Shallow gas accumulations in the sediments of Todos os Santos bay (Bahia, Brazil): origin and distribution

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Abstract

Several features indicating the presence of shallow gas in the sediment were observed during high-resolution seismic data acquisition in Todos os Santos bay (TSB). This study aimed to determine the origin and distribution of shallow gas in the sediments filling the Todos os Santos Bay, as well as establish the stratigraphic, sedimentological and geochemical arrangements that most favors the presence of gas. The interpretation of the seismic data and sedimentological and geochemical analysis of sediment samples allowed the preparation of various thematic maps showing the distribution of key parameters. We found a total area of gas accumulations of 161Km². This area corresponds to 15% of the total area of the TSB, or 27% of the surveyed area (600km²). The gas accumulations show great association with the spatial distribution of muddy rich in organic matter sediments. Cores subsamples analysis indicated anomalous concentrations of methane (> 90 ppm), in TSB sediments. The $^{13}C/^{12}C$ isotope ratio of methane indicates a biogenic origin for this gas.

Introduction

During the past six decades, numerous authors have reported different types of anomalies on echo sounder, side-scan and sub-bottom profiling records as indicative of gas escaping and accumulation on marine and estuarine/bay sediments (Baraza e Ercilla, 1996; Hampton et al., 2002; Emeis et al, 2004; Frazão e Vital, 2007).

Methane, the predominant gas found in sediments, may exist in three states: free gas (bubbles) , dissolved gas , and gas hydrate (Mazumdar et al., 2009; Diez et al., 2007). When present as gas bubbles, even at low concentrations (~0.1% of free gas content), methane can dramatically decrease the compressional wave velocity, and increase wave attenuation and scattering (Anderson and Hampton, 1980). Therefore, gas rich sediments attenuate the acoustic energy, resulting in lack of penetration of the acoustic signal, thus producing a characteristic masking of the underlying layers in seismic data (Wilkens e Richardson, 1998).

Methane is one of the most important biogenic greenhouse gases (Iglesias & García-Gil, 2007). Worldwide concern of global warming has attracted attention to the gas emissions from marine/transicional sediments as a significant contributor to atmospheric methane and CO_2 (Garcia-Gil et al., 2002), especially in coastal areas (Judd et al., 2002; Dimitrov, 2002). Also the presence of high pressured interstitial fluids in the sediment can reduce the shear strength of seabed (Prior and Coleman, 1984), causing the collapse of offshore structures (Davis, 1992). Gas trapping by impermeable layer, can also result in overpressure and blow-outs during drilling operations (Okyar and Ediger, 1999). In some cases, the presence of shallow gaseous hydrocarbons signals the existence of deeper and more extensive hydrocarbon accumulations (Okyar and Ediger, 1999).

The global compilation of Fleischer et al (2001) calls attention for the lack of data in the southern hemisphere, in comparison to the northern hemisphere.. These authors also emphasize the importance of identifying and cataloging these gassy-sediment deposits as critical first steps in the development of predictive models for gassy-sediment occurrences, benefiting defense and petroleum industries. Also accurate inventories of sources and sinks of methane are imperative to understand the dynamics of shallow-water methane generation, consumption, transport, and subsequent emission into the atmosphere. The present work represents a first study of the origin and spatial distribution of gassy sediments in Todos os Santos Bay, the second largest semi-enclosed bay in Brazil.

The aim of this research was to determine the origin and distribution of shallow gas in the sediments infilling the Todos os Santos Bay, as well as establish the stratigraphic, sedimentological and geochemical arrangements that most favor the presence of gas.

Methods

A total of 700km of high resolution seismic data were acquired in Todos os Santos Bay the Bay using a sub-bottom profiler, Edgetech, SB-216S, operating at frequencies of 2 to 16 kHz (Figure 1) during two surveys, from April to May, 2008 and December 2008 to January 2009.

The recorded digital data has been processed using SonarWiz.MAP® (Chesapeake Technology Inc.) software, for the determination of sediment thickness and depth of gas occurrence below the seaflor. After interpretation, the obtained data were exported to Arcview 9.2® GIS software and interpolated using Inverse

Distance Weighted method. The bathymetric data were obtained from bathymetric charts.

