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Improving Reserves and Production Using a CO_2 Fluid Model in El Trapial Field, Argentina

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Abstract

The El Trapial field is a 1.2 B bbl OOIP asset located onshore in Argentina, South America. The field was discovered in 1991. Water injection started in 1993 with current infill drilling and development of some areas still taking place. This field consists of several sandstone reservoirs with average permeability and porosity of 75 mD and 17% respectively. One unique challenge of El Trapial field is that the light oil coexist with gas that contains high CO_2 concentrations, greater than 75%. This is observed in both dissolved gas and in gas caps in various blocks of the field. Well documented production data have indicated variations in CO_2 concentration in different areas of the field. Conventional fluid modeling could not explain the formation of gas caps at dissimilar structural positions, nor could it explain the existence of oil legs at pressures below the apparent (predicted) bubble point pressure.

A fluid characterization model was performed in the El Trapial field in order to improve the understanding of the PVT behavior at reservoir conditions in the presence of the original high content of CO_2. An empirical model was created using the assumption that thermodynamic equilibrium was reached before the time of exploitation. This model shows that the bubble point pressure can increase with depth when light oil coexists with high concentrations of CO_2, showing an opposite behavior to what is observed when the gas phase is mostly hydrocarbons. Sensitivity analysis was conducted to identify the key variables that impact this distinctive behavior.

The developed model improved the understanding of the areal and vertical distribution of CO_2 in El Trapial. It was used to redesign the development strategy of an area of the field, taking advantage of the oil production at shallow structural depths previously identified as potential free gas zones. Also, the production strategy of the entire field in terms of surface CO_2 handling, corrosion prevention and production optimization was revised. This paper illustrates the characterization of this unique behavior, including modeling, application and results.

This proposed model can be applied to other reservoirs where CO_2 is present. A methodical approach is presented including laboratory tests, field surveillance and monitoring needs as well as resulting development improvements.

Introduction

The production of oil with content of CO_2 above 60% is a common pattern in many onshore fields of the Neuquen Basin in Argentina, South America. This high concentration of CO_2 is present in the formation gas as dissolved gas and as a gas cap and is not caused by gas injection.

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One unique challenge of El Trapial field is that the light oil coexists with a gas that contains high concentration of CO_2.

Conventional fluid modeling could not explain the formation of gas caps at dissimilar structural positions, nor could it explain the existence of oil legs at pressures below the apparent bubble point pressure.

Field Description

The El Trapial field is a 1.2 B bbl OOIP asset located onshore in the Neuquen Basin in the north of Neuquen Province of Argentina, South America. The field is part of one of the most productive zone in Argentina and is nearby several existing fields, including Chihuido de la Sierra Negra and Puesto Hernandez.

The field was discovered in May of 1991 and the discovery well was ChT.x-1. The PVT study performed in this discovery well is shown in Table 1. Peripherical water injection commenced in 1993 with current infill drilling and development of some areas still taking place. This field consists of several sandstone reservoirs of Lower Troncoso and Upper Agrio formations as well as Avile member with an average permeability and porosity of 75 mD and 17% respectively. Current oil field production is above 40,000 bbls/day with a water cut of 80%, total gas oil ratio (GOR) of

450 scf/bbl and an average content of CO_2 in the produce gas of 75%.

After an aggressive delineation campaign in 1993 two gas caps were found in different areas of the field in the main sand of Troncoso reservoir (Figure 1). The difference found of 40 meters (130 feet) between gas oil contacts (GOC) suggests an anomaly from a regular gas-oil model. A new delineation campaign was conducted in 1998 and because of it, a new gas cap was found in the North block of the field. The new GOC has a big discrepancy when compared with the ones found on previous campaigns. The difference found was around 300 meters (985 feet) as is shown in Figure2.

Study Objectives

A fluid characterization model was performed in the El Trapial field in order to improve the understanding of the PVT behavior at reservoir conditions in the presence of the original high content of CO_2.

The main identified drivers for the present study were:

- Build a consistent database of reservoir and produced fluid properties integrating all the available studies during the life of the field.
- Define reasonable limits to compositional variations throughout the entire field extension.
- Improve the understanding of the areal and vertical distribution of CO_2 to redesign the development strategy at shallow structural depths previously identified as potential free gas zones.
- Revise the production strategy in terms of surface CO_2 handling, corrosion prevention and production at a field scale.
- Focus the study in the main sand of Troncoso formation. (where 60% of the OOIP exists)

Model Fundamentals and Considerations

In order to make an interpretative model, the following assumptions were made:

- The reservoir achieves thermodynamic equilibrium previously to the beginning of exploitation.
- Available data have a good quality and are representative.

Hydrostatic Equilibrium

Fluid Heterogeneity. Hydrocarbons at reservoir conditions usually vary their composition both vertically and areally as mentioned in other industry publications. Theses variations are identified in the produced fluids. Main changes are exposed in the oil viscosity, CO_2 concentration, GOR and oil density.

