gas migrated up to the two higher seismic units, the youngest two of the Holocene (Fig. 3b), which constitute the gas seal. Alternatively, where porosity of the above-mentioned upper units is high enough, the gas escapes (Fig. 2).

If we assume that 70% of the gas escaping through the seabed reaches the atmosphere (Dimitrov, pers. com.), then this would mean that the total methane flux towards the atmosphere in the Ría de Vigo is within the range 145–4135 $\mathrm{t\,yr^{-1}}$.

Acknowledgements

This work has been supported by Projects PGIDTOOPXI30105PR, MAR95-1953 and MAR97-0626 of the Spanish Research Programme. This work is part of the 396 and 437 IGCP Projects. We thank M.O.P.T. (Spain) for the support with some available data. We also want to thank Dr. A. Judd and Dr. B. Haq for their useful suggestions to the first version of this paper, as well as to Dr. M. Hovland and Dr. D. Long for their worthwhile comments. All their indications have improved this paper greatly .

References

Acosta, J., 1984. Occurrence of acoustic masking in sediments in two areas of the continental shelf of Spain: Ria de Muros (NW) and Gulf of Cádiz (SW). Marine Geology 58, 427–434.

Baraza, J., Ercilla, G., 1996. Gas-charged sediments and large pockmark-like features on the Gulf of Cadiz slope (SW Spain). Marine and Petroleum Geology 13, 253–261.

Dando, P.R., Jensen, P., O'Hara, S.C.M., Niven, S.J., Schmaljohann, R., Schuster, U., Taylor, L.J., 1994a. The effects of methane seepage at an intertidal/shallow subtidal site on the shore of the Kattegat, Vendsyssel, Denmark. Bulletin of the Geological Society of Denmark 41, 65–79.

Dando, P.R., O'Hara, S.C.M., Schuster, U., Taylor, L.J., Clayton, C.J., Baylis, S., Laier, T., 1994b. Gas seepage from a carbonate-cemented sandstone reef on the Kattegat coast of Denmark. Marine and Petroleum Geology 11, 182–189.

Davis, A.M. (Ed.), 1992. Methane in marine sediments. Continental Shelf Research 12, 175.

Dimitrov, L., 1998. Contribution to atmospheric methane by natural seepages on the Bulgarian Continental Shelf. Abstract Volume of the Fifth International Conference on Gas in Marine Sediments, Bologna, Italy, pp. 171–173.

Driscoll, N., Uchupi, E., 1997. The importance of gas and groundwater seepage in landscape and seascape evolution. Thalassas 13, 355–448.

Emery, K.O., Hoggan, D., 1958. Gases in marine sediments. AAPG Bulletin 42, 2174–2188.

Fader, G.B.J., 1991. Gas-related sedimentary features from the eastern Canadian continental shelf. Continental Shelf Research 11, 1123–1153.

Fader, G.B.J., 1997. The effects of shallow gas on seismic reflection profiles. In: Davies, T.A., Bell, T., Cooper, A.K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M.S., Stravers, J.A. (Eds.), Glaciated Continental Margins. An Atlas of Acoustic Images. Chapman & Hall, London, pp. 29–30.

Fader, G.B.J., Buckley, D.E., 1995. Environmental geology of Halifax Harbour, Nova Scotia. Geoscience Canada 22, 152–171.

Fannin, N.G.T., 1980. The use of regional geological surveys in the North Sea and adjacent areas in recognition of offshore hazards. In: Ardus, D.A. (Ed.), Offshore site investigation. Graham & Trotman, London, pp. 5–21.

Floodgate, G.D., Judd, A.G., 1992. The origins of shallow gas. Continental Shelf Research 12, 1145–1156.

Gaedicke, C., Baranov, B.V., Obzhirov, A.I., Lelikov, E.P., Belykh, I.N., Basov, E.I., 1997. Seismic stratigraphy, BSR distribution, and venting of methane-rich fluids west off Paramushir and Onekotan Islands, northern Kurils. Marine Geology 136, 259–276.

Garcia-Garcia, A., Garcia-Gil, S., Vilas, F., 1998. Natural Gas Seepages Contribution from the Northwestern Spanish Coast. Abstract Volume of the Fifth International Conference on Gas in Marine Sediments, Bologna, Italy, pp. 111–112.

