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GOLFO SAN JORGE BASIN AND EL TORDILLO FIELD: UNDERSTANDING CO_2 PRESENCE USING BASIN MODELING

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RESUMEN

La distribución de CO_2 en la cuenca del Golfo San Jorge no es bien conocida y de acuerdo con los descubrimientos más recientes, generalmente se concentra en la parte inferior de la columna sedimentaria. En el área de El Tordillo (Tecpetrol), tres pozos alcanzaron la Formación Pozo D-129. Aunque no se han probado todas las secciones de los pozos, los reservorios convencionales dentro de la Formación Pozo D-129 produjeron cantidades considerables de CO_2 (hasta 87%). La composición isotópica de las acumulaciones gaseosas sugiere que el CO_2 presente en los pozos proviene principalmente de una fuente inorgánica (60% de una fuente de carbonato cortical).
Con el propósito de entender la generación y migración de CO_2 en el área de El Tordillo se construyó una línea 2D regional, para comprender el entorno geológico regional, la historia y entender cómo se generaron, migraron y acumularon todos los hidrocarburos, no solo el CO_2, dentro de la cuenca. Utilizando los resultados recopilados de una línea regional, se creó un modelo 3D para el área.
La descripción litológica y el análisis quimioestratigráfico de los pozos del área se utilizaron para caracterizar las facies carbonáticas dentro de la Fm. Pozo D-129. Se generó la energía de activación y el coeficiente de Arrhenius que permitió simular ladescarbonatación donde se dieran las condiciones termales. De acuerdo a los resultados la mayor parte del CO_2 generado se concentró en la sección superior de la Formación Pozo D-129, inmediatamente en la parte superior de las unidades con carbonatos. La generación tardía de CO_2 evitó que migrara verticalmente a las unidades menos profundas.
Como estudio preliminar en la generación de CO_2 inorgánico, los resultados del modelo muestran una buena correlacióncon la distribución del gas en el campo. Sin embargo, el volumen de CO_2 generado en el modelo para el área es menor al observado en los pozos, lo que puede deberse a una subestimación del espesor de carbonatos en el intervalo generador. Los resultados sugieren que la roca madre principal en la cuenca del Golfo San Jorge podría contener CO_2 cuando haya facies de carbonatos.

INTRODUCCIÓN

The Golfo San Jorge Basin is the most prolific oil basin of Argentina, containing mostly mature, conventional fields. After the boom of shale and unconventional reservoirs, new exploratory wells were drilled in order to better characterize the main source rock, PozoD-129 Formation, to fully evaluate its potential as an unconventional play. In the El Tordillo field (Tecpetrol, Fig. 1), three wells reached the PozoD-129 Formation with this aim. Although not all sections of the wells have been tested, the conventional reservoirs within PozoD-129 produced considerable amounts of CO_2 (up to 87%). With such high levels, gas production is not possible from either an economical or technical point of view. However, if CO_2 generation, migration and location of present day accumulations could be better predicted, a suitable deep drilling campaign could be designed in order to increase the gas production and fully evaluate the potential of the PozoD-129 Formation as an unconventional play.

Several basin modeling studies have been performed to understand conventional oil generation and accumulation in the Golfo San Jorge Basin (Rodríguez and Littke 1997; Strelkov and Lafourcade 1998; Rodríguez and Littke 2001). Although basin modeling is generally used to model a petroleum system and predict hydrocarbon accumulations; recent work suggested it could also be used to properly model how CO_2 is produced and migrates from an inorganic source. Basin modeling is the best tool to provide a regional understanding of (1) basin dynamics, (2) fluids (Hydrocarbon, CO_2) generation and migration. Then a local interpretation could be made regarding the El Tordillo Field. First, it was necessary to understand from a 2D regional model, the geological setting, basin history and to comprehend how all hydrocarbons andCO_2, were generated, migrated and accumulated within the basin. Second, it was possible to move from a 2D line to a local 3D model and try to understand the El Tordillo CO_2 distribution. The aim of this work is to understand the behavior of CO_2 (timing of generation, timing of migration, migration pathways) by using a regional 2D model line of the Golfo San Jorge Basin, and a 3D block created and populated for the El Tordillo Field by combining previous information and Tecpetrol results.