The 25 grab sediment samples were collected in locations coinciding with the seismic survey lines, including the various types of gassy sediments. Total organic carbon and organic matter content of the sediments were determined using the EMBRAPA method (1997).

Grain size analyses were carried out in Laser Particle Analyser HORIBA® (LA-950) and the obtained data were integrated to textural data provided by BAMPETRO (Banco de Dados Ambientais para a Indústria do Petróleo).

All obtained data were then exported to ArcView 9.2® (ESRI) software, and interpolated using the Inverse Distance Weighted method, to produce spatial distribution maps of the analyzed parameters.

Eight 1 to 3m length cores were colleted using 7cm-diameter acrylic liners by scuba divers in five stations coinciding with shallow gas ocurrences. 5cm long sub-samples were collected 20cm above the base of the liners, and immediately transferred to a Isojar® (~650ml) muddy gas sampling container to which 10 drops of *Zephiran Chloride* bactericidal were added. The containers were then ¾ filled with water, for posterior headspace analysis of the content of hydrocarbons (C1 – C6+). For the samples presenting a minimal methane concentration of 500ppm, the isotopic composition $^{13}C/^{12}C$ of the methane was determined.

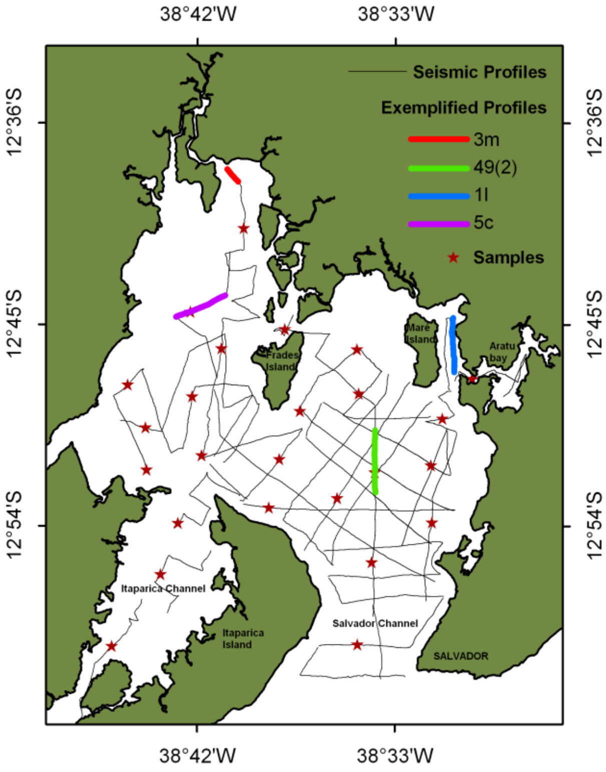

Figure 1 – Study area, and location of samples and seismic lines

Example of Gassy Sediments

Figure 2 (A) shows a seismic profile of gassy sediments found in the TSB. It's possible to observe three discrete areas of acoustic blanketing caused by the presence of gas. In between these gas accumulation the eroded pre-Holocene surface is visible . The green lines in figure 2B represent areas of strong reflection, and are considered to be the upper limit of free gas occurrences.

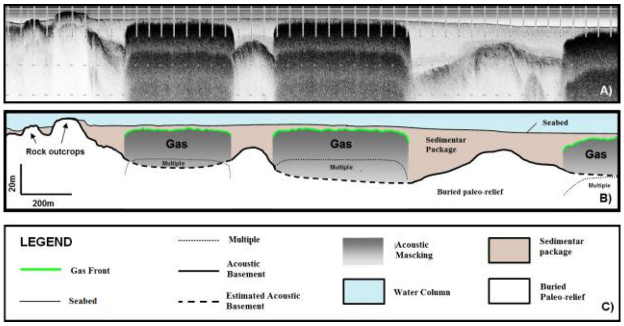

Figure 2 – (A) High resolution seismic profile recorded in Todos os Santos bay, (B) Interpreted seismic profile.

