

# Interpretation of Tectonosequence in a Structural High Containing Gas Fields in the Carupano Basin, Offshore Northeastern Venezuela

Valencia Y.<sup>1,\*</sup>, Ramírez R.<sup>1,\*</sup>

<sup>1</sup>PDVSA, Gerencia de Proyectos Exploratorios y Delineación Costa Afuera, Puerto La Cruz, Venezuela.

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## ABSTRACT

Gas fields offshore Venezuela were discovered in the 80's from the interpretation of "bright spots" in 2D seismic lines. These seismic anomalies occur on the top of a structural high, the "Patao High", which is located within the Carupano Basin. These discoveries led to identify four major reservoirs containing an estimated potential of 14 TCF.

In 2010 a new exploratory project started in the Patao High area using new 3D seismic survey. The main purpose of the project is to identify tectonosequences that explain the evolution and configuration of the area. On the basis of seismic strata terminations four tectonosequences were defined for the Neogene and Quaternary deposits.

Each tectonosequence comprises Cenozoic sediments covering Cretaceous strata. They are bounded above and below by unconformities. The deepest sequence (SM1-SM2) at the top of the paleo-structure, is characterized by incised-valley fill deposits. Biostratigraphic data suggest that this sequence was deposited during Early Miocene to Middle Miocene. It is related to basement uplift, transpression, and subsidence of the basin. The thickness map for this sequence suggests that the depocenter of the basin was located SW of the Patao High. The second sequence (SM3) is considered the most important in terms of hydrocarbon content. It is defined as a condensed section deposited in the Late Miocene. Reactivation of the basement uplift was the most significant regional tectonic event affecting the formation of SM3, the upper sequences SPL, and SPP. However, provenance of SPL sediments (Pliocene) suggest two uplifted areas within the Carupano Basin with the depocenter located to the NW of the Patao High. This is further confirmed by the architecture of the SPP sequence (Pleistocene) and overlying recent sediments.

In this study, ten opportunities are identified in the area with new estimated volumetric reserves of ~2,8 TCF. Eight of these opportunities are related to the SM3 stratigraphic sequence and two to the SM1-SM2.

## 1. Introduction.

The exploration of the Carupano basin initiated between 1978 and 1982 and was conducted by the state-owned company Lagoven S.A. who performed 2D line seismic survey of 3450 km in 1980. Out of 20 wells drilled in the area, 14 were successful and 13 of them led to the discovery of the Rio Caribe Field (2 wells), Mejillones field (3 wells), Patao field (5 wells), and Dragon field (3 wells).

After these fields were discovered, it took until early 1991 when a joint venture among the companies Lagoven, Shell, Exxon, and Mitsubishi was initiated to conduct a geological and geophysical study, in order to define the resources of initial gas in the area, to assess the economic feasibility for production, and to analyze the economic recovery potential of the fields Rio Caribe, Mejillones, Patao, and Dragon. Within this project 3D seismic volumes were recorded in the North of Paria area in 1992 and available information from the wells was used.

The Offshore Exploration Department of Petroleros de Venezuela (PDV) started another program (Proyecto de Exploración por Hidrocarburo Costa Afuera de Venezuela, PECA 2000), in order to document the opportunities that are in the resource base. Within this program, analysis and interpretation of four regional seismic transects (2D and 3D seismic) was performed. Besides that biostratigraphic and sedimentological data, well logs, geochemical data, and other information of interest was integrated. The major outcome of this study are six Leads-level opportunities that are all matured level prospects.

## 2. Location of the Study Area.

The area is located North of the Paria Peninsula, within the Carupano Basin on the NE Continental Shelf of Venezuela. It covers an area of approximately 2,450 km<sup>2</sup> and includes the Dragon, Patao, Mejillones, and the Rio Caribe fields (Figure 1).

The Carupano Basin is a structurally complex depression that covers an area of approximately 30,000 km<sup>2</sup> (Carnevali et al., 2000). It is bounded by the Margarita-Los Testigos Platform to the North, the Araya-Paria Peninsula and the Northern mountain range of Trinidad to the South, the Tobago Island to the East, and the Margarita, Coche, and Araya highs to the West. The Carupano Basin consists of a main depression at its northeast, referred to as the Caracolito Subbasin, and three minor, secondary subbasins; the Paria, the Araya, and the Southeast Margarita subbasins. All of which are separated by different structural highs like the Patao High, the San Juan de las Galdonas High, the Araya High, the Coche High, and the Margarita Island (Pereira., 1985) (Figure 1). The fields of interest in this study are located in the Patao High.

