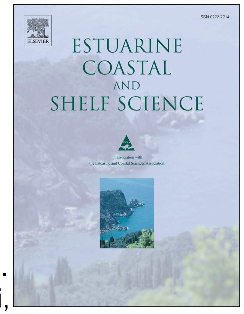
Accepted Manuscript



The control of palaeo-topography in the preservation of shallow gas accumulation: examples from Brazil, Argentina and South Africa

Jair Weschenfelder, Antonio H.F. Klein, Andrew N. Green, Salvador Aliotta, Michel M. de Mahiques, Arthur Ayres Neto, Laurício C. Terra, Iran C.S. Corrêa, Lauro J. Calliari, Isabel Montoya, Silvia S. Ginsberg, Gilberto H. Griep

PII: S0272-7714(16)30048-8

DOI: 10.1016/j.ecss.2016.02.005

Reference: YECSS 5046

To appear in: *Estuarine, Coastal and Shelf Science*

Received Date: 18 June 2015

Revised Date: 3 February 2016

Accepted Date: 5 February 2016

Please cite this article as: Weschenfelder, J., Klein, A.H.F., Green, A.N., Aliotta, S., de Mahiques, M.M., Neto, A.A., Terra, L.C., Corrêa, I.C.S., Calliari, L.J., Montoya, I., Ginsberg, S.S., Griep, G.H., The control of palaeo-topography in the preservation of shallow gas accumulation: examples from Brazil, Argentina and South Africa, *Estuarine, Coastal and Shelf Science* (2016), doi: 10.1016/j.ecss.2016.02.005.

THE CONTROL OF PALAEO-TOPOGRAPHY IN THE PRESERVATION OF SHALLOW GAS ACCUMULATION: EXAMPLES FROM BRAZIL, ARGENTINA AND SOUTH AFRICA

Jair Weschenfelder[1,*], Antonio H.F. Klein[2], Andrew N. Green[3], Salvador Aliotta[4], Michel M. de Mahiques[6], Arthur Ayres Neto[7], Laurício C. Terra[8], Iran C. S. Corrêa[1], Lauro J. Calliari[8], Isabel Montoya[6], Silvia S. Ginsberg[4,5], Gilberto H. Griep[8]

[1]Centro de Estudos de Geologia Costeira e Oceânica, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500. Caixa Postal 15001, 91501-970, Porto Alegre, RS, Brasil.

[2]Laboratório de Oceanografia Costeira, Departamento de Geociências, Centro de Filosofia e Ciências Humanas, Universidade Federal de Santa Catarina. 88040-900, Florianópolis, SC, Brasil.

[3]Geological Sciences, School of Agricultural, Earth and Environmental Sciences, Univ. of KwaZulu-Natal Westville Campus, Private bag x54001, South Africa.

[4]Instituto Argentino de Oceanografía, CONICET, La Carrindanga km 7, 8000 Bahía Blanca, Argentina. Departamento de Geología, UNS, San Juan 672, 8000 Bahía Blanca, Argentina.

[5]Departamento de Ingeniería Civil, UTN, FRBB, 11 de Abril 461, 8000 Bahía Blanca, Argentina

[6]Instituto Oceanográfico, Universidade de São Paulo. Praça do Oceanográfico, 191. 05508-120, São Paulo, SP, Brasil.

[7]Departamento de Geologia e Geofísica, Instituto de Geociências, Universidade Federal Fluminense. Av. Milton Tavares de Souza, S/N, Gragoatá. 24210-346, Niterói, RJ, Brasil

[8]Instituto de Oceanografia, Universidade Federal do Rio Grande. Av. Itália km 8, 96201-900, Rio Grande, RS, Brasil.

* Corresponding Author jair.weschenfelder@ufrgs.br / tel. +55 51 33089802

The control of palaeo-topography in the preservation of shallow gas accumulation: examples from Brazil, Argentina and South Africa

Abstract

Acoustic anomalies in seismic records have revealed that gas-charged sediments are very common features in the coastal environments around the world. The ubiquitous gassy sediments challenge the effective acoustic mapping of shallow stratigraphy by seismic means, as well as having an important influence on environmental issues related to the coastal zone occupation and management. This paper documents examples of gassy sediments from coastal lagoons, estuaries, rivers, bays and the inner shelf and nearshore environments of Brazil, Argentina and South Africa. Seismic echograms from selected areas show several gas-related anomalies, which present distinctive morphologies for sediment-trapped gas, leaking or free gas discharge into the water column. In several places the gas-charged sediments occur in areas of palaeo-topographic lows related to fluvial channels and valleys that developed in the coastal zone due to sea level oscillations during the Quaternary period. This forcing by palaeo-topographic features results in the occurrence of shallow gas being controlled in most coastal sites by the previous environmental scenario, the stratigraphic arrangement of the transgressive infilling elements, and the local hydrodynamic conditions.

Keywords: South America; South Africa; acoustic survey; shallow gas; coastal evolution.

1. Introduction

Gas accumulations in shallow shelf and coastal sediments are a common phenomenon worldwide (Park et al., 1991; Karisiddaiah et al., 1992; Papatheodorou et al., 1993; Garcia-Garcia et al., 1999; 2007; Okyar and Ediger, 1999; Fleischer et al., 2001; Missiaen et al., 2002; Garcia-Gill, 2003), the origins of which may be either biogenic (Kaplan, 1974) or thermogenic (Lee et al., 2005) in nature. The various gas sources and modes of accumulation are closely related to the sedimentary and evolutionary processes occurring in the coastal depositional environment (Garcia-Gil et al., 2002). Transgressive and regressive sea level fluctuations can produce dramatic changes in depositional environments and coastal physiography, sedimentation rates and sediment type. As a consequence, the distribution of organic matter and its quantity can vary considerably based on the coastal response to sea level fluctuations. Sandy packages may form gas reservoirs, while the finer, mainly muddy sediments may form sealing layers. Gas features can be formed in various types of environments, like shallow or enclosed seas and continental shelves (Emeis et al., 2004), lakes (Lafferty et al., 2006), bays (Jensen and Bennike, 2009) and rías (Garcia-Gil et al., 2002; Diez et al., 2007; Duarte et al., 2007; Iglesias and Garcia-Gil, 2007), since these sites provide favorable conditions for gas formation due the local high biological productivity of such environments. Ultimately the various gas reservoir and trapping sites, together with their associated types of gas accumulation, may provide windows into the evolution of the coastal and shallow marine environment (Garcia-Gil et al., 2002).

The presence of gas in sediments is especially well detected by high-resolution seismic surveying due to the change of speed of the acoustic wave between media with and without gas. The higher the speed gradient between the media, the stronger the echo response that will be generated by the variation of acoustic impedance between them. The intensity of the reflected acoustic signal recorded in the seismic profiles can be related to the concentration of gas bubbles occurring in the sedimentary package (Judd and Hovland, 1992; Aliotta et al., 2009). In echograms the gas structures may display various features comprising blankets/blanking, curtains, columns, acoustic turbidity zones, pinnacles, intra-sedimentary plumes and others, according to their seismic signature (Garcia-Gil et al., 2002; Frazão and Vital, 2007). Leak features are similarly common and occur as plumes and pockmarks, amongst other features (Garcia-Gil et al., 2002).

Gas is generated in the sediments and normally slowly released to the atmosphere and such total contribution to the global budget is poorly constrained (Judd, 2004). Further, gassy sediments may represent risks to engineering works and terrain stability (Premchitt et al., 1992). This paper thus aims to describe and discuss the various gas features found in shallow marine and coastal environments from a number of sites in the Southern Hemisphere. Diverse settings in Brazil, Argentina and South Africa are reported on, and several examples of gas-induced acoustic anomalies in echograms are shown. By comparing and contrasting the styles of gas accumulation and leakage in such diverse systems and settings, we hope to add to what is known concerning the controls on the accumulation and distribution of gas in coastal marine sediments.

2. Shallow gas accumulation signatures

Anomalous acoustic reflection responses observed in gas accumulations are related to the amount of gas concentration in the sediments. The acoustic turbidity is a phenomenon caused by diffusion of acoustic energy due to gas bubbles trapped in the sediments (Hart and Hamilton, 1993). Most of the common acoustic signatures of gas-charged sediments have been recognized in coastal sediments.

The gas occurrences can be described and classified from the echo-character signatures observed in sub-bottom profiles (SBP) and sidescan sonar (SSS) records. Various terms have been used to describe and classify the shallow gas occurrences. There is some overlap of names referring to the classification of different features, with different names for similar accumulations. The following list of gas features is not exhaustive, but summarizes those we have observed in the echograms from the focus regions in this study and the terminology used in this paper.

Acoustic blanking: in this acoustic phenomenon the seismic reflector below the gas horizon is very weak or absent due the attenuation of the sound wave traveling through the charged sedimentary package (Judd and Hovland, 1992; Orange et al., 2005). The top of the gas occurrence is very reflective, which masks any underlying seismic reflector, thus preventing connection of the trapped gas to the source or the mapping of seismo-depositional architectural elements. This acoustic phenomenon has been also referred to as blankets or acoustic masking (Garcia-Gil et al., 2002; Frazão and Vital, 2007; Mazumdar et al., 2009).

Gas curtain or pocket gas: a gas accumulation which usually shows a well-defined morphology, in the form of boxes of anomalous seismic reflection with an upper surface well marked by strong, relatively continuous, horizontal or gently dipping top reflectors. The acoustic response below the top reflectors is usually chaotic, masking the underlying sedimentary structures (Weschenfelder et al., 2006, 2014).

Acoustic turbid zone: a type of gas accumulation in which the acoustic anomaly is characterized by a more irregular and less pronounced top reflector than in zones with gas curtains. The seismic reflectors underlying the top of the gas accumulation are not entirely hidden, allowing the identification and mapping of the sedimentary structures beneath (Judd and Hovland, 1992).

Gas brightening: this is the phenomenon of brightening sectors of the echogram caused by the increasing contrast of the acoustic speed between zones with minor quantities of gas and gas free strata (Judd and Hovland 1992; Hart and Hamilton, 1993).

Acoustic windows: these refer to echogram sectors with strong gas-induced anomalies interspersed with sectors free of such anomalies. These windows occur due to an abrupt lateral change from gas-charged to gas-free sediments (Figueiredo et al., 1996; Costa and Figueiredo, 1998).

Black shadow: is marked by several multiples of the surface of the gas, which makes it impossible to identify any structure below it (Baltzer et al., 2005). The multiples are the expression of the reverberation of the seismic energy from the gas-induced extra reflectivity of the upper interface.

Turbidity pinnacles: a variation of acoustic blanking, which manifests in a downward concave U-shape and obscures any feature below it (Iglesias and Garcia-Gil, 2007; Souza et al., 2011).

Gas leaks or gas seeps have been classified into several types according to their specific echo-character signatures. These are:

Acoustic plumes: these appear as discrete hyperbolic curves in the water column which are related to free gas bubbles in the water. They are usually associated with zones of acoustic blanking, and represent the exhaust of gas into the water column (Taylor, 1992; Lee et al., 2005; Garcia-Gil et al., 2002; Frazão and Vital, 2007; Diez et al., 2007; Duarte et al., 2007).

Intra-sedimentary plumes: these are anomalies consisting of parabolic reflectors that cross-cut real reflectors (Iglesias and Garcia-Gil, 2007; Souza et al., 2011).

Pockmarks: these are crater-like features of different diameters (from centimeters to kilometers), evident on the sediment water interface, that are caused by fluids (gas and liquids) erupting and streaming through the sediments into the water column, which can cause destabilization of the sediment matrix, collapsing voids and liquefaction (King and McLean, 1970; Garcia-Gil et al., 2002; Iglesias and Garcia-Gil, 2007).

3. Methods

As we will outline, gas as a pervasive feature in the sedimentary record can be visualized by a number of different seismic tools at differing scales and resolutions. We describe the gas accumulation signatures of nine different environmental settings from the southern hemisphere. These include several large Brazilian coastal waterbodies and embayments (e.g. Patos Lagoon, Conceição Lagoon and North Bay, and Guanabara Bay), estuaries (e.g. Santos Estuary) and even shelf environments (e.g. Rio Grande do Sul continental shelf). Examples are also highlighted from Argentina's estuaries (e.g. the Bahía Blanca Estuary) and these are compared to examples of coastal water bodies from the east coast of South Africa (e.g. Durbarn Bay and Lake St. Lucia) where sediment supply is significantly lower.