Equilibrium Condition. When a fluid column under vertical communication exists in a reservoir at thermodynamic equilibrium, the composition accommodates to maintain a constant fluid density or an increasing monotonically density with depth.

The explanation of this equilibrium scenario can be made considering the relationship of density with pressure, temperature and composition.

If we consider a homogeneous fluid without neither pressure nor temperature gradient effects the system can be describe as in Figure 3 where the plain gray color indicates a uniform composition in the fluid column and the constant wide represent no chances on specific volume through the entire interval.

Figure 4 represent the influence of ordinary temperature and pressure gradients on the figure 3 analysis. Those gradients have an opposite effect on the specific volume but temperature gradient usually has a greater influence. That situation affects the density of the system building a gradient from high to low density when you move from the top to the bottom of the column.

This new condition that can be described as non-equilibrium produces convection streams like the ones shown on Figure 5. The necessary energy for that process is taken from the thermal gradient.

Under those conditions, the convection forces could never end unless the fluid suffers compositional changes along the fluid column. In fact, as observed in natural reservoirs, multi-component fluids tend to the equilibrium condition suffering compositional changes. Figure 6 shows that situation where the concentration of heavy components increases with depth.

Hydrocarbons and CO_2

The equilibrium situation showed on Figure 6 represents the subject of this study. The main identified components that influence density changes are:

- ***CH4:*** is the component with less density on liquid phase. It's density in a liquid phase is close to 0.3 g/cm3
- ***CO_2:*** It's density in a liquid phase is close to 0.8 g/cm3
- ***C20+ fraction:*** Those are the heaviest components of the mixtures with densities around 0.9 g/cm3.

Density of CO_2 as a liquid

When a gas component of a mixture is dissolved in a liquid phase, the component no longer is found like gas phase but in liquid phase. On that situation is it possible to designate a density for the gaseous component in a liquid phase.

That is the case recognize by Orr Jr. ands Jensen[1] when a gas with high concentration of CO_2 is in contact with light or heavy oils.

CO_2 and heavy oil

This situation was fully discussed on a recent publication. (Reference 3).

In this case, the hydrostatic equilibrium model leads to scenarios where highly sub-saturated oil coexists with an almost pure CO_2 gas cap. The explanation resides on the following reasons:

- Direct CO_2 dissolution leads to a mixture less dense than the original oil.
- Only mole to mole interchange between CO_2 and lighter oils components (Methane and Ethane) leads to a mixture more dense than the original oil.

Therefore, the CO_2 dissolution is a limited process that ends when no more light components are available for interchange. Then, as CO_2 is less volatile than methane or ethane, the resulting mixture has significant less bubble pressure than the original oil, as experimentally found in the presented case. Several experimental data, such as uniform density and the existence of methane and ethane free live oils, confirms the model predictions.

CO_2 and light oil

In this case, the density equilibrium tends to a state generated through the following sequence of conditions and events:

1. CO_2, as a gas phase, has a density lower than the light oil leading to the formation of a gas cap.
2. CO_2 is dissolved in the contact zone between the gas cap and the oil pool. The new liquid becomes rich in CO_2 and has a higher density than the column of light oil.
3. Convection stream are generated due to liquids with different, and unstable, density column (Figure 8)
4. The dissolution of CO_2 in light oil can evolve only until reaching the saturation point. After reaching that point the system accept more CO_2 only if light components are simultaneously extracted from the liquid (C1, N_2, C2).
5. The system is stabilized as function of CO_2 concentration in the complete column. The representation of that effect is the same as the one shown in figures 4 to 6. In this case, the CO_2 plays the role heavy components of the system stabilizing the density of the column by migrating to the bottom of the interval.
    - Because of this situation, it is very likely that CO_2 reach the bottom section of the structure, especially when the presence of hydrocarbon heavy component is, for some reason, decreasing.
6. The repetition of the previous points distributes the concentration of CO_2 through the entire column depending upon the hydrostatic equilibrium at any given pressure and temperature. The final state is represented in Figure 9.
7. After geologic time, the density becomes constant in the entire section and the fluids are close to the saturation point.
8. Taking on account what was expressed in previous points there are two limiting factors to increase the concentration of CO_2 with depth.
    - High concentration of heavy components with greater temperature in bottom section decreases the solubility of CO_2. Therefore, it is possible to get similar bubble pressure than in the upper levels with less CO_2 concentrations.
    - When the liquid density reaches the same density than the CO_2 as liquid. This situation can be predicted whenever the C3+ fraction has a density higher than that of CO_2 as liquid. In such cases, at some point of the C1+C2 / CO_2 interchange, the liquid density stops the convection currents.

Bubble point (Pb) and Hydrostatic Equilibrium

Pure Hydrocarbons. As mentioned before, the Pb follows the light components behavior on hydrostatic equilibrium. It decreases with increasing depths.

That situation corresponds to the analysis of figure 6. Figure 10 is a normal scheme of Pb behavior as found routinely in natural reservoirs.

