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Monitoring the Spanish gas fields in the Ría de Vigo (1991–2001)

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Abstract The Ría de Vigo is located on the NW coast of Spain, and includes gassy areas studied in several high-resolution seismic surveys between 1991 and 2001. The position of the acoustic blankings and gas seepages has been monitored vertically and spatially in the surveyed area. Also, a 253-cm-long vibrocore was recovered in a gas field in the inner part of the ría. The predominant facies of the core is dark mud with small bioclastic fragments and a very strong H_2S smell. The repeated surveys of this ría show that these shallow gas fields have been active in the last decade and were active in the past (buried collapse structures). Available direct gas analyses show that methane is one of the components of the gas in the ría. Thus, bacterial degradation of organic matter in shallow sediments is considered the most likely source for the gas in the Ría de Vigo.

Introduction

Since the earliest papers of gases in marine sediments, various authors have reported concentrations of methane and other gases in near-surface marine sediments and coastal areas such as bays and estuaries. Along the Spanish coast, shallow gas accumulations have been found in several marine environments and, in particular, along the Atlantic coast, the Rías Baixas, NW Spain (Fig. 1a). Areas with different types of gas accumulations and gas seeps have been mapped previously by the authors in the infill of one submarine incised valley, the Ría de Vigo (García-García et al. 1999; García-Gil et al. 2002). Margalef (1958) was one of the first to study the fauna in the ría seafloor, pointing out for the first time the existence of several species of *Beggiatoa*. The sites where this bacteria is found coincide with the sites where gas is located, along the main axis of the ría (García-García et al. 1999; García-Gil et al. 2002).

Gas signatures are present not only on the seafloor but throughout the sedimentary infill. Analysis of the high-resolution seismic stratigraphy of the Ría de Vigo shows four main seismic units comprising the ría infilling—a, b, c and d (García-García 2002). The most recent seismic units of the Holocene (c and d) are those which are mainly affected by gas, being the most recent seal for the trapped gas.

Available direct gas analyses show that the gas in the ría contains methane (García-Gil 2002). Thus, bacterial degradation of organic matter in shallow sediments is considered the most likely source for the gas in the Ría de Vigo. New seismic and acoustic data acquired during several seismic surveys in the area allow us to discuss the activity of these gas fields, not only from a seafloor point of view, but also from a vertical standpoint.

Setting

The Ría de Vigo (Fig. 1a) is located on the passive Atlantic margin of south-western Galicia (NW Spain), the ría coast known as Rías Baixas. The physiography of the Ría de Vigo presents a distinctive funnel shape, with an areal extent of 176.4 km^2. The Ría de Vigo trends at nearly right angles to the region's Palaeozoic basement structure. Its basement comprises Palaeozoic metamorphic and granitic rocks cut by NE-SW-, NW-SE- and N-S-trending faults. The entire ría coast is possibly related to the post-Pyrenean extensional phase, during both the Oligocene and Miocene (García-Gil et al.1999).

The water depths within the Ría de Vigo range from 7 m in its inner part to 53 m at the outer (southwest) entrance to the sea (Fig. 1b). The north entrance is shallow, with a maximum depth of 30 m, whereas the