3.1. Brazil

To study the sub-bottom features of the *Patos Lagoon* (Fig. 1), 3.5 kHz seismic records were obtained with a GeoAcoustics sub-bottom profiler, consisting of a GeoPulse transmitter (5430A), a GeoPulse receiver (5210A), a 132B transducer array (4 mount), a GeoPro processor system and the *SonarWiz*® acquisition software (saved in SEG-Y format; vertical resolution ~ 10 cm). 7 kHz echograms with vertical resolution of ~ 20 cm were also considered, these were acquired during a previous survey with a Raytheon shallow seismic system (details in Toldo et al., 2000).

Shallow seismic records were acquired on the adjacent Rio Grande do Sul (RS) continental shelf ~20 kilometers from the Patos Lagoon mouth (Fig. 2). Data were collected using a Bathy 2010 CHIRP sub-bottom profiler with four transducers of different frequencies ranging from 3.5 to 33 kHz. Processing of the seismic images was performed using the *SonarWiz*® software. The vertical resolution is ~ 10 cm.

Further north, the echo-characters of gaseous sediments and their spatial distribution in the *Conceição Lagoon and North Bay* (Florianópolis) (Fig. 3) were also examined, based on high-resolution CHIRP seismic records. The Conceição Lagoon was surveyed with an Edgetech 3200, model SB 512-I, sub-bottom profiling system. The selected frequency range was of 1 to 6 kHz, resulting in a vertical resolution of ~ 15 cm. The North Bay was surveyed using an Edgetech 3200, model SB216-s, sub-bottom profiling system, with frequency range from 2.5 to 15 kHz, resulting in a vertical resolution of ~ 6 cm. In both surveys, a wideband frequency modulation was used employing Edge Tech´s Full Spectrum CHIRP technology. In tandem with the seismics, an Interferometer Bathymetric and 540 kHz Sidescan Sonar (SSS) system (Edge Tech 4600) was used to map the bottom of the Conceição Lagoon. Furthermore, *in situ* scuba diving photographs were obtained of features suspected to be gas leaks.

To characterize the gas features in the *Santos estuarine complex* (SE Brazil) (Fig. 4), a shallow seismic survey was performed using a Meridata MDDSS (Multi-Mode Sonar System) system, with two CHIRP sound sources (2-8 and 10-20 kHz). Processing and interpretation were done with the dedicated software packages SVIEW and MDPS (Meridata Finland®). The vertical resolution is ~ 10 cm.

To locate the gas occurrences within the Jurujuba Sound of *Guanabara Bay* (Fig. 5) a high-resolution seismic survey was conducted using an EdgeTech 3200 XS sub-bottom profiling system with a SB-512i towfish. The system uses CHIRP technology and the frequency of operation was 1 to 6 kHz, with a vertical resolution of ~ 10 cm.

3.2. Argentina

Numerous seismic surveys have been conducted in the *Bahía Blanca Estuary* (Fig. 6), totaling over 1,000 line km of profiles. The information was obtained from high resolution seismic profiles (3.5 kHz), with a Geopulse Transmitter 5430A. Four GeoAcoustics 137D transducers were arranged with this equipment with a maximum power of 10 kW, thus optimizing the seismic penetration. Data positioning during the acoustic surveys was obtained in real time with a DGPS. The processing and analysis of the seismic data allowed the areal distribution of several shallow gas reservoirs to be defined. The vertical resolution is ~ 15 cm.

3.3. South Africa

The southeast coast of South Africa is characterized by several marine embayments and coastal waterbodies, most notably the *Durban Bay* harbor and *Lake St. Lucia*, Africa's largest estuarine system. Sub-bottom data were collected from both Durban Bay and Lake St. Lucia (Figs. 7 and 8) using a 200J boomer system, coupled with an 18-element hydrophone array. The vertical resolution is ~ 20 cm. Data were recorded digitally using HYPACK™ and processed for visualization. The Durban Bay bathymetry was also mapped using a Reson 8101 multibeam echosounder, the data processed with HYSWEEP™ and visualized in Fledermaus.

4. Gas-charged sediments in Brazil

Acoustic surveys in Brazil have recorded anomalous reflections related to gas disseminated in sediments of several coastal environments. In the North of the country, gas commonly occurs in the Amazonas Continental shelf (Costa and Figueiredo, 1998), the Amazon submarine delta (Figueiredo and Nittrouer, 1995; Figueiredo et al., 1996) and in the lower Amazon River (Vital and Stattegger, 1997). The Açu River canyon and the Potengi Estuary are areas with gas occurrences in NE Brazil (Schwarzer et al., 2006; Frazão and Vital, 2007). In SE Brazil, gassy sediments occur in Guanabara Bay (Baptista Neto et al., 1996, Quaresma et al., 2000; Catanzaro et al., 2004; Marino et al., 2013) and Lagoa Rodrigo de Freitas (Baptista

Neto et al., 2011), both sites in Rio de Janeiro State, and in the Bertioga Channel in São Paulo State (Félix, 2012; Félix and Mahiques, 2013). In the South, such occurrences have been reported in the Patos Lagoon (Weschenfelder et al., 2006, 2008, 2010) and in the inner continental shelf of Rio Grande do Sul State (RS) (Terra et al., 2014), and in the North Bay and Conceição Lagoon in the Santa Catarina State (Souza et al., 2011; Guesser et al., 2012).

4.1. Gas in the Patos Lagoon, Southern Brazil

The RS coastal plain is a wide lowland covering around 33,000 km^2, bordering highlands to the west and a wide (average width of 125 km) and very gentle gradient (1.3-1.4 m/km) continental shelf to the East. The Patos Lagoon is the most remarkable physiographic feature of the lowland, covering an area of 10,000 km^2, with a NE-SW oriented length of 240 km, an average width of 40 km and a depth of 6 m (Fig. 1). The lagoon environment is protected from the nearby high-energy wave-dominated ocean, yet the lagoon bottom and margins are influenced by local waves that may reach up to 1.6 m (Toldo et al., 2000).

The seismic data revealed anomalous acoustic configurations that have been attributed as typical for sediments loaded with gas (Fig. 1). Overall, gassy sediments in the Patos Lagoon are concentrated in the deeper areas, where muddy sediments occur, as opposed to the sandier margins.

The gas curtains typically occur in the central part of the lagoon, associated mainly with topographic depressions (Fig 1d, e). A gas curtain occurring in front of the Camaquã River mouth is well-defined by a large (~ 7 km wide), continuous gas box with a strong reflector marking the upper surface (Fig. 1e, right side). However, in the same section, but separated by a palaeo-topographic high (middle), the echogram shows a gas curtain with a diffuse upper limit (Fig. 1e, left side). Further southwestward the gas curtain grades into an acoustic turbid zone and beyond to a zone with minor to no quantities of gas. The occurrence of gas-charged sediments is notably common in the palaeo-topographic lows inherited from the former coastal plain topography (Fig. 1d).

Gas curtains span a lateral range from between a few meters to several kilometers in the lagoonal sub-bottom (Fig. 1). Several acoustic windows can occur along the seismic profiles enabling the internal structure of the seismic and sedimentary units to be established.

The lateral extent of the acoustic turbid zones can span up to several kilometers in the Patos Lagoon records (Fig. 1e). In some places the upper surfaces of these gas accumulations are diffuse, sometimes reaching the lagoonal bottom. A gradual lateral transition from acoustic turbid zones to gas curtains or to zones without gas was observed in some echograms (Fig. 1e). Typically, acoustic turbid zones form at the border of pocket gas along the lagoon margins and in sandier sedimentary packages.

In the northern sector of the lagoon , several gas curtains interspersed with acoustic windows, in sectors with minor quantities of gas or gas free, occur also mainly in the innermost lagoonal area (Fig. 1a).

4.2. Gas in the Rio Grande do Sul Continental Shelf, Southern Brazil

The seismic records acquired ~ 20 km offshore from the Patos Lagoon mouth (Fig. 2), show mainly gas curtain features. Figure 2a shows a gas curtain 1.3 km wide and its top is located 10 m below the seabed (segment a–a', Line 4040). The gas curtain in the profile segment b–b' (Fig. 2d, Line 0922), has a width of 1.7 km and occurs at a depth of 8.4 m below the seabed. The gas curtain of the segment c–c' (Fig. 2e, Line 0922) has a width of 5 km and is found at a depth of 8.6 m. The gas curtain d–d' (Line 4551) in figure 2b has a width of 2.35 km and is at a depth of 10.5 m, whereas the gas curtaining depicted in segment e–e' (Fig. 2c) is 1.6 km wide and its top is located 12 m below the seabed.

These five occurrences display anomalous reflections characterized by acoustic turbidity zones with a well-defined upper surface, abrupt endings, columnar disturbances and obscuration of sedimentary structures. These features are characteristic of gas curtaining or pocket gas, the high content of which may be due to the upper plane-parallel layers acting as seals precluding significant gas seeps (Fig. 2b, c). It is notable that several incised valleys have been recognized in the area (Abreu and Calliari, 2005; Terra et al., 2014).

4.3. Shallow gas in the Conceição Lagoon and North Bay, Santa Catarina, Southern Brazil

The Conceição Lagoon and the North Bay of Santa Catarina are located on the rugged bedrock headland-strand plain coast of Santa Catarina State, Southern Brazil (Fig. 3). These areas are dominated by large bedrock headlands, reentrants, and bays and lagoon systems (Klein et al., 2010; McBride et al., 2013). The surficial sediment of the Conceição Lagoon is predominately very fine to fine sand in shallow waters (0 to 2 m), and becomes increasingly muddier with depth (2 to ~10 m) (Gré and Horn Filho, 1999). The North Bay surface sediments are predominately mud, rich in organic matter and total sulfur (SO_4), especially in localized hot spots of accumulation (Bonetti et al., 2007).

The shallow gas accumulations frequently cause the complete masking of the seismic record and the underlying reflectors (Fig. 3a, b, c, d). This hinders the determination of any stratigraphically deeper features, the connection to a gas supply, and any seismo-depositional characterization of the system.

There are three main types of shallow gas features which appear in the North Bay seismic records: acoustic blanking, turbidity pinnacles and intra-sedimentary plumes (Fig. 3a, b). Acoustic blanking is most common, and normally occurs in the northern part of the bay. The presence of pocket gas in the central North Bay coincides with the palaeo-topographical low in front of the Biguaçu River delta.

In the Conceição Lagoon the most common feature found in the echograms is acoustic blanking, followed by acoustic plumes and black shadows (Fig. 3e, f). Only in the southern part of the lagoonal system do these features occur deeper in the subsurface. The presence of gas in SBP is accompanied by pockmarks structures observed in SSS records (Fig. 3c, d), coupled with the presence of acoustic plumes in the water (Fig. 3f). The pockmarks were also photographed during scuba diving operations (Fig. 3g). The average diameter of the pockmarks is ~ 1.0 meter and the density of pockmarks ranges from 53 to 242 per 50 m^2. They are generally linearly oriented and regularly spaced in area c and dispersed in area d (Fig. 3c. d).

4.4. Gas-charged sediments in the Santos Estuary, SE Brazil

The Santos estuary is located in the State of São Paulo (SE Brazil) and comprises a complex of estuarine channels (Fig. 4). The Santos Channel, also named Harbor Channel, forms the primary connection to the sea. This channel houses the most important harbor of Latin America, one of the most important industrial zones of the country and one of its most populated coastal metropolises (Alfredini et al., 2013).

The characterization of gas features and their relationship with the Quaternary evolution in the Santos estuarine complex has been partially described by Félix and Mahiques (2013). These authors analyzed these aspects in the Bertioga Channel, a secondary estuarine channel which flows into the Harbor Channel to the ocean. Moreover, both gas accumulation and escape features were analyzed as a tool to determine the age of the gas formation and sedimentary patterns and dynamics.

Figure 4 shows the location of gas occurrence and gas features in the middle and lower Harbor Channel. As observed, there is a prevalence of gas curtains in most of the seismic lines (b, c, d, e). Exceptions occur to the innermost profile (f), in which acoustic blankets seem to be the only gas features; also, the outermost profile (a), located at the entrance of the estuarine system, where turbidity pinnacles are the most common features. The presence of turbidity pinnacles is strongly related to the sandy grain size of the overlying sediments, which allow the leakage of gas. Notably, gas curtaining is associated with onlapping drape fills and abruptly blanks the uppermost stratigraphy of the fill succession (Fig. 4e). These appear to be infilling an incised valley form.