Results

The interpretation of high resolution seismic records allowed the identification and mapping of zones of acoustic masking, and consequently, of zones of gas occurrence in the Todos os Santos bay. Furthermore, it was possible to identify different types of gas accumulation and to generate an isopach map of the holocene sediments infilling the TSB.

Garcia-Gil et al (2002), taking into account the seismic signatures, geometry and dimensions, classified the gas accumulations found in Ría de Vigo, Spain, into four different types: acoustic blankets, acoustic curtains, acoustic columns and acoustic turbidity. Similar accumulation types were found in seismic profiles of TSB. Those authors suggest that the porosity in both the facies in which the gas accumulates and the seal facies are the main controls determining the type of gas accumulation.

Acoustic blankets (Figure 3) are identified by an upper enhanced reflection causing a complete masking of the underlying seismic record. The upper boundary is characterized by a gently sloping geometry that follows one or two bedding planes. These accumulations are typically few kilometers long along the seismic profiles.

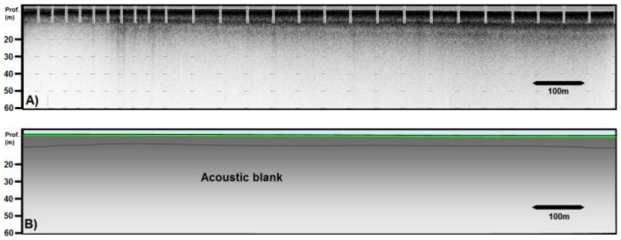

Figure 3 – (A) Acoustic blank type of gas accumulation recorded in the NW of Todos os Santos bay. (B) Interpreted seismic profile

The *a*coustic courtain type (figure 4) also causes a complete masking of the underlying seismic record, but shows a characteristic convex upper boundary, which appears as a strong phase-reversed reflector. The average lateral extension along seismic profiles ranges from tens to a few hundred meters. 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.

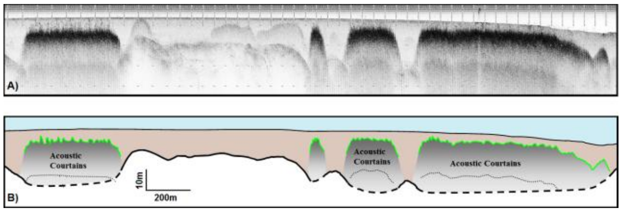

Figure 4 – (A) Acoustic courtains accumulations recorded in the NE sector of Todos os Santos bay. (B) Interpreted seismic profile

Acoustic columns (Figure 5) are identified as vertical smearing features that occasionally appear as transparent zones. 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. Similar seismic signatures were described by Hovland and Judd (1988) as transparent columnar perturbations originated by the upward migration of fluids, probably gas. Acoustic turbidity (Figure 5) consists of a variable degree of disturbance on the seismic record that occasionally allows to see faint reflectors through the disturbance. This effect can be produced with just only 1% by volume of gas in the sediment.

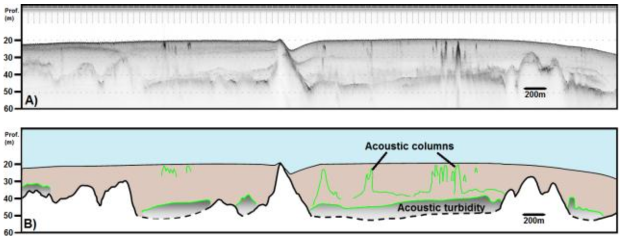

Figure 5 – (A) Acoustic turbidity and acoustic columns accumulations from the central-north zones of Todos os Santos bay. (B) Interpreted seismic profile

The average thickness of the Holocene sediments infilling the TSB is 12.5m (Figure 6). Acoustically transparent sediment packages of 5 – 15m thickness are present in almost the totality of the northwest and north-central zones of the bay. The smaller thicknesses are found in association with rock outcrops and coral reefs located mainly around islands and in some isolated spots inside the bay. Sediment packages of intermediate thickness ranging from 15 to 35m are present in large areas of the central, north and east zones of the TSB, Aratu bay and Itaparica Island. Sediment thickness of almost 42m are present in two points in the central and north areas of TSB.

