

A review of the gas hydrate distribution offshore Chilean margin

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Abstract. In last decades, the Chilean margin has been extensively investigated to better characterize the complex geological setting through the acquisition of geophysical data and, in particular, seismic lines. The analysis of seismic lines allowed identifying the occurrence of gas hydrates and free gas in many places along the margin. Clearly, the gas hydrate reservoir could be a strategic energy reserve for Chile, but, on the other hand, the dissociation of gas hydrate due to climate change could be an issue to face. Moreover, this region is characterized by large and mega-scale earthquakes that may contribute to gas hydrate dissociation and consequent submarine slides triggering. In this context, Chilean margin should be considered a natural laboratory to study the hydrate system evolution.

1 Introduction

In last decades, the Chilean margin has been extensively investigated to better characterize the complex geological setting through the acquisition of geophysical data and, in particular, seismic lines. The analysis of seismic lines allowed identifying the occurrence of gas hydrates in many places along the Chilean margin [1-17]. Moreover, their occurrence has also been confirmed by the presence of cold seeps emitting methane at the seafloor (e.g., [18-23]).

Along this margin, the gas hydrate reservoir was perforated for the first time with the ODP Leg 141, located near the Chilean triple junction (i.e. [1, 2]). These direct measurements estimated an average concentration of gas hydrate and free gas equal to 18% and 1% of volume, respectively [1, 2]. Similar concentrations have been estimated in other places along this margin through the analysis of the seismic data (e.g., [9, 10, 12, 14, 16, 24]). In fact, the seismic data allow identifying the base of the gas hydrate reservoir because of the presence of a high-amplitude reflector, known as bottom simulating reflector (BSR). This reflector represents the transition from the high seismic velocity characterizing gas hydrate-bearing sediments to the low seismic velocity of sediments containing free gas. In some cases, it is possible to recognize also the base of the free gas, known as Base of free Gas Reflector (BGR). The seismic velocity extracted from

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seismic data analysis is translate in term of gas hydrate and free concentrations by using theoretical models, such as the Tinivella method [25, 26] that was adopted in the review here presented.

Clearly, the gas hydrate reservoir could be a strategic energy reserve for Chile, but, on the other hand, the dissociated of gas hydrate due to climate change could be an issue to face. Moreover, this region is characterized by large and mega-scale earthquakes [27] that may contribute to gas hydrate dissociation and consequent submarine slides triggering. In fact, the geological and tectonic setting of this margin is very complex and manly driven by the interaction between three main plates: Antarctica, Scotia, and South America. In fact, the oceanic plates, Nazca and Antarctica, subduct toward East under the South American plate. The intersection of these three plates is named Fuegian Triple Junction [6], and it is interpreted as a diffuse area of deformation [28, 29]. In the northern portion, the convergence rate is about 8 cm/y [30-36], decreasing toward south, until it reaches a minimum rate of 2 cm/y south to the Fuegian Triple Junction [11, 15, 33].

Table 1. Seismic lines reported in this paper.

Seismic line	Location in the margin	Reference
RC2901-727	North	[13]
SO161-44	North	[9]
SO161-35	North	[14]
RC2901-731	North	[14]
SO161-29	North	[13]
SO161-40	Centre	[12]
RC2901-734	Centre	[9-10]
RC2902-790	South	[16]

2 Data and methods

The seismic lines presented in this work (Table 1) were acquired in the frame of following researcher projects:

- 1) SO161 profiles acquired by the RV SONNE cruise in 2001 in the frame of "Subduction Processes off Chile (SPOC)" project;
- 2) RC2901 profiles acquired by the RV CONRAD cruise in 1988 in the frame of the project "Mid-Ocean Spreading Ridge" of the ODP Program.

The seismic lines were processed with the following procedure in order to evaluate gas hydrate and free gas concentrations (see details in [9]):

1. Identification of BSR: Processing of the seismic profiles to identify the BSR and BGR, if possible, and selection of portion of seismic lines showing the presence of them.
2. Detection of gas hydrate and free gas: Kirchhoff pre-stack depth migration application to obtain a depth seismic section and a reliable velocity model. For details see [9].
3. Estimation of gas hydrate and free gas concentrations: the difference between velocity model, obtained by pre-stack depth migration, and theoretical velocity curves in absence of gas-phase allows estimating the gas-phase concentrations. Gas hydrate presence is characterized by positive anomalies, while negative anomalies indicate the free gas presence. The theoretical velocity is calculated by using the Tinivella method [25, 26]. It is important to mention that an error is introduced because some assumptions about sediment property are required due to direct measurements lack.

The seafloor and BSR depth extracted from the depth seismic section is adopted to evaluate the regional geothermal gradient (GG), as described in [9]. Sensitive tests were performed to verify the reliability of the final velocity models, estimating an error of about 5% (e.g., [9]). The propagation of the error in depth is evaluated about 2%. Finally, average

percentage error of the gas hydrate and free gas concentrations was estimated about 1% and 2.5%, respectively, as described by [9].