The gas escape features could be related to the removal of sealing cap curing dredging activities in the Harbor Channel, which took place since 2010. This intensive dredging activity makes it difficult in some cases to identify the original signatures of gas activity along the channel. Moreover, this practice leads to a potential environmental problem, since the removal of the sealing layers promotes the escape of an unmeasured amount of gasses to the water column and to the atmosphere. This is particularly important in such a densely populated region (Alfredini et al., 2013).

4.5. Gas-charged sediments in the Guanabara Bay, Rio de Janeiro, SE Brazil

The Guanabara Bay is one of the most prominent bays along the Brazilian coast (Fig. 5). Located on the coast of Rio de Janeiro State, it has an area of approximately 400 km^2 and is a typical coastal estuary dominated by tidal currents (Quaresma, 1997). Presently the whole area is undergoing severe environmental degradation driven by intense anthropogenic activities in the 7 municipalities located along its margins. The drainage system around the bay, responsible for most of the organic matter transport to the bay, arose ~ 200 ka BP. The Jurujuba Sound is located in the Niterói municipality, on the eastern margin of Guanabara Bay. The Sound ranges in depth from 5 to 7 m at its entrance to 3 to 4 m at the centre. It is surrounded by a small, steeply sloping catchment that is typical of the southeast coast of Brazil (Baptista Neto et al., 2000).

The gas features seems to occur in the weakly stratified onlapping drape packages within the incised valley fill of the study area (Fig. 5). Gas pockets have been recognized at or below the seafloor. When the gas is located at the seafloor (or at least close enough to the seafloor that the resolution of the seismic data does not allow the correct definition of its position) it occurs as an acoustic blanking feature (Fig. 5b). This form of occurrence usually has several associated seafloor multiples (black shadowing). When the gas accumulation is located below the seafloor, it takes the form of intra-sedimentary plumes and turbidity pinnacles (Fig. 5a). In the Jurujuba Sound, gas occurrences takes the form of diffuse gas pockets with small isolated hyperboles associated with gas leaks from the main area of concentration. This occurs between 3 ms and 6 ms (2.4 – 4.8 m) below the seafloor.

5. Gas-charged sediments in Argentina (Bahía Blanca Estuary)

Shallow gas occurrences have been reported in several areas along the South American Atlantic coast. Examples have been documented in Argentina from the Rio de La Plata estuary (Parker and Paterlini, 1990), in the San Matias Gulf (Aliotta et al., 2000), and in the central Argentina basin (Manley and Flood, 1989). Gassy sediments occurs also in the Bahía Blanca estuary (Aliotta et al., 2013, 2014).

The Bahía Blanca estuary is formed by a dense net of tidal channels that are separated by low altitude islands and sand shoals (Fig. 6). This mesotidal system has a major channel called Principal, which is the entrance to the main harbor complex in this region. The estuary is also characterized by the presence of large tidal mudflats formed during the last postglacial regression (Aliotta et al., 1996, 2004; Giagante et al., 2011).

Inside the estuary, the gas occupies a large area of the marine sub-bottom, spanning much of the maritime front and Bahia Blanca harbor (Fig. 6). In this sector, the acoustic signal suffers from partial or complete concealment of the underlying strata (Fig. 6a, b). Also, the gas concentrations are located at various depths and in some cases are in contact with the bottom water interface, though no plumes are evident (Fig. 6b).

Acoustic blanking occurs from the middle of the estuary and onto the adjacent offshore platform (Fig. 6c, d, e). Depending on the stratigraphic characteristics and porosity of sediments the top of the gas may occur coincident with the sediment stratification (Fig. 6c), likely along sealing layers which acts as a barrier for the ascension of gas. Areas of larger gas occurrences are elongated and generally associated with prograding facies with inclined strata toward the gas field (Fig. 6d, e). The base of this sequence corresponds to a discontinuity with associated onlap terminations (Fig. 6d). These configurations are generally related to the infilling package of palaeo-valleys, whose presence in the sub-bottom is correlated to the ancient coastal drainage network.

6. Gas-charged sediments in South Africa: marine embayments and waterbodies of the east coast

In southern Africa, several gas accumulations in the upper sedimentary packages of the Namibian and western South African shelves have been documented (Ben-Avraham et al., 2002; Emeis et al., 2004). On the east coast, gas charged sediment appears to be mostly absent from shelf strata (c.f. Green, 2011), though several authors documented the occurrence of gas accumulations in the coastal water bodies, lagoons and embayments of the region (Wright et al., 2000; Mkhize, 2014; Green et al., 2015). Acoustic surveys show the presence of gas-charged sediments in the Durban Bay harbor (Fig. 7) and Lake St. Lucia (Fig. 8), Africa's largest estuarine system; both sites are addressed below.

6.1. Gas-charged sediments in Durban Bay

The Durban Bay (Fig. 7, inset) is a large, microtidal estuarine complex underlain by several bedrock-hosted incised valleys that formed during the last glacial-deglacial cycle. The valley fills comprise a typical transgressive package of infilling, characterized by clay-rich deposits, intercalated with tidal sand bodies and capped by silt-rich sands (Mkhize, 2014).

In the deeper areas of the Durban Bay (> 5 m water depth), gas accumulation features manifest mainly as sheets of acoustic blanking (Fig. 7a). In the shallower areas occur the features turbidity pinnacles, gas brightening and acoustic blanking (Fig. 7b). Several gas escape structures are evident in the main subtidal channel of Durban Bay (Fig. 7c), especially where current scour is pronounced and the bottom sediment is sandier. These gas escape features comprise acoustic plumes and seafloor pockmarks. The sheltered nature of the Durban Bay, together with the very small drainage systems that now enter the system, are likely to foster accumulation of finer grained material known for their association with gas trapping (e.g. Weschenfelder et al., 2006). Fringing the system are several mangrove growths from which organic rich material is derived.

6.2. Gas-charged sediments in Lake St. Lucia, NE South Africa

The large estuarine lake system of Lake St. Lucia has many features of gaseous sediments (Fig. 8). The system comprises a series of incised valleys with multiple compound fills, the most pronounced of which was formed during the Last Glacial Maximum (LGM) of 18 ka BP. The fills comprise a typical transgressive package, characterized by clay-rich deposits, intercalated with tidal sand bodies and capped by lacustrine clays and silts (Green, 2011).

The more proximal landward portions of the lake system are dominated by pronounced acoustic blanking, gas brightening and the occurrence of prominent black shadowing of the seismic records (Fig. 8a, b). The proximal areas are typically muddy-bottomed and gas bubbling from the lake floor is often observed. Gas shadowing is associated with layers of stiff clay that cap the valley fills of several of the LGM aged valleys. Where this layer is not as well-developed, the dominant mode of gas obscuration is by blanking.

In certain areas, acoustically turbid zones may grade vertically into diffuse structures with inter-sedimentary plumes becoming prominent (Fig. 8a, c). In these areas, the upper clay layer is missing due to erosion and the gas is not as effectively trapped within the sediments. Acoustic windows are evident throughout the records, especially in areas where the lake floor is sandier. The almost complete masking of the records occurs in shallow topographic depressions, usually characterized by the most recent incised valley forms (Fig. 8c).

In the more seaward part of the system, particularly where the bottom is sandier, gas masking and gas features are less pronounced (Fig. 8d, e). Here, gas curtaining is the most common feature, with isolated zones of gas brightening occurring in the infilling-drapes of several of the older pre-LGM incised valleys (Fig. 8d, e). Gas tends to be more weakly diffused throughout the substrata and the quality of the seismic records is not as compromised as that of the proximal areas.

7. Discussion

Here we discuss, based on our examples, the various factors contributing to the genesis, preservation style and overall preservation potential of gas bodies in shallow coastal and marine sediments. We outline the general stratigraphic architectures associated with various gas signatures and relate these to the depositional environments they are associated with.

7.1. Generation of gas

Biogenic degradation of organic matter in sediments is reported by Kaplan (1974) as a main source of gas in marine sediments. On the basis of our own examples, we consider that the gas accumulations described occur in dominantly fine-grained sedimentary deposits of the Quaternary and most notably of the central basin deposits within transgressive incised valley systems. In almost all of our examples, the main gas occurrences are found in the inner to middle segments of incised valley systems. We assume that the majority of the gas we observe is derived from the settling of organic-rich material in the central estuarine basins of these hosting incised valleys. The strong association with the onlapping, drape type reflector arrangements of these areas is strongly supportive of this. Gas concentrations may have thus originated from the degradation of organic matter ensnared in sediment, resulting in the formation of interstitial gas. Much of the organic material in these systems is introduced as flocculants (central basin) or from bayhead deltaic growth into the estuary (e.g. Zaitlin et al., 1994). García-García et al. (2007) show that the source of shallow gas in Holocene strata can vary, with many of their examples of gas, especially in deltaic areas, associated with organic material delivered by flood incursions. This is the case for the Patos Lagoa (Fig. 1d), the Conceição Lagoon (Fig. 3e) and the Santos Estuary (Fig. 4) where gas is clearly associated with the upper stratigraphic packages near the main bayhead deltaic entry points to the lagoon systems. In the case of the Brazilian and South African coasts, the tropical to subtropical climate favors the development of mangroves and swamps, which are highly productive and further provide autochthonous organic matter.

Irrespective of source, most of the gas we describe has experienced an upward migration (curtaining, acoustic turbidity, intrasedimentary plumes), which is then controlled, to a greater or lesser extent, by the stratigraphic layout and sedimentological characteristics of the overlying materials as discussed below.

7.2. Stratigraphic signatures on gas preservation and style

7.2.1. Acoustic blanking and gas curtaining

We contend that gas curtaining is dependent on the stratigraphic characteristics and porosity of sediments that have transgressively infilled a series of palaeo-lows or incised valleys. The gas signature may be further altered by the location along the incised valley profile, in addition to the inherent hydrodynamic characteristics that occur.

Apart from the Bahia Blanca estuary, all of the systems that we describe and which experience strong gas curtaining are inevitably associated with the trapping of fine-grained sediments during the transgressive infilling of palaeo-lows within a predominantly low energy, sheltered setting. This is evidenced from the general trend for gas curtaining to occur in areas of low-amplitude, draped reflector configurations that are commonly interpreted as the central basin deposits of either wave-(Green et al., 2013) or tide-dominated (Zaitlin et al., 1994) estuaries. These seismic facies have been verified by many authors (e.g. Nordfjord et al., 2006; Chaumillon et al., 2008) as comprising muddy, organic-rich material.

In many of the areas examined, the top of the gas occurs coincident with an upper sealing layer, which acts as a barrier for the ascension of gas (Figs. 1, 2, 5 and 8). Lin et al. (2010) show that clay-rich upper horizons provide effective cap beds for the shallow gas system. In the outer segment of the incised valley, these cap beds may comprise old estuarine remnants of the incised valley (e.g. Lin et al., 2010), overlain by shoreface sands. In the inner and middle segments, cap layers may be derived from tidal channel abandonment (e.g Moslow and Tye, 1985), muddy intertidal flat deposition (Fenies and Faugères, 1998; Lin et al., 2010) or compaction of settled flocculants in microtidal settings (e.g. Hughes et al., 1998).

Lake St. Lucia in South Africa (Fig. 8), the Patos Lagoa and RS shelf (Figs. 1 and 2) and the Guanabara Bay (Fig. 5) show clear transitions from the incised valley to an upper unconfined lagoonal/lacustrine or shoreface environment. The gas trapping horizon extends between interfluves and terminates at roughly the same stratigraphic height within the valley, though this layer can be discontinuous. In the more tidally influenced examples (e.g St. Lucia and Guanabara Bay), we consider this level as consistent with that of the tidal ravinement surface, which has truncated, but not completely eroded the older abandoned muddy facies. Where small windows occur, this may be due to the localized erosion of tidal channel migration that has cut small channels into the underlying central basin repository and allowed gas to escape. Guanabara Bay is the best example of this (Fig. 5), with small channels of the scale of the contemporary tidal channels that are gas free, interspersed by strong gas curtaining. In the more extreme microtidal settings of the Patos Lagoa (Fig. 1), the gas windows may be a result of discontinuous lateral deposition of the sealing layer, likely a function of the very wide valley forms (> 4 km) over which several hydrodynamic conditions operate to produce lateral variability in the facies (e.g. Calliari et al., 2009).