GOLFOSAN JORGE BASIN

The GolfoSan Jorge Basin is located in central Patagonia, between 44 and 47°S and 66 and 71°W. It covers a surface of approximately 170,000 km^2, with one third located offshore. The Somuncurá Massif bounds the basin towards the north, the Deseado Massif to the south, the continental margin of the Atlantic Ocean to the east and the Cordillera de Los Andes to the west.

The basin developed during a Late Jurassic – Early Cretaceous extensional event related to the opening of the South Atlantic, and experienced Cenozoic reactivation and compression. Most of the hydrocarbon accumulations are found in the northern and southern flanks of the basin, with very few accumulations in the center, mainly due to lack of structuration, and less well developed reservoirs.

The economic basement of the basin is the Complejo Volcánico Sedimentario Jurásico Superior (Clavijo, 1986). The sedimentary column is composed of continental Mesozoic and

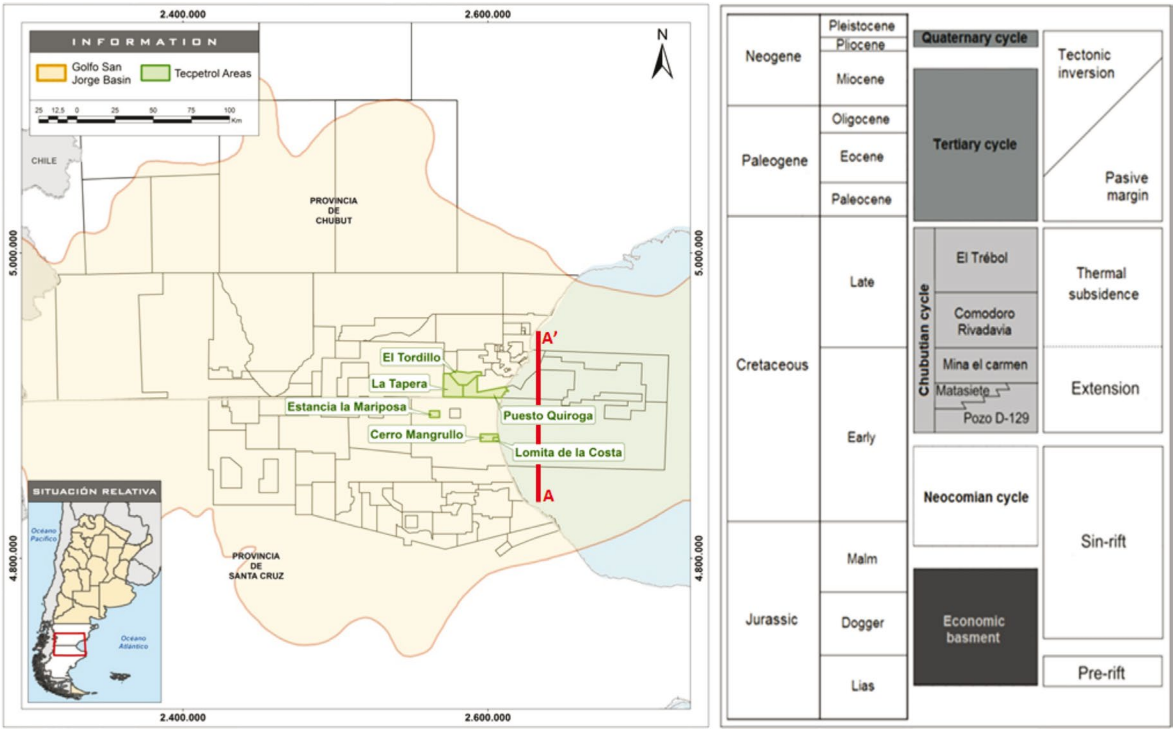

Figure 1. El Tordillo Field and 2D regional line location in GolfoSan Jorge Basin (A'A) and stratigraphic column.