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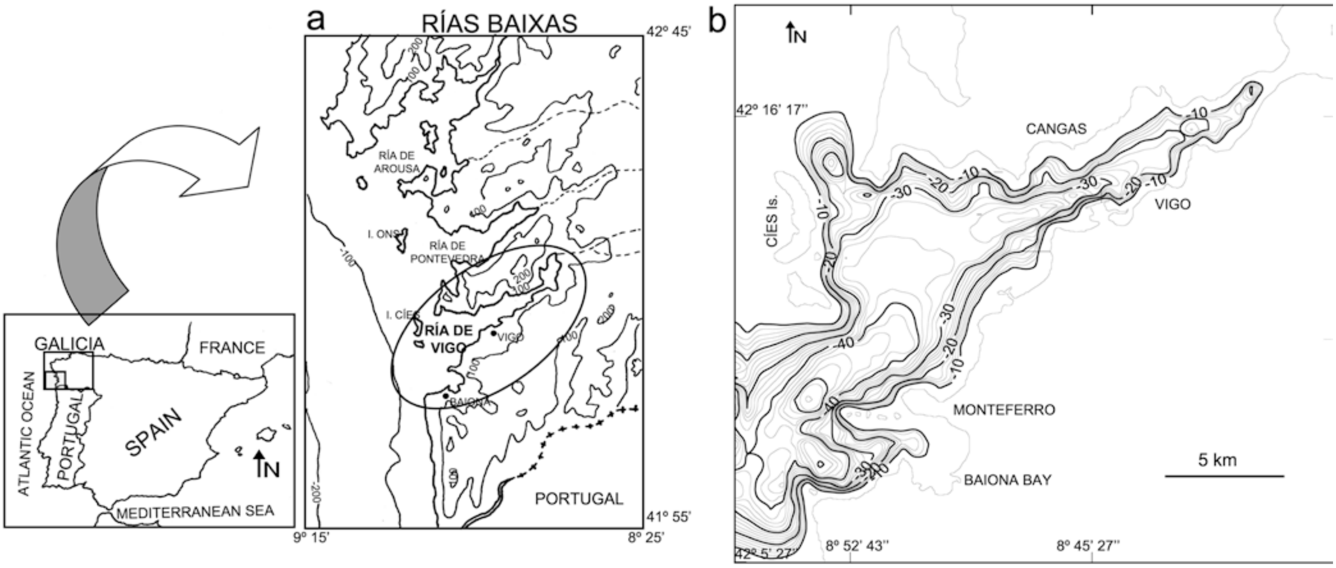

Fig. 1 **a** Geographical setting of the Ría de Vigo, located on the NW coast of Spain. **b** Map showing the bathymetry of the Ría de Vigo. Bathymetric contours at 2-m intervals

deeper southern entrance is more than 50 m deep. The grain-size distribution of the present-day seafloor (Fig. 2a) consists of mixed siliciclastic and skeletal gravels in both the outer area and the edges of the ría, whereas the central and inner parts of the ría are dominated by clay and silt with up to 10% organic matter content (Vilas et al.1995).

Materials and methods

A first survey was performed during the summer of 1991 (Fig. 2b). A total of 640 km of seismic lines was acquired and interpreted in detail aboard R/V *El Investigador*, in order to detect gas signatures in the Ría de Vigo (García-Gil et al.1999, 2002). The survey was performed as a rectangular grid with lines spaced 66 m (N–S) to 550 m (E–W) apart. A second survey was performed six years later, during the summer of 1997, aboard R/V *Francisco de Paula Navarro*. A total of 67 km of seismic lines with a layout of lines NW–SE and NE–SW was acquired. Finally, the most recent survey was performed during the summer of 2001, aboard R/V *El Investigador*. A total of 34 km of seismic lines, oriented N–S and NE–SW, was acquired and interpreted in order to detect and compare the gas signatures found in previous years (Fig. 2b).

The data were acquired using high-resolution single channel reflection profilers (EG&G Uniboom Catamaran Model 230 operating at 300 J, an ORE 3.5-kHz Model 1036 subbottom profiler), and a 4,500-J EG&G multi-electrode Sparker. 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. Also, a 253-cm-long vibrocore was recovered in a gas field in the inner part of the ría with an ASTHER-1 equipment.

Results and discussion

The authors have mapped in time the indications of gas accumulations in sediments from occurrences of acoustic blankings, acoustic curtains, gas plumes in the water from acoustic plumes, and gas escape features such as pockmarks and collapse structures (Fig. 3).

Collapse structures

Apart from the gas signatures found previously (García-García et al.1999; García-Gil et al.1999, 2002), we identified some gas collapse structures (Fig. 4) disturbing the top of unit c. Their average dimensions are 95-m diameter and 7.5-m depth. They are present 4 m below the present-day seafloor between the isobaths −20 and −40 m. These structures are interpreted to be formed by the collapse of the sediment as a result of dewatering or degassing, and not by the erosion of the sediment material (Hovland and Judd 1988). Therefore, the mechanism of their origin is different from pockmark generation. In the Uniboom records of the Ría de Vigo, both pockmarks and collapse structures show different seismic characters. Pockmarks are typically V-shaped (see Fig. 3a) whereas collapse structures have steeper lateral boundaries and a flat bottom without clear basal reflectors. Lack of transversal seismic lines crossing to the individual collapses does not allow to reconstruct their three-dimensional shape.

