Research Article

Assessment of Marine Gas Hydrates and Associated Free Gas Distribution Offshore Uruguay

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Natural gas hydrates are crystalline solids formed by natural gas (mainly methane) and water that are stable under thermobaric conditions of high pressure and low temperature. Methane hydrate is found in polar areas of permafrost and in offshore basins of continental margins. These accumulations may represent an enormous source of methane. Based on global estimations of methane concentration in natural gas hydrates, the methane content may be several times greater than those of technically recoverable, conventional natural gas resources. In the continental margin of Uruguay, seismic evidence for the occurrence of gas hydrate is based on the presence of (bottom simulating reflectors) BSRs in 2D seismic reflection sections. Here we present results regarding gas hydrates and associated free gas distribution assessment offshore Uruguay, based on BSR mapping and applying a probabilistic approach. A mean value of 25,890 km² for the area of occurrence shows a great potential for this nonconventional resource, encouraging further research.

1. Introduction

Natural gas hydrates are crystalline solids formed by natural gas (mainly methane) and water that are stable under thermobaric conditions of high pressure and low temperature [1].

Methane hydrate occurs in sediments within and below thick permafrost in Arctic regions and in the subsurface of most continental margins where water depths are greater than 500 meters [2].

Gas hydrate accumulations may represent an enormous source of methane. Based on global estimations of methane concentrations, the methane content is about 2 to 10 times greater than those of technically recoverable conventional natural gas resources [2]. The existence of such a large methane hydrate resource has provided a strong global research incentive and international interest, which has grown in the last years.

The first acoustic indication of gas hydrate occurrence is given by presence of (bottom simulating reflection) BSR

in seismic sections due to a significant change in acoustic impedance between sediment containing hydrates and sediments containing free gas [3, 4]. The seismic appearance is parallel to seafloor reflection with a polarity reversal with respect to the seafloor.

The BSR is usually a good indication of gas trapped below the base of the gas hydrate stability zone (GHSZ) implying that gas hydrates are present [1]. On the other hand, gas hydrate can exist without creating a well-defined BSR, especially when gas fluxes are directed through faults or comparable permeable fluid pathways [1].

In offshore basins around the world the base of the GHSZ can have different seismic expressions such as continuous, segmented, and high-relief BSRs depending on the stratigraphic, fluid, and geothermal setting [5].

Another seismic response associated with the presence of gas hydrates in marine sediment is the blanking (reduction of the amplitude of seismic reflections). It can be used to identify sediments, in which hydrates have been formed. However, blanking is not a good indicator of the base of

FIGURE 1: Sedimentary basins of Uruguay. After Soto et al. [7].

GHSZ because there are several possibilities leading to signal attenuation, like the original or diagenetic character of strata as well as artifacts produced during seismic processing [1].

The study area for this work is the continental margin of Uruguay. This margin was formed during continental rifting and seafloor spreading, which included strong volcanic activity [6]. Three offshore basins were created during this process: Punta del Este, Pelotas, and Oriental del Plata basins (Figure 1) [7], which have a total extent, within the 200 nautical miles limit, of near 85,000 km² and a maximum volcano-sedimentary fill of 8,000 m based on seismic data [7]. This volcano-sedimentary fill comprises Juro-Cretaceous to recent sequences and is worth to mention the presence of a Paleozoic pririft correlative with Parana Basin records.

These basins are genetically related to the Western Gondwana breakup (~130 Ma ago) and the subsequent

development of the Atlantic Ocean and thus, are part of an important series of depocenters which include offshore hydrocarbon productive basins such as Santos and Campos basins (Brazil) and also the conjugate Orange Basin (South Africa and Namibia) [7].

The Punta del Este Basin is a mainly NW-SE trending aborted rift, perpendicular to the general trend of the continental margin [8]. In contrast, the NE-SW trending Pelotas Basin belongs to the flexural border of a precursor rift structure and continues in the Brazilian margin up to the Florianópolis Platform [7].

