A complex bimodal fluid gradient in a simple tilted sheet reservoir is explained and modeled by (biogenic) gas addition to an oil column

Morten Kristensen,[1] Tarek S. Mohamed,[2] Carlos Torres-Verdin,[2] Oliver C. Mullins,[1] 1. SLB, 2. UT Austin

Summary

A deepwater Gulf of Mexico reservoir exhibits a simple geologic structure of a tilted sheet reservoir, three-way seal against salt. However, the (well-connected) oil column is complex and bimodal. The top half of the oil column exhibits an enormous gradient of gas-oil ratio (GOR) of 8000 scf/bbl to 2000 scf/bbl (standard cubic feet per barrel) while the lower half of the oil column exhibits a small GOR gradient which is in "local equilibrium". In addition, the methane carbon isotope shows that there is a large increase in the fraction of methane that is biogenic towards the top in the upper half of the oil column, while the lower half of the column shows an invariant 50% solution methane that is biogenic. The asphaltene concentration is very low where solution gas is high, and shows an equilibrium gradient to appreciable values in the lower half of the column. The GOR gradient of the top half of the column has previously been shown to result from a diffusive gradient of biogenic gas into the top of the column. But the diffusive flux is nearly zero into the lower half of the column. Here, we show the simple fluid geodynamic processes that gave rise to this enigmatic bimodal distribution of GOR and biogenic solution gas. 2D reservoir simulations with different reservoir geometries are used to show the fluid properties over the course of oil and biogenic gas charges into this reservoir. The sequence of events is as follows: 1) oil charge into reservoir 2) biogenic gas charge at the oil-water contact (OWC) into an undersaturated oil resulting in increased GOR and excellent fluid mixing across the reservoir. 3) With sufficient biogenic gas charge, the reservoir oil reached saturation pressure. Continued gas charge caused formation of a gas cap. 4) Reservoir subsidence with its concomitant pressure increase led to higher saturation pressures; the gas in the gas cap then diffused into the oil column. Complex fluid columns can be understood with thermodynamic and geochemical analysis coupled with reservoir simulation of charge history.

Introduction

Reservoir charges of primary biogenic gas and oil are readily differentiated both by analysis of the methane carbon isotope and by gas composition. There has been the assumption that reservoirs that contain both fluids must have received the biogenic gas first because it is necessarily produced at reduced temperatures (<80 degC) while thermogenic hydrocarbons are produced at much higher temperatures. However, gas chimneys corresponding to seal failures of (subsided) gas reservoirs are ubiquitous and provide a means delivery biogenic gas to deep reservoirs.

Recently, a detailed analysis of the chemical composition of three classes of reservoirs establishes that biogenic gas can charge into oil reservoirs with elevated temperatures.[1] These classes included a Pliocene reservoir with very well mixed and equilibrated gas and oil charges in two stacked sands. Moreover, even though the reservoir connectivity between the sands is limited, the fraction of methane that is biogenic is invariant. 2D reservoir simulation utilizing simple rectangular reservoirs of biogenic gas charging into the lower sand at the OWC produces the observed results. Gas charge into the base of an (undersaturated) oil column induces convection and mixing to yield an invariant ratio of biogenic to thermogenic methane. A second reservoir showed gas washing at the OWC such that 90% of the methane was biogenic. Above a shale baffle in the same column, the gas washing was less at 80%. This requires biogenic gas addition at the OWC. The third reservoir is the subject of this paper.

Bimodal fluid composition in a tilted sheet sand.

This simple tilted sheet reservoir has a complex bimodal distribution of fluid properties as a function of height in the column as shown in Fig. 1.