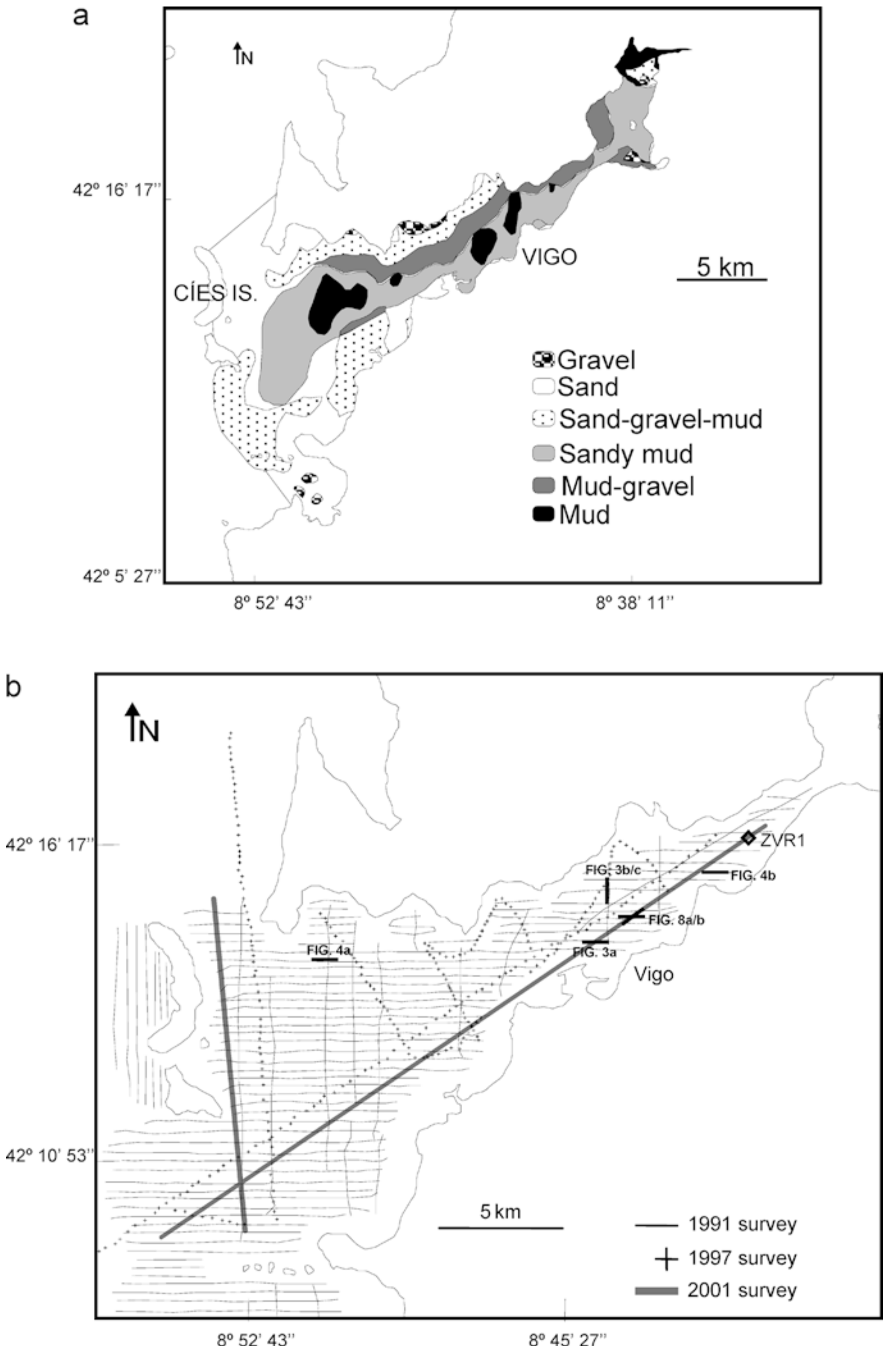

Fig. 2 **a** Map of seafloor sediments in the Ría de Vigo (modified from Vilas et al. 1995). **b** Map of the survey tracklines in the area in 1991, 1997 and 2001. Also shown are the location of vibrocore ZVR-1 in the inner part of the ría, and the locations of the seismic profiles discussed in the text