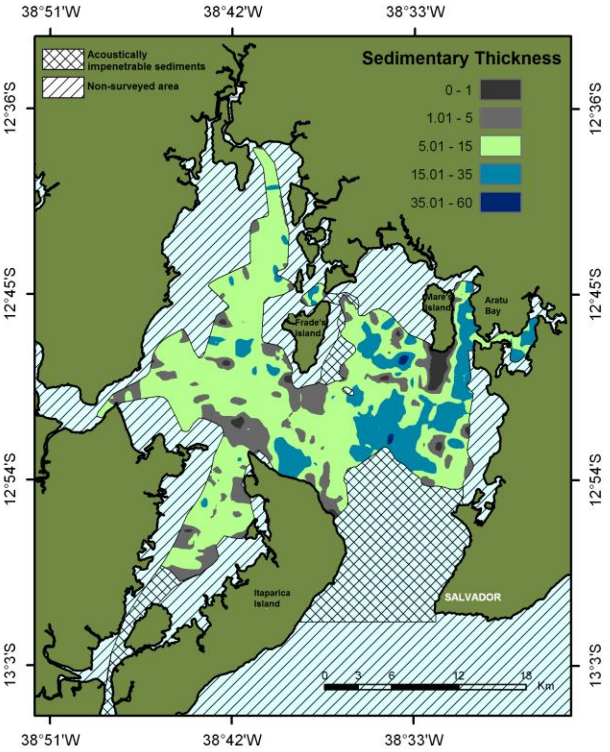

Figura 6 – Isopach map of Holocene sediments infilling the Todos os Santos bay.

Using as a criteria the presence of gas in the sediments, the Todos os Santos Bay was sub-divided in 06 major zone of gas occurrence (Figure 7):

(1) Northwest Accumulation Zone (NWA): Is the most extensive zone, totalizing 125km^2 and is located entirely in NW portion of TSB. The seismic profiles at this zone reveal the presence of acoustically transparent sedimentary packages. The main type of gas accumulation is the acoustic blank. In the most part of this zone the gas accumulations are almost coincident with the seabed. About 90% of the gas occurrences are found in depths shallower than 3m below the seabed and 30% in less than 1m. The occurrences are continuous and are present virtually along the entire seismic profile.

(2) Northeast Accumulation Zone (NEA): includes two zones of gas accumulation located inside the Aratu bay and adjacencies, comprising an area of 21km^2 . Acoustic blanketing is identified in relatively deeper layers reaching up 26m below the seabed. Nearly 60% of the occurrences

are located between 2 and 6m below the seafloor. The dominant type of gas occurrence are acoustic curtains, frequently noncontinuous.

(3) Center-north Accumulation Zone (CNA): cover a total area of 15km^2 and shows rare occurrences of gas, mainly of the acoustic turbidity type, but also including acoustic blankets and acoustic columns.

(4) Acoustically transparent, gas free zone: represents the areas where no gas was found, despite they were gas-prone areas

(5) Outcrop and Thin Sediment Cover zones: encompass areas where the rocky substrate outcrops or is thinly covered with sediments.

(6) Acoustically impenetrable, coarse-grained sediments zone (AIC).

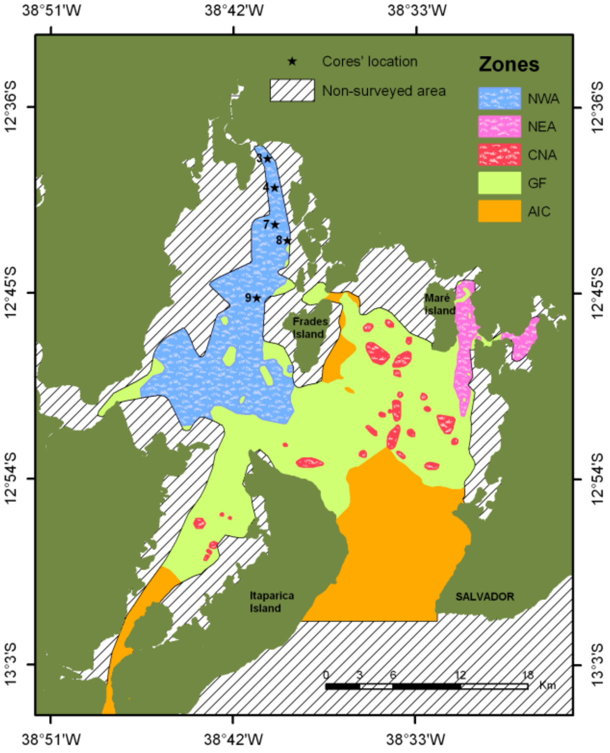

Figure 7 – Gas occurrence Zones of the TSB. See text for details.

