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High gas hydrate and free gas concentrations: an explanation for seeps offshore south Mocha Island

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Abstract: Recent studies have reported shallow and deep seep areas offshore Mocha island. Gas hydrate occurrences along the Chilean margin could explain seeps presence. Gas phases (gas hydrate and free gas) and geothermal gradients were estimated analysing two seismic sections. Close to Mocha island (up to 20 km) were detected high (up to 1900 m/s) and low (1260 m/s) velocities associated with high gas hydrate (up to 20 % of total volume) and free gas (up to 1.1% of total volume) concentrations respectively. These values are in agreement with a variable and high geothermal gradient (65 to 110 °C/km) related to high supply deep fluids canalised by faults and fractures. Faraway from Mocha island (more than 60 km), free gas concentrations decrease to 0.3 % of total volume and low geothermal gradient (from 35 to 60 °C/km) are associated with low fluids supply. Finally, we propose gas hydrate dissociation processes as the main supply source for seeps in the vicinity of Mocha island. These processes can be triggered by ancient sliding reported in literature.

Keywords: gas hydrate; BSR; Mocha island

1. Introduction

The studies regarding gas hydrate occurrences worldwide are important for three main reasons: a) energy resource; b) submarine geohazard and c) global climate change [1]. Gas hydrate distribution has been mapped mostly by using indirect measurements. From multichannel seismic data, it is possible to detect the principal indicator of gas hydrate presence known as bottom simulating reflector (BSR). The worldwide distribution of BSR occurs mainly in marine sediments along the active continental margins (predominantly circum-Pacific belt) and the permafrost regions (Antarctic and Arctic).

In Chile the interest for gas hydrate occurrences plays an important role due to the high seismicity that characterises the entire region. Several scientific studies have reported gas hydrate dissociation triggered by earthquakes e.g. Great Sumatra, Japan and Norwegian margins [2-6]. The BSR along the Chilean margin is recognized in the continental slope covering a wide extension close to 3000 km (from 33°S until 56°S). In this context, gas hydrate estimates contribute to evaluate submarine geohazards associated with gas hydrate dissociation and the potential methane reservoir. Moreover, the estimates of methane stored as gas hydrate and free gas phases in marine sediments can be used to model more realistic scenarios associated with gas hydrates dissociation and its effects as a greenhouse gas. Several studies along the Chilean margin have reported gas phases concentrations by modelling the seismic velocity [7-16] covering already 10% of the entire margin.

The present study add new information regarding gas phase concentrations southernwards offshore Mocha Island by using seismic and theoretical velocity models (Fig. 1). The Mocha island is characterised by active seismicity and constitutes an uplifted block during the Quaternary and emerged today in the Arauco peninsula [17,18]. Moreover, Mocha island is known by intertidal and subtidal gas seepage system [19,20] and deeper seeps at 1400 water depth [21], whose presence probably is related to gas hydrates dissociation. In this context, gas phases estimates contribute to map and understand its role in fluid escapes supply.

In order to quantify gas phases a procedure already tested in previous studies is performed [11-16,22]. The method includes: a) Obtaining seismic velocity model by using Kirchhoff Pre-Stack Depth Migration (PSDM); b) Velocity anomalies evaluation; c) Gas phases estimates by fitting seismic velocity with theoretical velocity and d) Geothermal gradient calculation by using seafloor and BSR depths and water bottom temperature.