Light Hydrocarbons and CO_2. Based on the thermodynamic equilibrium presented before, when the light hydrocarbons and CO_2 coexist Pb increases with depth.

Figure 11 shows the density and Pb as function of depth. The behavior of the bubble point is also well discussed by recent laboratory research[2].

The trend of Pb with depth does not necessarily have to be a straight line. The relative position of it will be depend on the previously describe variables that affect the final equilibrium.

PVT Studies

Along the production history of El Trapial field several PVT studies were performed. Main observations include:

- The Pb of the reservoir fluid is not constant. All the samples belong to more or less sub-saturated fluids.
- The CO_2 concentrations, dissolved gas and viscosity show some variations.
- The density of the fluid can be considered as a constant (within the experimental acceptable dispersion) at reservoir pressure on the entire vertical section, in coincidence with formation pressure measurements.

The last statement was taken as a strong indicator for the hydrostatic equilibrium assumption made at the beginning of this study. The PVT studies performed reported densities values from 0.79-0.80 g/cm^3 and they are supported, by several RFT pressure logs taken at original conditions. This small discrepancy falls within the expected dispersion of PVT measurements. In addition, the tests were performed at different laboratories and dates.

Data Integration with Conceptual Model

In brief, the proposed model was developed according to the following assumptions and experimental points:

- Original oil composition has null o negligible concentration of CO_2 in the mixture.
- The contact of the oil with a gas with a high concentration of CO_2 occurs at some point in geologic history. There is no difference, for the model concerning which fluid (CO_2 or oil) was first in placed.
- Subsequence equilibrium follows the path described for CO_2 and light oil.
- The system was on hydrostatic equilibrium and constant density before the field was discovered.

In order to replicate and to get a numerical description of the events it is necessary to get an estimation of the original oil composition using the existing PVT data base.

Original PVT

Original Pb: Certainty of this value could not be accurately achieved. The necessary assumption is that pressure and temperature at any given depth, were the same as the one currently observed.

The selected values were 120°F (50°C) and 570 psi (40 kg/cm2) for temperature and pressure respectively. Those values are close enough compared to the ones recently measured on the top of Troncoso formation.

Original Oil Composition A thermodynamic simulator, based on equilibrium constants, was used to get a reasonable approximation of original fluids composition beginning with the actual known fluids composition and making the necessary assumptions.

Thermodynamic Simulator Calibration. The first step was to adjust the simulator to reproduce the main values of the experimental PVT studies. Figure 12 & 13 compare measured against simulated values of FVF and density respectively. Both plots demonstrate the excellent match achieved with the simulator.

Initial Composition and properties of the original oil without CO_2. After the simulator was satisfactory adjusted, the next step was to eliminate CO_2 from the reported composition. Then the content of C1 was increased until Pb of 570psi at 120°F was achieved.

The density of the resulting oil at these conditions was 0.785 g/cm^3.

Original oil with CO_2. The following step was to simulate a contact between the previous oil with CO_2 (100%). The border condition was the laboratory measured density already documented (0.80 g/cm3).

As an example of the sensitivity of the proposed methodology, using the same equilibrium and border conditions, it is possible to change the density of the C20+ from 0.912 to 0.902 g/cm3 and as a result of that the CO_2/C1 ratio varies from 2:1 to 4:1.

If the quantity of C20+ was changed instead of changing the density, similar results were observed. These circumstances indicate that at the same equilibrium and border conditions the quality of the heavy fraction has similar impact than the quantity of it on the original mixture.

Additional equilibriums of light oil and CO_2. If the situation described in the last section was the only one ruling the compositional distribution along the entire oil column, the CO_2 concentration could increase far from the GOC until achieved saturation pressure along the oil leg. This saturation state was not reported on the PVT studies and was not observed on the presented model.

Two main drivers could be identified to prevent the additional dissolution of CO_2 in the entire column:

- The column is not in equilibrium.
- The additional dissolution of CO_2 makes no change in the system density. As a result of that, the convection streams are not generated.

The first driver is mentioned only as a general rule since this could be the situation in other field studies. In the present study non-equilibrium was initially discarded and is very hard to assume once uniform density was experimentally confirmed.

This situation strongly supports the second driver.

CO_2/C1 Interchange. As a consequence of the previous considerations, a main question to answer is why the light oil does not complete the CO_2/C1 interchange.

At final equilibrium with CO_2, the residual quantity of C1 (and C2) is greater in light oils than in heavy ones (Ref 3). This result could be identified as an anomaly if we consider only that the density of the fluid due to the CO_2/C1 interchange produce greater instability in light than in heavy oils. However this interchange is also a function of equilibrium parameters and CO_2, C1 concentration in both phases.

As mentioned before, the liquid phase near the contact with a gas rich in CO_2 (figure 8) has a high concentration of CO_2 due to direct dissolution (without C1+C2 interchange). Under that scenario the thermodynamic forces do not “obligate” (as in heavy oil scenarios) the interchange as a previous step for the generation of convection conditions.