Anomalous concentrations of methane were found in 5 of 8 cores, collected in the NWA zone of gas accumulation. Samples showing free methane concentrations higher than 90 ppm can be considered anomalous, since the background values of methane in similar coastal environments are typically below 30ppm (Garcia-Garcia et al, 2007). In the sediment cores in which the gas concentration was determined at two depths (7, 8 and 9 – Figure 7), the concentrations of methane increased substantially with increasing depth. This is expected because methanogenesis occurs typically below the base of the sulfate reduction zone. The levels of free gas found in the sediment confirms the theory that the acoustic anomalies present in high resolution seismic records of TSB are caused by the presence of high concentrations of free gas in the sediment (up 0.01% or 100ppm), and that the gas is primarily composed of methane. The gas levels found in this study for free methane and other hydrocarbons in the sediment are in agreement with the values reported for coastal and marine sediments from various parts of the world.

δ^{13}C values determined for the methane (between -77 and -81.2 ‰) indicate a biogenic origin for this gas. The preferential use of the low mass isotope (^{12}C) by bacteria during methanogenesis results in a strong depletion in ^{13}C in CH_4 bacterial substrates in relation to their precursors (Whiticar, 1999; Borowski et al, 1997). δ^{13}C levels of biogenic methane in sediments vary widely, from -110 to -50 ‰, but the commonest values are between -90 and -60 ‰, similar to those found in this study (Blair, 1998).

In general, biogenic methane production requires environments that present (Garcia-Garcia et al, 2007; Rice and Claypool, 1981, Boone et al, 1993): (1) anoxia; (2) depletion in sulfate; (3) temperatures between 0 and 75°C, depending on the species of the methanogenic organism; (4) a minimum of 0.5% of bioavailable organic matter; (5) sufficient interstitial space for methanogenic bacteria (~ 1um); and (6) rapid sediment deposition.

These environmental conditions are met in most of the Holocene sediments of the northern half of the Todos os Santos bay. Hydrogen-rich substrates and bioavailable organic matter are associated with new and shallow sediments, which typically contain sufficient interstitial space to sustain methanogenic organisms (Garcia-Garcia et al, 2007). In fact, according to Dominguez and Bittencourt., (2009), the beginning of significant sedimentation in the BTS, dates from 8000 years AP. According to Lessa et al (2000), sedimentation rates associated with muddy facies in which the gas is sealed ranged 0.8 - 4mm/ano for the last 5000 years. Moreover, high organic carbon levels (> 0.5%) necessary to sustain the production of methane in sediments of marine environments were found in 23 of the 25 grab samples collected , including all locations where gas occurrence was recorded. The average TOC content for the gas occurrence sites was 2.08%, whereas for the sites without gas, the average was 0.97%. Temperatures in the sediment of a shallow tropical bay naturally lie within the required range (0 - 75 ° C) and anoxic conditions are easily generated within a few centimeters of the seabed in coastal organic matter rich sediments , as is the case inside the TSB. The sulfate reduction zone is probably shallow for this region. A core examined in the laboratory presented a strong H_2S smell between ~ 80 - 210 cm below the interface sediment/water. The sample collected just below this level (at 240 cm) showed very high levels of methane.

The coincidence of areas of gas accumulation with those of fine sediments (Figure 8) show that gas occurrences are restricted to predominantly muddy areas. In fact, except for the eastern and southern boundaries of the ANW Zone, gas accumulations are present in areas where mud concentrations are greater than 50%, prevailing in areas with greater than 90% mud.