Cenozoic sediments. Based on the concept of megasequences Hubbard(1988) and Figari *et al.* (1999) divided the stratigraphic record into 5 megasequences representing tectonic and eustatic changes: Megasequence 0 (economic basement), Megasequence I (the Neocomian cycle), Megasequence II (the Upper Cretaceous Chubutian cycle), Megasequence III, (the Tertiary cycle), Megasequence IV (the Quaternary cycle). These megasequences can be divided into sequences that agree with the formal stratigraphic units. The Chubutian Cycle concentrates the petroleum system modeled in this work. This cycle represents the first stage of a sag basin evolution (Fitzgerald *et al.*, 1990) coinciding with the tilt of the basin axis and the consequent movement of the main depocenter towards the East (Figari *et al.*, 1999). It is composed of four formations: Pozo D-129, Mina del Carmen, ComodoroRivadavia and Yacimiento El Trébol. For the model, each unit was divided into minor segments according to Tecpetrol facies analysis for the El Tordillo Field.

2D AND 3D MODELS

The models (Fig. 1) were generated using TemisFlowTM. A first 2D model (Fig. 2) was built at basin scale to understand the basin history in terms of thermal stress and impact on source rocks maturity, timing of hydrocarbons expulsion and migration. Stratigraphic, lithological and geochemical data were integrated in this model to make it robust and reliable.

The model was calibrated using data from 6 wells, including temperature and vitrinite reflectance (Ro) information when available, and main accumulation contours were used to validate migration scenarios. Faults are particularly important in this basin as they act as conduits for fluid migration through geological time, and hence a precise definition and tuning of the faults had to be performed. The extensional setting acting since the Early Cretaceous until the Oligocene generated very good migration pathways all over the basin (Figari *et al*, 1999). First faults acted as migration pathways while the fault network formed but through the basin history, compaction and diagenesis changed their hydraulic properties and faults started to work as seals defining the shape of the actual hydrocarbon accumulation. For the 2D model the principal faults were interpreted as deep faults associated with the initial extension; and the antithetic faults related with the Late Cretaceous and Early Tertiary reactivation. The faults were picked on the line and for the modeling their permeability was modified by a factor according to the fault type and timing. For the 3D block faults were modeled cell by cell with a defined lithology. Three different facies were used for the fault modeling (open faults, an intermediate state and closed faults). The permeability change over time was defined according to the timing used in the 2D line for the antithetic faults.

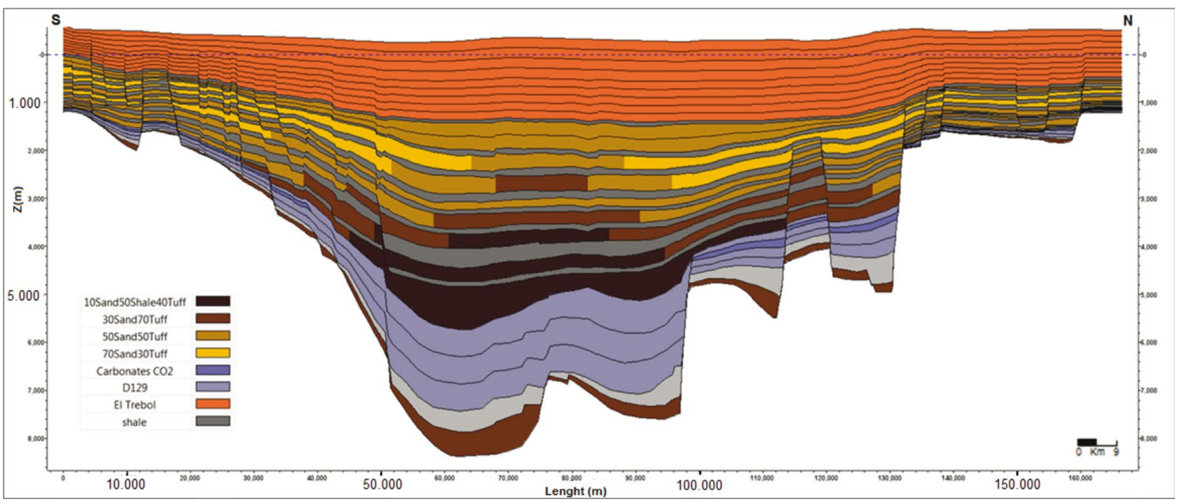

Figure 2. 2D line taken from Figari *et al.* (1999) Facies distribution representing a lacustrine facies arrangement for the source rock and fluvial for the reservoirs.