As shown in Fig. 4, the location of these structures is confined to two coastal areas. Where seismic unit c is disturbed by these collapses, it has a thick sedimentary section. Therefore, these sites could have been ancient sources of sediment (rivers), and the seismic unit could have been a deltaic progradational form in the past.

Taking into account that these collapses affect the top of unit c, this implies that degassing of sediments took place at that time, representing an ancient seeping seafloor. The ^{14}C date from the vibrocore taken in the central part of the Ría de Vigo gives a date of 2,953 years B.P. for a bed located 3.8 m below the present seabed (Diz et al. 2001), very close to the base of unit d, 4 m thick, which would mean that the collapses would have occurred approximately 3,000 years B.P.

Nevertheless, the appearance of both pockmarks and collapse structures in the Ría de Vigo leads us to propose that sedimentary facies may be the main factor determining whether gas accumulates or seeps, and also the ways in which gas escapes. Porosity and permeability are important factors which determine if gas escapes as seeps, pockmarks or bigger collapse structures.

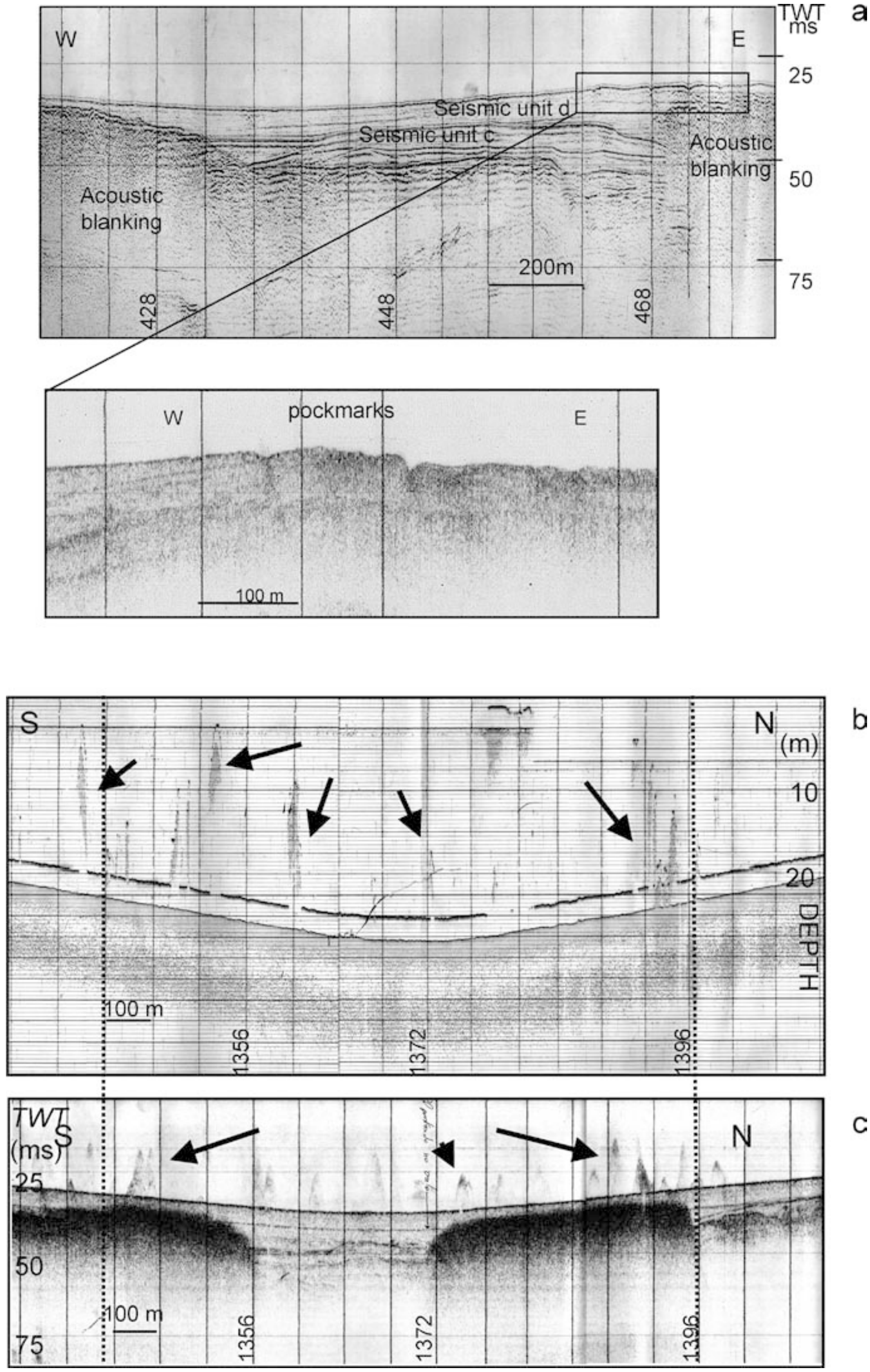

Fig. 3 **a** Uniboom seismic line showing part of the sedimentary infill in the ría disturbed by gas features, in particular, pockmarks. The most recent seismic units of the infill (*c* and *d*) are also indicated. **b**, **c** Echosounder line and 3.5-kHz subbottom profile showing acoustic plumes seeping from the ría seafloor, with accumulations of gas below some acoustic plumes. See Fig. 2b for seismic line locations

The ZVR1 vibrocore

A 253-cm-long vibrocore was recovered in a gas field (ZVR1) in the inner part of the ría with an ASTHER-1 equipment (Fig. 5). It was recovered in one of the gas fields of the ría. The main facies of the core is dark mud with small bioclastic fragments and a very strong H_2S smell. A *Venerupis* sp. shell was recovered 47 cm below the top of the vibrocore (Fig. 5). Radiocarbon AMS dating (Geochron Laboratories) provides an age of 500 ± 30 ^{14}C years B.P.

Gas spatial and vertical variation analyses

The gas fields identified by the authors in 1991 cover an area of 13 km^2 in the ría (García-Gil et al. 2002). Apart from that, the seafloor area affected by seeps is