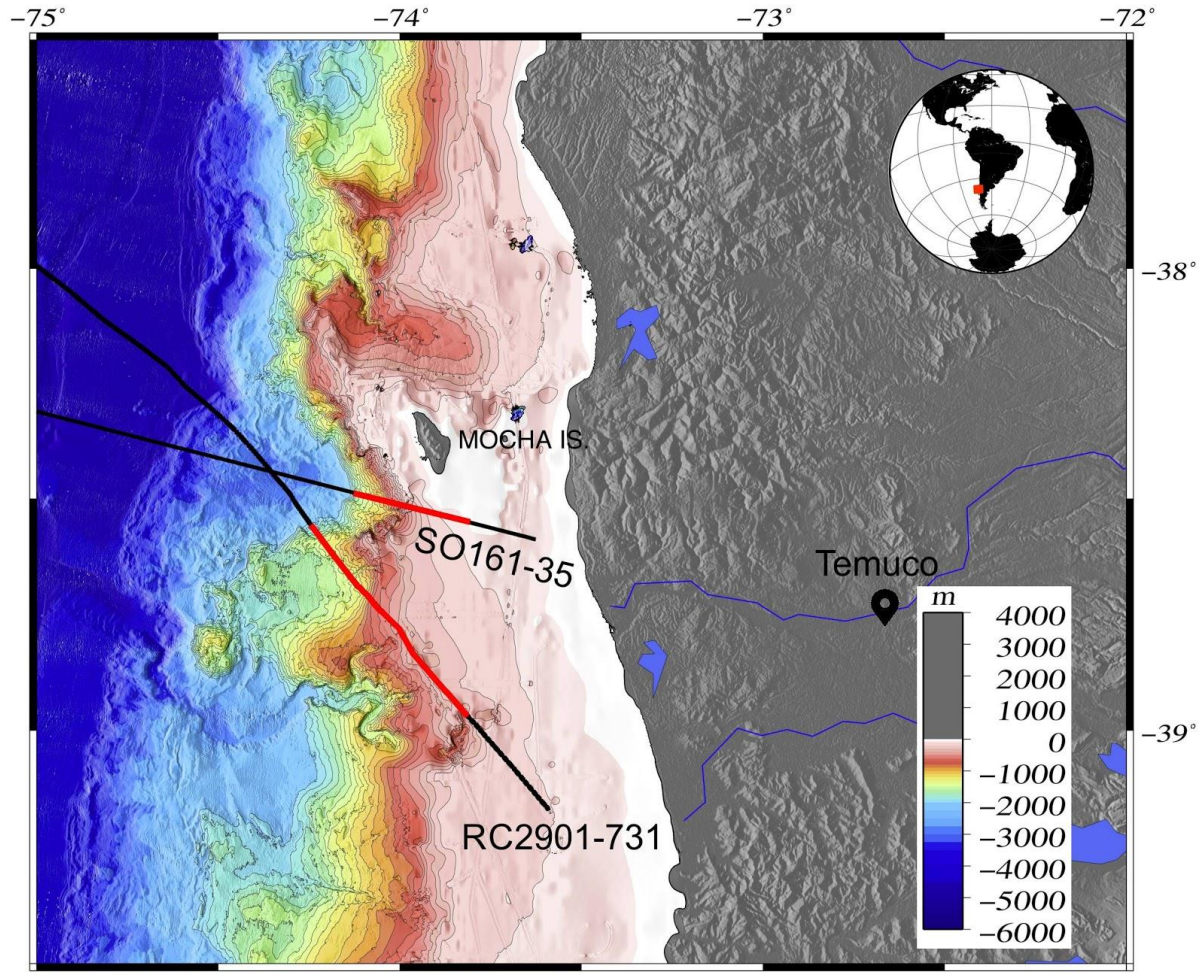

Figure 1. Location map. Red lines indicate the parts of the seismic sections analysed in this study.

2. Materials and Methods

2.1. Seismic Data

RC2901-731 and SO161-35 seismic lines were analysed. Seismic data were acquired during 1988 and 2001 in the framework of ODP (Mid-Ocean Spreading Ridge, Chile Ridge; RC2901-731 seismic line) and SPOC (Subduction Processes off Chile; SO161-35 seismic line) projects, respectively. Seismic acquisition parameters are detailed in Table 1. Open-source Seismic Unix [23] software was used to perform the seismic processing.

66 **Table 1:** seismic acquisition parameters

Seismic lines	Research Vessel	Long streamer	Channels	Intertrace	Shot spacing	Airguns/total volume
RC2901-731	RV/Conrad	3000 m	240	12.5 m	50 m	10/61.3 L
SO161-35	RV/Sonne	3000 m	25 108	12.5 m 25 m	50 m	20/54.1 L