On the shelf (e.g. the RS shelf), the preservation potential of shallow gas is complicated by additional erosion in the form of wave ravinement. However, where sufficient accommodation existed in the form of incised valleys, the central basin stratigraphic facets are preserved and capped by shoreface deposits (e.g. Green et al., 2013). Lin et al. (2010) consider that the greater overburden depth, the greater the increase in the sealing ability of cap beds. The extra overburden of the shoreface deposits is likely to contribute to this. Where gas is not confined to incised valleys (e.g. Okyar and Ediger, 1999; Emeis et al., 2004), the signatures are more diffuse (e.g. acoustic blanking and pinnacles) suggesting the trapping potential is not as significant as that provided by the incised valley stratigraphy.

7.2.2. Acoustic turbidity, intrasedimentary plumes and pockmarks

Gas signatures indicative of partial diffusion within the stratigraphy, or escape of gas to the water column can be related to several factors. We consider the environmental setting to be an important one. Where the setting is predominantly sandy, often times related to either sediment supply (e.g. supply of sandier sediment) or local hydrodynamic regime (e.g. preferential whittling by tides or wave circulation patterns in shallow areas), these may preclude effective cap horizons from forming and promote the permeation and diffusion of gas through a more porous sandy body. The Bahia Blanca estuary is a good example of this. Presently large areas of acoustic blanking and acoustic turbidity are found in the estuary (Fig. 6) and adjacent continental shelf. These appear as large prograding sand packages (Fig. 6c, e), likely related to the tidal processes of the mesotidal system. The preservation potential of these gas accumulations seems poor for several reasons. Firstly, the current regime is high, precluding the deposition of fine cap horizons and promoting the dissemination of gas in the sandy, tidal bedform units (e.g. Lin et al., 2010). Secondly, the inevitable tidal ravinement of these bedforms from a mesotidal perspective, will certainly remove whatever layers are acting as temporary seals. Specific to the Bahía Blanca estuary, the shallow occurrence of the gas may also affect preservation style and potential, with little overburden to promote an increase in cap effectiveness.

In shallow areas dominated by wind-wave reworking of the sea and estuarine floor, this consistently high energy will act to remove any muddy material and preclude the development of muddy cap layers in the stratigraphy. The bed of Lake St. Lucia is commonly mobile during prolonged periods of wind (Schoen et al., 2014), especially so in the more distal areas (Fig. 8d and e). Though no studies have been undertaken on this, personal observations by the authors from the Conceição Lagoon and the Durban Harbour of similar phenomena have been made. In all these examples, we consider the shallow and well-mixed areas of the systems to be related to gas release through intrasedimentray plumes, turbidity pinnacles and pockmarking of the sea/estuary floor. The pockmarks are the morphological expression of gas leakage and local erosion (Dando et al. 1994; Driscoll and Uchupi, 1997). The pockmark morphology and associated plumes demonstrate that gas is being leaked to the water column in both environments. The gas escape structures occurring in the channel of Durban Bay (Fig. 7) occur in close association with sandier substrates due to wind-wave winnowing. In the deeper areas of the system, gas accumulations manifest as sheets of acoustic blanking, gas curtaining, brightening, and gas shadows where the impermeable layers are below the wind-wave base.

The gas-related features presented and discussed here may provide some significant clues for the modeling of the geological evolution of coastal environments mainly during the Quaternary, a period recognized worldwide as being marked by significant shifts in coastal depositional systems triggered by oscillating sea levels during the Pleistocene. Where gas accumulates, this suggests the association of transgressive infilling packages within low-lying topography of the palaeo-coastal plain. This may be a key factor in interpreting the transgressive evolution of various sub-tropical/tropical coastlines where gas is found obscuring the seismic records. The shallow gas-accumulations identified here are also all related to the most recent post-glacial transgression. Despite there being evidence of compound incised valleys in the systems described (e.g. Figs. 1, 7 and 8), gas is invariably associated with the youngest post LGM-aged infill packages.

8. Conclusions

Gas interspersed in sediments causes a significant effect on the geoacoustic behavior, thus the gas accumulation can be clearly identified in echograms as anomalous or chaotic reflections. The gas-related anomalies show distinctive morphology for sediment-trapped gas, leaking or free gas in the water column.

Gas-charged sediments occur in the several Brazilian coastal waterbodies and embayments (Patos Lagoon, Conceição Lagoon and North Bay, and Guanabara Bay), estuaries (Santos Estuary) and shelf environments (RS shelf); also occur in the Bahía Blanca Estuary (Argentina) and in the coastal water bodies from E South Africa (Durbarn Bay and Lake St. Lucia). In several of the coastal sites the gassy sediments occur in areas of former topographic lows related to fluvial channels and valleys developed in the coast due to Quaternary sea level oscillations. The gas occurrences are best preserved in former topographic lows, either in actual inner/mid segment of incised valleys or if in the outer segment, in the central basin deposits. Their preservation may be reduced by the tidal ravinement/wave ravinement processes that can remove the muddy sealing layers, or by the inherent hydrodynamic processes that occur in shallow, wind-wave mixed lagoons and estuaries. Where the gas is capped by sandy material, pockmarking and gas plumes occur (with a low preservation potential). These are also areas where organic detritus accumulates best, so the gas sources are preferentially supplied in these areas. This forcing by former topographic features results in the occurrence of shallow gas being controlled in most places by the previous environmental scenario and the spatial distribution of the sedimentary facies. The various gas-related features provide clues for modeling the geological evolution of coastal environments, mainly in the Quaternary period when the coast was severely affected by previously oscillating sea level and associated shifts in the depositional systems characteristics. In most instances, the gas is relatively young and is associated with the most recent postglacial transgressive infilling period.

Acknowledgments

The research has been supported by CNPq (300437/2009-9, 471518/2010-7, 141975/2011-3), CAPES (BEX0267-13-9, CIMAR23038.004306/2014-17) and CECO-UFRGS. AHFK acknowledges PROSUL/CB&I for the North Bay data, Dr. Carla Bonetti for the Conceição Lagoon data (CNPq 401851/2010-9), and Diego Porpilho and Charline for the lagoon pockmark photographs. In Argentina the research was supported by the projects: PGI 24/H099 and 24/H107 (Secretaría de Ciencia y Técnica, UNS); PIP Nº 5538 and Nº00699 (CONICET); PID 25/B028 (UTN, FRBB). AG acknowledges grants by the Water Research Commission (Project K5/2336) and the National Research Foundation of South Africa (Grant 87654), together with data grants from Marine Geosolutions Pty Ltd and the National Ports Authority of South Africa. We acknowledge the thoughtful reviews of three anonymous reviewers that helped contribute to the paper's clarity.

References

Abreu, J.G., Calliari, L.J., 2005. Paleocanais da plataforma continental interna do Rio Grande do Sul: evidências de uma drenagem fluvial pretérita. Revista Brasileira de Geofísica 23(2), 123-132.

Alfredini, P., Arasaki, E., Pezzoli, A., Fournier, C.P., 2013. Impact of climate changes on the Santos Harbor, São Paulo State (Brazil). TransNav 7(4): 609-617.

Aliotta, S., Ginsberg, S.S., Giagante, D., Vecchi, L.G., Salvatierra, M.M., 2014. Seismic Stratigraphy of

Pleistocene Deltaic Deposits in Bahía Blanca Estuary, Argentina. Anais da Academia Brasileira de Ciências 86(2), 649-662.

Aliotta, S., Ginsberg, S.S, Spagnuolo, J., Farinati, E., Giagante, D., Vecchi, L.G., 2013. Late Quaternary in a South Atlantic estuarine system: Stratigraphic and paleontologic indicators of coastal evolution. Journal of South American Earth Sciences 45, 194-208.

Aliotta, S., Kostadinoff, J., Lizasoain, G., 2000. Sísmica somera com 3.5 kHz de la Plataforma Continental norpatagónica, Argentina. In: II Congresso Latinoamericano de Sedimentología. Mar del Plata, Argentina. Resúmenes, p. 26-27.

Aliotta, S., Lizasoain, G., Ginsberg, S.S., 2004. Dinámica sedimentaria y evolución morfológica de un profundo canal del estuario de Bahía Blanca, Argentina. Revista de la Asociación Geológica Argentina 59(1), 14-28.

Aliotta, S., Lizasoain, G., Lizasoain, W., Ginsberg, S.S., 1996. Late Quaternary sedimentary sequence in the Bahía Blanca Estuary, Argentina. Journal of Coastal Research 12(4), 875-882.

Aliotta, S., Spagnuolo, J.O., Farinati, E., 2009. Origen de una roca de playa en la región costera de Bahía Blanca, Argentina. Pesquisas em Geociências 36(1), 107-116.

Baltzer, A., Tessier B., Nouzé, H., Bates, R., Moore, C., Menier, D., 2005. Seistec Seismic Profiles: a Tool to Differentiate Gas Signatures. Marine Geophysical Researches 26 (2/4), 235-245.

Baptista Neto, J.A., Silva, C.G., Dias, G.T.M., Fonseca, E.M., 2011. Distribuição sedimentar da Lagoa Rodrigo de Freitas através de sísmica de alta resolução. Revista Brasileira de Geofísica 29(1), 187-195.

Baptista Neto, J.A, Silva, M.A.M., Figueiredo Jr, A.G., 1996. Sísmica de alta frequência e o padrão de distribuição de sedimentos na Enseada de Jurujuba (Baía de Guanabara) - RJ/Brasil. Revista Brasileira de Geofísica 14(1), 51-57.

Baptista Neto, J.A., Smith B.J., McAllister J.J., 2000. Heavy metal concentrations in surface sediments in a nearshore environment, Jurujuba Sound, Southeast Brazil. Environmental Pollution 109, 1-9.

Ben-Avraham, Z., Smith, G., Reshef, M., Jungslager, E., 2002, Gas hydrate and mud volcanoes on the southwest African continental margin off South Africa. Geology 30, 927-930.

Bonetti, C., Bonetti, J., Barcelos, R. L., 2007. Caracterização sedimentar e geoquímica de sistemas costeiros com ênfase na avaliação da influência de sítios de cultivo de moluscos. In: Barroso, G. F., Poersch, L. H. S., Cavalli, R. O., Galvez, A. O. (Eds.). Sistemas de cultivos aquícolas costeiros no Brasil: recursos, tecnologias e aspectos ambientais e sócio-econômicos. Rio de Janeiro. Museu Nacional, p. 139-149.

Calliari, L.J., Winterwerp, J.C., Fernandes, E., Cuchiara, D., Vinzon, S.B., Sperle, M., Holland, K.T., 2009. Fine grain sediment transport and deposition in the Patos Lagoon–Cassino beach sedimentary system. Continental Shelf Research 29, 515–529.

Catanzaro, L.F., Baptista Neto, J.A., Guimarães, M.S.D., Silva, C.G.I., 2004. Distinctive sedimentary processes in Guanabara Bay - SE/Brazil, based on the analysis of echo-character (7.0 kHz). Revista Brasileira de Geofísica 22 (1), 69-83.

Chaumillon, E., Proust, J., Menier, D., Weber, N., 2008. Incised-valley morphologies and sedimentary-fills within the inner shelf of the Bay of Biscay (France): A synthesis. Journal of Marine Systems 72, 383-396.

Costa, E.A., Figueiredo Jr., A.G., 1998. Echo-Character and Sedimentary Processes on the Amazon Continental Shelf. Anais da Academia Brasileira de Ciências 70(2), 87-200.

Dando, P.R., Jensen, P., O'hara, S.C.M., Niven, S.J., Schmaljohann, R., Schuster, U., Taylor, L.J., 1994. 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.

Diez, R., García-Gil, S., Durán, R., Vilas, F., 2007. Gas accumulations and their association with particle size distribution patterns in the Ría de Arousa seabed (Galicia, NW Spain) an application of discriminant analysis, Geo-Marine Letters 27(2/4), 89-102.

Driscoll, N, Uchupi E., 1997. The importance of gas and groundwater seepage in landscape and seascape evolution. Thalassas 13, 35-48.

Duarte, H., Pinheiro, L.M., Teixeira, F.C., Monteiro, J.H., 2007. High-resolution seismic imaging of gas accumulations and seepage in the sediments of the Ria de Aveiro barrier lagoon (Portugal). Geo-Marine Letters 27(2/4), 15-126.