Three tectonic events were considered in the model. The extensional Late Jurassic–Neocomian and Barremian-Aptian events controlled the deposition of all the units composing the studied petroleum system (Figari 1999; Sylwan 2001). Thereafter a Cenozoic tectonic reactivation period is postulated as the origin of a second heating event in the basin (Rodríguez and Littke 1997; Figari *et al* 1999). During the modeling step, this secondary event was necessary to reach the Ro values observed in the wells in the area.

The 3D model was thus calibrated to the wells located in the area of interest, both in temperature and vitrinite reflectance (Fig. 3). An oil-prone kerogene was used for the source rock and the resulting timing of hydrocarbons expulsion and migration were compared with previous works published (Rodríguez and Littke 1997; Strelkov and Lafourcade 1998; Rodríguez and Littke 2001). At this step a typical basin modeling workflow was followed. Thereafter CO_2 sources were finally integrated in the model for simulation.Results allowed us to estimatethe timing of CO_2 generation, expulsion, and eventually migration within the field.

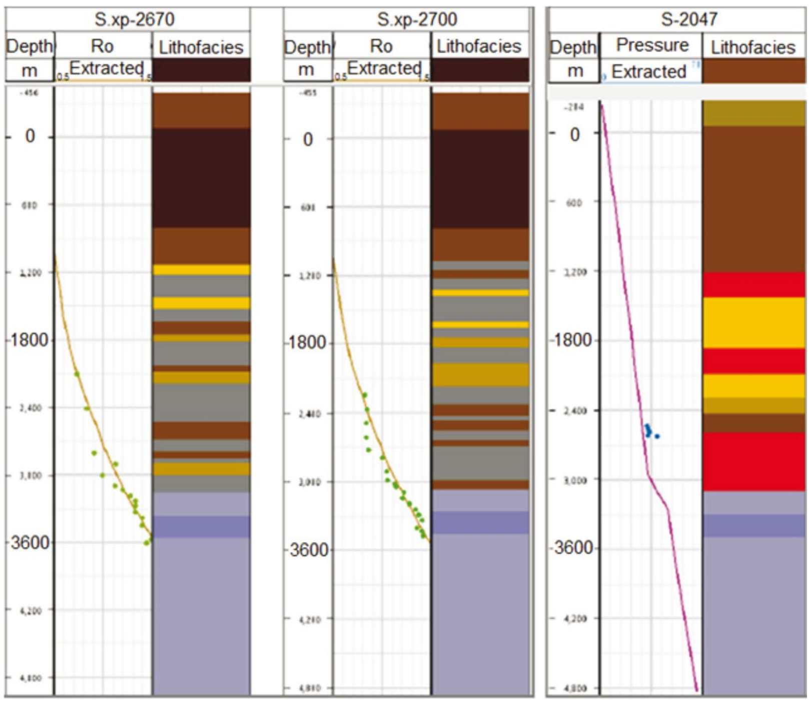

Figure 3. Present days temperature and pressure profiles obtained with the 3D block. The dots correspond to the well measurements, the lines are the basin modeling results.

INORGANIC CO_2

In order to understand the origin of the CO_2 in the GolfoSan Jorge Basin and in the El Tordillo Field, isotopic data from a single well (S.xp-2670) was used. According to Sano and Marty (1995) where an active gaseous accumulation is identified, it is possible to estimate the contribution proportions of the different sources that would be generating the CO_2 enrichment. To do so a three-component mixture model is used that involves the main sources of contribution: sediments enriched in organic matter, a deep magmatic source with mantle characteristics andcortical material enriched in carbonates. Results of the $\delta^{13}C$ and $CO_2/^3He$ diagram (Fig. 4) shows that the accumulation of CO_2 in the well corresponds to 60% of a cortical carbonate source, 35% is mantellic source and 5% corresponds to an organic source.

