

# HEAVY OIL-CO<sub>2</sub> SCENARIOS: NUMERICAL MODELLING OF STRUCTURES WITH GAS CAPS AND SUB-SATURATED OIL

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## Summary

Oil reservoirs containing significant amounts of CO<sub>2</sub> usually translate into scenarios with high compositional complexity. This complexity is manifested not only in strong areal and vertical compositional changes, but also in behaviours that deviate from what is usually called “thermodynamic equilibrium”.

Using a compositional reservoir simulator, we analyse in this work a scenario already documented in previous studies, where a CO<sub>2</sub> cap coexists with a heavy sub-saturated oil. We numerically show that the equilibrium state, for geological events time-lengths, does not correspond to a complete mixture of the components of the system, but to the exchange of the different components until a column of equilibrated densities is reached.

For high density oils in equilibrium with an excess of CO<sub>2</sub>, this situation may correspond to stable systems characterized by a strong sub-saturation.

In this work we analyse the dependence of the final composition distribution on the initial composition and the equilibrium time.

This development illustrates the methodology to be used to generate a fluid model compatible with an apparently non-equilibrium initial situation.

## Introduction

A study on the characterization of a similar scenario to the present work was presented by Crotti et al. [1], where, in order to justify the sub-saturation of the heavy oil in contact with the CO<sub>2</sub> cap, three main hypotheses were introduced:

1. Since usually CO<sub>2</sub> has an origin and a migratory path independent on hydrocarbons, both fluids enter the reservoir at different times and locations. As a consequence, a mixing mechanism should exist such that both fluids, sharing the same structure, reach their thermodynamic equilibrium.
2. This thermodynamic equilibrium is not reached by complete mixing (the equivalent of mechanical mixing in a laboratory cell), but by component exchange and convection currents until a column of equilibrated densities is reached.
3. The component exchange which maximizes convection currents is that of a molar 1:1 CO<sub>2</sub> for methane at the GOC. This hypothesis was rooted in the fact that direct dissolution of CO<sub>2</sub> within the oil results in a lesser dense fluid, thus precluding post-dissolution convection.

Even though these hypotheses allowed the validation of the representativeness of three independent PVT studies characterized by a strong sub-saturation, and improved the estimation of reserves and production, the third hypothesis was not rooted in any direct experiment or calculation.

This work is precisely aimed to confirm whether the third hypothesis is valid or not, with the aid of a compositional reservoir simulator to analyse the time-evolution of the CO<sub>2</sub>-heavy oil equilibrium, starting from a situation compatible with the first two hypotheses.

We represented this scenario with only three components (C<sub>1</sub>, CO<sub>2</sub>, C<sub>20+</sub>), where the C<sub>20+</sub> component represents the heavy fraction of the fluid, which is essentially non-volatile and has a much higher density than CO<sub>2</sub> when dissolved in the mixture.

The trap was modelled as a vertical structure with very high permeability in all directions and a source of CO<sub>2</sub> at the top, very large compared to the initial amount of oil in the system.

The equilibrium state was obtained after letting the isolated system evolve until no significant compositional changes were observed within the structure.

The variables considered were the initial oil composition and the simulation time.

## Methodology and Results

The geometry of the system was defined by a T-shape grid (Figure 1), where regions **I** and **IIa** consist of 10x1x20 cells, and the **IIb** region of 10x1x50 cells (each cell has 1x1x1 m<sup>3</sup>). Region **II** has a porosity of 0.3, and region **I** of 100.0 (this region serves as a buffer of CO<sub>2</sub> to avoid an unrealistic pressure drop throughout the simulation; a porosity of 100.0 is equivalent as having a large reservoir of fluid, thus circumventing the need of injecting CO<sub>2</sub> to maintain pressure). The isotropic permeability was 2000 mD.