Emeis, K.C., Brüchert, V., Currie, B., Endler, R., Ferdelman, T., Kiessling, A., Leipe, T., Noli-Peard, K., Struck, U., Vogt, T., 2004. Shallow gas in shelf sediments of the Namibian coastal upwelling ecosystem. Continental Shelf Research 24(6), 627-642.

Fenies, H., Faugères, J-C., 1998. Facies and geometry of tidal channel-fill deposits (Arcachon Lagoon, SW France). Marine Geology 150, 131-148.

Félix, C.A., 2012. Evolução Quaternária Superior e Formação de Gás Raso em Ambiente Estuarino Tropical: O Caso do Canal de Bertioga. MSc. Dissertation, Universidade de São Paulo, SP. pp 115.

Felix, C.A., Mahiques, M.M., 2013. Late quaternary evolution and shallow gas formation in a tropical estuarine environment: the case of the Bertioga channel, Brazil. In: IEEE/OES Acoustics in Underwater Geosciences Symposium. DOI: 10.1109/RIOAcoustics.2013.6684003.

Figueiredo Jr., A.G., Nittrouer, C.A., 1995. New insights to high-resolution stratigraphy on the Amazon continental shelf, Marine Geology 125(3/4), 393-399.

Figueiredo, A.G., Nittrouer, C.A., Costa, E.A., 1996. Gas-charged sediments in the Amazon Submarine Delta. Geo-Marine Letters 16, 31-35.

Fleischer, P., Orsi, T.H., Richardson, M.D., Anderson, A.L., 2001. Distribution of free gas in marine sediments: A global overview. Geo-Marine Letters 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(1), 17-26.

García-García, A., Orange, D.L., Miserocchi, S., Correggiari, A., Langone, L., Lorenson, T.D., Trincardi, F., Nittrouer, C.A., 2007. What controls the distribution of shallow gas in the Western Adriatic Sea? Continental Shelf Research 27(3/4), 359-374.

García-García, A., Vilas, F., Garcia-Gil, S., 1999. A seeping sea-floor in Ria environment: Ria de Vigo (Spain). Environmental Geology 38, 296-300.

Garcia-Gil, S., 2003. A natural laboratory for shallow gas: The Rías Baixas (NW Spain). Geo Marine Letters 23, 215-229.

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

Giagante, D., Aliotta, S., Ginsberg, S., Vecchi, L., Spagnuolo, J., 2011. Evolution of a coastal alluvial deposit in response to the last Quaternary marine transgression, Bahía Blanca estuary, Argentina. Quaternary Research 75, 614-623.

Gré, J.C.R.., Horn Filho, N.O., 1999. Caracterização Textural dos Sedimentos de Fundo da Lagoa da Conceição, Ilha de Santa Catarina, SC, Brasil. In: Sierra de Ledo, B., Sofiano-Sm, E. J. (Eds). O Ecossistema da Lagoa da Conceição. NEMAR/CCB/UFSC, SDMEEPEMA p. 25-34.

Green, A.N., 2011. The late Cretaceous to Holocene sequence stratigraphy of a sheared passive upper continental margin, northern KwaZulu-Natal, South Africa. Marine Geology 289, 17-28.

Green, A.N., Dladla, N.N., Garlick, G.L. 2013. Spatial and temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa. Marine Geology 335, 148-161.

Green, A.N., Cooper, J.A.G., Wiles, E.A., De Lecea, A.M., 2015. Seismic architecture, stratigraphy and evolution of a sub-tropical marine embayment: Maputo Bay, Mozambique. Marine Geology 369, 300–309.

Guesser, V., Demarco, L.F.W., Klein, A.H.F., Ayres, A., Felix, C., Souza, J., Bonetti, J., 2012. Identificação das feições rasas de gás na região da Lagoa da Conceição e da Baía Norte na Ilha de Santa Catarina. In: V Simpósio Brasileiro de Geofísica, Salvador, Anais, 2012.

Hart, B.S., Hamilton, T.S., 1993. High resolution acoustic mapping of shallow gas in unconsolidated sediments beneath the Strait of Georgia, British Columbia. Geo-Marine Letters 13, 49-55.

Hughes, M.G., Harris, P.T., Hubble, T.C.T., 1998. Dynamics of the turbidity maximum zone in a micro-tidal estuary: Hawkesbury River, Australia. Sedimentology, 45, 397-410.

Iglesias, J., García-Gil, S., 2007. High-resolution mapping of shallow gas accumulations and gas seeps in San Simón Bay (Ría de Vigo, NW Spain).Some quantitative data. Geo-Marine Letters 27(2/4), 103-114.

Jensen, J.B., Bennike, O., 2009. Geological setting as background for methane distribution in Holocene mud deposits, Arhus Bay, Denmark. Continental Shelf Research 29(5/6), 775-784.

Judd, A.G., 2004. Natural seabed gas seeps as sources of atmospheric methane. Environmental Geology 46, 988-996.

Judd, A.G., Hovland, M., 1992. The evidence of shallow gas in marine sediments. Continental Shelf Research 12(10), 1081-1095.

Kaplan, I.R., 1974. Introduction. In: Kaplan, I.R. (Ed.) Natural gases in Marine Sediments. Planum Press, New York, USA, p.1-10.

Karisiddaiah, S.M., Veerayya, M., Vora, K.H., Wagle, B.G., 1992. Gas-charged sediments on the inner continental shelf off western India. Marine Geology 110, 143-152.

King, L.H., Maclean, B., 1970. Pockmarks of the Scotian Shelf. Geological Society of America Bulletin 81(10), 3141-3148.

Klein, A.H.F., Ferreira, Ó., Dias, J.M.A., Tessler, M.G., Silveira, L.F., Benedet, L., Menezes, J.T., Abreu, J.G.N., 2010. Morphodynamics of structurally controlled headland-bay beaches in southeastern Brazil: A review. Coastal Engineering 57(2), 98-111.

Lafferty, B., Quinn, R., Breen, C., 2006. A side-scan sonar and high-resolution CHIRP sub-bottom profile study of the natural and anthropogenic sedimentary record of Lower Lough Erne, northwestern Ireland. Journal of Archaeological Science 33, 756-766.

Lee, G.H., Kim, D.C., Kim, H.J., Jou, H.T., Lee, Y.J., 2005. Shallow gas in the central part of the Korea Strait shelf mud off the southeastern coast of Korea. Continental Shelf Research 25(16), 2036-2052.

Lin, C.M., Li, Y.L., Zhuo, H.C., Shurr, G.W., Ridgley, J.L., Zhang, Z.P., Xue, T.,2010. Features and sealing mechanism of shallow biogenic gas in incised valley fills (the Qiantang River, eastern China): a case study. Marine and Petroleum Geology 27,909–922.

Manley, P.L., Flood, R. D., 1989. Anomalous sound velocities in near-surface, organic-rich, gassy sediments in the central Argentine basin. Deep-sea Research 36, 611-623.

Marino, I.K., Santos, M.A.C. Silva, C.G., 2013. Processing the high-resolution, shallow seismic profiles, Guanabara bay - Rio de Janeiro State, Brazil. Revista Brasileira de Geofísica 31(4), 579-594.

Mazumdar, A., Peketi, A., Dewangan, P., Badesab, F., Ramprasad, T., Ramana, M.V., Patil, D.J., Daya, A., 2009. Shallow gas charged sediments off the Indian west coast: Genesis and distribution. Marine Geology 267(1/2), 71-85.

McBride, R.A., Anderson, J., Buynevich, I. V., Cleary, W.J., Fenster, M. S., FitzGerald, D. M., Harris, M.S., Hein, C.J., Klein, A.H.F., Liu, B., Menezes, J.T., Pejrup, M., Riggs, S.R., Short, A. D., Stone, G.W., Wallace, D.J., Wang, P., 2013. Morphodynamics of Barrier Systems: A Synthesis. In: Shroder, J.; Sherman, D.J. (Org.). Treatise on Geomorphology (Coastal and Submarine Geomorphology). 1º Ed. San Diego. Academic Press 10, 174-244.

Missiaen, T., Murphy, S., Loncke, L., Henriet, J., 2002. Very High-Resolution Seismic Mapping of Shallow Gas in the Belgian Coastal Zone, Continental Shelf Research 22 (16), 2291-2301.

Mkhize, N.E., 2014. Sequence and lithostratigraphy of incised valley fills: evolution of the Durban Bay system. Unpubl. Mac Thesis, University of KwaZulu-Natal, Westville, pp. 126.

Moslow, T.F., Tye, R.S., 1985. Recognition and characterization of Holocene tidal inlet sequences. Marine Geology 63, 129-151.

Nordfjord, S., Goff, J.A., Austin, J.A., Gulick, S.P.S., 2006. Seismic facies of incised valley fills, New Jersey continental shelf: implications for erosion and preservation processes acting during latest Pleistocene-Holocene transgression. Journal of Sedimentary Research 76, 1284-1303.

Okyar, M., Ediger, V., 1999. Seismic evidence of shallow gas in the sediment on the shelf off Trabzon, Southeastern Black Sea. Continental Shelf Research 19(5), 575-587.

Orange, D., García-García, A., Lorenson, T., Nittrouer, C., Milligan, T., Miserocchi, S., Langone, L., Correggiari, A., Trincardi, F., 2005. Shallow gas and flood deposition on the Po Delta. Marine Geology 222/223, 159-177.

Papatheodorou, G., Hasiotis, T., Ferentinos, G., 1993. Gas-charged sediments in the Aegean and Ionian Seas, Greece. Marine Geology 112, 171-184.

Park, S.C., Kim, Y.S., Hong, S.K., 1991. Shallow seismic stratigraphy and distribution pattern of late Quaternary sediments in a macrotidal bay, Gunhung Bay, west coast of Korea. Marine Geology 98, 135-144.

Parker, G., Paterlini, M., 1990. Apantallamientos acústicos en sedimentos gasíferos del Rio de La Plata. Revista de la Associación Geológica Argentina 45, 17-28.

Premchitt, J., Rad, N.S., To, P., Shaw, R., James, J.W.C., 1992. A Study of Gas in Marine Sediments in Hong Kong. Continental Shelf Research 12(10), 1251-1264.

Quaresma, V.S., 1997. Caracterização da dinâmica sedimentar da Baía de Guanabara, RJ. MSc. Dissertation. LAGEMAR, Universidade Federal Fluminense, 97p.

Quaresma, V.S., Dias, G.T.M., Baptista Neto, J.A., 2000. Caracterização da ocorrência de padrões de sonar de varredura lateral e sísmica de altafreqüência (3,5 e 7,0 kHz) na porção sul da Baía de Guanabara-RJ. Revista Brasileira de Geofísica 18(2), 201-214.

Schoen, J.H., Stretch, D.D., Tirok, K. 2014. Wind-driven circulation patterns in a shallow estuarine lake: St Lucia, South Africa. Estuarine, Coastal and Shelf Sciece 146, 49-59.

Schwarzer, K., Stattegger, K., Vital, H., Becker, M., 2006. Holocene coastal evolution of the Rio Açu Area (Rio Grande do Norte, Brazil). Journal of Coastal Research, SI 39, 141-145.

Souza, J. de, Tessler, T., Felix, C., Franklin, L., Benedet, L., Suthard, B., Demarco, L.F.W., Bonetti, J., Klein, A.H.F., 2011. Gas features detected with ultra shallow water high resolution seismic in the North Bay, Santa Catarina state, Southern Brazil. In: XIV Congresso Latino Americano de Ciências do Mar, Anais. Balneário Camboriú, SC.

Taylor, D.I., 1992. Nearshore shallow gas around the U.K. coast. Contimental Shelf Res. 12(10), 1135-1144.

Terra, L.C., Calliari, L.J., Griep, G.H., 2014.Acumulações de gás nos sedimentos da plataforma continental interna do Rio Grande do Sul. In. VI Simpósio Brasileiro de Geofísica. Porto Alegre, RS. 3p.

Toldo Jr, E.E., Dillenburg, S.R., Corrêa, I.C.S., Almeida, L.E.S.B., 2000. Holocene sedimentation in Lagoa dos Patos Lagoon, Rio Grande do Sul, Brazil. Journal of Coastal Research 16(3), 816-822.