For this study, the amount of CO_2 from a magmatic source was not taken into account as it

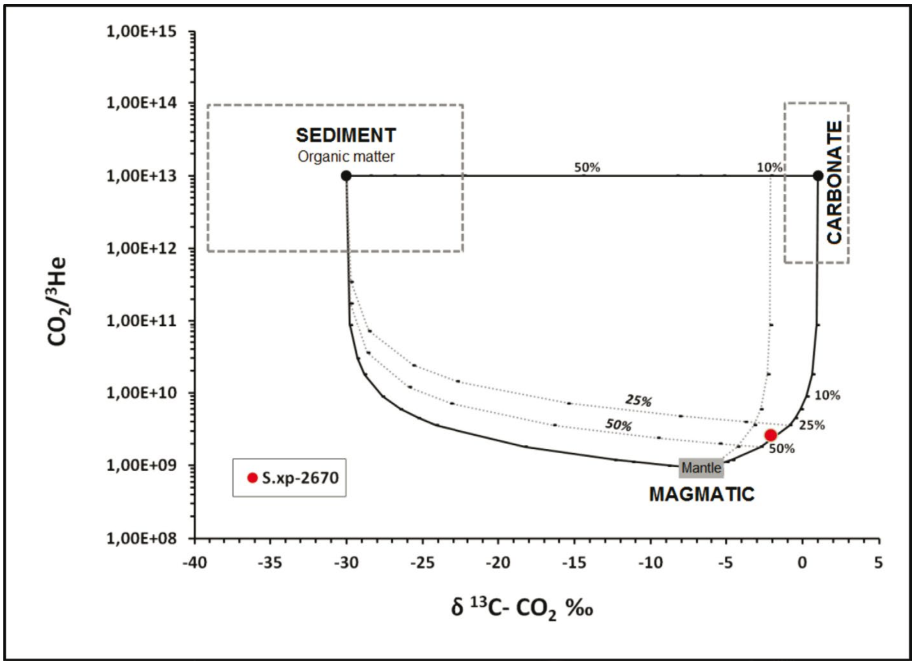

Figure 4. $\delta^{13}C$-CO_2 vs $CO_2/^3He$ diagram. Sediment, magmatic and carbonate fields are indicated according to Sano y Marty (1995).

could not be modeled gas coming from outside of the physical model. However the magmatic CO_2 is significant in the area and would affect the material balance.

As a first approximation a simple scenario was considered where all inorganic CO_2 came from a cortical carbonate source. In this scenario the risk of encountering significant CO_2 contamination in a natural gas prospect in the Golfo San Jorge basin can be assessed by evaluating where the conditions necessary for metamorphism of carbonate minerals are set and how the carbonate minerals are distributed in the basin. In other words, it is necessary to understand the basin thermal history, which units the carbonates are related to and whattheir facies distribution is. In this scenario the amount of CO_2 generated depends on the amount of carbonates reaching the thermal condition for metamorphism.

The principal source rock, the PozoD-129 Formation, is the main suspect for the inorganic CO_2 generation since it is the only formation with carbonate components. In 2014 Basile *et al.* presented a detailed work recognizing different petrological and geochemical heterogeneities inside this unit, defining three sections. The carbonates are concentrated in the upper section and are controlled by its facies distribution. The authors interpreted the enriched carbonate sections as shallow lacustrine facies. Thisfacies is only present along the northern and southern flanksof the basin.

For the modeling of CO_2 generation, potential inorganic CO_2 sources were integrated in addition to regular thermogenic sources. A CO_2-prone lacustrine facies was defined using the lithological description and the chemostratigraphic analysis of the deep wells and the work from

Basile *et al* (2014). This facies is normally composed of phyllosilicate and dolomite and it is present in the wells S.xp-2670, S.xp-2700 and S.2047 in the El Tordillo Field (Fig. 5).

The bulk chemical composition of the lacustrine facies is used as input for thermodynamical calculations, that follows a modelling approach commonly used in metamorphic petrology (Brosse *et al.*, 2017). At given bulk composition and temperature-pressure (T-P) conditions relevant for the basin, the composition and proportions of solid and fluid phases that coexist at equilibrium are computed using a Gibbs Energy Minimization (GEM) algorithm. Finally, a protocol that integrates the decarbonation scheme derived from thermodynamics into a CO_2-generation formalism compatible with the usual formalism of a basin model is used to define the activation energy and Arrhenius coefficient valuesfor the “artificial kerogen” in other words the CO_2-prone lacustrine facies.

