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Shallow gas occurrence in a Brazilian ría (Saco do Mamanguá, Rio de Janeiro) inferred from high-resolution seismic data

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ABSTRACT

Semi-enclosed areas, such as *rías*, offer low-energy sedimentary conditions, which allow the necessary environment for the deposition of clays and organic-rich deposits that generate gas through methanogenic bacteria. In Saco do Mamanguá (Rio de Janeiro, Brazil), acoustic data from low frequency echo sounder and high-resolution seismic-reflection data from chirp sonar and boomer from three surveys – February 2009 and January and June 2014 – enabled for the first time the identification of acoustic disturbances related to gas occurrences. Saco do Mamanguá hosts shallow gas accumulation throughout its entire area, expressed as acoustic turbidity, enhanced reflections or acoustic blanking, intra-sedimentary plumes and acoustic plumes. However, gas occurrence evidence decreases towards the open ocean. A lithological control occurs on the sealing layer in the inner area, whereas the smaller gas occurrence in the outer area can be due to (1) absence of a sealing layer and/or (2) the re-oxidizing of methane as more oxygenated waters are available. We propose a sequence stratigraphic model in which the gas formation is Holocene or either pre-Holocene age.

1. Introduction

Marine release of greenhouse gasses is of fundamental importance for climate change (Judd et al., 2002). The characterization and occurrence of marine shallow gas in low-energy coastal environments, associated with weathering that produced fine sediments under tropical climatic conditions, represents a key point for understanding the link between gas production/release and climate and its environmental causes and consequences.

Shallow coastal semi-enclosed environments such as estuaries, lagoons, or *rías*, are often characterized by the presence of gas in the sediments. In these regions, continental discharge and local biological contribution support the deposition and accumulation of organic matter in the sediments, which generates gas via its degradation (Whitman et al., 2007; Zeikus, 1977). Methanogenic bacteria consume organic matter by anaerobic respiration and produce methane gas within the sediment, especially in fine-grained matrix clays (Floodgate and Judd, 1992; Ulyanova et al., 2014). Marine shallow sediments may include deposits of carbon dioxide, ethane, and hydrogen sulfide (Schroot and Schüttenhelm, 2003), but methane is the only one found in considerable quantity (Floodgate and Judd, 1992).

Because methane is among the most important greenhouse gases, increasing attention has been given to gassy sediments regarding global studies of climate changes (Hovland and Judd, 1992). Furthermore, some shallow gas accumulations represent an economic interest, for example, the late quaternary shallow biogenic gas reservoirs discovered and exploited in the Qiantang River estuary area, China (Lin et al., 2010).

Fleischer et al. (2001) quantified the global distribution of free gas in shallow marine sediments, based on over 100 documented cases. Because there are only a small number of studies on the Southern Hemisphere, gas systems are more recognized in the Northern Hemisphere. In Brazil, coastal shallow gas systems have been reported in the Amazon submarine delta (northern Brazil) (Figueiredo et al., 1996), in the Potengi river estuary (northeast Brazil) (Frazão and Vital, 2007), in Guanabara Bay (Rio de Janeiro) (Catanzaro et al., 2004), in the Bertioga channel (southeast Brazil) (Félix and Mahiques, 2013) and in the Patos lagoon (southern Brazil) (Weschenfelder et al., 2006).

Overall, the presence of shallow gas in sediment is easily detectable on the seismic record as acoustic anomalies or even morphologic disturbances of the seafloor, such as pockmarks (Anderson and Bryant, 1990). The acoustic expression of shallow gas in seismic records has various characteristic structures, such as acoustic blanking, acoustic turbidity, enhanced reflections, acoustic columns, intra-sedimentary plumes, and acoustic plumes (Hovland and Judd, 1988; Iglesias and García-Gil, 2007; Judd and Hovland, 2007; Karisiddaiah et al., 1993; Lee et al., 2005; Missiaen

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et al., 2002; Schroot and Schüttenhelm, 2003).

Acoustic turbidity is the most frequently cited evidence to infer the presence of seafloor gas (Fleischer et al., 2001). Acoustic turbidity can be recognized in seismic sections as amorphous echoes that cut across and mask the internal stratification of the sediment body (Schubel, 1974). Studies of shallow gas – rich sediments in the Western Baltic have shown that acoustic turbidity may occur in sediments with less than 0.5% gas (Abegg and Anderson, 1997). The presence of these sediments produces an anomalous seismic signal that does not completely mask the stratigraphic record (Durán et al., 2007; Jensen and Bennike, 2009; Mathys et al., 2005; Thießen et al., 2006).

Enhanced reflections – which usually occur with the feature described above – are reflectors that have their amplitude intensified by the presence of gas (Hovland and Judd, 1988). A research study conducted in the Belgian coast by Missiaen et al. (2002) attributed the presence of *enhanced reflections* to a local increase in gas concentration. According to Iglesias and García-Gil (2007), *enhanced reflections* can indicate gas accumulation along a horizontal path constrained by an impermeable bed.

Seismic profiles can also present *intra-sedimentary plumes* (Iglesias and García-Gil, 2007) or *acoustic columns* (Durán et al., 2007; Laier and Jensen, 2007), which are parabolic-shaped anomalies with high amplitude reflections and are related to small packages of gas within the sediment (Garcia-Gil et al., 2002; Taylor, 1992). Similar expressions are frequently observed in the water column and are known as *acoustic plumes* or *hydroacoustic plumes* (Judd and Hovland, 2007). Various authors (Durán et al., 2007; Iglesias and García-Gil, 2007; Martínez-Carreño and García-Gil, 2013) suggest that their origin is related to the presence of free gas bubbles in the water column and it is related to subsurface gas features.