67 *2.2. Inversion Modelling*

68 Once identified the BSR along seismic lines, two sections close to 20 km-long were chosen. The
69 seismic analysis uses pre-stack data to perform Kirchhoff depth migration in order to model
70 migration velocity by using an iterative algorithm [24]. The seismic migration analysis builds
71 iteratively the velocity model by using a layer stripping approach [25], in which each layer is
72 modelled in depth. The velocity model is built by selecting continuous reflectors. In our case the
73 seafloor (SF), the horizon 1 (H1), the BSR and the base of the free gas (BGR) were selected. The grid
74 was defined considering a vertical and horizontal spacing equal to 10 and 25 m for RC2901-731 and
75 SO161-35 seismic sections, respectively. The migration velocity analysis uses the output of PSDM to
76 evaluate the reliability of velocity by measuring the flatness in Common Image Gathers (CIGs). At
77 each iteration, the migration velocity analysis is corrected for the purpose of to flat the events in the
78 CIGs; when the events became flats, the velocity layer is fixed and a new horizon is analysed. The
79 number of iterations of each layer necessary to flat the events are detailed in Table 2:

80 **Table 2:** Layer iteration numbers

RC2901-731 seismic section		**SO161-35 seismic section**	
Layers	Iterations	Layers	Iterations
Seawater	3	Seawater	4
From SF to H1	5	From SF to BSR	15
From H1 to BSR	18	Free gas	10
Free gas	4	-	-

81 A velocity gradient was introduced below the BGR and the final velocity models were smoothed
82 in order to improve the stacked depth migrated image. The stacking of the CIGs was performed by
83 using a maximum offset of 2500 m in order to attenuate stretching effects. Finally, a mixing and band-
84 pass filter was applied; the final sections are shown in Fig. 2.