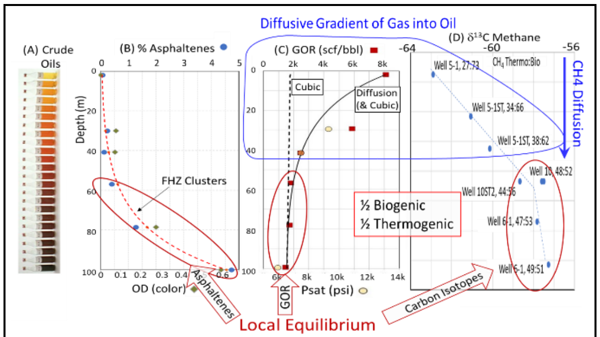

Figure 1. Complex reservoir fluid column. (A) Photos of dead oils vs height showing a huge gradient of asphaltenes. (B) Downhole color measurements (OD) and lab measurements of asphaltene content. (C) GOR and saturation pressure measurements of the oil column. (D) Methane isotope. The top half of the column exhibits a diffusive gradient of biogenic gas into oil. The bottom half of the oil column exhibits 'local equilibrium' for GOR, methane isotope and asphaltenes.

Fig. 1 shows the asphaltene gradient visually in a series of dead oil samples vs height in the column. The asphaltene content is measured downhole using optical spectroscopy; the optical density (OD) at a select wavelength of light is 'color' and is linear in asphaltene content. The lab measurement is determined by asphaltene phase separation.

The GOR and saturation pressure measurements plotted here are measured in the lab.

The measurement of methane carbon isotope is referenced against Pee Dee Belemnite in the usual way and are listed per mil (‰). More negative numbers correspond to enrichment of ^{12}C. Primary biogenic methane is characterized by -70‰ whereas thermogenic methane is roughly -40‰; calculation of fractions of methane origins are performed using these values. Variation of the endpoints is small versus the range of 30‰. Values of < -56‰ show that there is a substantial fraction of biogenic methane throughout this column. This bimodal distribution of isotope values and other fluid properties needs to be explained.

The diffusional gradient of gas into oil from the top of the column is readily understood.[2] In addition, this diffusive process has been shown repeatedly to produce asphaltene migration, often to the base of the reservoir.[3] The diffusional gradient could have resulted from an original gas charge with a subsequent undersaturated oil charge below the gas cap. The diffusive flux loading of gas into oil is highest at the top of the column and decreases asymptotically with distance into the oil column. Diffusion is a random walk process; the square of the displacement distance scales with time. Fig. 1 shows curve fitting of the large GOR gradient with the simplest solution to Fick's 2nd law of diffusion, the error function; the boundary conditions match this solution.[2] This huge GOR gradient occurs in only 40 meters of height in the column. However, the true vertical depth corresponds to sin(θ) where θ is the dip angle, but diffusion occurs in the reservoir sand so along the hypotenuse; for small dip angle, most of the diffusive distance is lateral. It is clear that the large nearly constant loading of biogenic gas in the bottom half of the column cannot occur from diffusion. It would be contrived to argue that a second, unrelated (and unclear) biogenic gas process led to this mixing. What is needed is a single process with several reasonable step to lead to the observed distributions.

Figure 2 shows a simple, four step sequence of fluid events in the reservoir that can explain the bimodal distribution of GOR and methane isotopes observed in the reservoir of Fig. 1. This is also consistent with the asphaltene distribution. Fig. 2 shows the schematics and 2D simulation results of the steps. The stacked 2D simulation results, represented in color scales, are the GOR scale on the top, oil-phase saturation in the middle and gas-phase saturation on the bottom.

Step 1 in Fig. 2 shows an oil charge of zero GOR oil. In reality, the initial oil charge contained dissolved gas but for simplicity, we assume that the initial oil charge contained no dissolved gas. In this manner, the increase of GOR above zero corresponds to addition of biogenic gas, which thus scales with GOR. Also, the bottom half (or so) of the column in the 2D simulations is water with no dissolved gas (thus blue), no oil saturation (thus blue), and no gas saturation (thus blue) in the three stacked fluid plots for each step in Fig. 2.