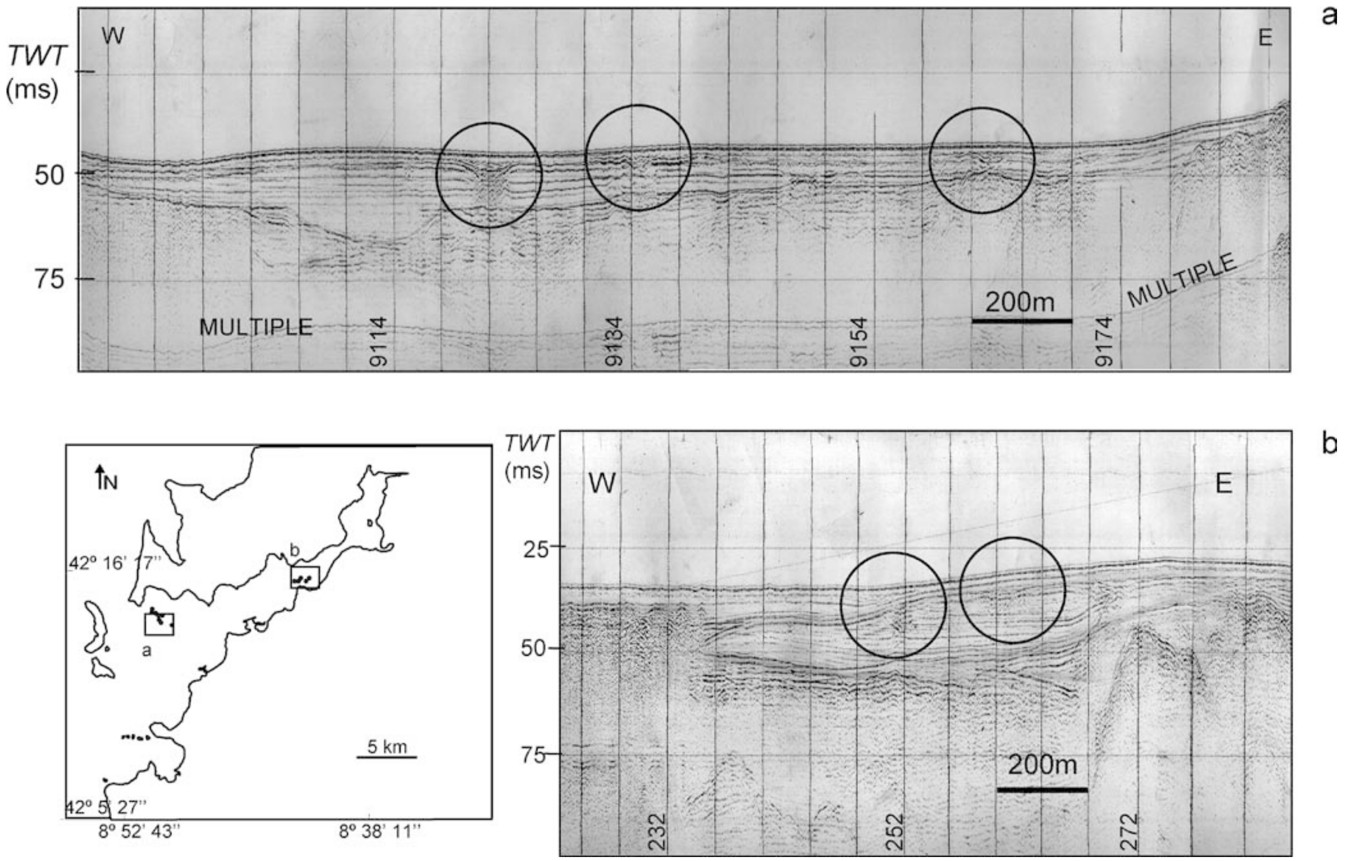

Fig. 4a, b Examples of the collapse structures found in the ría sedimentary infill. See Fig. 2b for seismic line locations

about 54% (i.e. 96 km^2) of the whole Ría de Vigo area.

The analysis of the new seismic data from 1997 shows the gas accumulations mainly in the same region as they were in 1991 (see Fig. 6), but the gas may not behave the same between the two surveys. The 1997 data identify new seeping areas where there was no gas signature at all six years before. Also, there are zones whose seeps come from accumulations which were effectively sealed in 1991. This means that the gas fields in the ría are active and they do not stay at the same spatial position, although these variations are small. Between 1995 and 1997, the seismic movements have been fully felt by the Galician population. One of the strongest was triggered in May 1997, with a Richter magnitude of 5.1 (Araújo 1997). This earthquake could explain the new seeping areas found in the summer of 1997 which came from the underlying gas accumulations, where there were no seeps in 1991. The new data from 2001 confirm the location of the shallow gas in the central part of the ría (Fig. 6). As shown in Fig. 6, all indirect gas evidences through time are localized along the central axis of the ría. Also, Margalef (1958) had found direct indications of bacteria associated with gassy sediments—*Beggiatoa* sp.—in the same area along the central axis of the ría (Fig. 6).

The vertical position of the top of the acoustic blankings has been mapped in all the surveys (Fig. 7). This top can migrate vertically due to seasonal variations of temperature (Wever and Fiedler 1995), changes in the effectiveness of the seal, neotectonics (Laier et al.1992) and/or seismic movements (Field and Jennings 1987; Laier et al.1992; Hasiotis et al.1996; Dando et al. 2000). Hagen and Vogt (1999) find in Chesapeake Bay movements in the front of the gas accumulations up to 0.5 m. From the available data in Vigo, the analysis of the variations in the depth of the top of the gas through time indicates that these are not very significant (<1 m variation on average), although some small changes were found—the top of the gas in 1991 seems to be in a slightly shallower position in comparison to the 2001 data. As all the surveys have been run in summer time, the seasonal factor cannot be the cause in this case. A possible explanation for a lowering of the gas front could be the degassing area via active seeps. The seismic and human activities can have acted as triggering mechanisms for these gas escapes.