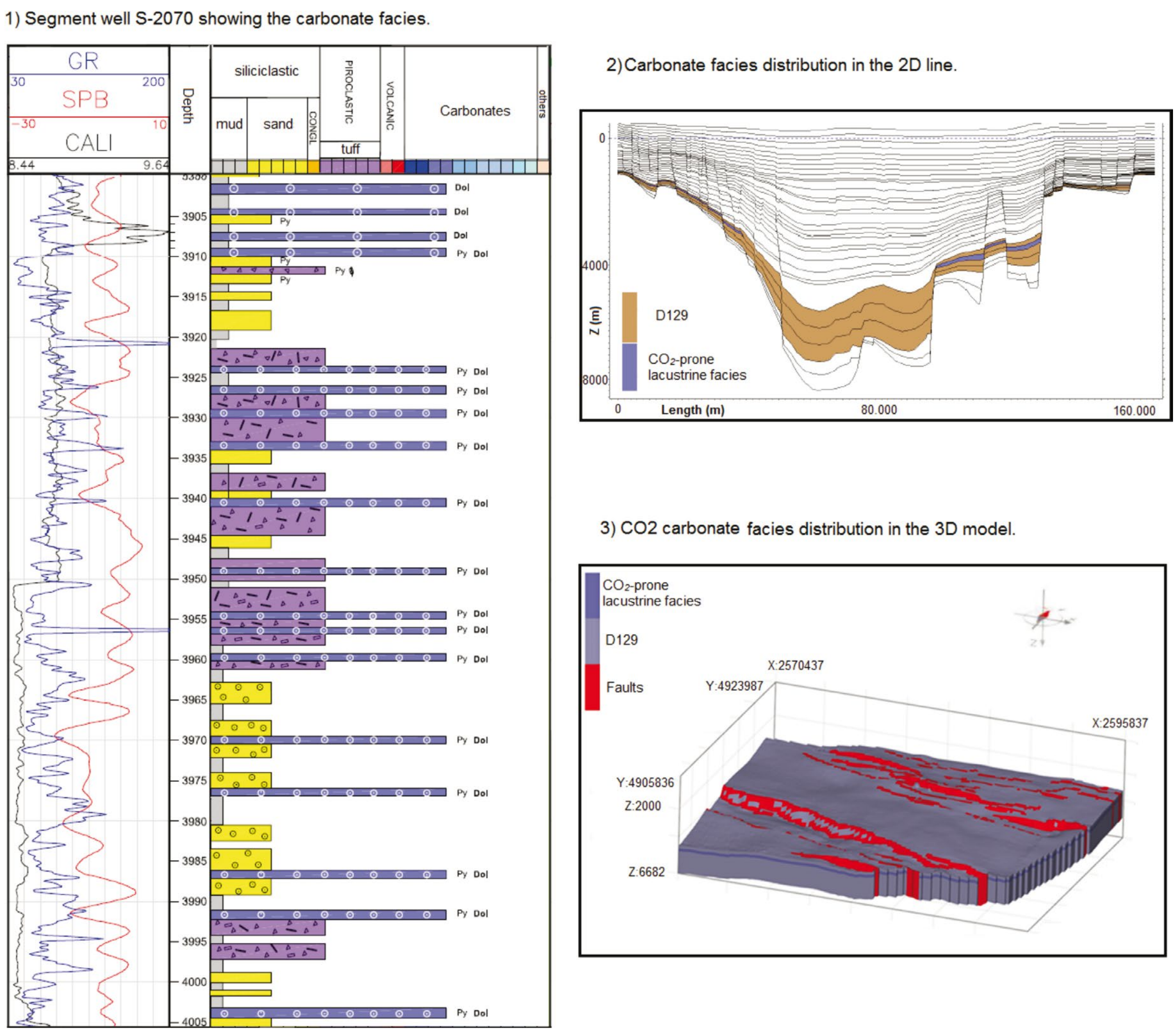

Figure 5. 1) Segment of well S-2070 showing the carbonate facies. 2)CO2 carbonate facies distribution in the 2D line. 3) CO2 carbonatefacies in the El Tordillo block.