Morphologic disturbances of the seafloor are mainly represented by *pockmarks,* which consist of depressions on the seabed caused by the removal of sediments by seeping fluids, in the majority of the cases as gas (Baltzer et al., 2014; Hovland and Judd, 1992; Judd and Hovland, 2007, 1992). These depressions tend to be circular in shape and measure a few to hundreds of meters in diameter and between 1 m and 20 m in depth (Taylor, 1992). Following the works from Iglesias and García-Gil (2007), Hovland and Judd (1988) and Judd and Hovland (2007), there is a direct relationship between pockmarks and the presence of the muddy seafloor. Fluid escape features such as pockmarks are manifestations of localized zones where high fluid pressure has occurred in the sub-surface as a result of rapid generation or storage of methane occurring in low-permeability environments (Judd and Hovland, 2007). Also, pockmarks coincide with zones of gas seepages caused by overpressure of shallow gas (Baltzer et al., 2014; Moss et al., 2012).

Based on the pattern of the acoustic features and sea-bottom disturbances, it is possible to obtain important information regarding the reservoir characteristics and sediments (Durán et al., 2007; Ferrín et al., 2003; Garcia-Gil et al., 2002; Iglesias and García-Gil, 2007; Judd and Hovland, 1992; Karisiddaiah et al., 1993; Lee et al., 2005; Missiaen et al., 2002; Okyar and Ediger, 1999). Garcia-Gil et al. (2002) suggested that the type of gas accumulation and escaping features depend on the porosity of the sediment where gas accumulates and on the sealing layer. Moreover, there is a direct correspondence between muddy sediments and gas accumulations (Abegg and Anderson, 1997; Floodgate and Judd, 1992; Iglesias and García-Gil, 2007; Laier and Jensen, 2007; Missiaen et al., 2002). Nevertheless, for Ferrín et al. (2003), seeps are associated with the presence of coarse material in the muddy matrix of sediment, which increases the permeability of the sealing layer allowing the gas release. Furthermore, degassing due to tidal variation may occur in the form of seeps as demonstrated by Duarte and Pinheiro (2007).

This work involves (Daniel Pavani Vicente Alves) a preliminary study of shallow gas occurrence in a ría-type environment area of Brazil. Here, acoustic data from a low frenquency echo sounder and high-resolution seismic-reflection data from chirp and boomer are analyzed to characterize and map the different gas appearances in Saco do Mamanguá for the first time. The controls of different gas appearances in this environment and a Late-Quaternary context of gas formation are also evaluated.

2. The setting

Saco do Mamanguá is located near the historical city of Paraty (Rio de Janeiro) inside Ilha Grande Bay and presents an elongated configuration, similar to a drowned river channel, with dimensions of 11 km in length and 2 km in width. The mean depth of Saco do Mamanguá is approximately 5 m, with a maximum of 20 m in the outer part. The region is contoured by an Atlantic forest with high biodiversity and by an important aquatic area for marine organisms that breed and reproduce in the Ilha Grande Bay (Gasalla, 1995).

Saco do Mamanguá has a restricted circulation and low intensity tidal action, which ranges between 64 and 125 cm (Bernardes, 1996). Mangroves are present in its inner portion, where discharges of small rivers are found. The inner part receives organic matter from the continent, as in an estuary, while the outer area is influenced by marine production (i.e., the autochthone organic matter) (Spera, 2012). The continental organic matter in the inner area is found to be more relevant than the marine organic matter, reflecting the importance of the rivers as an organic matter source (Spera, 2012).

Surface sediments are predominantly composed of clay and silt (99.9–100%), with low bulk density (2.45–3.12 g/cm^3) and high water content (71.6–77.0%). The high content of organic phosphorus (199–324 μg/g) points to a significant contribution from land; however, the C/N ratio between 8.0 and 9.0, δ^{13}C of -22.60% to -21.66% and δ^{15}N of 6.32 to 7.18% points to marine phytoplankton production (Teixeira, 2009).

The small longitudinal and vertical salinity gradient, with values ranging between 34.4 and 35.5 PSU, indicates conditions similar to a well-mixed estuary. There is also temperature stratification, which is weak for most of the year (22–24 °C) but stronger in summer, when the rise of the South Atlantic Central Water (SACW) provokes a cooling in the bottom water, thereby intensifying the thermic stratification (19–27 °C). The circulation dynamics can be considered as a low energy system, with a mean current velocity of 14 cm/s (Ambrósio Júnior et al., 1991).

As the Saco do Mamanguá presents a long, narrow configuration and is surrounded by high relief, it has a morphology similar to a "*ría*". The term *ría* is used to describe incised coastal areas surrounded by high relief consisting of ancient river valleys drowned by the sea level rise during the Holocene (Castaing and Guilcher, 1995). The Saco do Mamanguá has often been considered a type of estuary; however, only the portion closer to the continental drainage is influenced by estuarine processes (Evans and Prego, 2003).

The adjacent emerged lands are formed by Precambrian granites and migmatites strongly controlled by two main orthogonal systems of faults and fractures (SW-NE and SE-NW), which control the coastline disposition and geomorphologic features. Throughout Saco do Mamanguá, the Precambrian rocks enter the sea with gentle cliffs from elevations of 300 m. The dating of oyster samples in a rocky boulder located in the eastern part of Ilha Grande Bay testifies that the sea-level reached +4.8 m at approximately 5200 years B.P. (Suguio and Martin, 1978). According to these authors,