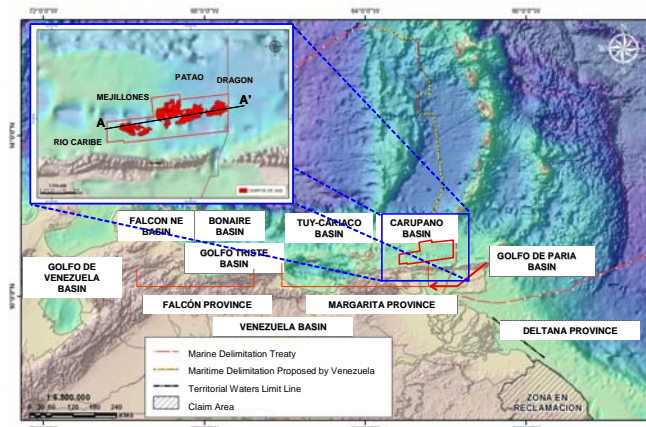


Figure 1. Location of the study area

The Dragon, Patao, Mejillones, and Rio Caribe fields are considered to contain associated reserves of 3.1 MMPCN, 4.08 MMPCN, 4.95 MMPCN, and 2.13 MMPCN yielding a total of 14.26 MMPCN. These fields are characterized by high amplitude anomalies the seismic transects (Figure 2).

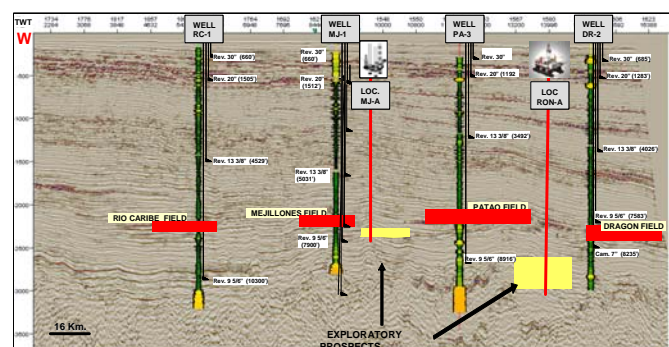


Figure 2. W-E seismic line showing amplitude anomalies associated with fields tested in Patao High

## 3. Stratigraphy of Alto de Patao

The stratigraphic column of the drilled wells in the Patao High contain sediments from the Early Miocene to Pleistocene. According to the stratigraphic lithology of the Geological Code in Venezuela, the stratigraphic column contains (from bottom to top) the Tres Puntas, the Cubagua, and the Cumana Formations (Figure 3).

The Tres Puntas Formation (Early Miocene - Middle Miocene) is mainly constituted by greenish gray shale, massive and often layered glauconitic pyrite nodules, iron oxide and lignite, siltstone interbedded with gray, laminated, sandstones. The latter are fine to medium grained of gray color, sub rounded, moderate sphericity, good culling, and they are somewhat calcareous (From M. Castro and A. Mederos, 1984, p. 52).

The Cubagua Formation (Late Miocene - Pliocene) is constituted at its top by banks of molluscs and bryozoans,

calcareous reef sacaroideas, gray quartz sandstone, fine-grained, sub-rounded, calcareous sandstone with medium sphericity, gray micritic limestone, calcarenite, bioclastic limestone interbedded with olive colored shale, massive and layered gray glauconite clays, and gray siltstone. Accessory material is quartz, lignite, and pyrite. At the lower part of the formation the record changes to deep water sediments with a uniform lithology of gray shale with abundant glauconite and pyrite nodules as well as sandy intervals that are intercalated with the fine-grained clastic material. (<http://www.pdv.com/lexico/c148w.htm>).

The Cumana Formation (Quaternary) is composed mainly of mollusc and bryozoan banks, remnants of corals, micritic, fragmented limestone, organic, light-colored limestone, oolitic limestone, mudstone, light-gray clay interbedded with light-gray to bluish-gray clay, the latter having abundant fragments of echinoderms, bivalves, and other molluscs, fossiliferous calcarenites, calcareous sandstones, and fine to very fine-grained gray quartz sandstone. (<http://www.pdv.com/lexico/c156w.htm>).