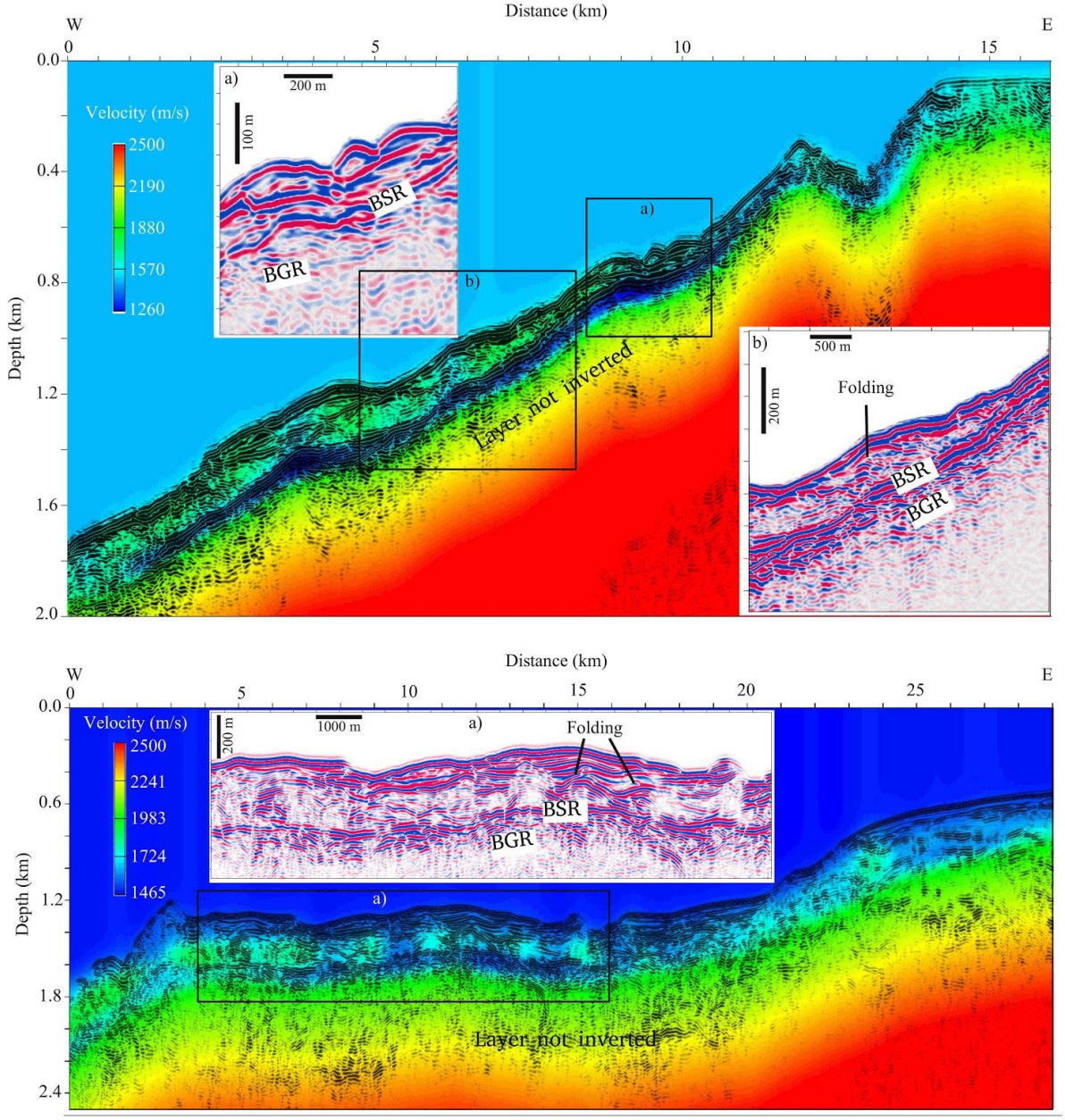

Figure 2. Pre-stack depth sections with superimposed velocity models. Top: SO161-35 seismic section. Bottom: RC2901-731 seismic section. Black boxes indicated with letters show the blow-ups.

2.3 BSR-Derived Geothermal Gradient

It is possible to calculate the geothermal gradient (dT/dZ) by using BSR information, as reported in literature [15,16]. The main parameters to consider are: 1) BSR depth (Z_{BSR}), 2) seafloor depth (Z_{SEA}), 3) BSR temperature (T_{BSR}) and seafloor temperature (T_{SEA}). Thus the geothermal gradient can be obtained by using the following relationship:

$$dT/dZ = (T_{BSR} - T_{SEA})/(Z_{BSR} - Z_{SEA})$$

where T_{SEA} was obtained from ODP information and reported studies in Central Chile [26,27]. The T_{BSR} is based on gas hydrate stability curves reported by [28]. Finally, Z_{BSR} and Z_{SEA} were taken from seismic data analysis.

98 *2.4 Gas phase concentrations*

99 Gas phases (gas hydrates and free gas) concentrations are estimated by using a simplified
100 method [29-31] of the Biot theory [30]. The velocity anomalies (i.e., the difference between the
101 background and seismic velocities) are evaluated considering the geological context in order to
102 associate positive velocity anomalies with gas hydrate concentrations and negative velocity
103 anomalies with free gas concentrations. A qualitative estimate can be obtained by comparing
104 theoretical velocity curves in absence of gas (i.e., the background velocity; [32, 33]) with our seismic
105 velocity curves obtained as described in the section 2.2. The method calculates the free gas
106 concentration in the pore space by considering uniform (gas and water in pore space) and patchy (all
107 gas in patches without water) distributions. In our case, an uniform distribution was considered [30].
108 Theoretical velocity was modeled by supposing a porosity at the seafloor of 65%, as measured during
109 ODP leg 202 and reported in [27].