3 The BSR

The presence of gas hydrate, free gas and features related to them, such as the BSR, was recognized along the entire Chilean margin.

The most northern analyzed seismic line (RC2901-727), located at about 36°S, shows a strong and continuous BSR [13]. Below it, it is possible to recognize a low velocity layer (1380-1450 m/s) associated to free gas, showing the lowest velocity in the uplift section. Here, the GG, extracted from BSR depth, is about 87°C/km, and it decreases to 32°C/km in the western part. This variable GG could explain the variable BSR depth (400 to 200 mbsf). This seismic line shows a strong variability in gas hydrate and free gas distributions. High-concentration of gas hydrate (about 17% of total volume) is identified in western part of the line, while it is negligible in the uplift sector. The distribution of gas hydrate and free gas concentrations seems to have an opposite trend: in correspondence of high concentration of gas hydrate, low free gas concentration is present and vice versa. In fact, high concentration of free gas (0.6% of total volume) is located in correspondence of uplift sector where the concentration of gas hydrate is negligible.

Moving south, offshore Arauco, the seismic line SO161-44, characterized by strong velocity variations, shows a high velocity layer (1800-2000 m/s) above the BSR that it is associated with gas hydrates presence, while below it low velocity is recorded (about 1550 m/s) and associated to free gas [9]. It is possible to recognize a discontinuous BSR at a depth of 500 mbsf. The accretionary wedge is characterized by high concentration of gas hydrate (about 15% of total volume). In this sector, the GG is quite constant showing an average value of about 30°C/km.

North to Mocha Island, located at about 38.3°S, two marine campaigns have been performed acquiring bathymetric data, seawater samples and marine sediments. The analysis of the acquired data allowed discovering a positive relief, composed by five aligned mud cones. The authors hypothesized that these features are located in proximity of the intersection of the theoretical gas hydrate stability zone with the seafloor where hydrates are not stable favouring flow escapes. This hypothesis is supported by the analysis of seismic lines located south to the Mocha Island and performed by [24]. The line SO161-35, at about 12 km south to the Mocha Island, shows a strong and continuous BSR showing a variable depth with a maximum thickness of about 200 mbsf in the western portion.

Along the RC2901-731 seismic profile, located approximately 60 km south to the Mocha Island and direction NW-SE, it is possible to recognize a discontinuous and locally strong BSR. The BSR depth equal to about 250 mbsf is quite constant from 4 to 16 km of distance, while in the other portions of the line, the BSR is weak or disappears. The BGR is recognized on both seismic lines with an average thickness of about 70 m. In both sections, a drop in seismic velocity below the BSR is associated to the free gas presence, while high velocity (ranging from 1700 to 1900 m/s) is detected above BSR and associated with gas hydrates presence. In correspondence of the portion characterized by low velocity in both sections, it is possible to recognize faults and fractures with small slips affecting the seafloor. The eastern part of the seismic line SO161-35 show the presence of a submarine canyon. The average concentration of gas hydrate is about 7.5% of total volume in both sections. Also for these sections, an opposite trend in gas hydrate and free gas distribution was recognized. In fact, below high gas hydrate concentrations (ranging from 12 to 20% of total volume) it is present low free gas concentrations (< 0.4% of total volume for RC2901-731 line and < 0.1% of total volume for SO161-35 line), while, locally, above high free gas concentrations (up to 1.1% of total volume for SO161-35 line and up to 0.3% of total

volume for RC2901-731 line), low gas hydrate concentrations (< 4% of total volume in both sections) are present. Even if the GG has a variable trend along the seismic profiles, a higher GG (from 60 to 110°C/km) is identified in correspondence of SO161-35 section and a lower GG (from 35 to 65°C/km) was observed along the RC2901-731 section. The high free gas concentration in proximity of Mocha Island could be or relate to gas hydrate dissociation caused by past sliding processes reported by [37], or to free gas stored below an impermeable gas hydrate layer [14]. On the other hand, the lowest free gas concentration on the seismic line RC2901-731 could be explained by a high fluid escape through faults and fractures, preventing free gas storing, associated to a limited a fluid supply from deep zones.

Moving south, the seismic profile SO161-29, located offshore Valdivia, shows the presence of many faults and fractures affecting the shallowest sediments confirming a high tectonic activity of this area [13]. This high tectonic activity could be the explanation for a weak and discontinuous BSR with a depth of about 550 mbsf recognized along this line, allowing estimating a GG equal to 35°C/km. Two portions along the line (from 3 to 5 km and from 12 to 15 km) show high concentration of gas hydrate ranging from 10 to 17% of total volume. Low seismic velocity below the seafloor suggests the presence of small concentration of free gas, while not free gas is recognized below the BSR because it was not possible to recognize the BGR. The absence of free gas could be related to the faults and fractures. Some faults and fractures above the BSR are characterized by low seismic velocity, which could be explained with a variation of porosity along the accretionary prism [13].

