



TDT monitors gas saturation in heterogeneous reservoir

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Gharib M. Hamada, Musaed N.J. Al-Awad

King Saud University

Riyadh, Saudi Arabia

Thermal decay time (TDT) logs were used for determining the gas/oil contact in wells in the Zeit Bay field in Egypt.

Gas/oil contact in the field was revised using the results from the model that was developed. This revision led to an accurate definition of the oil leg and to the drilling of three additional wells in the field.

The analysis was based on more than 70 TDT (thermal decay time) runs, open hole logs, pressure data from 12 infill wells, and production records from all Zeit Bay wells.

The analysis followed the Polyachenko model of functional relationship between count rates and gas saturation. Several crossplots were made for the same range of porosity and connate water saturation. These crossplots included:

- Formation capture cross section (SIGM)
- Total selected near detector counts (TSCN)
- Total selected far detector counts (TSCF)
- Capture cross section of the borehole (SIBH)
- Inelastic far detector counts (INFD).

Each crossplot gave a definite diagnostic shape around the depth of the gas/oil contact.

By using these crossplots, it is possible to calculate gas saturation from a stand-alone run.

The model was validated by RFT (reservoir formation tester) and open hole log data from infill wells. Also, the analysis was successfully applied in wells without an ambiguous gas/oil contact.

Zeit Bay

The Zeit Bay field has a northwest-southeast trending structure comprising clastic and carbonate rocks overlaying a tilted block of granitic basement.

The field was discovered in 1981. About 40 development wells were once active producers. A total of 25 wells remain active. Production from the field commenced in 1984 and reached about 200 million bbl, in 1996. The average field GOR started to increase by the end of 1987 ([Fig. 1 \[94,694 bytes\]](#)).

The reservoir in the Zeit Bay field is in complete hydraulic communication and has a complex drive mechanism.¹

The primary recovery mechanism is a solution gas drive supported by gas-cap expansion, gravity drainage, and aquifer support. Gas injection is optimized to a level of more than 70% of total gas production.

A secondary-recovery scheme of gas reinjection into the original gas cap was initiated to maintain reservoir energy and minimize pressure decline. Hence, accurate detection of gas movement is very critical.

In a considerable number of wells, difficulties were encountered for monitoring gas/oil contacts, and conventional methods, based on the response of gas indicator curves, led to a false indication of formation gas/oil contacts.

The gas movement in Zeit Bay field is affected by a large number of factors such as cumulative production, well location, formation dipping, fracture direction, and the degree of communication between producing and gas-injection wells.²

These factors made the determination of the gas/oil contact a difficult task without running cased hole logs and taking reliable data from these logs.

The TDT-P log run, unfortunately, in most of the high GOR wells gave an apparent response of the gas/oil contact in the shut-in pass ([Fig. 2 \[103,483 bytes\]](#)) that was deeper than in the flowing pass ([Fig. 3 \[89,223 bytes\]](#)). Therefore, the results from these TDT-P runs became inconclusive for reservoir monitoring.

These inconclusive logging results are due to the effect of the following factors on the TDT-P measurements:

- Gas channeling behind the casing due to bad cement
- Well bore fluid changes
- Gas coning
- Porosity and lithology changes
- Presence of formation stimulation fluid (hydrochloric acid)
- Borehole fluid invasion into the reservoir.

Model objectives

The objective was to develop a functional relationship between the TDT-P records and a crossplot model.

This approach can distinguish the gas/oil contact change attributed to reservoir performance behavior.

This model is based on the data base constructed for each well in the field and includes:³⁻⁵

- Well performance
- Original gas/oil contact
- Raw data from both open hole logs and TDT-P.

Gas saturation detection

Data from about 70 TDT runs in the Zeit Bay field, with the assistance from open hole logs, outlined the behavior of the TDT near and far rate counts in the oil and gas zones. This behavior is represented by a set of crossplots for the same range of porosity and connate water saturation and for the same lithology.

This model was consistent with the behavior of the count rates for the near and far detectors based on the Polyachenko analytical model.⁶⁻⁸

These crossplots can differentiate between the response of the formation gas and gas in the borehole. All TDT data were plotted in a linear scale to produce the model that is composed of the crossplots of TSCF-TSCN, SIGM-TSCN, SIGM-INFD, and SIGM-SIBH.

The gas saturation model was applied in the Zeit Bay field. Each model crossplot had a definite shape for the cases of:

- Bore hole gas stage
- Formation gas saturation changes
- Formation fully saturated by gas.

Borehole fluid change

If borehole fluid is water and/or oil and the formation has no gas, there is no significant change in both near and far counts. This phenomenon is represented by the interval A-B on the different crossplots in [Figs. 4a-d. \[130,851 bytes\]](#)

When the borehole fluid changes to gas, both near and far counts increase abruptly. This is represented by interval B-C on Figs. 4a-d. This phenomenon is a straight line on the TSCF-TSCN crossplot with a slope less than unity because the increase in the near count is greater than that of the far count.

On both SIGM-TSCN and SIGM-INFD crossplots, interval B-C is a nearly horizontal line because the SIGM value is not affected by the borehole fluid change; however, both TSCN and INFD counts increase abruptly.

On the SIGM-SIBH plot, B-C also is a straight line but in reverse direction because SIBH decreases steeply.

Formation gas saturation

Interval C-D represents the effect of formation gas saturation.