C1 – C20+ Ratio. In order to maintain a constant density value along the oil column, the quantity of light components must be compensated by the heavy ones. Since the mid density of fluid column in equilibrium gets stabilization in a density value close to the CO_2 density as a liquid, the most significant components in both extremes are C1 for light ones and C20+ for heavy components.

Figure 14 illustrates different cases with a constant density.

It also shows how C1 and C20+ must play an important role to maintain the equilibrium around the constant density value.

Field Validation

Through the production history of El Trapial Field, areal variation of CO_2 content in the produced gas has been reported but without a detailed support that explains the reasons. These differences are more notorious when comparing wells located close to the GOC with the ones that are down dip in the structure (close to the OWC)

The production of El Trapial is on commingling stream and therefore, it is not possible to analyze the variation of CO_2 on the produced gas for the main Troncoso layer at a field scale. The mentioned analysis was performed on the east block of the field where most of the wells have been completed only in the layer analyzed in the present study.

Chromatography tests of the produced gas were analyzed in those wells observing that the CO_2 content of the gaseous fraction has an increase tendency from 60% to 70%, with some fluctuation. The data evaluated covers the history range between 1996 and 2006. A small fraction of the increment found in this block is understandable by the increase of the water cut on the same period of time, since the CO_2 is also soluble in water.

This effect and the continuous development of wells close to the GOC are the main contributions to the increment of CO_2

content at field level. Those wells provide more quantity of gas and more concentration of CO_2 due to the proximity to the gas cap. The last statement is on agreement with field data and the present model.

Field Application

The developed model improved the understanding of the areal and vertical distribution of CO_2 in El Trapial. It was used to redesign the development strategy of an area of the field, taking advantage of the oil production at shallow structural depths previously identified as potential free gas zones.

In 2005 a new development strategy was implemented on the North Block of El Trapial field. A gas cap was identified on the block during the delineation phase. The good production history with an incomplete waterflood strategy made the area an interesting target for new prospects.

Due to the average low pressure of the block, around 200 psi below of the initially assumed Pb, the block was not incorporated in the previous development plans of the field.

The present study was used as a key component to mitigate the risk and to narrow the uncertainty ranges in order to re-rank the project into the development portfolio. Being this block re-ranked to the first place.

The project development execution consisted in drilling 14 wells into the block. Four of them were injectors and the remaining ten were completed as producers. In order to complete the waterflood project of the block on a pattern basis, 3 wells were additionally converted to injectors.

Figure 15 consist of the production curves of the block showing the incremental oil production and consequently an increment of the proved reserves.

Conclusions

After a detailed and well documented study of the equilibrium variable that rules the relation between a gas cap with high concentration of CO_2 in contact with a light oil column, the following conclusions were drawn:

- The areal and vertical variation of the concentration of CO_2 in the produced gas can be explained in El Trapial field as a function of the composition of the oil and the equilibrium constants.
- The concentration of CO_2 along the oil column is intimately related to the properties of the heavy fraction.
- The bubble pressure increases with depth in a CO_2 - light oil system and depends on the content of C1, CO_2 and C20+ and the equilibrium constants. This is a very different behavior than that found in conventional reservoirs where Pb decreases when depth increases.
- The CO_2 begins the dissolution in light oil in the zone next to GOC and later equilibrium steps leads to a final stable column.
- The proposed model can be applied to other reservoirs and fields where CO_2 is present as free gas or with high concentrations of it.

Acknowledgments

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Nomenclature

GOC = *Gas Oil Contact*
OWC = *Oil Water Contact*
Pb = *Bubble Pressure, psi*
GOR = *Gas/Oil Ratio, scf/bbl*
OOIP = *Original Oil in Place, bbl*