The Punta del Este and Pelotas basins are separated in shallow waters by the Polonio High. The distal part of both basins, where the Polonio High is not present and comprises a thick Cenozoic package, is called by some authors the Oriental del Plata Basin (Figure 1) [9, 10], which according to a recent redefinition has been restricted to the

TABLE 1: Offshore Uruguay seismic survey's details.

Survey	Acquisition company	Year	Number of lines	Length (km)
UR70	CGG	1970	12	2571
UR71	CGG	1971	32	2696
UR74	GSI	1974	35	2578
UR75	GSI	1975	28	1897
UR77	GSI	1977	16	1050
UR82	WESTERN	1982	23	1402
UR02	CGG	2002	6	1850
UR07	WAVEFIELD-INSEIS	2007	32	7125
UR08	WAVEFIELD-INSEIS	2008	22	2909

southern region of the continental margin, comprising only transitional and oceanic crust [7].

Different water masses and currents coexisting in the area play a fundamental role in the occurrence of gas hydrates considering temperature, salinity, and pressure conditions as well as sediment erosion and deposition.

Today, the continental margin of Uruguay is characterized by strong contour currents and the important input of huge amounts of sediments from the Río de la Plata river [11].

The area comprises a very complex and dynamic oceanographic regime. At surface level, dense and cold antarctic water masses from the Malvinas/Falkland Current flowing northward converge with the warm and saline Brazil Current flowing towards the South, resulting in the Brazil-Malvinas Confluence [12].

However, the confluence is not confined to surface currents, and also the interaction of intermediate water masses results in a complicated flow pattern. While antarctic intermediate water (AAIW) and circumpolar deep water (CDW) are flowing northward, the southward flowing north atlantic deep water (NADW) separates the CDW into Upper-CDW and Lower-CDW. The deep basins are under the influence of the antarctic bottom water (AABW) [13].

Interaction between these currents strongly affects sedimentary processes as well as margin morphology. The existence of strong contour currents leads to the generation of a large Contouritic Depositional Complex, which at least extends from southern Argentine margin to the margin of Uruguay, including various kinds of erosive and depositional sedimentary features [14].

Although strong deep currents are not favorable for organic matter deposition and preservation, contouritic deposits have been frequently associated both with conventional hydrocarbon reservoirs and with gas hydrate accumulations [15]. Indeed, big hydrate accumulations inferred from BSRs have been found in contouritic deposits along Atlantic margin [15].

In addition, these along-slope processes interact with downslope sedimentary gravitational processes, which have a large impact in the study area. In this way, mainly in the southern region (Punta del Este Basin), a series of submarine channels are developed.

Conventional hydrocarbon reservoirs associated with turbiditic sequences are well known while methane hydrate accumulations in this type of sequences have been reported as drilling targets offshore Japan [16].

First work regarding gas hydrates offshore Uruguay was performed by de Santa Ana et al. [17], where the presence of a BSR was recognized for the first time. Gas hydrate distribution and thickness were afterwards estimated based on the available seismic grid allowing first approximations on resource potential. Initial determination of mineralized area was 5,000 km² resulting in 86 trillion cubic feet (TCF) of natural gas under normal conditions [17], based on seismic information available at that time in nondigital format.

In 2005, the presence of gas hydrates was reported by Neben et al. from the German institute BGR after a 2D seismic survey in the area [18]. In this work, the BSR area was mapped from seismic sections acquired at that survey, resulting in a minimum of approximately 7,000 km².

Even if the BSR represents the most reliable indication of the existence of gas hydrates within the study area, high methane concentrations and (anaerobic oxidation of methane) AOM within the upper few meters of the sediments suggest the existence of methane hydrate in the study area [19].

Hydrocarbon generation and migration offshore Uruguay have been confirmed through fluid inclusion analysis [20], which were recognized in synrift and postrift sequences from two wells drilled in the area [21].