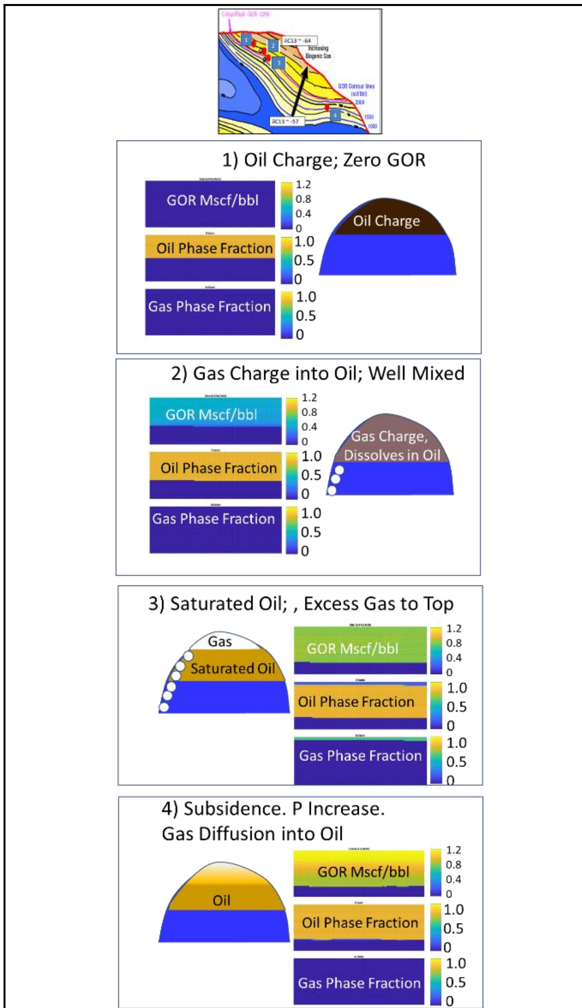

Figure 2. The tilted sheet reservoir with the bimodal distribution of fluid components (cf Fig. 1) is shown at the top of the figure. The sequence and simulations of four steps that lead to this bimodal distribution are shown and discussed in the text.

The sequence of events in Fig 2 are: Step 1) undersaturated oil charged into the reservoir. Step 2) biogenic gas charge at the left flank of the OWC leading to i) rapid gas dissolution into oil and density reduction of the oil, ii) convection and mixing of the reservoir fluid across the entire reservoir and iii) increase of solution gas and saturation pressure. The duration of the charge is 100,000 years; the results of the simulation are not sentiive to large changes in this duration unless it gets very short. Step 3) sufficient gas is added such that the oil is saturated; all further gas added remains as a separate gas phase and forms a gas cap. 4) With subsidence, the saturation pressure inceases and gas diffuses into the oil column. Here, a discrete pressure increase is assumed.

Figure 2 shows that a simple scenario coupled with simple 2D reservoir simulation accounts for the observed, present day GOR and isotope distributions. Previously, the GOR distributions were shown to account for the observed asphaltene gradients; however, at present the asphaltene processes are not incorporated into reservoir simulation. In addition, this black oil simulator does not account for equilibrated GOR gradients, but rather presumes GOR homogeneity as the final state. Incorporating equilibrium modeling along with convection in simulations is a research issue. In addition, the compositional simulator will allow light oil components to diffuse into the gas cap while allowing gas to diffuse into the oil column. This helps account for the observation today of no gas-oil phase boundary.

A question arises whether the absence of a tilt angle in the simulations in Fig. 2 substantially impacts the results in some misleading way. In addition, the aspect ratio (width to height) of the reservoir in the simulations is rather small. Both these parameters might give rise to unrealistic extents of fluid mixing due to convection induced by gas charge.