Conclusions

The gas fields of the Ría de Vigo in NW Spain have been monitored between 1991 and 2001. The vertical position

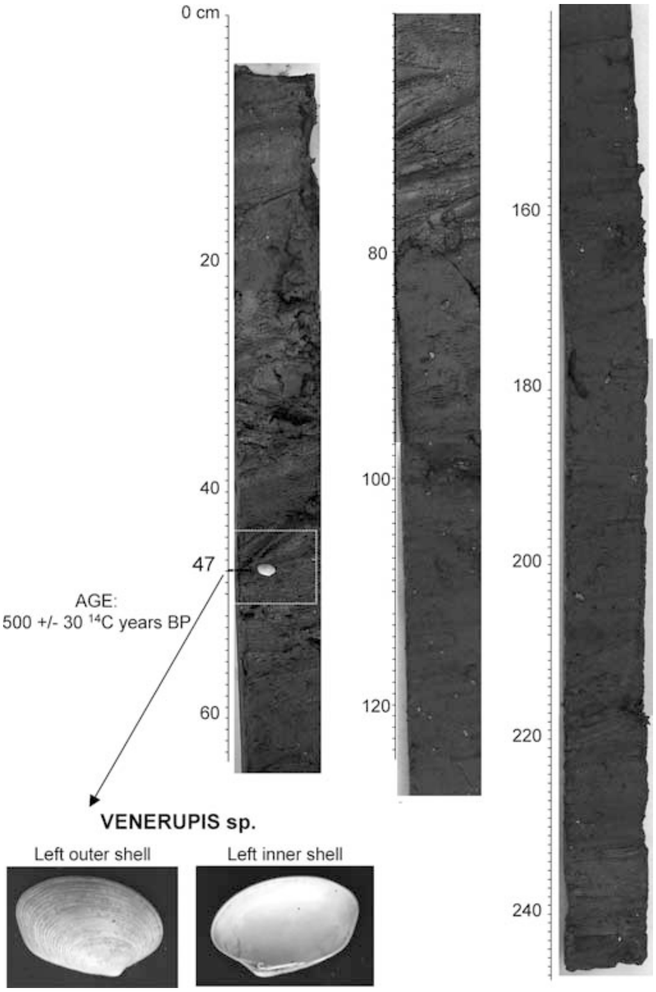

Fig. 5 Vibrocore ZVR-1 with muddy facies and a *Venerupis* shell at 47-cm depth. See Fig. 2b for vibrocore location

of the top of the acoustic blankings has not changed significantly, although there are spatial variations in the surveyed area. Also, a 253-cm-long vibrocore was recovered in a gas field in the inner part of the ría, and was composed of dark muds with small bioclastic fragments and a very strong H_2S smell. Available direct gas analyses show the gas in the ría is mainly methane and indicate that bacterial degradation of organic matter is the likely source for the gas. The monitoring of this ría's gas fields shows that these shallow fields have been active in the last decade and also in the past (buried collapse structures).