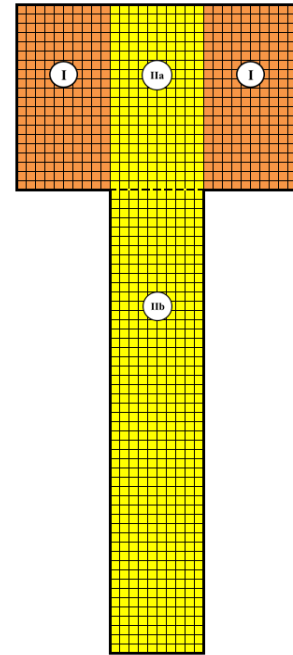
After several different runs, changing initial conditions, the one selected to illustrate the mechanism and the conclusions we arrived is the following: The GOC was assigned a pressure of 70 Barsa, and the simulation temperature was 60 °C. Initially, regions **I** and **IIa** were saturated with CO<sub>2</sub>, and **IIb** with a mixture of C<sub>1</sub>/C<sub>20+</sub> of different concentrations: 30/70%, 20/80% and 10/90% (hereafter, the initial GOC depth will be referred as 20m, and the bottom of the grid as 70m). The simulations were performed using a compositional simulator for ~12 million days (~33000 years) (cf. Appendix for a justification of this simulation time).

The final concentrations for each mixture at the bottom of the grid are shown in Table 1. It should be noted that the 90/10 system shows no change throughout the simulation between the bottom and 30 m above. The time evolution of concentrations are depicted in Figs. 2 and 3, for the 30/70 and the 20/80 initial concentrations, respectively. As it can be seen, the simulations show an adequate convergence.

In view of the results thus obtained, it is straightforward to verify that the hypothesis regarding the molar 1:1 exchange between C<sub>1</sub> and CO<sub>2</sub> (used in Ref. [1]) is not valid to describe these scenarios: in the case of an initial 10/90 C<sub>1</sub>/C<sub>20+</sub> mixture, basically no CO<sub>2</sub> is incorporated into the oil column (see Table 1), although within the cells close to the GOC, a saturated fluid with 51.6% of CO<sub>2</sub> and 48.4% of C<sub>20+</sub> is observed. Notice that this is also the final composition of the initial mixture 30/70, and it will be always the final composition of a saturated or near-saturated fluid whenever all C<sub>1</sub> is extracted from the system at 60 °C, regardless the initial composition. Notice also that the saturation pressure of the fluid corresponding to an initial 20/80 composition, which has a final small amount of C<sub>1</sub>, is ~60 Barsa, around 10 Barsa below the reservoir pressure.

As stated in 2003 [1], the loss of C<sub>1</sub> and the associated incorporation of CO<sub>2</sub> to the original mixture, due to liquid-vapor equilibria, results in a denser fluid than the original oil. But the simultaneous incorporation of CO<sub>2</sub> by direct dissolution results in a lighter fluid, below the density of the original oil, thus preventing the generation of convection currents. In other words, convection can only be present when C<sub>1</sub> removal has a larger impact on density than CO<sub>2</sub> incorporation. However, the balance between both processes is a function of temperature and pressure, and thus each scenario should be solved on a case-by-case basis.

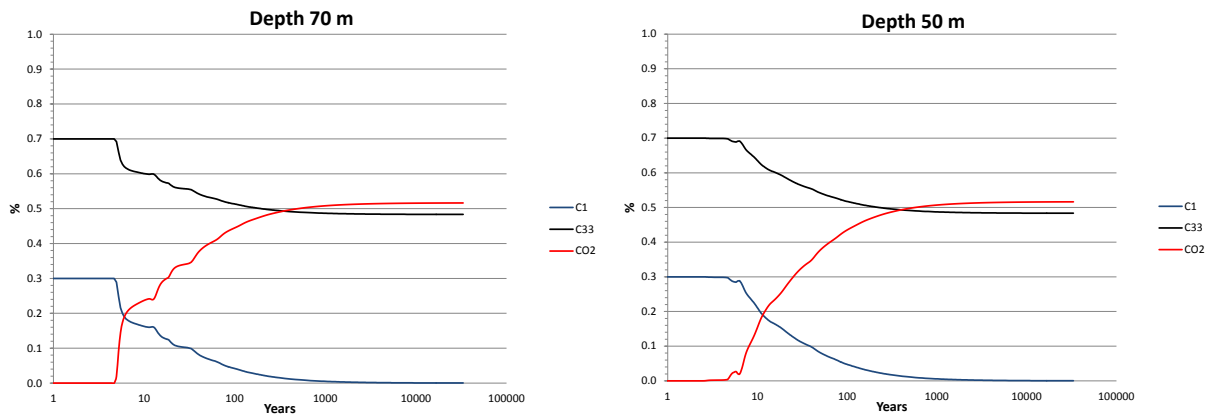
On the other hand, the hypothesis that brings to a halt of compositional changes after the generation of a stable density column, can be considered as probed. It is so even in the case where the process leads to the coexistence of an undersaturated fluid below a remaining gas cap. In this case must be noted that the degree of subsaturation, far from the GOC, depends on the original mixture composition. This condition would allow the reconstruction of the original hydrocarbon composition through an inverse analysis.