Figure 3 shows the results from 2D reservoir simulation for a tilted reservoir and with an aspect ratio of the sandstone of about 13 compared to 6 for Fig. 2. The main features evident in the fluid columns in Fig. 2 are reproduced in the simulations in the tilted reservoir in Fig. 3. The tilt of the reservoir does not alter the fundamental processes the fluids undergo such as convective mixing with gas charge. In addition, the aspect ratio is much smaller in this tilted reservoir used in the simulations compared to the reservoir in Fig 2. Nevertheless, tilt and aspect ratios are important parameters and will be tested further.

The four steps in Fig. 3 are the same as those for Fig. 2 as described above. Briefly, Step 1 is the charge of an undersaturated black oil of zero GOR. Step 2 is the addition of (biogenic) gas to the base of the oil column at the OWC. The exact point of gas entry is on the high side of the interval corresponding to fluid migration along the crest of a migration zone. Step 3 involves excess gas addition above that required to saturate the oil; this creates a gas cap. Step 4 involves subsidence, pressure increase and gas diffusion into oil. With sufficient passage of time, all separate gas phase has diffused into the oil producing a GOR gradient. Simple 2D reservoir simulation with flat and tilted reservoirs are shown to account for the bimodal distribution of reservoir fluids. History matching of reservoir charge is a powerful new method to test geologic models prior to oil production.

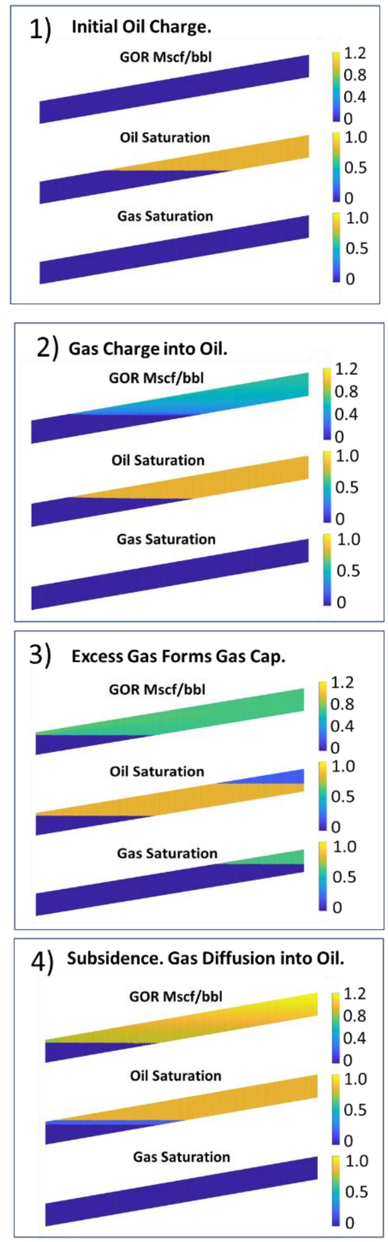

Figure 3. The sequence of events of the reservoir charge fluids that lead to results observed in Fig. 1. 2D reservoir simulations in a tilted reservoir are performed. The results here are similar to those in Fig. 2 as discussed in the text.

REFERENCES

Mullins, O. C., 2019, Reservoir fluid geodynamics and reservoir evaluation: Schlumberger.

Mullins, O. C., H. Elshahawi, L. Chen, J. C. Forsythe, S. S. Betancourt, B. Hakim, T. Messonnier, T. S. Mohamed, M. Kristensen, S. Pan, K. Wang, and C. Torres-Verdin, 2023, Compositional mixing characteristics of separate gas and oil charges into oil field reservoirs: Energy & Fuels, **37**, 7760–7776, doi: https://doi.org/10.1021/acs.energyfuels.3c00796.

Zuo, J. Y., S. Pan, K. Wang, O. C. Mullins, J. H. Harfoushian, and E. Elshahawi, 2016, Delineation of gravitational instability induced by gas charges into oil reservoirs using diffusion and Flory-Huggins-Zuo equations: Asia Pacific Oil & Gas Conference and Exhibition, SPE.

10.1190/image2023-3910817.1