110 **3. Results**

111 BSRs were recognized in both seismic sections. Along the whole SO161-35 seismic section the
112 BSR is continuous, strong and shows a variable depth reaching maximum thickness in deepest areas
113 (up to 200 m below seafloor -mbsf; see from 0 to 6 km of distance in Fig. 2), while minimum thickness
114 are located in correspondence to shallowest areas (80 mbsf). On the contrary, RC2901-731 seismic
115 profile shows discontinuous and locally strong BSR, while a constant BSR depths of about 250 mbsf
116 are evidenced from 4 to 16 km of distance (Fig. 2). Note that in this section from 16 to 25 km of
117 distance, the BSR is weak or disappear (Fig. 2). In both sections, the BGR is detected and it is
118 characterized by an average thickness of about 70 m (see blow-up in Fig. 2).
119 The velocity distribution across SO161-35 and RC2901-731 sections shows strong vertical and
120 lateral variations. The vertical velocity distribution across SO161-35 and RC2901-731 shows a drop
121 below the BSR reaching minimum values of 1260 m/s and 1465 m/s respectively that can be associated
122 to the free gas presence (see Fig. 2). Regarding lateral velocity variations, high velocity values
123 (ranging from 1700 m/s to 1900 m/s) were recognized above the BSRs (Fig. 2). In both sections, faults
124 and fractures with small slips affecting the seafloor were identified in correspondence to low velocity
125 values (Fig. 3). Moreover, in the eastern part of the SO161-35 section a submarine canyon was
126 identified (Fig. 2 and Fig. 3) and a normal fault that configures a lower and upper sector of the
127 RC2901-731 line (see bottom panel of Fig. 3 at 22 km of distance). Finally, in both sections locally
128 dipping reflections were associated to folding (see blow-ups in Fig. 2).
129 Variable gas hydrate and free gas concentrations were identified, even if the gas hydrate average
130 concentrations are equal to 7.5% of total volume in both sections. On the contrary, the free gas average
131 concentrations are different and equal to 0.4% and 0.12% of total volume in the SO161-35 and RC2901-
132 731 sections respectively. An opposite gas phase concentration trend was observed, in which high
133 gas hydrate concentrations (ranging from 12% to 20% of total volume) overlies to low free gas
134 concentrations (< 0.4% of total volume for RC2901-731 section and < 0.1% of total volume for SO161-
135 35 section), while low gas hydrate concentrations (<4% of total volume in both sections) are in
136 correspondence with high free gas concentrations (up to 1.1 % of total volume for SO161-35 and up
137 to 0.3% of total volume for RC2901-731 sections; see Fig. 3).