According to the methodology described in Brosse *et al.* (2017), TemisFlow^{TM} software can be used to assess the generation of inorganic CO_2 that occurs during low grade metamorphism conditions undergone by the carbonates within the lacustrine depositsof the basin.The migration of the generated CO_2 in the sedimentary basin occurs in the gas phase. The dissolution of the CO_2 in the formation waters is neglected in the present work.

In the model the carbonate facies were integrated with the Pozo D-129 Formation. These facies were placed on the upper section of the source rock, and modelledonly at the flankson the 2D line. In the 3D block a constant 100 m layer was defined. On the wells the CO_2-prone lacustrine facies correspond to carbonate rocks interbedded with tuffaceous sandstone, vitreous tuffs and tuffaceousshales. According the facies description from the well, it was assumed in the model that 40% of the total thickness of the cells containing the CO_2-prone lacustrine faciesare efficient to generate CO_2 (Fig. 5).

RESULTS

In the models, oil generation started at 120 Ma in the center of the basin reaching its maximum at 100 Ma. Oil generation starts at 105 Ma in the Northern flank, having its maximum at 60 Ma. The second heating step in the basin controls oil and gas generation in the flanks with a peak at 15 Ma. Most of the CO_2 generationis associated to this last thermal peak. It means that when most

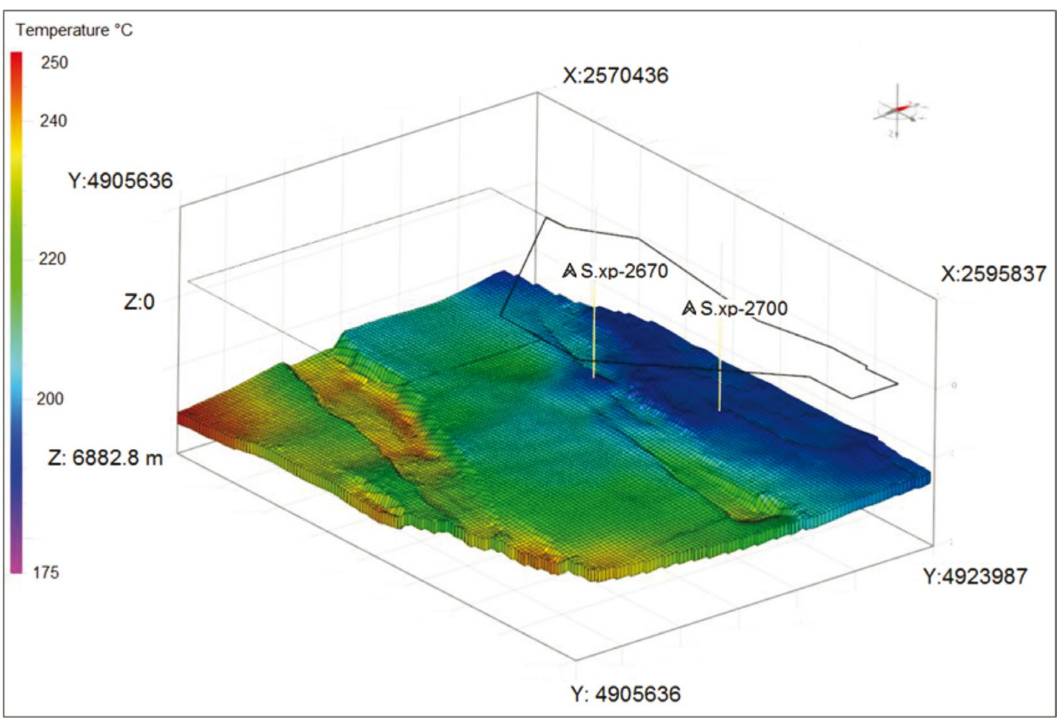

Figure 6. Temperature results for the CO_2-pronefacies. Z=1.

of the CO_2 was produced, the stratigraphic column wasalready saturated with oil and most of the faults had alowpermeability.