Vital, H., Stattegger, H., 1997. Gas-charged sediments on the lowermost Amazon River. In: 5º Congresso Internacional da Sociedade Brasileira Geofísica, Anais, São Paulo, 1, 85-88.

Weschenfelder, J., Baitelli, R., Corrêa, I.C.S., Bortolin, E.C., Santos, C.B., 2014. Quaternary incised valleys in the southern Brazil coastal zone. Journal of South American Earth Science 55, 83-93.

Weschenfelder, J., Corrêa, I.C.S., Aliotta, S., Baitelli, R., 2010. Paleochannels related to late Quaternary sea-level changes in southern Brazil. Brazilian Journal of Oceanography 58, 35-44.

Weschenfelder, J., Corrêa, I.C.S., Aliotta, S., Pereira, C.M., Vasconcellos, V.E.B., 2006. Shallow gas accumulation in sediments of the Patos Lagoon, Southern Brazil. Anais da Acadêmia Brasileira de Ciências 78(3), 607-614.

Weschenfelder, J., Medeanic, S., Corrêa, I.C.S., Aliotta, S., 2008. Holocene paleoinlet of the Bojuru region, Lagoa dos Patos, southern Brazil. Journal of Coastal Research 24(1), 99-109.

Wright, C.I., Miller, W.R., Cooper, J.A.G., 2000. The late Cenozoic evolution of coastal water bodies in Northern KwaZulu-Natal, South Africa. Marine Geology 167, 207-229.

Zaitlin, B.A., Dalrymple, R.W., Boyd, R., 1994. The stratigraphic organization of incised valley systems associated with relative sea-level change. In: R.W. Dalrymple, R.J. Boyd, B.A. Zaitlin., Eds., Incised valley systems : Origin and sedimentary Sequences, SEPM Spec. Pub. 51, 45-60.

Figure Captions

Fig. 1. Gas-related acoustic anomalies in echograms from the Patos Lagoon, S Brazil. The blue box represents the area shown in the Google Earth image, with the position of the seismic lines analyzed.

Fig. 2. Gas-related acoustic features of the Rio Grande do Sul inner continental shelf, S Brazil. The blue box represents the area shown in the Google Earth image.

Fig. 3. Locality map and seismic profiles, side scan sonar and scuba diving photographic surveys in the North Bay and Conceição Lagoon, Santa Catarina State, S Brazil (from Klein et al., *in preparation*). The blue boxes in the Google Earth image represent the area of study.

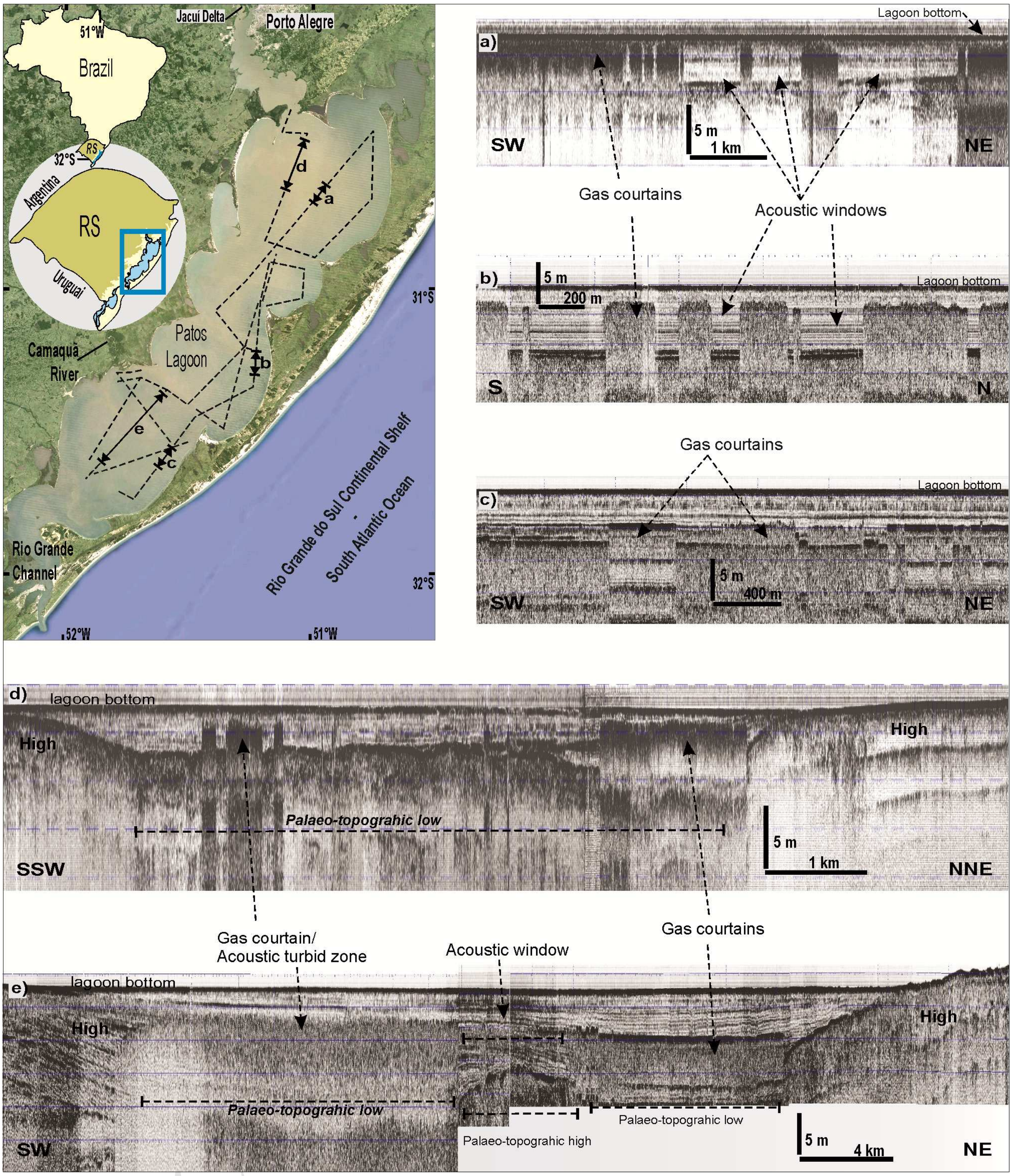
Fig. 4. Location of seismic profiles and gas features in the Santos Harbor Channel, SE Brazil. The blue box represents the area shown in the Google Earth image.

Fig. 5. Location of the seismic survey and gas occurrences and gas-related features in the Guanabara Bay, Rio de Janeiro, SE Brazil. The blue box represents the area shown in the Google Earth image.

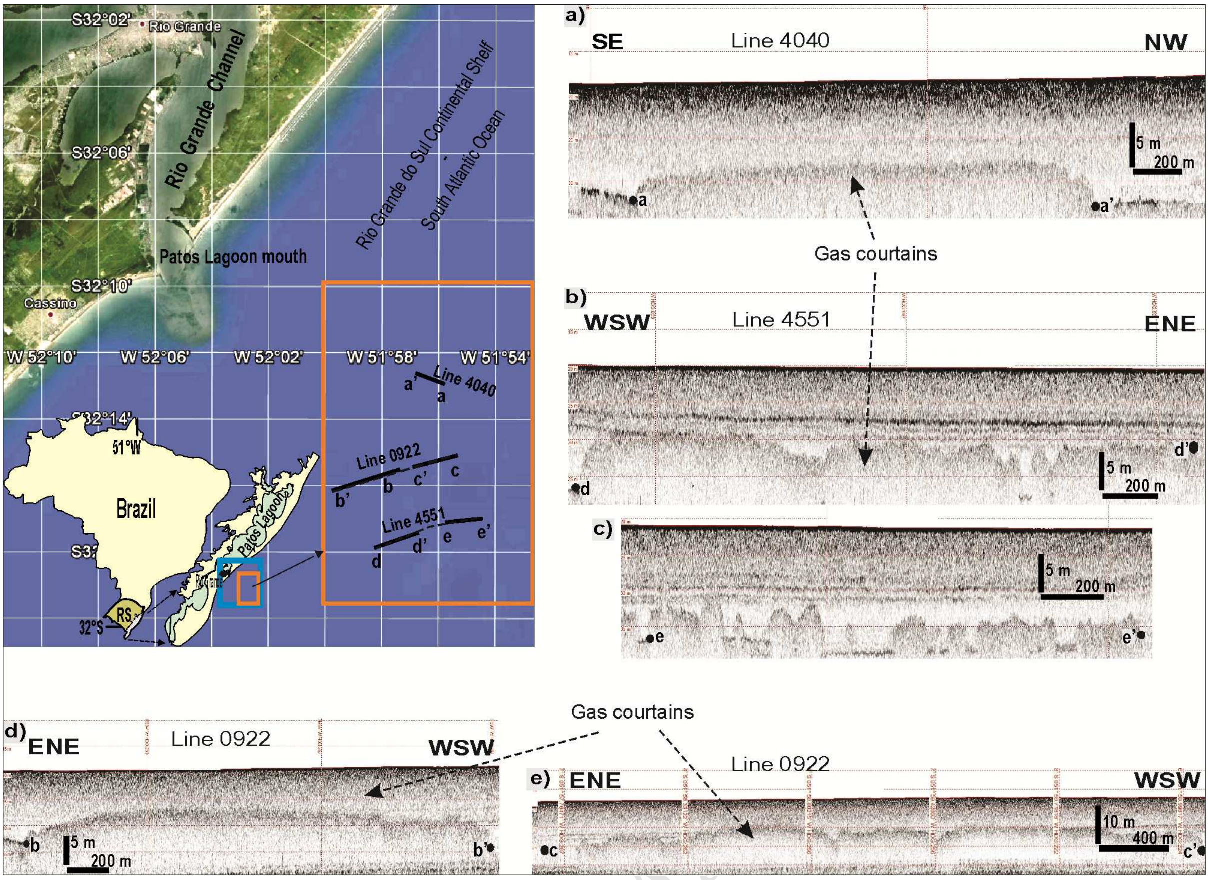
Fig. 6. Shallow gas occurrences in the Bahía Blanca Estuary, Argentina.

Fig. 7. Gas accumulation features in Durban Bay, E South Africa (profile locations shown on Google Earth image). White dashed box shows location of bathymetry survey.

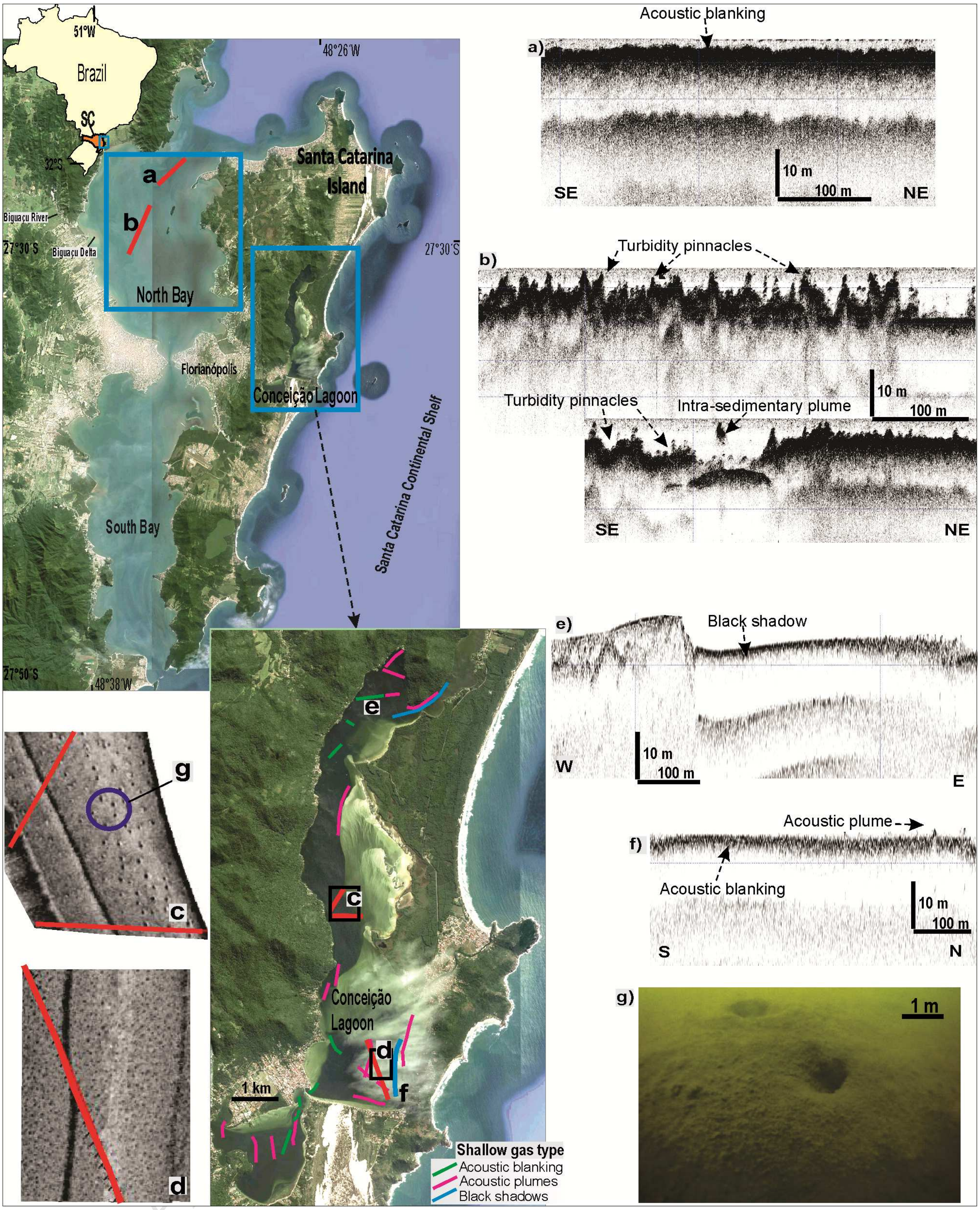
Fig. 8. Examples of gas accumulation features of Lake St. Lucia, NE South Africa. Red arrows on schematic indicate the position of the deepest point of the LGM incised valley.