In 2008, oil seeps were identified by satellite images [10, 22], and poststack processing for gas chimney identification [23] was performed on 2D seismic sections, which showed vertical disturbances of the seismic signal. These signal anomalies, reaching into higher depths, were interpreted as hydrocarbon migration pathways and suggest a thermogenic origin of the gases that reach gas hydrate reservoirs [24].

All these evidences of hydrocarbon generation strongly indicate that thermogenic provenance of gas to form gas hydrates in upper sequences, as the only or combined with biogenic gas origin, is very plausible.

In this work, the integration of a dense grid of different 2D seismic surveys acquired offshore Uruguay was done for first time in order to identify the base of the GHSZ and assess gas hydrate and associated free gas distribution within

FIGURE 2: Theoretical response of seafloor and base of GHSZ.

the studied area. A probabilistic approach was considered in order to reflect the uncertainty of the interpretation, taking into account both high and low side of the mapped area and reporting a final mean value.

2. Methodology

For this work we used 2D reflection seismic data, acquired during different surveys for hydrocarbon exploration offshore Uruguay between 1970 and 2008.

More than 24,000 km of 2D reflection seismic sections were interpreted (Table 1). Seismic-stratigraphic interpretation was performed using commercial seismic interpretation software, considering reflectors attributable to the base of GHSZ, based on its theoretical response (Figure 2) and known characteristics of BSRs [1, 3, 4].

Once seismic interpretation was performed on available sections, gas hydrate and free gas spatial distribution was mapped and calculated.

3. Results

Interpretation of the base of GHSZ from seismic data in the area shows a widespread distribution of gas hydrate bearing sediments.

Continuous and segmented BSRs were observed while “high relief” BSRs were not identified. In Figure 3 we present an example of seismic wiggle showing the characteristic polarity reverse of BSR regarding the seafloor. For some sections, acoustic blanking is observed above a BSR cross-cutting sedimentation strata (Figure 4). In Figure 5 we present a seismic section from UR08 survey shot at Punta del Este Basin; a clear example of BSR is observed while seismic anomalies of enhanced amplitudes are present below it.

BSR was interpreted in UR70, UR71, UR74, UR77, UR82, UR02, UR07, and UR08 surveys. It is present below water

FIGURE 3: Seismic response of seafloor and base of GHSZ in seismic section from the area.

FIGURE 4: Section UR82_004 from Pelotas Basin. BSR present at 1982 survey showing blanking at the hydrate zone.

FIGURE 5: Seismic section from Punta del Este Basin showing a BSR at 0.330 sec TWT from the seafloor and enhanced amplitudes below the BGHSZ. Modified from [24]. Courtesy of CGG Veritas.

FIGURE 6: Results of BSR interpretation offshore Uruguay, showing a widespread distribution of gas hydrate bearing marine sediments. Color scale represents reflector depth in ms (TWT).

FIGURE 7: Maximum area of gas hydrate and free gas distribution, considering the envelope of BSR interpretations.

depths from 500 to 3,200 m and has high continuity in Pelotas Basin but is more discontinuous at Punta del Este Basin (Figure 6).

BSR interpretations showed in Figure 6 corresponds to 25,000 km² and for probabilistic calculation purposes is considered as the P50 of the occurrence area.

For the high side, we have mapped the total maximum area of sediments that may contain gas hydrates offshore Uruguay considering the envelope of BSR interpretations. The total maximum area corresponds to 32,500 km² (shown in Figure 7) and was considered as a P5 percentile ("larger than" convention).

The distribution chosen for the area assessment was of log-normal type as being the most common followed by nature and in particular for resource area [25]. Considering $\mu = \text{Ln}(P50)$ and truncation for values greater than P1 in order to disregard the extremely high values of the distribution, the resulting mean value for the area is 25.89×10^3 km² as shown in Figure 8.