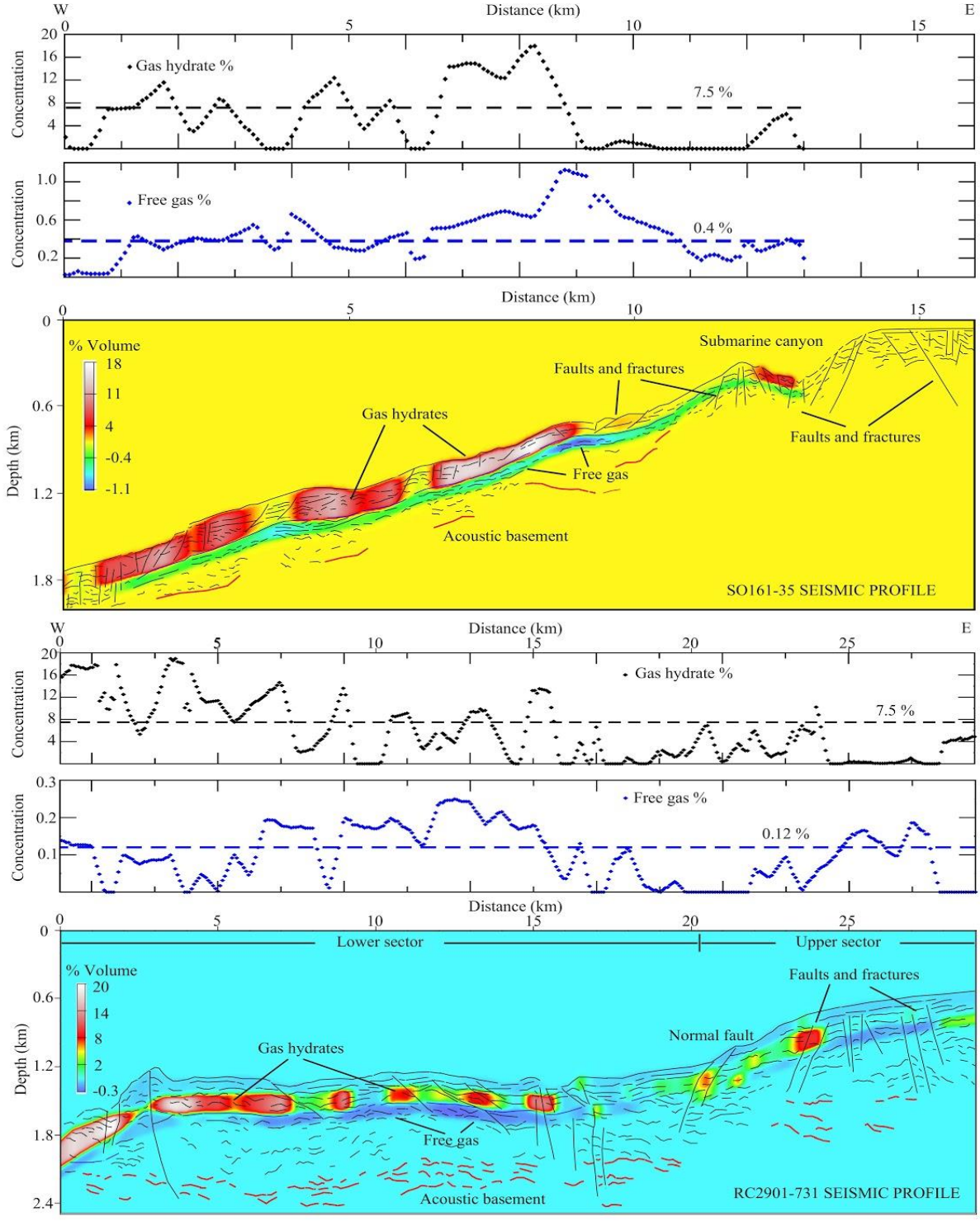

Figure 3. Line drawing sections with superimposed gas phase (gas hydrate and free gas) concentration models. Top three panels: SO161-35 seismic profile. Bottom three panels: RC2901-731 seismic profile. Above each sections are reported gas hydrate (black diamonds) and free gas (blue diamonds) concentration values. Dashed black and blue lines show average values.

A variable geothermal gradient across sections was obtained. However, a recognisable higher geothermal gradient was identified across SO161-35 section (ranging from 60 to 110 °C/km), while lower geothermal gradient across RC2901-731 section was observed (ranging from 35 to 65 °C/km). The seismic and line drawing sections (Figs. 2 and 3) underline that the lowest geothermal values are

located upwards in correspondence with the submarine canyon for SO161-35 section (see Fig. 3 above section at 12 km of distance) and the normal fault for RC2901-731 section (see Fig. 2 below section at 22 km of distance).