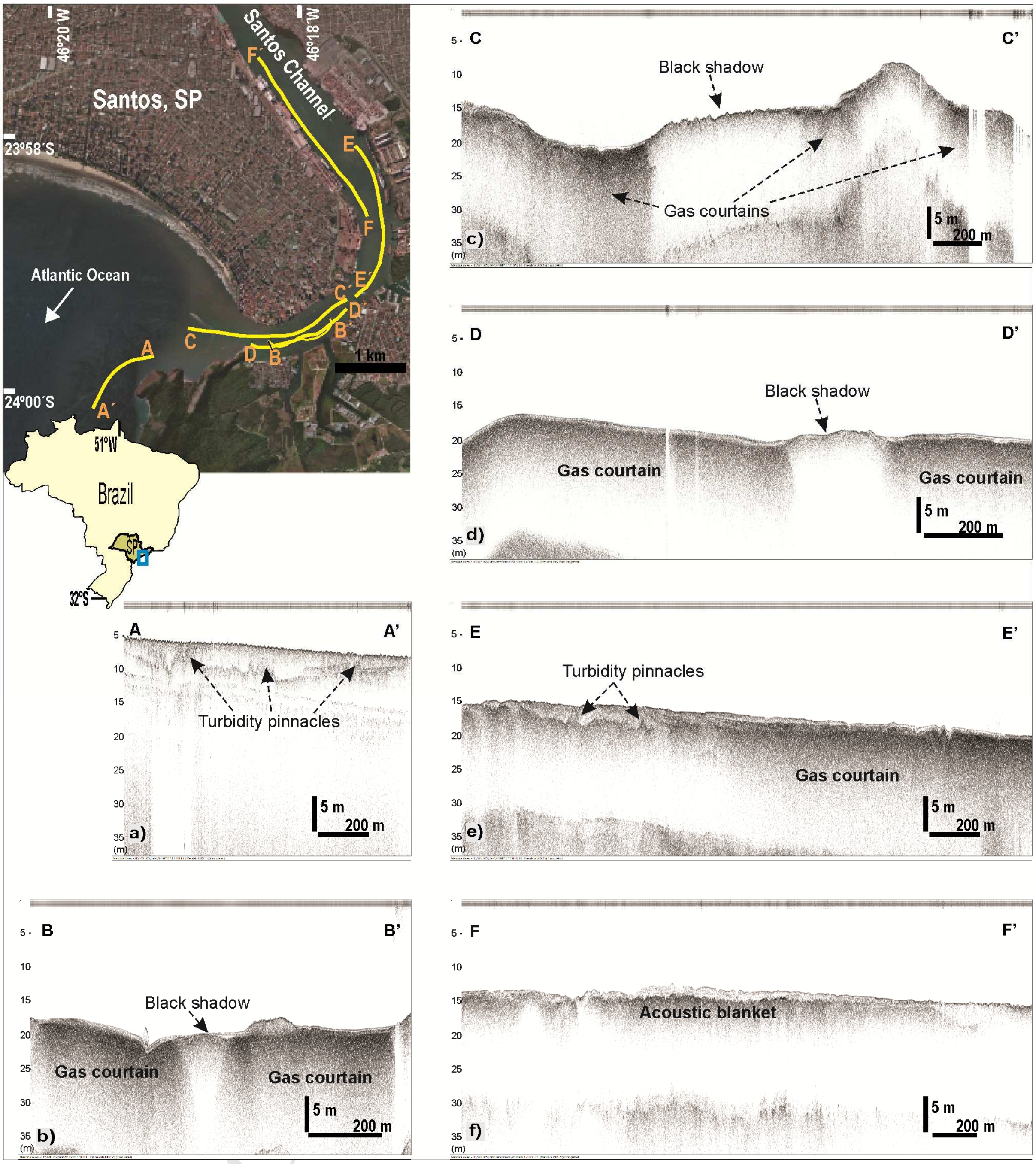


Jacuí Delta
Porto Alegre
51°W
Brazil
RS
32°S
Argentina
RS
Uruguai
Camaquã River
Patos Lagoon
Rio Grande Channel
Rio Grande do Sul Continental Shelf
South Atlantic Ocean
31°S
32°S
52°W
51°W
a
b
c
d
e
Lagoon bottom
a)
5 m
1 km
SW
NE
Gas courtains
Acoustic windows
b)
5 m
200 m
Lagoon bottom
S
N
Gas courtains
c)
Lagoon bottom
5 m
400 m
SW
NE
d)
lagoon bottom
High
High
Palaeo-topograhic low
5 m
1 km
SSW
NNE
Gas courtain/
Acoustic turbid zone
Acoustic window
Gas courtains
e)
lagoon bottom
High
High
Palaeo-topograhic low
Palaeo-topograhic high
Palaeo-topograhic low
5 m
4 km
SW
NE

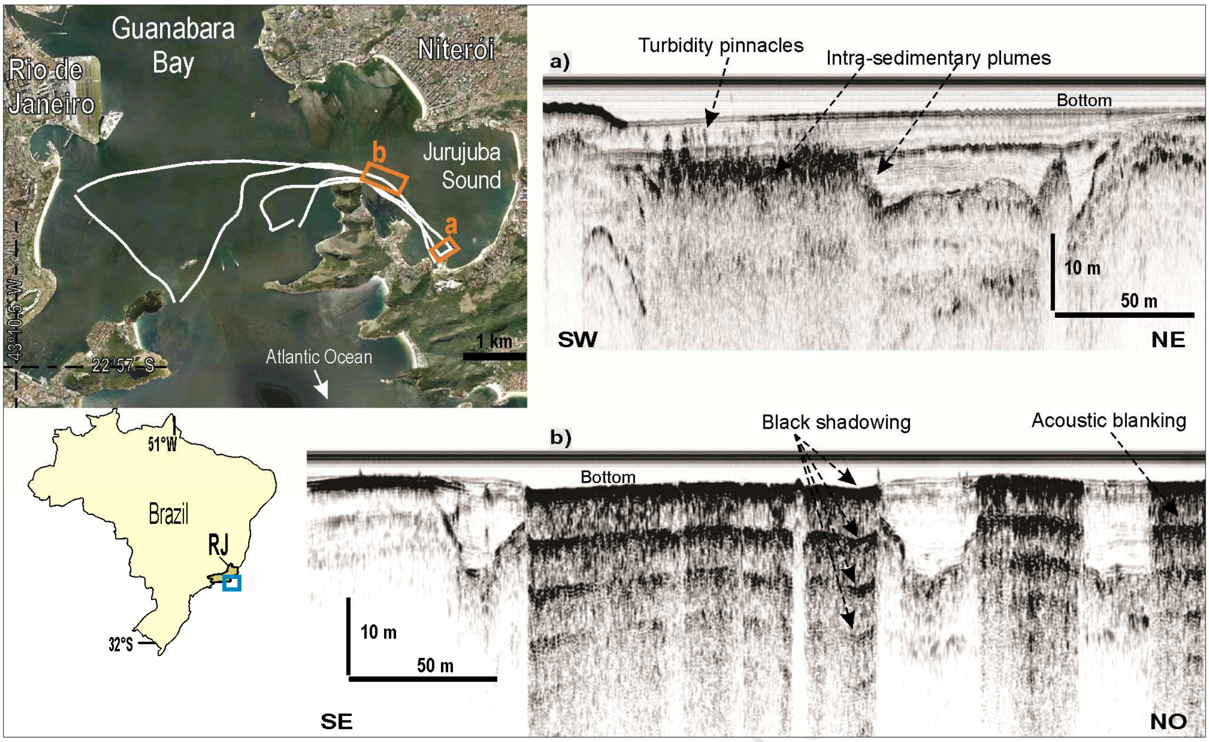


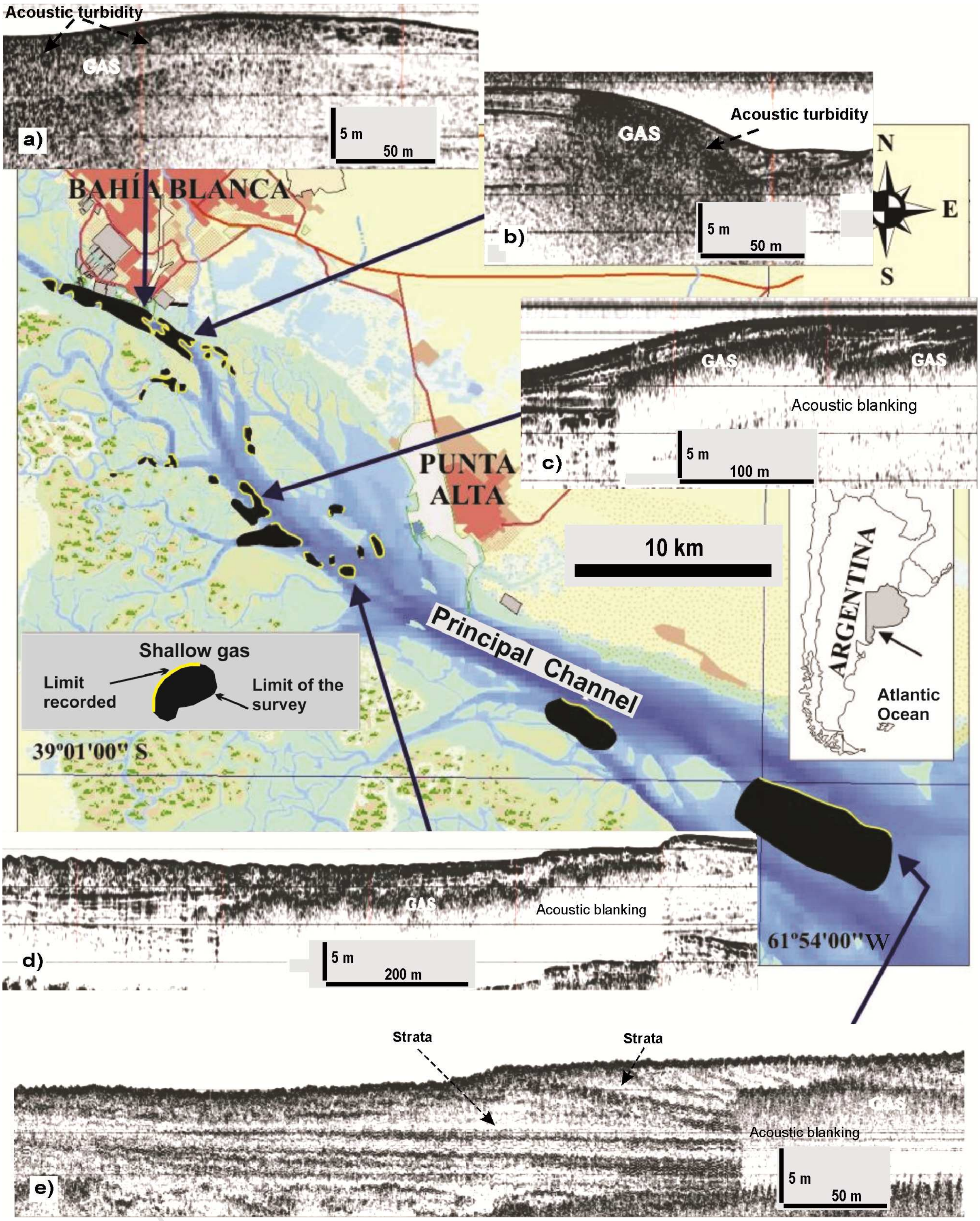
S32°02'
Rio Grande
Rio Grande Channel
S32°06'
Rio Grande do Sul Continental Shelf
South Atlantic Ocean
Patos Lagoon mouth
S32°10'
Cassino
W 52°10'
W 52°06'
W 52°02'
W 51°58'
W 51°54'
Line 4040
Line 0922
Line 4551
Brazil
51°W
32°S
RS
Patos Lagoon
a)
SE
Line 4040
NW
5 m
200 m
Gas courtains
b)
WSW
Line 4551
ENE
c)
d)
ENE
Line 0922
WSW
e)
ENE
Line 0922
WSW
10 m
400 m