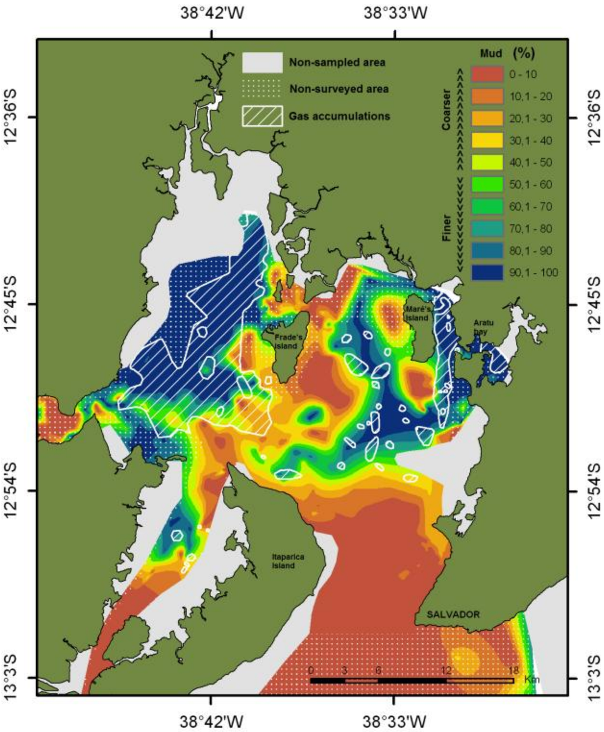

Figure 8 – Map showing the overlapping of gas accumulation areas and the fine sediments distribution.

The gassy sediments cover an area of 161Km². This area corresponds to 15% of the total area of the TSB, or 27% of 600km² imaged. Thus, due to the possibility of existence of gas fields in places not covered during the seismic survey, these accumulations are likely to extend for an even larger area. Many of the non-imaged areas present sedimentological and geochemical characteristics similar to those found in places where gas accumulations have been identified.

At AIC zone, the gas accumulations cannot be identified by the seismic method employed. Anyway, the existence of gas accumulations in this area is not antecipated due to the fact that coarse sediments are unable to trap the gas.Also particle size does not favor organic matter accumulation.

Conclusions

The spatial distribution of gassy sediments infilling Todos os Santos bay was identified and mapped. The gas accumulations identified occupy almost the entire northwest and northeast area of the TSB, while localized occurrences were found in the north-central bay and the Itaparica channel. .

Analysis of gas bearing sediments from the NW portion of the bay have shown anomalous concentrations of methane (> 90 ppm), reaching up to 10^4 ppm between 1.3 and 2.4 m below the seabed, confirming that the acoustic anomalies found in the seismic profiles were caused by the presence of free gas in the sediment. The determination of the $^{13}C/^{12}C$ isotope ratio showed a strong depletion of ^{13}C in the methane gas, indicating a biogenic origin for this gas.

However, several issues still need to be addressed. It is recommended acquisition of new seismic records covering the non-imaged area of TSB for a complete mapping of gas occurrences. The spatial distribution of gassy sediments in the TSB, presented herein , provides the adequate background for further studies of these occurrences.

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References

Anderson, A.L.,Hampton, L.D.. Acoustics of gas-bearing sediments I. Background. **Journal of the Acoustic Society of America,** 1980. 67(6):1865-1888.

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(2):253-261

Blair, N.. The δ13C of biogenic methane in marine sediments: The influence of C(org) deposition rate, 1998. **Chemical Geology**, 152 (1-2), pp. 139-150.
Boone, D.R. Whitman W.B., Rouviere P.. Diversity and taxonomy of methanogens. In: J.G Ferry, Editor, *Methanogenesis*, Chapman and Hall Co, New York (1993), pp. 35–80.

Borowski, W.S., Paull, C.K., Ussier III, W.. Carbon cycling within the upper methanogenic zone of continental rise sediments: An example from the methane-rich sediments overlying the blake ridge gas hydrate deposits, 1997. **Marine Chemistry**, 57 (3-4), pp. 299-311

Davis ,A., 1992. Methane in marine sediments. **Continental Shelf Research**, 12:175

Diez, R., García-Gil, S., Duran, R., Vilas,F.. Gas accumulations and their association with particle size distribution patterns in the Ría de Arousa seabed (Galicia, NW Spain): an application of the discriminant analysis. **Geo-Marine Letters**, 2007. 89-102.