Although the stratigraphic column of the area is well defined, a tectono-stratigraphic sequence that may help to understand the distribution of reservoirs at the basin level has yet not been available.

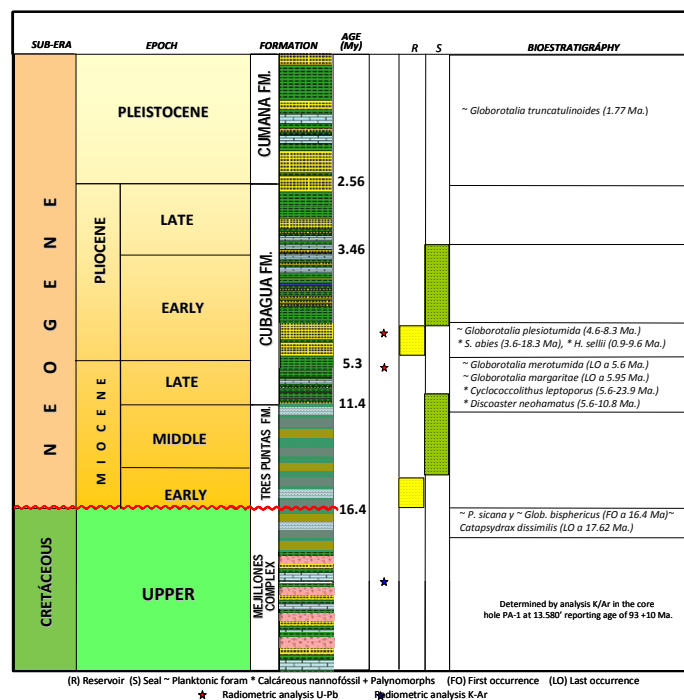


Figure 3. Stratigraphy of the Patao High

### 5. Methodology.

Figure 4 shows a general workflow illustrating the methodology used in this study. The work starts with a review of the available data from wells and seismic transects and its quality.

Next, regional seismic-stratigraphic transects were defined, in order to identify the stratigraphic surfaces, of which the maximum flooding surfaces (MFS) and the subaerial unconformities (SU) are the most relevant.

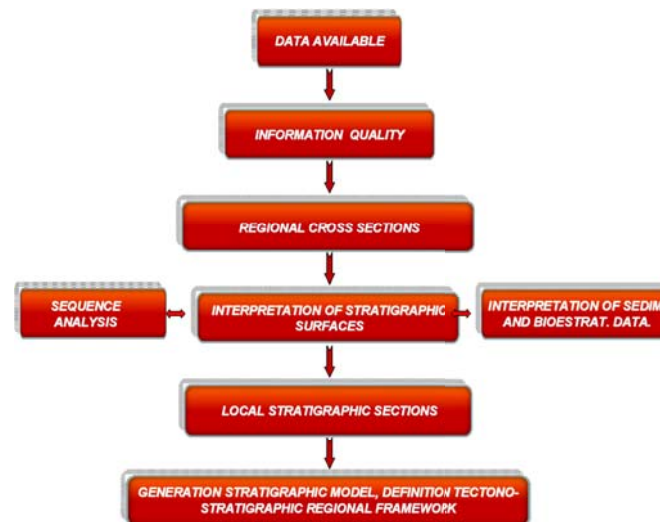


Figure 4. Workflow of the methodology used in this study.

These crucial areas were defined, on the basis of stacking patterns of well logs (increasing and decreasing grain size, respectively), as well as from seismic interpretation and analysis of the seismic reflector terminations such as onlap, toplap, downlap, offlap, and truncations (Mitchum and Vail, 1977; Mitchum et al., 1977).

The integration of geophysical and geological data available from the structural high of Patao allowed to define the tectono-stratigraphic reference model by using the stratigraphic depositional model I proposed by Mitchum et al. (1977) to define tectonosequences of 1st and 2nd order.