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Table

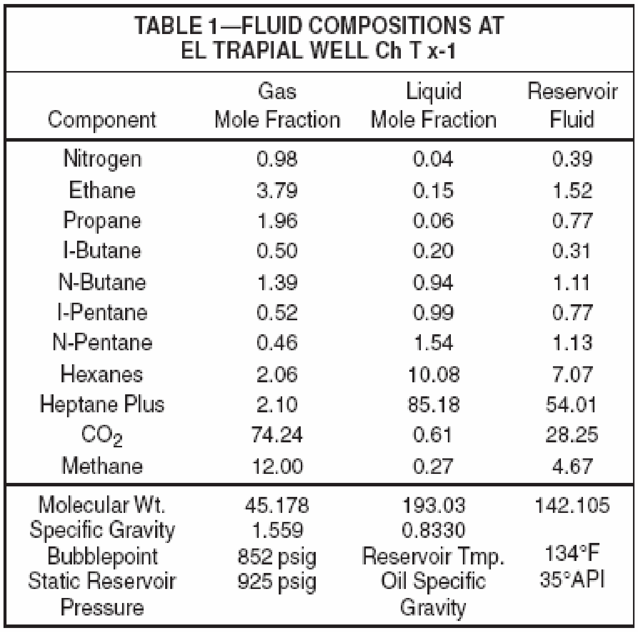

TABLE 1—FLUID COMPOSITIONS AT EL TRAPIAL WELL Ch T x-1

Component	Gas Mole Fraction	Liquid Mole Fraction	Reservoir Fluid
Nitrogen	0.98	0.04	0.39
Ethane	3.79	0.15	1.52
Propane	1.96	0.06	0.77
I-Butane	0.50	0.20	0.31
N-Butane	1.39	0.94	1.11
I-Pentane	0.52	0.99	0.77
N-Pentane	0.46	1.54	1.13
Hexanes	2.06	10.08	7.07
Heptane Plus	2.10	85.18	54.01
CO_2	74.24	0.61	28.25
Methane	12.00	0.27	4.67
Molecular Wt.	45.178	193.03	142.105
Specific Gravity	1.559	0.8330	
Bubblepoint	852 psig	Reservoir Tmp.	134°F
Static Reservoir Pressure	925 psig	Oil Specific Gravity	35°API

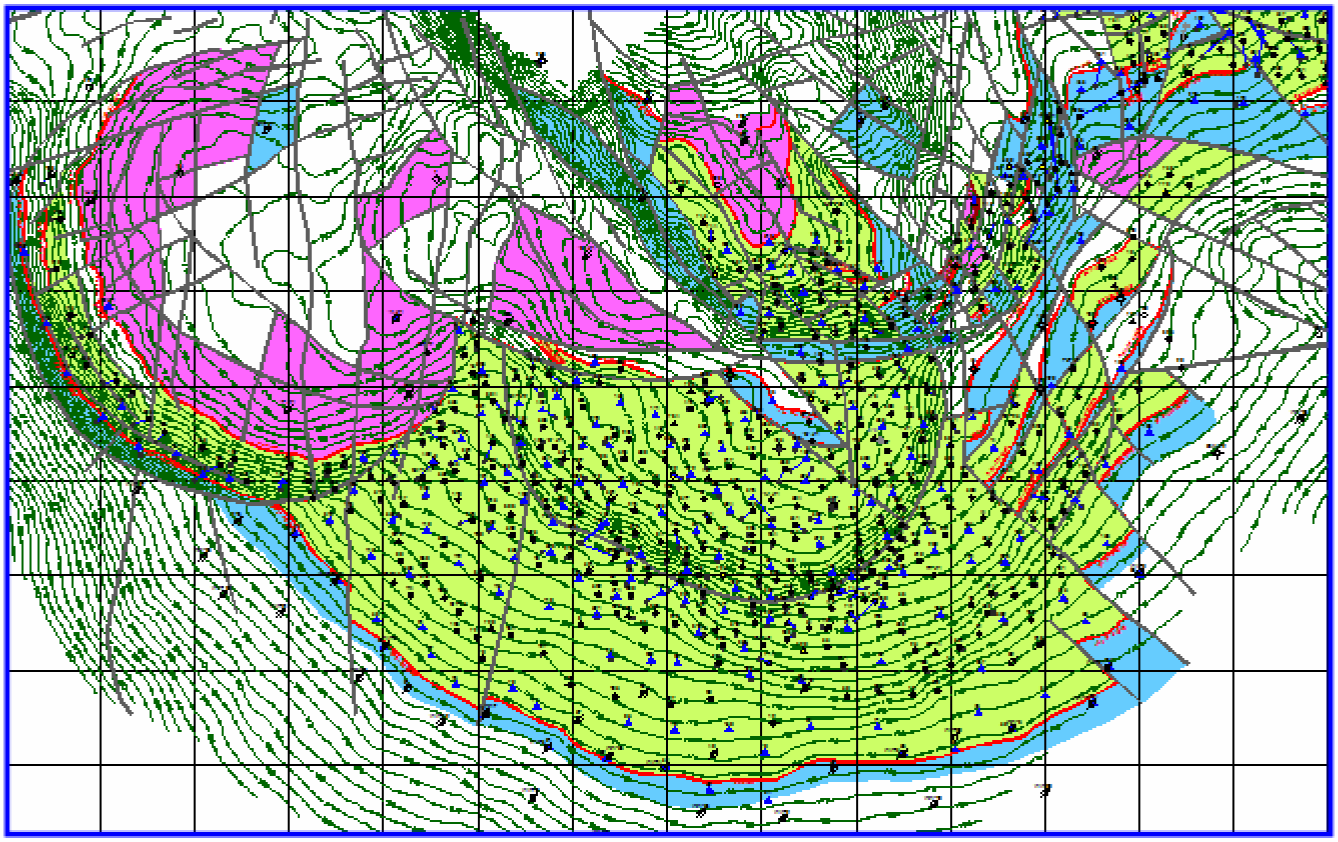

Figure 1: El Trapial Field structure map and fluid distribution. In purple are the identified main gas caps.