This seismic line SO161-40, located south to Chiloe Island, shows a strong and continuous BSR [12]. A strong and continuous reflector is recognised below the BSR, locally interpreted as BGR. The maximum depth of the BSR (about 600 mbsf) is identified in proximity of the boundary between the lower and upper continental slope where the estimated GG is about 25°C/km. Moving toward the upper slope, the BSR depth decreases due to an increase of GG reaching the valued of 45°C/km. The concentration of gas hydrate and free gas is variable along the seismic line, reaching the maximum value in the lower part of the upper slope. Here, the highest concentration of gas hydrate and the free gas is about 9.5 and 0.5% of total volume, respectively.

The seismic line RC2901-734, located offshore Coyhaique (44°S), shows a strong BSR from the middle part of the accretionary prism to the first part of the fore arc basin [9-10]. The BSR depth is variable reaching maximum depth in correspondence of fore arc basin (330 m) and the accretionary prism (250 m), while the minimum depth (130 m) is in correspondence of structural high. The BSR is not present where there are intensive deformations with faults and fractures. Below BSR, a free gas layer is recognized with an average thickness of 70 m and associated to the presence of a BGR. The estimated GG, ranging from 95 to 10°C/km, can explain the variable BSR depth along the line. In fact, the maximum GG is in proximity of the structural high where the BSR depth is minimal. The fore arc basin is characterized by the highest gas hydrate concentration (about 23% of total volume), which becomes negligible in the proximity of the structural high. The concentration varies from 4 to 9% in the accretionary complex. The free gas concentration shows an opposite trend respect to the gas hydrate concentrations. In fact, the higher values (3% of total volume) are recorded in correspondence of the structural high and decrease toward fore arc basin and accretionary prism (1% of total volume). [9] supposed that structural high is a trap for the accumulation of fluid in the pore space. The seismic signal character suggests a strong variability in the sediments characteristics. The low velocity recorded above the BSR in correspondence of structural high can be explain with a porosity change and the seismic character suggests the presence of finer grained lithology. In the fore arc basin turbidite deposit could explain the seismic character, hypothesis in agreement with studies performed in the southern part [38]. The high velocity could be related to gas

hydrate presence or change in petrophysical properties due to dewatering or uplift of the structural high.

Moving south to the Fuegian Triple Junction at about 320 km, the seismic line RC2902-790 was recently analysed to perform the first estimation of phase-gas in Patagonia [16]. High velocity was recognised above the BSR and could be associated to gas hydrate presence, while the seismic velocity (1600-1700 m/s) below it is too high to justify free gas presence, but too low for water-bearing sediments (i.e., [39]). A possible explanation could be that these sediments host a mix of free gas and water and the real base of free gas is not detected. The average gas hydrate concentration is equal to about 3.4% of total volume with a maximum value of 10% of total volume, where the BSR is strongest.

Anyway, in this part of the Chilean margin, the presence of BSR was already supposed by other authors (e.g., [4, 7, 8]). The line IT95-171, located in proximity of the line RC2902-790, shows the presence of a continuous and high-amplitude BSR occurring from the forearc basin to the back-thrust [4]. Moving toward north, BSR disappears and is not recognised along the line IT97-251 located in proximity of the Fuegian Triple Junction. Clearly, the absence of the BSR does not exclude the gas hydrate presence.

4 Theoretical modelling of gas hydrate stability vs. climate change

Recently, the gas hydrate stability zone was modelled to identify the zone where exist the conditions for its stability along the Chilean margin (from Valparaíso to Taita Peninsula [40]) by using a steady state approach. The input data were collected in literature, as described in [40]. The GGs were estimated from the heat flow/thermal conductivity ratio considering the data published by [15]. Seafloor temperature and salinity water column were downloaded from the National Oceanographic Data Center website, while the water depth from the GMRT website. The gas composition was considered as pure methane on the basis of ODP Legs 141 and 202 [41-42]. This study allowed verifying where gas hydrate could be interesting by energy point of view, but also define the areas where gas hydrate are sensitive to climate change. In fact, different future scenarios based on the IPCC and NASA forecasts were considered to better understand the effects of climate change on gas hydrate stability. The modelling pointed out that at the present day the base of gas hydrate stability zone could be at 580 mbsf. In addition, climate change could strongly affect gas hydrate stability and, in particular, the increase in temperature would determine the gas hydrate dissociation along the upper slope.

5 Conclusions

The Chilean margin shows a strong variability in the distribution of gas hydrate and free gas concentration. This variability seems driven by an interaction between regional and local factors.

It is important to recall that the Chilean Margin is characterized by high seismicity, which could trigger slope failure and consequently affect gas hydrate stability. Clearly, the potential gas hydrate reservoir exploitation requires a deep knowledge of the natural and anthropogenic factors that could affect gas hydrate stability. Consequently, more effort should be devoted to gaining a better understanding of the relationship between the gas hydrate system and complex natural phenomena, such as climate change, slope stability and earthquakes. In this context, Chilean margin should be considered a natural laboratory to study the hydrate system evolution.

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