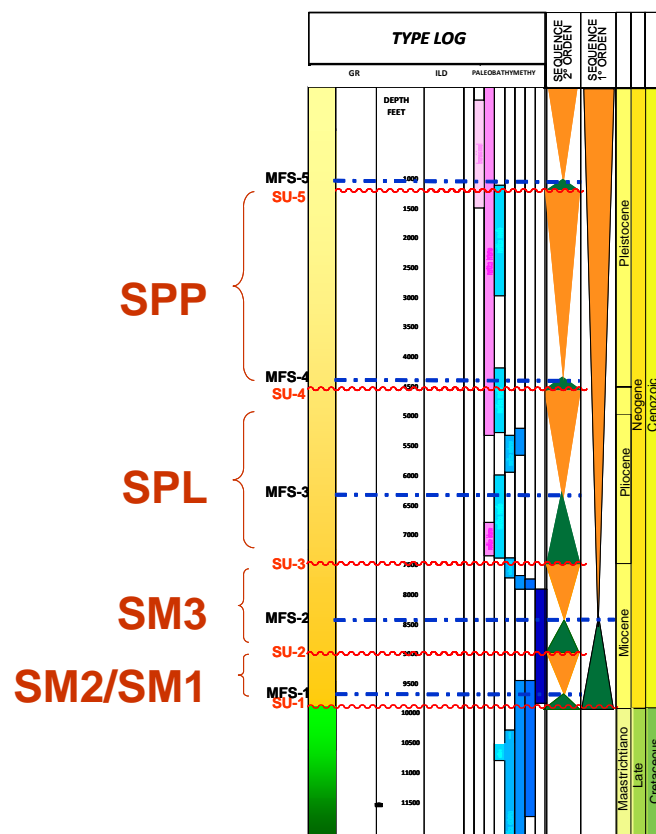
Tectonosequences defined in the regional seismic transects were integrated with sedimentological models, as well as with petrophysical and geochemical data. The exploratory prospects were economically evaluated, documented, and finally included in the Exploratory Drilling Plan of PDVSA Exploration.

### 6. Results.

The chronostratigraphy of the Patao High is framed into one mega-tectono-stratigraphic sequence or a first-order stratigraphic cycle, ranging from the early Miocene to Pleistocene. This mega-sequence has been divided into four tectonic sequences corresponding to depositional cycles of second order, which are defined between two sub aerial unconformities (Mitchum et al, 1977). These four tectonosequences were designated as follows (Figure 5):

- SM2 / SM1 correspond to the depositional sequence during Early to Middle Miocene.
- SM3 corresponds to depositional sequence during Late Miocene.

- SPL corresponds to depositional sequence during Pliocene.
- SPP corresponds to depositional sequence during Pleistocene.



**Figure 5.** Depositional sequences of the Patao High.

It is noteworthy that the largest reservoirs developed within the interval of the SM3 (Late Miocene-Early Pliocene), which corresponds to the bottom of the Cubagua Formation.

#### Early Miocene – Middle Miocene Sequence SM2/SM1

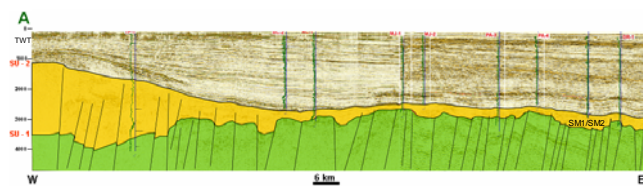
This sequence is defined by the subaerial unconformity 1 (SU-1) at its base and SU-2 at its top.

The SU-1 is interpreted as the limit of a 1<sup>st</sup> order sequence that overlies the crystalline rocks of the Caribbean plate on which the Carupano Basin developed. Seismic reflector terminations end in truncations, indicating that SU-1 is associated with an unconformity. The Middle Miocene age of SM2/SM1 is further indicated by biostratigraphic information from well BO-1 (Furrer et al. 1984). The Caribbean plate is interpreted in terms of a lithospheric domain that originated from Pacific Ocean spreading centers, thickened anomalously by oceanic plateau basalts in Abtian to Cenomanian times (e.g. Pinto, 2008, Wright and Wyld, 2011). The relation of the basaltic basement of the Carupano Basin with the Caribbean plate is suggested from K-Ar whole rock ages of tholeiitic basalt from core samples of well PA-1 ranging from  $87 \pm 9$  Ma to  $102 \pm 10$  Ma (Talukdar, 1983). The relations on the base of the sequence indicate that SU-1 places Middle Cretaceous rocks in contact with Middle Miocene rocks further indicating a hiatus of at least 50 myr. The missing sedimentary record is explained either by erosion or no deposition or both.