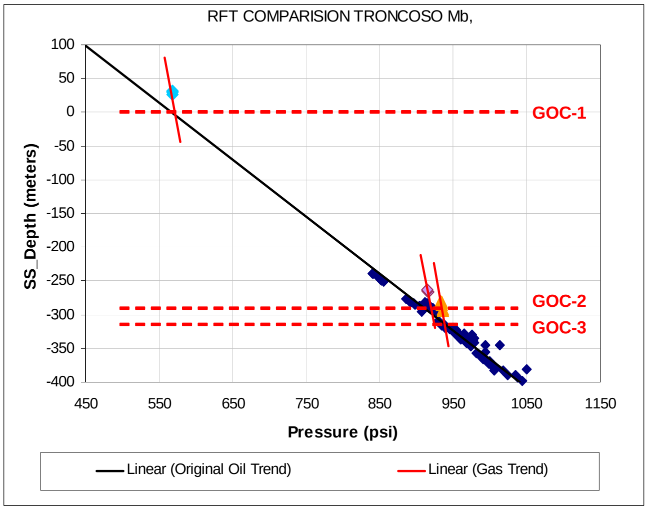

Figure 2: RFT data showing different GOCs found in the field.

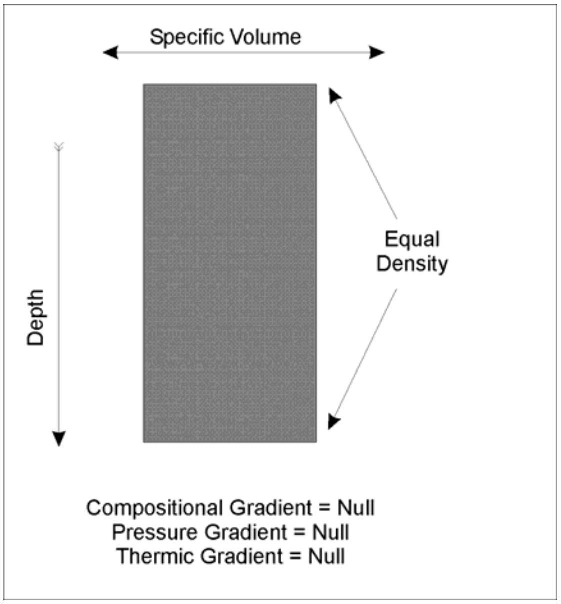

Figure 3: Homogeneous fluid without pressure and temperature gradient.

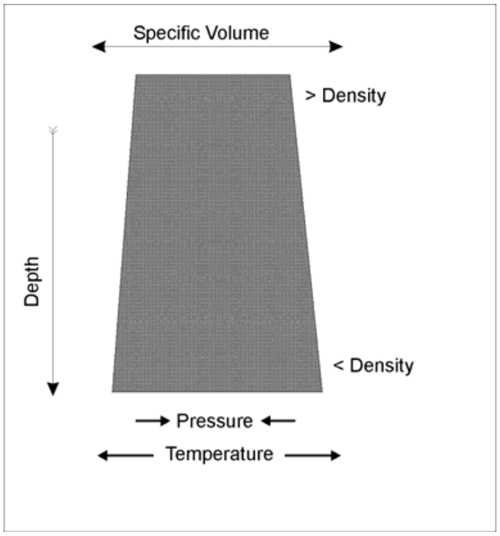

Figure 4: Homogeneous fluid with pressure and temperature gradient.

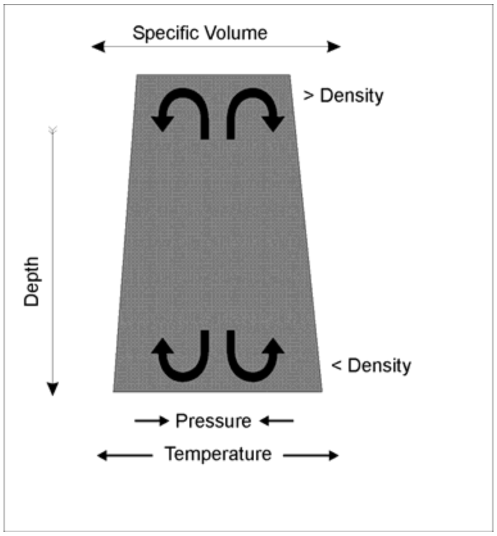

Figure 5: Convection streams in a column of homogeneous fluid

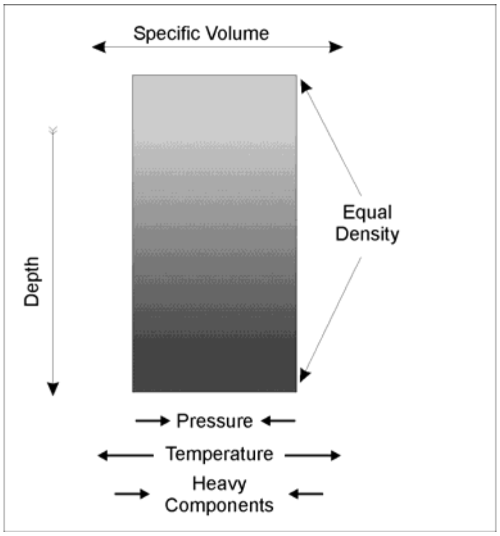

Figure 6: Compositional changes leads to homogeneous density through the entire column.