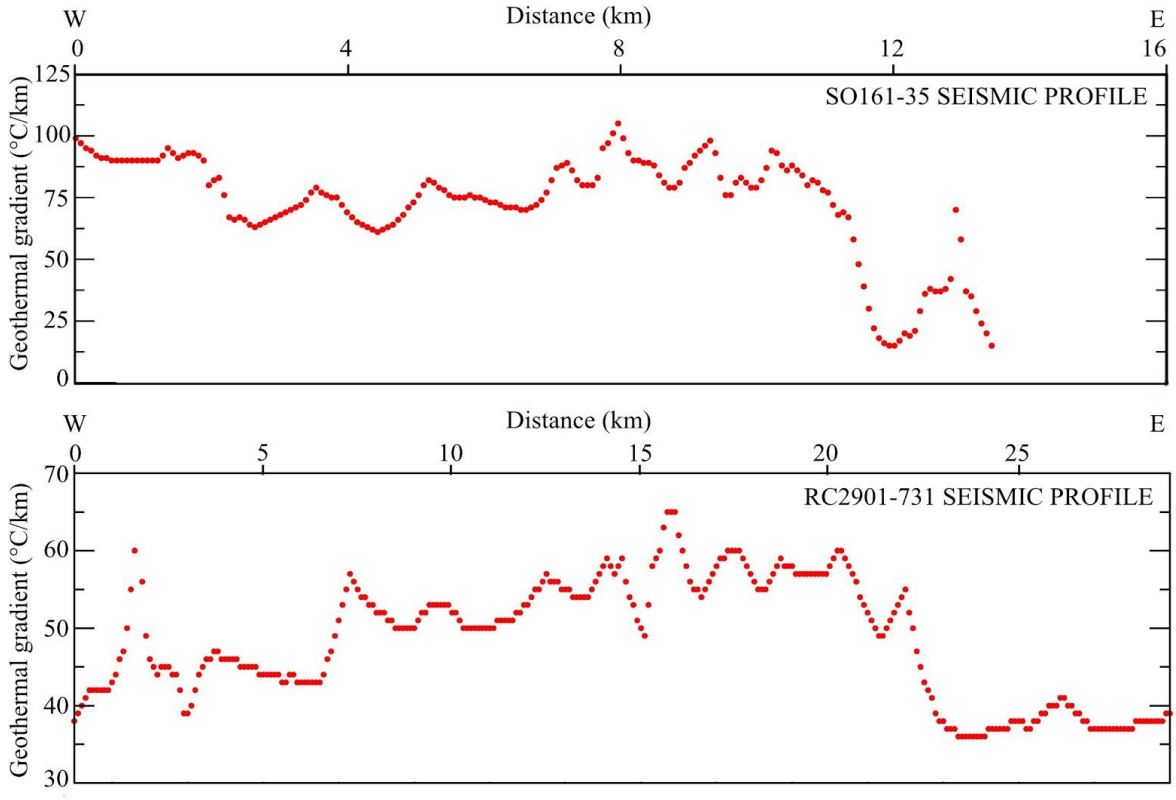

Figure 4. Estimated geothermal gradients. Top: SO161-35 seismic profile. Below: RC2901-731 seismic profile.

4. Discussion

Faults, fractures and folding affecting the shallow sediments in both sections are related to an active domain. In fact, Mocha island is characterised by high seismicity and the uplifting process started during Quaternary [18]. The SO161-35 seismic profile is located approximately 12 km southern Mocha island and shows a strong and continuous BSR, while SO161-731 seismic profile, distant from Mocha island approximately 60 km south, evidences a discontinuous and locally strong BSR. Moreover, a lateral variable BSR depth close to Mocha island (SO161-35 section) was identified, while along RC2901-731 only a slight variation in the BSR depth was recognisable. The BSR seismic character and its depth variability can be related to the gas phase concentrations and the geothermal gradient distribution. Regarding BSR seismic character, several studies argue that strong and continuous BSRs are related to significative free gas concentrations and strong vertical velocity variations [8,34,35]. In our case, across SO161-35 seismic profile the highest free gas concentrations up to 1.1% of total volume (associated to the lowest velocity equal to 1260 m/s) are related to strong vertical velocity variation of 640 m/s, which is the velocity difference between gas hydrate and free gas velocity layers. On the other hand, faraway from Mocha island (RC2901-731 seismic profile), the lowest velocity below BSR increases to 1450 m/s and the difference between gas hydrate and free gas velocities decreases to 400 m/s with respect to the seismic velocity determined in proximity of the Mocha island. The variable depth of the BSR along the SO161-35 section can be explained by a variable geothermal gradient, in which high geothermal gradient values ranging from 60 to 110 °C/km, while a constant BSR depth along the RC2901-731 section could be asociated to low geothermal gradient values ranging from 35 to 65 °C/km, characterized by a slightly lateral variation.

Along the RC2901-731 line, the discontinuous and locally strong seismic character of the BSR can be related with lateral folding presence, in which the gas hydrate and the free gas appear trapped by least across faults and fractures and are highly concentrated at the folding crest. In fact, along this section, areas characterized by high/low velocity above/below the BSR in correspondence to small folding and faults are detected (see RC2901-731 seismic profile in Figs. 2 and 3). Our result is in agreement with several authors that have reported anticlinal structures as structural traps for fluid storing associated to gas hydrate occurrences [12,36-38].

Higher geothermal gradient values were obtained close to Mocha island with average value equal to 85 °C/km against lower geothermal gradient values far off Mocha island with average value equal to 50 °C/km. These results are in agreement with anomalous heat flows reported by [15] in the same area. The former authors argue that the high heat flow variability would be related to ancient sliding processes, in which the headwall slide constitutes a fluid advection zone altering the geothermal gradient at the present. In addition, some authors have proposed this area as a hydrated and/or fluid saturated forearc region [39]. In this context, the fluid supply from deep including gas can be canalised by faults and fractures (Fig. 5) and reaches the hydrate stability zone altering the thermal state giving place to high geothermal gradients as reported in this study. Decreased geothermal gradient faraway from Mocha island is associated with the regional geothermal gradient [15,26,27].