The SU-2 is interpreted in terms of a depositional sequence boundary of 2nd order. The seismic reflector associated with this unconformity is variable along the Patao High. In some areas the lower reflectors are truncated.

The observed discrepancies of the seismic record of this unconformity suggest uplift and inverse faulting in the area at the end of the Middle Miocene. The duration of erosion is also variable along the Patao High. Biostratigraphic data from well DR-1 in the Dragon field to the east indicate a hiatus of ~3.5 myr from 11.8-8.5 Ma by the absence of fossils corresponding to this time interval. To the west, in the Rio Caribe field, biostratigraphic data from well RC-1 suggest an even longer, ~4.2 myr, time of erosion by the absence of fossil register from 12.5-8.3 Ma. These data suggest increasing time interval of erosion or no deposition from east (Dragon field) to west (Rio Caribe field).

Figure 6 shows the seismic transect A-A' in W-E direction in which the SM2/SM1 sequence and its stratigraphic surfaces are observed. SU-1 appears as a high angular unconformity with high impedance contrasts in the seismic reflectors. This sequence represents the first sedimentary filling of an interbedded facies with clays, shales, and fine-grained skeletal sandstones. Some volcanic and metamorphic rock detritus is also observed (Parra, 2012).



**Figure 6** Regional Seismic Line in W-E direction showing depositional sequence SM2/SM1.

From the tectonic point of view, this sequence is characterized by dextral oblique collision along the southern boundary of the Caribbean Plate. The "Patao" and the "Los Testigos" highs were developed during the Oligocene and Early Miocene when the "Margarita-Los Testigos" block was separated from the "Araya-Paria-Tobago". (Speed et al, 1997, Pindell et al., 1988)

#### Late Miocene Sequence SM3

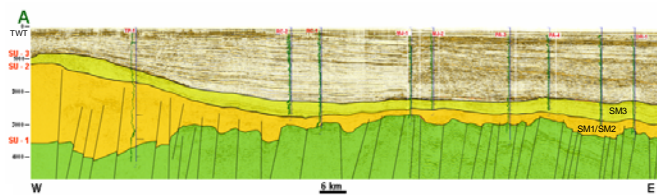
This sequence is defined at its base by the SU-2 and at the top by the SU-3. The regional tectonic event associated to this sequence is the oblique collision that reached the area during the Late Miocene. This sequence is by far the most prolific in the area because hosts the hydrocarbon fields discovered in the area. The sequence is characterized by deltaic front deposits and by turbidities.

The SU-3 at the top of the sequence is interpreted as a 2nd order unconformity (Figure 7). It is a composite surface, which passes laterally from a subaerial unconformity that is subject to erosion to a correlative surface (CC) that is not eroded and behaves like a condensed section. This lateral shift is indicated from the seismic transect AA', in which

truncations of lower seismic reflectors are observed against the SU-3 surface within the Dragon field. This horizon is observed up to the center of Patao and Mejillones fields where clinofolds of overlying sediments fall into downlapping on the surface. At this point the subaerial unconformity becomes a correlative surface without erosion. To the west, at wells TP-1 and TI-1, the area was again subject of erosion and the surface is a subaerial unconformity.

From well DR-3 the time no corresponding fossils goes from 5.3 to 3.3 Ma (D. Sanchez, O. Rodriguez and Mata L. 2008-2011), indicating a hiatus of ~2.0 myr. In well PA-1 the time range of missing fossil record goes from 3.47 to 3.25 Ma, suggesting a 1.4 myr lasting hiatus. It is concluded that the time without deposition decreases from the Dragon field to the Patao field, where the SU-3 passes laterally into the CC (condensed surface). The latter goes from the Patao field to the Rio Caribe field. This interpretation is also consistent with the interpretation of sismo-stratigraphic data.

The Late Miocene to Early Pliocene age of the Cubagua Formation was recently confirmed by U-Pb ages of the youngest detrital zircons from several wells of the Patao High yielding an average maximum time of deposition at  $\sim 5.6 \pm 0.3$  Ma.