Garcia-Gil, S., Garcia-Garcia, A., Vilas, F., 1997. Presencia de gas somero en la Ría de Vigo (NW España). Abstract Volume of the 2° Simposio sobre el Margen Continental Ibérico Atlántico, 17–20 Septiembre, Cádiz, pp. 197–198.

Garcia-Gil, S., Garcia-Garcia, A., Vilas, F., 1998. Quantitative Study of the Ría de Vigo Gas Fields (NW Spain). Abstract Volume of the Fifth International Conference on Gas in Marine Sediments, Bologna, Italy, pp. 1133–114.

Garcia-Gil, S., Vilas, F., Muñoz, A., Acosta, J., Uchupi, E., 1999. Quaternary sedimentation in the Ría de Pontevedra (Galicia) Northwestern Spain. Journal of Coastal Research, in press.

Hempel, P., Spieß, V., Schreiber, R., 1994. Expulsion of shallow gas in the Skagerrak-evidence from sub-bottom profiling, seismic, hydroacoustical and geochemical data. Estuarine, Coastal and Shelf Science 38, 569–582.

Hovland, M., 1989. Modern analogues to Middle Ordovician sedimentary mounds and washout depressions. Journal of Sedimentary Petrology 59, 585–589.

Hovland, M., Judd, A.G., 1988. Seabed Pockmarks and Seepages. Impact on Geology, Biology and the Marine Environment, Graham and Trotman, London, 294pp.

Hovland, M., Sommerville, J.M., 1985. Characteristics of two natural gas seepages in the North Sea. Marine and Petroleum Geology 2, 319–326.

Judd, A.G., Davies, G., Wilson, J., Holmes, R., Baron, G., Bryden, l., 1997. Contributions to atmospheric methane by natural seepages on the UK Continental Shelf. Marine Geology 140, 427–455.

Karisiddaiah, S.M., Veerayya, M., 1996. Potential distribution of subsurface methane in the sediments of the eastern arabian sea and its possible implications. Journal of Geophysical Research 101 (D20, D25), 887–895.

Karisiddaiah, S.M., Veerayya, M., Vora, K.H., Wagle, B.G., 1993. Gas-charged sediments on the inner continental shelf off western India. Marine Geology 110, 143–152.

Kelley, J.T., Dickson, S.M., Belknap, D.F., Barnhardt, W.A., Henderson, M., 1994. Giant sea-bed pockmarks: evidence for gas escape from Belfast bay, Maine. Geology 22, 59–62.

King, L.H., McLean, B., 1970. Pockmarks on the Scotian Shelf. Bulletin of the Geological Society of America 81, 3141–4148.

Pickrill, R.A., 1993. Shallow seismic stratigraphy and pockmarks of a hydrothermally influenced lake, Lake Rotoiti, New Zealand. Sedimentology 40, 813–828.

Schüller, F., 1952. Untersuchungen über die Machtigkeit von Schlickschichten mit Hilfe des Echographen. Dt. Hydrographiche Zeitung 5, 220–231.

Solheim, A., Larson, F.R., 1987. Seismic indications of shallow gas in the Northern Barents Sea. Rapportserie Norsk Polarinstitutt no. 36, Oslo, 30pp.

Taylor, D.I., 1992. Nearshore shallow gas around the UK coast. Continental Shelf Research 12, 1135–1144.

Veerayya, M., Karisiddaiah, S.M., Vora, K.H., Wagle, B.G., Almeida, F., 1998. Detection of gas-charged sediments and gas hydrate horizons along the western continental margin of India. In: Henriet, J.-P., Mienert, J. (Eds.), Gas Hydrates. Relevance to World Margin Stability and Climate Change, Vol. 137. Special Publication. Geological Society, London, pp. 239–253.

Vilas, F., Nombela, M.A., García-Gil, E., García-Gil, S., Alejo, I., Rubio, B., Pazos, O., 1995. Mapa de distribución de los sedimentos del fondo de la Ría de Vigo. Consellería de Pesca, Marisqueo y Acuicultura, Xunta de Galicia, 41pp.

Wever, T.F., Fiedler, H.M., 1995. Variability of acoustic turbidity in Eckernförde Bay (Southwest Baltic Sea) related to the annual temperature cycle. Marine Geology 125, 21–27.