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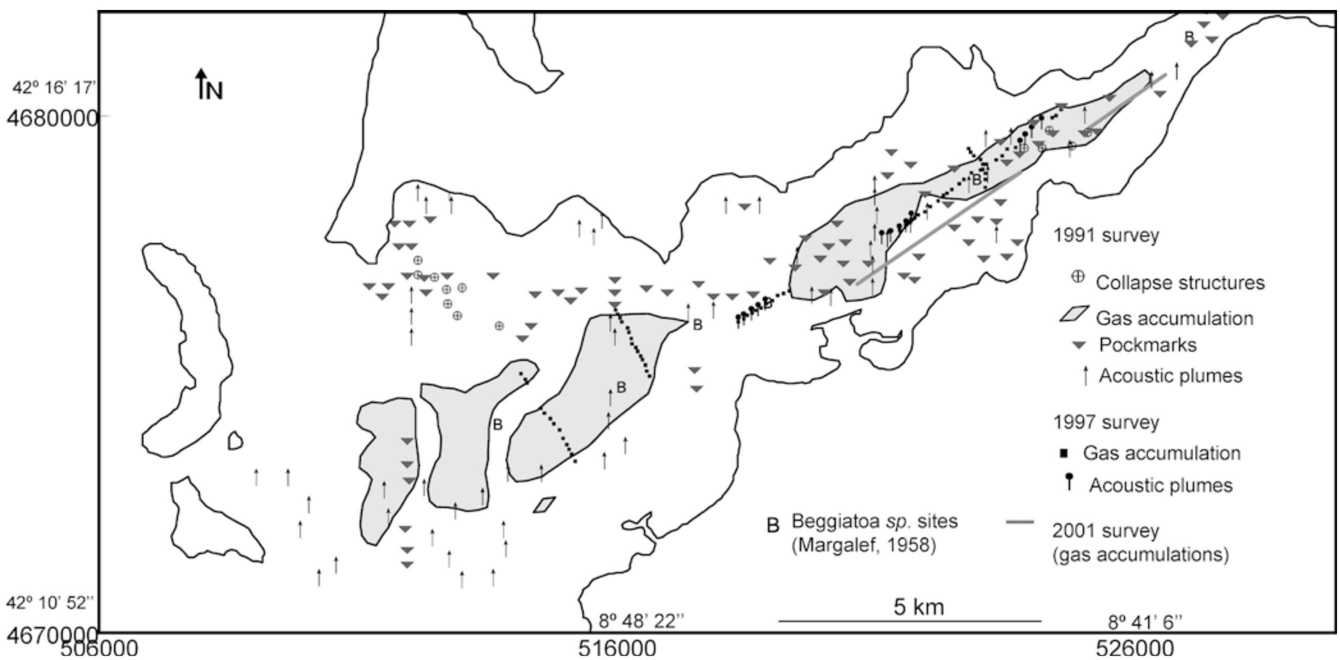
Fig. 6 Mapping of the different gas signatures found in the last decade in the ría area (1991–2001)



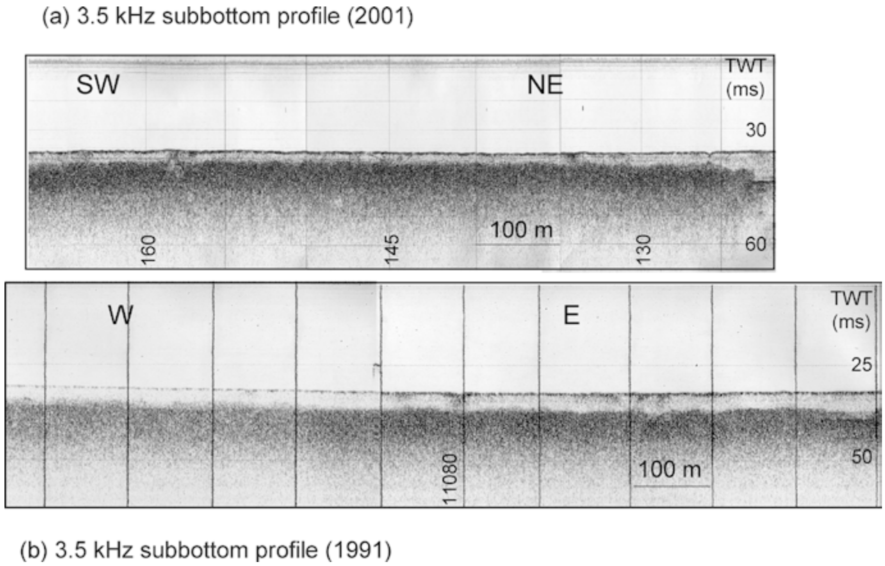


Fig. 7 **a** 3.5-kHz seismic line showing the top of the gas accumulation in 2001. **b** 3.5-kHz seismic line at the same site showing the top of the gas accumulation in 1991. See Fig. 2b for seismic line location

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