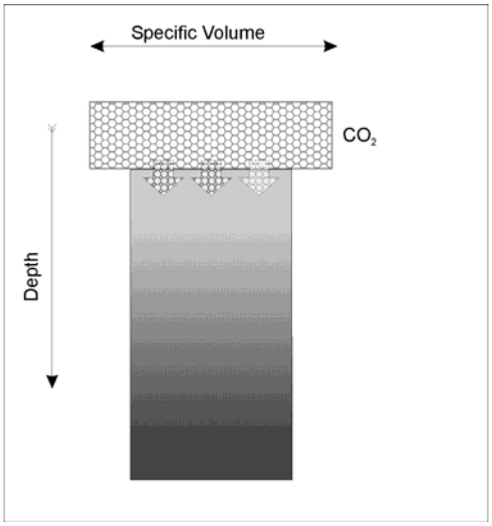

Figure 7: CO_2 as gas has less density than the oil. That condition support an initial Gas cap with high content of CO_2

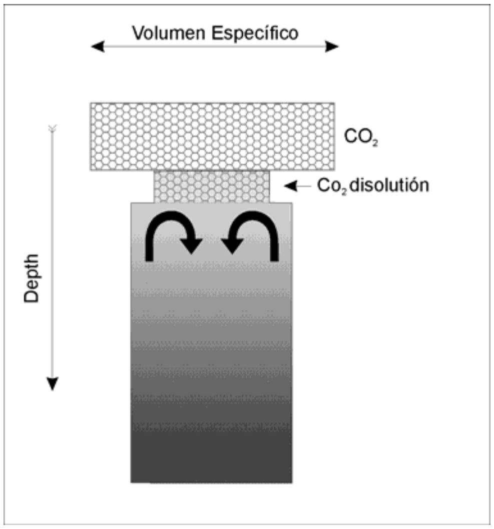

Figure 8: CO_2 is distributed in the entire column achieving hydrostatic equilibrium.

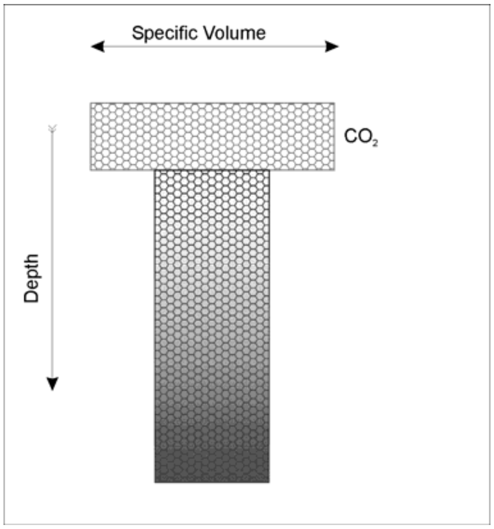

Figure 9: Final hydrostatic equilibrium

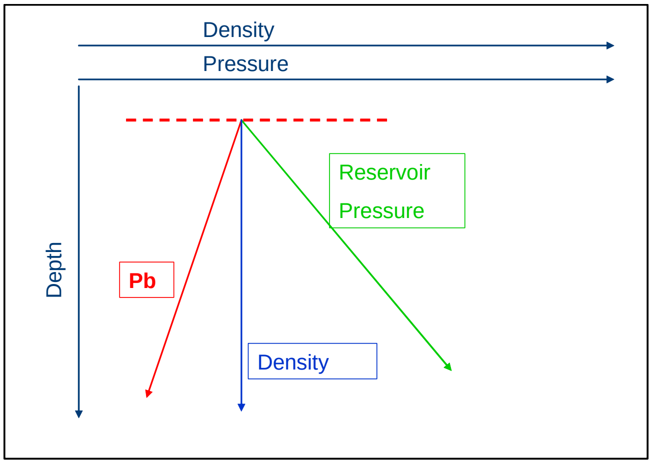

Figure 10: Reservoir pressure and Pb behavior of an oil column below a Hydrocarbon Gas cap on hydrostatic equilibrium.

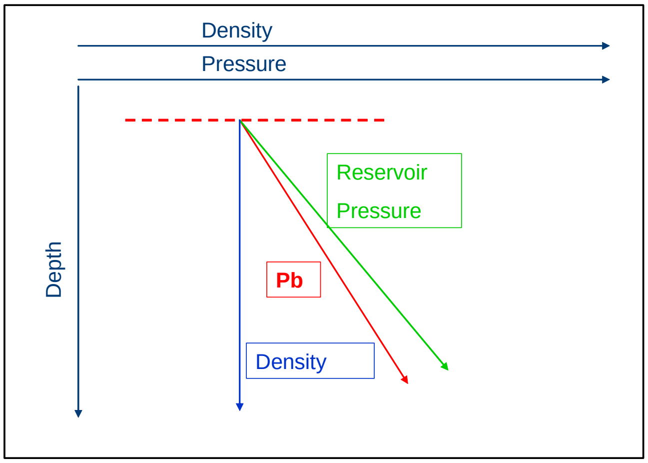

Figure 11: Reservoir pressure and Pb behavior of a light oil column below a CO_2 Gas cap on hydrostatic equilibrium.