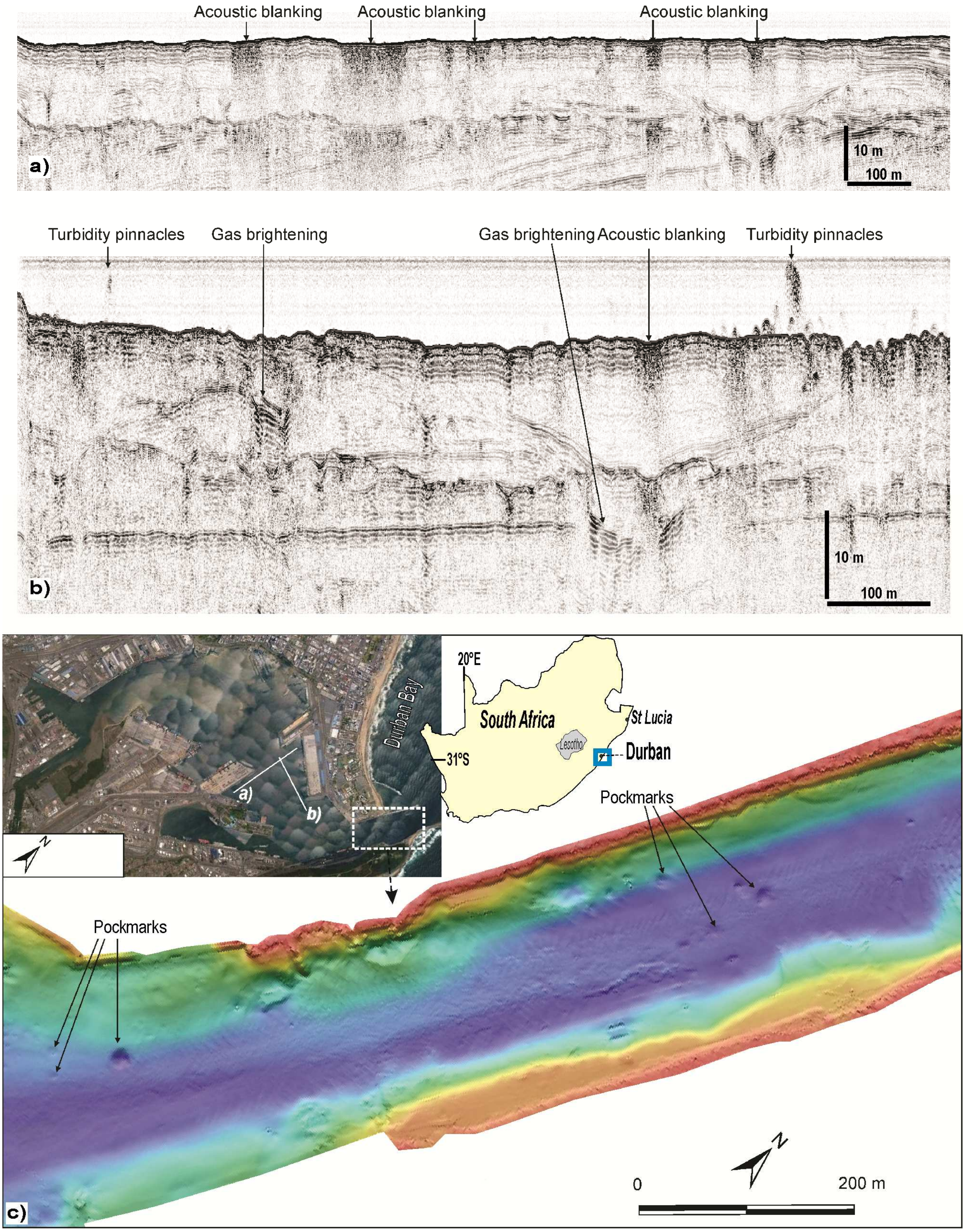

51°W
Brazil
SC
32°S
48°26'W
Santa Catarina Island
a
b
Biguaçu River
Biguaçu Delta
27°30'S
North Bay
Florianópolis
Conceição Lagoon
Santa Catarina Continental Shelf
South Bay
27°50'S
48°38'W
Acoustic blanking
a)
10 m
100 m
SE
NE
b)
Turbidity pinnacles
Intra-sedimentary plume
e)
Black shadow
W
E
f)
Acoustic plume
S
N
g)
1 m
c
d
e
f
1 km
Shallow gas type
Acoustic blanking
Acoustic plumes
Black shadows

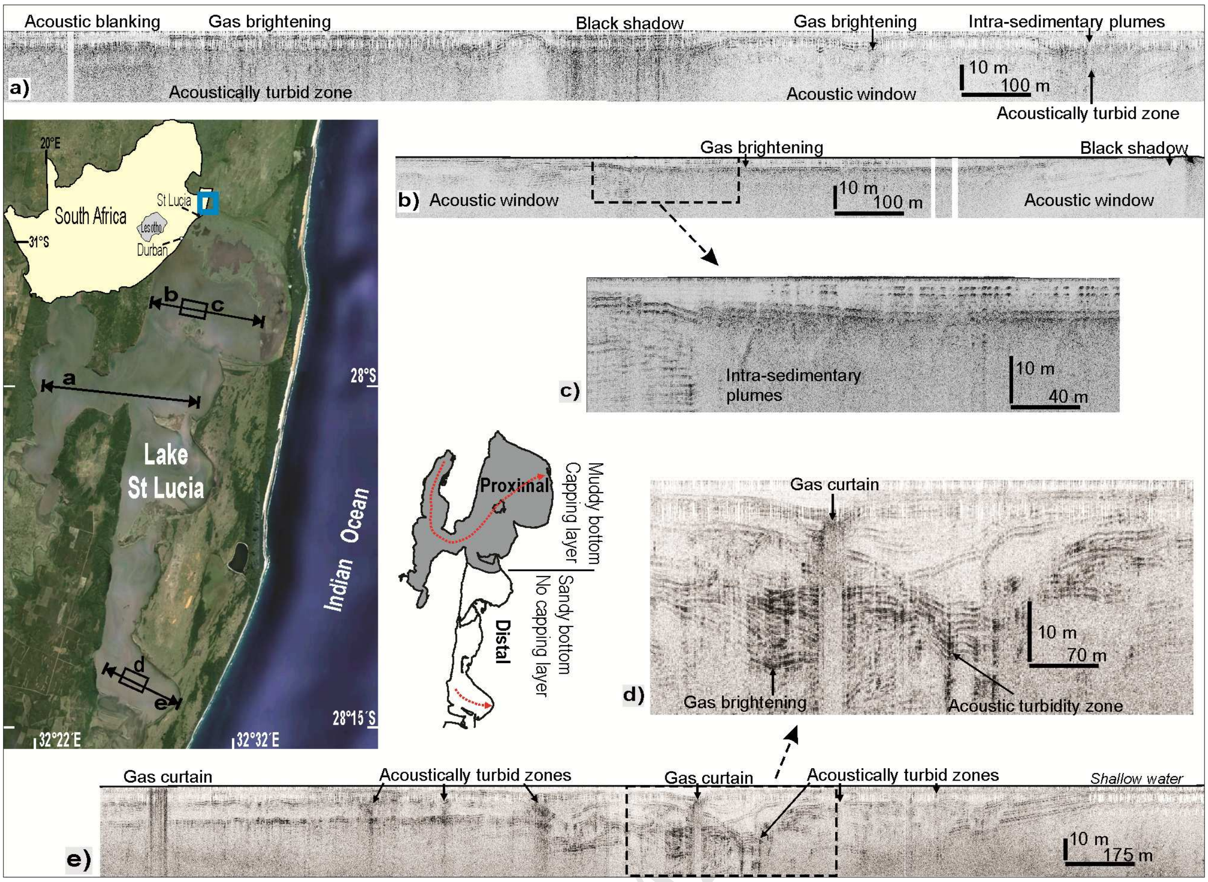


46°20´W
46°18´W
Santos Channel
Santos, SP
23°58´S
24°00´S
Atlantic Ocean
1 km
51°W
Brazil
SP
32°S
A
A´
B
B´
C
C´
D
D´
E
E´
F
F´
Black shadow
Gas courtains
Gas courtain
Turbidity pinnacles
Acoustic blanket
5 m
200 m
a)
b)
c)
d)
e)
f)
(m)


Guanabara Bay
Niterói
Rio de Janeiro
Jurujuba Sound
b
a
1 km
Atlantic Ocean
22°57' S
43°10.5' W
51°W
Brazil
RJ
32°S
a)
Turbidity pinnacles
Intra-sedimentary plumes
Bottom
10 m
50 m
SW
NE
b)
Black shadowing
Acoustic blanking
Bottom
10 m
50 m
SE
NO


Acoustic turbidity
GAS
a)
5 m
50 m
GAS
Acoustic turbidity
b)
5 m
50 m
N
E
S
BAHÍA BLANCA
GAS
GAS
Acoustic blanking
c)
5 m
100 m
PUNTA ALTA
10 km
ARGENTINA
Atlantic Ocean
Principal Channel
Shallow gas
Limit recorded
Limit of the survey
39°01'00" S
61°54'00" W
GAS
Acoustic blanking
d)
5 m
200 m
Strata
Strata
GAS
Acoustic blanking
e)
5 m
50 m


Acoustic blanking
Acoustic blanking
Acoustic blanking
10 m
100 m
a)
Turbidity pinnacles
Gas brightening
Gas brightening
Acoustic blanking
Turbidity pinnacles
10 m
100 m
b)
Durban Bay
a)
b)
N
20°E
South Africa
St Lucia
Lesotho
Durban
31°S
Pockmarks
Pockmarks
N
0
200 m
c)


Acoustic blanking
Gas brightening
Black shadow
Gas brightening
Intra-sedimentary plumes
a)
Acoustically turbid zone
Acoustic window
10 m
100 m
Acoustically turbid zone
20°E
South Africa
St Lucia
Lesotho
Durban
31°S
b
c
a
28°S
Lake
St Lucia
Indian Ocean
d
e
28°15´S
32°22´E
32°32´E
Gas brightening
Black shadow
b) Acoustic window
10 m
100 m
Acoustic window
c)
Intra-sedimentary
plumes
10 m
40 m
Proximal
Distal
Muddy bottom
Capping layer
Sandy bottom
No capping layer
Gas curtain
d)
Gas brightening
10 m
70 m
Acoustic turbidity zone
Gas curtain
Acoustically turbid zones
Gas curtain
Acoustically turbid zones
Shallow water
e)
10 m
175 m

Highlights

Describe gas-related anomalies in echograms from Brazil, Argentina and South Africa

Discuss gas structure variability amongst diverse settings

Type of gas features depend on palaeo-environmental scenario and sediment grade

Gas is associated with the postglacial transgression and infilling of low topography