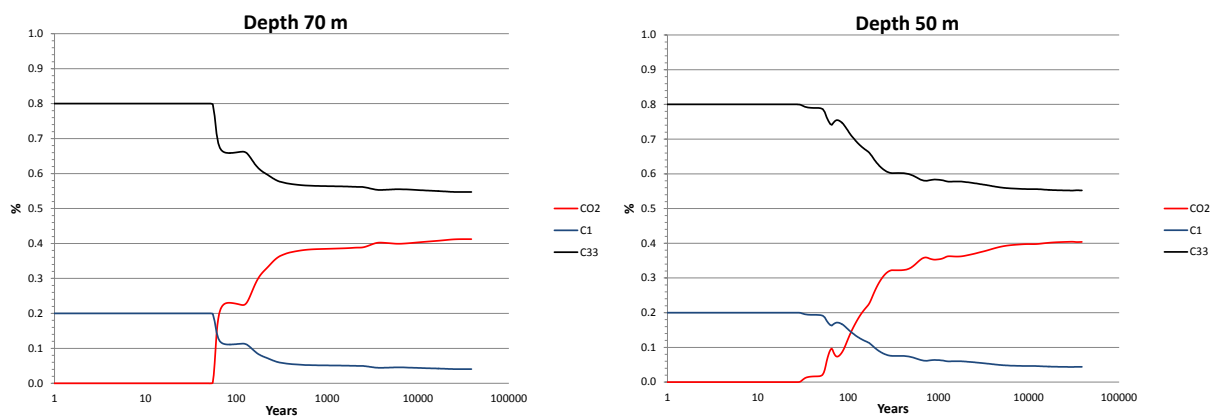
**Figure 1:** Geometry of the grid

**Table 1:** Final concentrations at the bottom of the grid for the three oil mixtures considered

Mixture (C <sub>1</sub> /C <sub>20+</sub> )	CO <sub>2</sub>	C <sub>1</sub>	C <sub>20+</sub>
30/70	0.516	0.000	0.484
20/80	0.412	0.041	0.547
10/90	0.000	0.100	0.900



**Figure 2:** Time evolution of the component concentration for the initial 30/70  $C_1/C_{20+}$  mixture



**Figure 3:** Time evolution of the component concentration for the initial 20/80  $C_1/C_{20+}$  mixture

The analysis of these results lead us to identify the following steps during the period when the density equilibrium occurs:

- The degree of removal of  $C_1$  and incorporation of  $CO_2$  in the GOC, depends on the mixture equilibrium constants and the system pressure and temperature.
- The  $CO_2$  disseminates into the lower part of the structure only when the mixture obtained in the previous point is denser than the liquid below.
- Convection currents, while diffusing the mixture obtained in the GOC, produce intermediate mixtures between such composition and the composition remaining in the bottom of the structure.
- As a result of the above steps, the average density of the liquid column remains changing during the diffusion process.
- If, during the exchange by convection, a composition is generated whose density equals that generated in the GOC, the convection stops and the liquid column can retain part of the initial  $C_1$  content. This is the situation of the 10:90 mixture from the start and when the 20:80 mixture reaches the composition shown in Table 1.

The previous sequence leads to a final scenario in which if the total amount of  $C_1$  present in the original mixture were removed, the column would end the process attaining conditions very close to saturation. This is so because the saturated mixture in the GOC diffuses to the entire structure.

Only when some of the original  $C_1$  content remains in the final fluid, it is possible to end the process with an undersaturated column.

Using the mechanism proposed in this paper, in order to reach the stage analyzed in 2003 characterized by an almost complete lack of  $C_1$  in the oil below the GOC coupled with a marked undersaturation, we would need to assume a two-step process.

1. An initial stage with complete loss of  $C_1$ , resulting in a fluid almost saturated with  $CO_2$ . A similar case to the 30:70 scenario analyzed in this work.
2. A subsequent over-pressurization which does not allow direct dissolution of  $CO_2$  due to lower density liquids originated during this process.