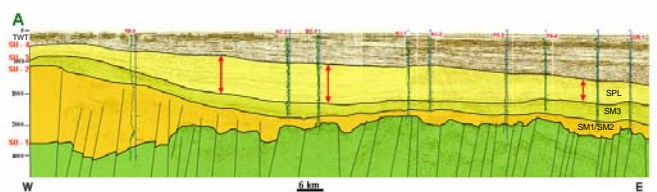


**Figure 7.** Regional Seismic Line in W-E direction showing the SM3 Depositional Sequence.

#### Pliocene Sequence SPL

This sequence is defined at its base by the SU-3 and at its top by the SU-4. In this sequence, the depocenter of the basin is located in the northwest. The sediments are mainly composed of mollusk and bryozoan banks, sacaroidea reef limestone, fine-grained gray subrounded quartz sandstone, calcareous sandstone, and gray micritic limestone.

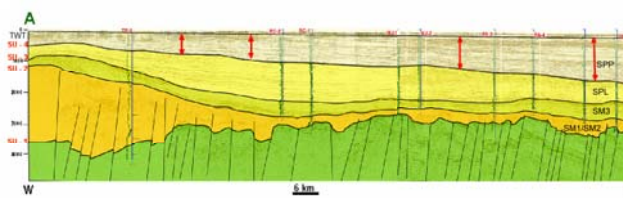
The SU-4 is interpreted as 2nd order unconformity. The terminations of seismic reflectors suggest a discordant relationship between the sedimentary deposits. The age of SU-4 is interpreted to be Pliocene to Pleistocene. This unconformity suggests tilting of the depocenter since the Pliocene. It is further suggested that the depocenter deposits move during the Pliocene from west to east (Figures 8 and 9).



**Figure 8.** Regional seismic line in W-E direction showing SM3 Depositional Sequence.

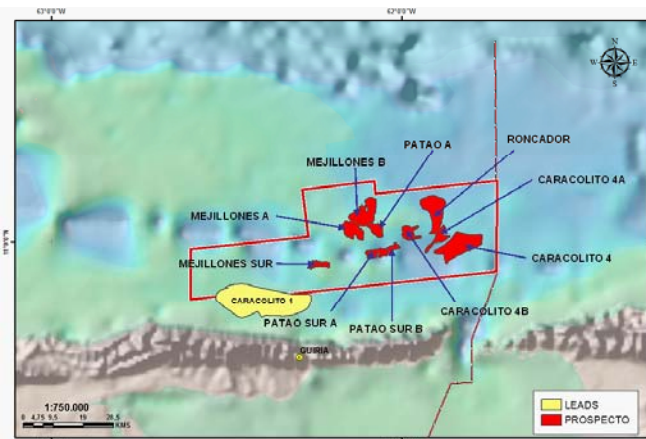
#### Pleistocene Sequence SPP

This sequence is defined at its base by the SU-4 and at the top by the SU-5. This sequence is characterized deformation and tilting of the Caracolito sub-basin towards the southeast of the Carupano Basin. At this time period, the area occupied by the basin became part of an extensive shallow shelf that characterizes the entire offshore region of the NE (Figure 9).



**Figure 9.** Regional Seismic Line in W-E direction showing SM3 Depositional Sequence.

The results obtained from tectono-stratigraphic interpretation were applied in a multidisciplinary study for the technical and economic assessment of the area. Ten opportunities were identified: eight within SM3 and two in the SM2/SM1 sequence. It is noteworthy that the latter two represent a border exploration target (Figure 10).



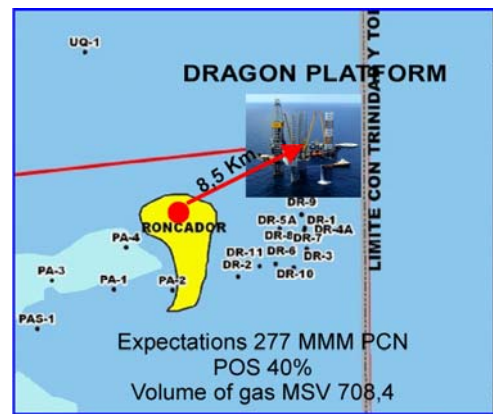
**Figure 10.** Map showing the ten opportunities in the Patao High.