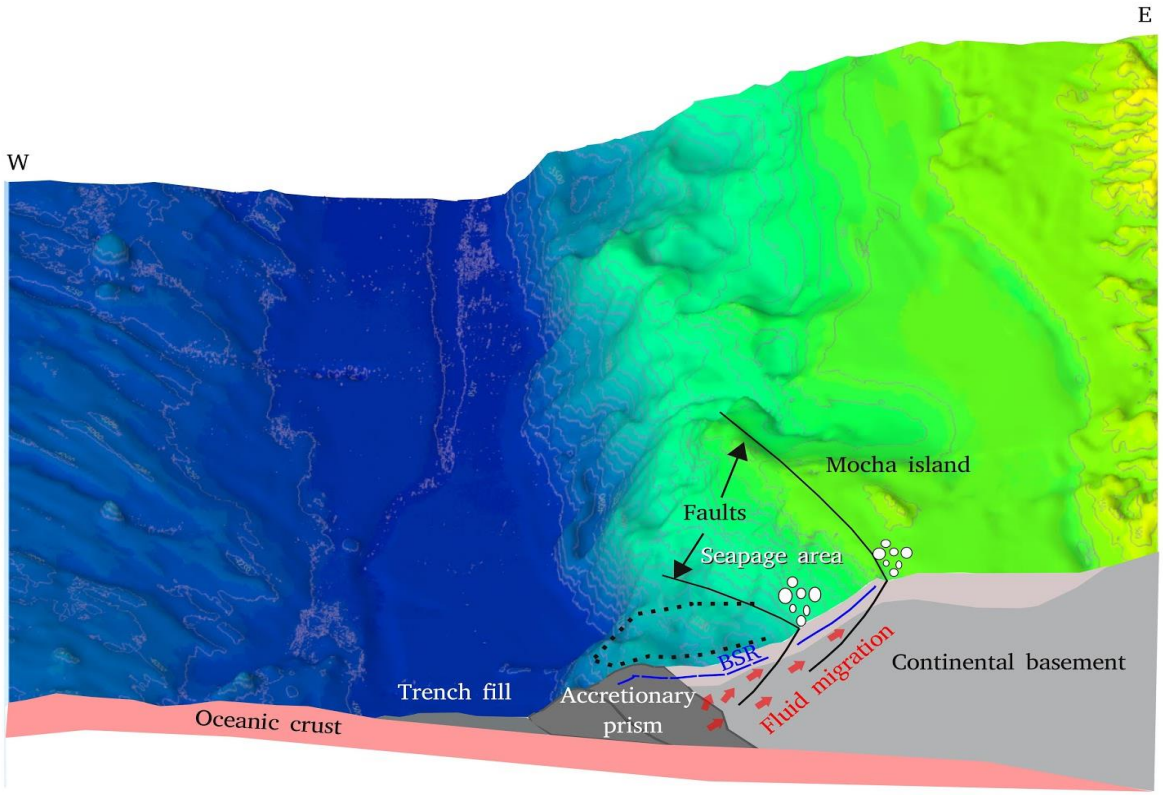

Figure 5. Schematic diagram of SO161-35 seismic profile located close to 38°30'S (see Fig. 1), explaining fluid migration processes close to the Mocha island. Faults are reported by [17,18]. Dashed line shows part of the ancient sliding reported by [40].

High gas hydrate concentrations up to 20% of total volume are reported in both sections, but the highest free gas concentrations up to 1.1% of total volume are located near to the Mocha island (SO161-35 seismic profile), while the lowest free gas concentrations up to 0.3% of total volume are found faraway Mocha island (across RC2901-731 section). In both sections, the highest gas hydrate concentration can be explained as follows: a) high fluid supply from deep zones that can favour gas hydrate formation, as suggested by several authors [15,38] and b) overestimates by compaction due to deformation processes. On the other hand, the highest free gas concentration located near the

Mocha island would be related to the gas hydrate dissociation associated to past sliding processes reported by [40] or free gas stored below an impermeable gas hydrate layer (see Fig. 5), while the lowest free gas concentrations across RC2901-731 seismic line can be explained by lower fluid supply from deep zones and high fluid escape rates preventing free gas storing. These fluid escapes are canalised by faults and fractures affecting seafloor and releasing gas like seeps.

Finally, considering high gas hydrate (average 7.5 % of total volume) and free gas concentrations (0.4 % of total volume) reported in this study, we conclude that close to the Mocha island gas hydrate dissociation processes occurring in the past and, potentially, in the present can constitute the main seepage supply source along this part of the Chilean margin.

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