However, we have no experimental evidence to confirm this hypothesis. Therefore, after discarding the “ad-hoc” 1:1  $C_1$ - $CO_2$  exchange, the authors will continue to work in the analysis of mechanisms that can lead to conditions allowing for simultaneous subsaturation and almost complete elimination of  $C_1$  during natural process

## Conclusions

The extended numerical simulation of vapor liquid equilibriums between high density oils and  $CO_2$  confirms some of the hypotheses presented in an earlier conceptual work (Crotti et al, 2003).

The simulations were performed following a vapor-liquid equilibrium mechanism at the interface which originates density currents until convection phenomena ceases. Under these conditions, the variables that control the exchange endpoint are densities and equilibrium time. Different initial compositions lead to final scenarios ranging from an almost zero  $C_1$ - $CO_2$  exchange until complete replacement of  $C_1$  by  $CO_2$  with additional dissolution of the latter.

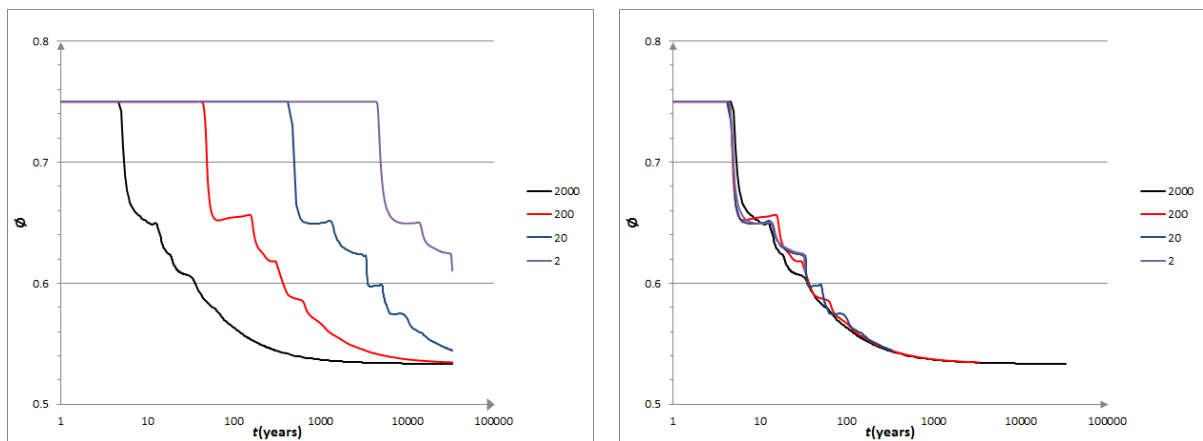
Final undersaturation is only obtained if the initial mixture is undersaturated and some part of  $C_1$  remains in the final mixture. The complete elimination of  $C_1$  leads to very near saturation conditions throughout the full oil column.

## Appendix

In Figure A1 the concentration of  $C_{20+}$  at the bottom as a function of time for the 30/70 mixture is depicted for different permeabilities [ $\emptyset(K/n, t)$ , where  $K = 2000$  mD and  $n = 1, 10, 100, 1000$  and  $\emptyset$  represents the functional dependence of composition with other variables]. From the representation of  $\emptyset(K/n, n^*t)$  (Figure A1, right panel), it is interesting to note that  $\emptyset(K/n, n^*t) \sim \text{constant}$ , and thus it can be concluded that

$$\emptyset(k, n^*t) \sim \emptyset(n^*k, t)$$

This clearly shows that performing a very long simulation ( $T = n^*t$ ) using a given permeability  $k$  is equivalent to performing a shorter simulation ( $T = t$ ) but using a scaled permeability  $n^*k$ . It can be thus concluded that our simulation using  $k = 2000$  mD for  $\sim 33000$  years corresponds in fact to simulation with a permeability in the range  $k = 2-20$  mD for 3.3-33 million years, a time-frame which can be considered as realistic.



**Figure A1:** Left panel: Concentration of  $C_{20+}$  at the bottom as a function of time for the 30/70 mixture using different permeabilities  $k$  [ $\emptyset(K/n, t)$ , where  $K = 2000$  mD;  $n = 1, 10, 100, 1000$ ]. Right panel: Normalized curves  $\emptyset(K/n, n^*t)$ .

## References

Crotti M.A., Fernández Badessich M. 2003, "Coexistencia de Petróleo Subsaturado con un Casquete de Gas - El Dióxido de Carbono en Equilibrio con Petróleos Pesados". Presentado en el II Congreso de Hidrocarburos - 2003 - IAPG - Buenos Aires - 29 de junio al 2 de julio de 2003.

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