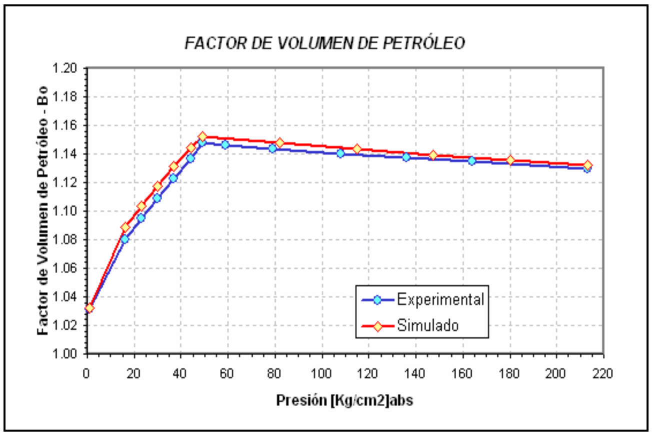

Figure 12: Fluid volume Factor experimental vs. simulated.

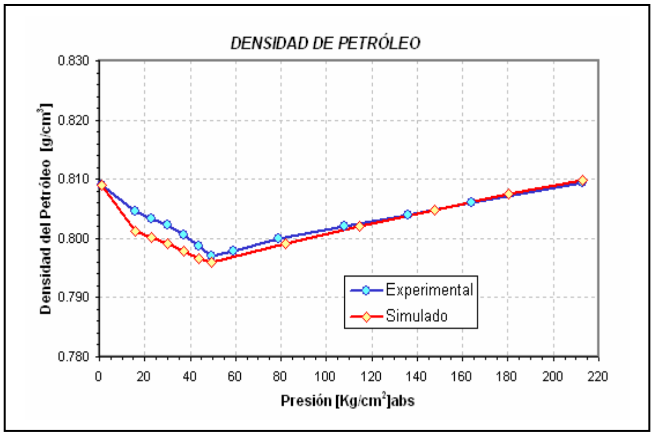

Figure 13: Oil density (g/cm3) experimental vs. simulated.

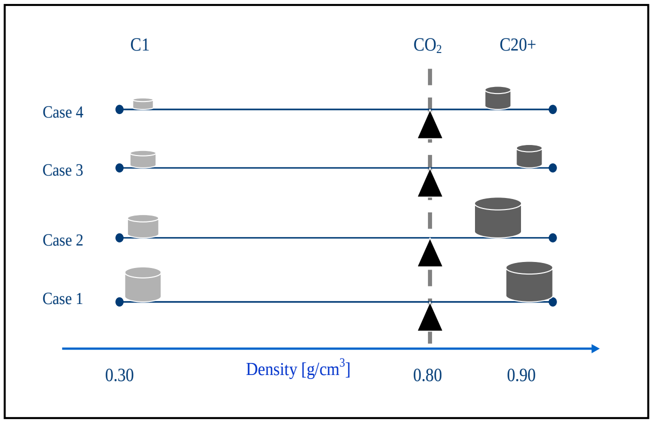

Figure 14: Relative proportions of C1 and C20+ to obtain a mean density equal to that of CO_2 when dissolved in the oil phase.

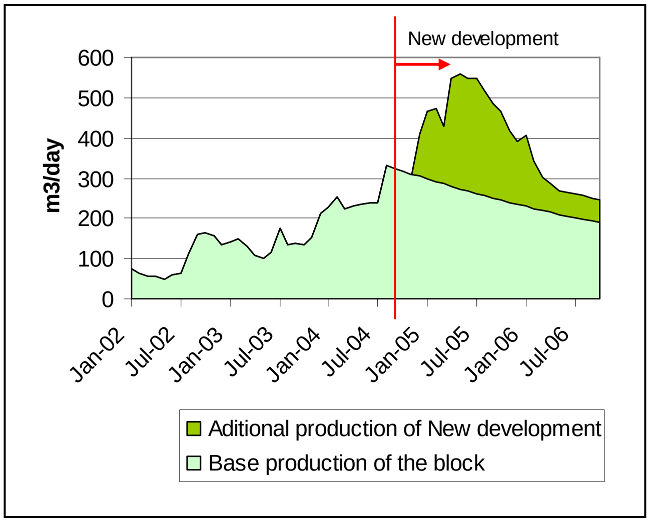

Figure 15: Impact on production of the block after aggressive perforation of 10 producers, 4 injectors and 3 injector conversions.