4. Discussion

In Figure 4, acoustic blanking is observed above BSR. As showed by Max et al. [1], this seismic character may have a relation with gas hydrate presence. In this case, the fact of finding

FIGURE 8: Probability density function of the lognormal distribution of gas hydrates occurrence area offshore Uruguay. $P90 = 23.54 \times 10^3 \text{ km}^2$; $P10 = 29.45 \times 10^3 \text{ km}^2$.

blanking associated with BSR supports the interpretation of hydrate occurrence. In Figure 5, seismic anomalies of enhanced amplitudes suggests the presence of free gas below the base of GHSZ opening new opportunities for further research on subhydrate prospects exploration in the area.

At basin scale, as water depth increases, the base of the GHSZ progressively extends farther below the seafloor. This increment in thickness of GHSZ responds to pressure increasing and temperature decreasing at higher water depths as showed by Max et al. [1]. As reported for several offshore basins around the world [2], gas hydrate occurrence offshore Uruguay starts developing at approximately 500 m of water depth (Figure 6). This agrees with the P-T seafloor conditions for phase equilibrium [26] of approximately 4903 KPa, 5°C, and seawater salinity of 35 PSU for a $\text{CH}_4 + \text{NaCl} + \text{H}_2\text{O}$ system [27]. Further studies are needed in order to assess possible gas hydrate formation and destabilization cycles with eustasy and its effects on seafloor stability and geohazards potential.

Towards NE direction, BSR interpretation stops at or close to the end of strike lines, as the available database does not cross the Uruguay-Brazil maritime boundary. Nevertheless, interpreted gas hydrate area offshore Uruguay is probably part of a much greater gas hydrate province, shared with Brazil, extending further north at the Pelotas Basin. This basin has the largest gas hydrate occurrence of the Brazilian coast [28, 29].

At SE direction, BSR was interpreted up to a maximum water depth of 3,200 m. Below this ultradeep water domains, parallelism of sedimentary reflectors makes the identification of BSR difficult. Nevertheless, gas hydrate may be present beyond this range of water depth as found at other locations around the world and reported by Booth et al. [30].

Distribution of gas hydrate deposits offshore Uruguay presents high continuity in the north area (Pelotas Basin) but is more discontinuous in the Punta del Este Basin (while it cannot be assessed in the Oriental del Plata Basin due to limited seismic data; Figure 6). This may be due to various factors, including the presence of submarine channels. The existence of this kind of morphologies associated with sediment transport processes down slope has a special importance in Punta del Este Basin and may be the cause of BSR interpretation absence in certain zones, mainly due to complex sedimentary disposition.

In addition, the base of GHSZ has different expressions depending on lithological characteristics of sediments, leading to cases where the BSR may not be evident. In these cases, different relative sand-clay contents may play an important role.

On the other hand, the presence of BSRs indicates the coexistence between Free Gas and Gas Hydrate phases therefore situations may exist where sediments contain hydrates but not enough free gas at the phase boundary as to generate a BSR-like seismic response.

All these different aspects regarding BSR imaging and interpretation support the importance of the probabilistic approach applied to report area of occurrence.

5. Conclusions

Gas hydrate and associated free gas occurrence presents a widespread distribution offshore Uruguay, resulting in a mean value of $25,890 \text{ km}^2$, being much higher than reported by previous studies. Results show a great potential for this nonconventional resource, encouraging further research.

Further studies are needed about possible gas hydrate formation and destabilization cycles that may take place at the landward limit of the occurrence zone in order to evaluate its effect on seafloor stability and geohazard potential.

Seismic evidence of discrete free gas accumulations below the gas hydrate stability zone through amplitude anomalies was found. Those accumulations could be considered as subhydrate prospects and may play an important role considering future gas field developments offshore Uruguay.

From the exploratory point of view, determination of locations with good reservoir characteristics is critical for a comprehensive resource assessment.

Identification and quantification of high porosity and permeability sand deposits within the mapped area and GHSZ is needed in order to define exploratory targets. This will be the key element for the eventual development of gas hydrate prospects offshore Uruguay, once international research manages to prove that methane from marine gas hydrates can be produced as a technically safe, environmentally compatible, and economically competitive energy resource.

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