Dimitrov, L.. Contribution to atmospheric methane by natural seepages on the Bulgarian continental shelf. **Continental Shelf Research**, 2002. 22:2429-2442.

Dominguez, J.M.L, Bittencourt, A.C.S.P., 2009. Geologia . In Hatje, V.; Andrade, J.B. Baía de Todos os Santos – Aspectos oceanográficos. Salvador: EdUFBa

EMBRAPA – EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. 1997. Manual de Métodos de Análise de Solo. 2ª ed. Rio de Janeiro: Centro Nacional de Pesquisa de Solos (CNPS), 211p.

Emeis, K.-C., Brüchert, V., Currie, B., Endler, R., Ferdelman, T., Kiessling, A., Leipe, T., Noli-Peard, K., Struck, U., Vogt, T., 2004. **Continental Shelf Research**. 24:627-642.

Fleischer, P., Orsi, T.H., Richardson, M.D., Anderson, A.L.. Distribution of free gas in marine sediments: a global overview. **Geo-Marine Letters**, 2001. 21:103-122.

Frazão, E., Vital, H., 2007. Estruturas rasas de gás em sedimentos no estuário Potengi (Nordeste do Brasil). **Revista Brasileira de Geofísica**. 25:17-26.

García-García, A., Orange, D.L. Miserocchi, S. Correggiari, A. Langone, L. Lorenson, T.D. Trincardi F., Nittrouer, C.A., What controls the distribution of shallow gas in the Western Adriatic Sea?, 2007.**Continental Shelf Research 27**, pp. 359–374.

Garcia-Gil, S., Vilas, F., Garcia-Garcia,A.. Shallow gas features in incised-valley fills (Ría de Vigo, NW Spain): a case study. **Continental Shelf Research**, 2002. 22:2303-2315.

Hampton, M.A, Karl, H.A., Murray, C.J., 2002. Acoustic profiles and images of the Palos Verdes margin: implications concerning deposition from the White’s Point outfall. **Continental Shelf Research**. 22:841-857.

Iglesias, J., García-Gil, S.. High-resolution mapping of shallow gas accumulations and gás seeps in San Simón Bay (Ría de Vigo, NW Spain). Some quantitative data. **Geo-Marine Letters**, 2007. 27:103-114.

Judd, A.G., Sim, R., Kingston, P., McNally, J.. Gas seepage on an intertidal site: Torry Bay, Firth of Forth, Scotland. **Continental Shelf Research**, 2002. 22:2317-2331.

Lessa, G.C., Bittencourt, A.C.S.P., Brichta, A., Dominguez, J.M.L, 2000. A Reevaluation of the Late Quaternary Sedimentation in Todos os Santos Bay (BA), Brazil. **Anais da Academia Brasileira de Ciências.** 72(4):573-590.

Mazumdar, A., Peketi, A., Dewangan, P., Badesab, F., Ramprasad, T., Ramana, M.V.. Shallow gas charged sediments off the Indian west coast: Genesis and distribution. **Marine Geology**, 2009. 267:71-85.

Okyar, M., Ediger, V.. Seismic evidence of shallow gas in the sediment on the shelf off Trabzon, southeastern Black Sea. **Continental Shelf Research**, 1999. 19:575-587.

Prior, D. B., J. M. Coleman, 1984. Submarine Slope Instability, in *Slope Instability*, D. Brunsden and D. B. Prior, pp. 419–455, John Wiley, New York

Rice, D.D., Claypool, G.E.. Generation, accumulation, and resource potential of biogenic gas, 1981. **American Association of Petroleum Geologists Bulletin**, 65 (1), pp. 5-25.

Whiticar, M.J.. Carbon and hydrogen isotope systematics of bacterial formation and oxidation of methane, 1999. **Chemical Geology**, 161 (1), pp. 291-314.

Wilkens, R.H., Richardson, M.D.. The influence of gas bubbles on sediment acoustic properties: in situ, laboratory, and theoretical results from Eckernförde Bay, Baltic sea. **Continental Shelf Research**, 1998. 18:1859-1892.