The economic analysis of these opportunities has shown that the Patao High contains the largest hydrocarbon exploration potential (Figure 11), named "Roncador", having a 708.4 MMMPCG volume (MVS) with an associated probability of success of 40%. This opportunity is characterized by a stratigraphic trap associated with a westward wedging and lateral facies change at the Early-Middle Miocene (SM2/SM1) level.

The economic evaluation of Roncador prospect was developed with the methodology and assumptions proposed in the Guidelines for Economic Evaluation of Capital Investment Projects (LEEPIC) 2014, specifically developed for exploration and exploitation of non-associated gas.

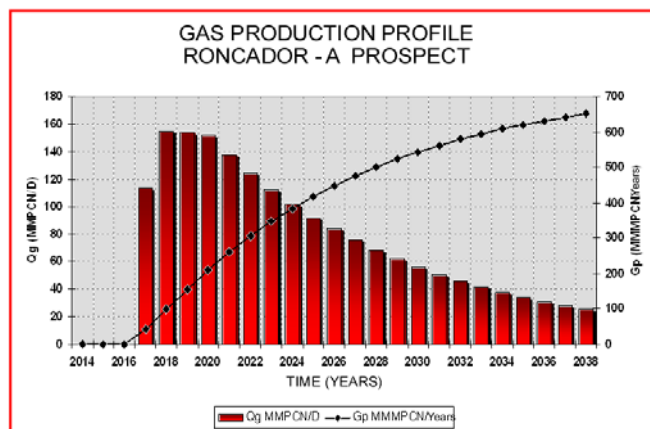
In order to optimize the investment, a conceptual scheme was developed that considers the exploitation of leaflets, grouped

according to their production potential, the distance between them, and the distance to the place of delivery.



**Figure 11.** Map showing the location of the Roncador opportunity and considerations for economic evaluation.

The profile of the potential initial gas production (Figure 12) is supposed to be in the order of 60 MMPCND considering a production time of 22 years and an annual decline of 10%.



**Figure 12.** Profile of the potential gas production from Roncador prospect.

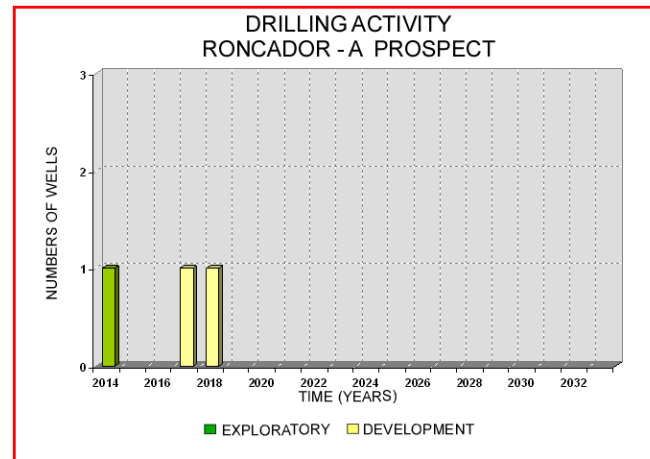
The proposed production scheme includes drilling of three production wells (one for exploration and two for development, Figure 13). The proposed investment for the development of the opportunity is in the order of 285 MM \$, a present neto value of 137,83 MM\$, and a payment time of 7 years.

### 7. Conclusiones.

Four tectonosequences were defined:

- Sequence SM1/SM2 is characterized by incised-valley fill deposits at the top of the paleo-structure. This sequence was deposited during Early Miocene to Mid Miocene and is related to basement uplift, transpression, and subsidence of the basin.

- Sequence SM3 is the most important in terms of hydrocarbon content because it contains the main reservoirs. It is defined as a condensed section deposited in the Late Miocene. In addition, the reactivation of the basement uplift was the most significant regional tectonic event affecting the formation of SM3.



**Figure 13.** Profile of drilling activity for the development of Roncador

- The provenance of sequence SPL sediments (Pliocene) suggests two uplifted areas in the Carupano Basin. The depocenter was located in the NW of the Patao High.

- The architecture of the SPP Sequence (Pleistocene) and the overlying recent sediments confirm that the depocenter is currently located in the NE area of the Patao High.

- Ten opportunities were identified in the area with new volumetric estimated reserves of 2,8 TCF. Eight of these opportunities are related to SM3 and the other two to SM1/SM2.

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