In the El Tordillo Field, the model shows good correlation with the presence of CO_2 within the wells. The two deepest wells in El Tordillo show an important volume of CO_2 and tests in S.xp-2670 discovered CO_2 % up to 87%. The gas was expelled in the last 30 Ma years. We observe a quick decrease of CO_2 saturation moving upwards in the sedimentary column. The model clearly shows the CO_2 concentration decrease in the wells but substantially underestimates the volume of CO_2 generated. While the well S.xp-2670 shows a large amount of gas being produced in a single test (66%), CO_2 saturation in the model at the same position represents 10% of the oil content. Migration of CO_2 occurs frequently along the faults. Only the base of Mina del Carmen Fm shows small percentages of CO_2, and this occurs mostly in the south of the area, where the temperature is higherreaching 250 °C while at the central part of the area temperatures are lower than 200 °C (Fig. 6).

As a preliminary study of inorganic CO_2 generation in the basin, the results of the model show a strong correlation with well data. However, the main cave at is the mismatch with volume of CO_2 generated. Explanations for this inconsistencycan be related to (1) the small areal extent of the model, (2) bad distribution of the carbonatefacies, (3) not considering the mantle CO_2 contributionor (4) a different heat flow history.In this work we tested the possibility of using basin modeling analysis, a process that was created to simulate how organic products were generated and how they migrated alonga basin, also as powerful toolto simulate CO_2 generation from an

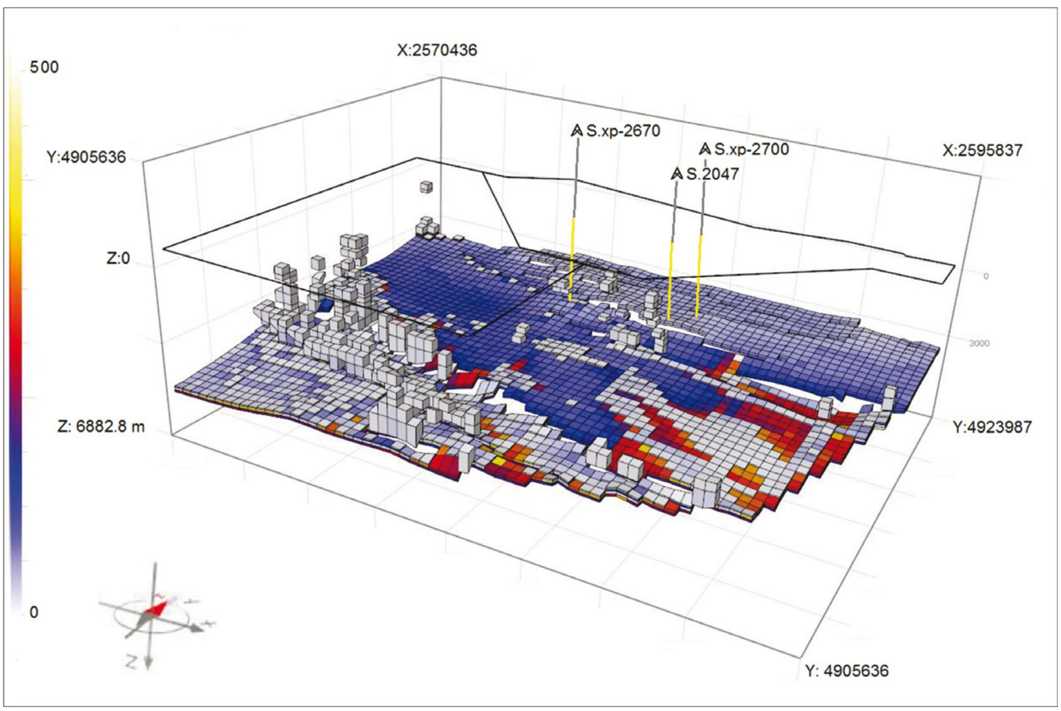

Figure 7. Mass of CO_2 in the Cell per Area (kg/m²). Filtered by CO_2 presence.

inorganic source (Fig. 7). The methodology was successfully used and allowed us to create a complex scenario where both, organic and inorganic fluids were generated and interact along the sedimentary column.

More scenarios must be tested to reach a final conclusion regarding the CO_2 generation and the economic potential of the Pozo D-129 Formation in the El Tordillo field. However, the work done in this study gives a new outlook to the CO_2 problem and improved the understanding of CO_2 presence in the Golfo San Jorge Basin.

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