The TSCF-TSCN crossplot (Fig. 4a) shows that as the gas saturation increases, the near count rates remain without significant changes. However, the far counts increase, and therefore, the curve points upward.

The SIGM-TSCN crossplot (Fig. 4b) shows a decrease in SIGM value; therefore, the curve points downward.

The SIGM-INFD crossplot (Fig. 4c) shows that the INFD values stay at their higher values without a significant change; therefore, the curve points downward.

The SIGM-SIBH crossplot (Fig. 4d) shows that the SIBH is not affected by the change in the formation fluid; therefore, the curve points downward.

Gas saturated formation

The TDT-P was run in gassed-out zones in many of the Zeit Bay field wells. Interval D-E represents the TDT-P response in gas-saturated formations.

The TSCF-TSCN crossplot shows that the near and far count rates decrease, so that the curve bends backward, at a certain point representing the gas/oil contact.

The SIGM-TSCN crossplot indicates that the SIGM value showed a slight decrease; therefore, the curve bends backwards at the gas/oil contact.

The SIGM-INFD crossplot indicates that there is a significant decreases in the INFD values; therefore, the curve bends backward at the gas/oil contact.

The SIGM-SIBH crossplot shows that the SIBH is not affected by this phenomenon; therefore, the curve does not change.

Acid effect

Acid treatments are used in the Zeit Bay field to improve formation permeability around the borehole in carbonate reservoirs.

The TDT-P in an acid-treated interval gives high SIGM values. Also TSCF and TSCN slightly increase, because these are porosity and lithology dependent. The INFD and SIBH values are independent of this phenomenon. The DS_{acid} calculated by comparing the before and after acid logging runs is as follows:⁹

$$DS_{acid} = DS_{log} - DS_{base} \quad (1)$$

where:

DS_{acid} = Increase in SIGM because of the acid effect

DS_{log} = SIGM values logged after acid

DS_{base} = SIGM values logged before acid.

The effect of the acid on the SIGM value should be subtracted for use in the model as following.

$$SIGM = S_{monitor} - 2 S_{base} \quad (2)$$

where: $S_{monitor}$ is SIGM of the interpreted log.

In cases where the base run was absent, the open hole logs were used with the value of the capture cross section of the matrix S_m to construct a base run "synthetic base run," using the following equation:

$$S_{syn} = S_m(1-f_{oh}-V_{SH}) + S_{SH}V_{SH} + f_{oh}[S_w S_{woh} + S_h(1-S_{woh})] \quad (3)$$

where:

S_{syn} = The estimated values of SIGM

S_m = Matrix Sigma estimated

f_{oh} = Formation porosity from open hole logs

V_{SH} = Volume of shale per unit volume

S_{SH} , S_w , S_h = Capture cross sections of shale, water, and hydrocarbon, respectively.

The S_m was estimated from the SIGMA-PHIOH crossplot (Fig. 5 [50,320 bytes]).¹⁰ Fig. 5 shows that this crossplot has been used for data of average S_{woh} of about 10%. Using the field parameter, the intersect section of the Y axis was defined when $f_{oh} = 1$ and calculated using Equation 3 at 35.85 c.u. While the intersect with the Y axis when $f_{oh} = 0$ gives $S_m = 7$ c.u.

Lithology, porosity

Fig. 6 [50,389 bytes] shows the behavior of TSCF-TSCN crossplot in both sandstone and limestone reservoirs with the same porosity. This figure indicates that the tool response in gas carbonate reservoirs, which are the points clustered around B, has the same response as the oil sand, which are the points clustered around C.

These phenomena made it necessary to define a well's lithology before using the model. On the other hand, Fig. 7 [48,768 bytes] shows the behavior of the same crossplot for 15 and 30% porosity in a limestone reservoir. It is clear that there is an insignificant change in both TSCF and TSCN counts in the 25 and 30% porosity range.

For low porosity, 15% average, the reading of the TSCF higher than that of the high porosity may give a false indication of a gas zone unless these phenomena are included in the interpretation.

Gas coning

Gas coning is a well-known phenomenon in some reservoirs, especially in those with a primary gas cap. To overcome this problem, several shut-in and flowing passes need to be run with the TDT.

The gas coning phenomenon was detected in some wells by comparing the SIGM values in both shut-in and flowing passes. Fig. 8 [135,265 bytes] shows the SIGM values recorded in both shut-in and flowing passes, SIGM94S and SIGM94F in the second track.

Below 5,530 ft, there is an apparent similarity of both readings because as the two curve reflect the oil readings, and above 5,030 ft the curves reflect the gas reading. This depth represents gas/oil contact.

Between these two depths, SIGM94F is less than SIGM94S. This is due to gas coning.

The shut-in pass reading detects the gas/oil contact, with the gas saturation charts.

Gas saturation

Two TDT-P runs in Well No. 8 in 1992 and 1994, gave the response of gas/oil contact in the shut-in pass lower than that in the flowing pass (Figs. 2 and 3). Based on well performance and the TDT reading, the gas/oil contact was determined from the flowing pass at 4,786 ft.

This matched the results of the gas-saturation model with the data of the TDT-P run in 1994. [Fig. 9 \[51,696 bytes\]](#) illustrates the behavior of the SIGM-INFD crossplot at the gas/oil contact at 4,623 ft.

The gas saturation model was used to interpret the gas/oil contact in 18 wells in the field. These detected gas/oil contacts were plotted on the Zeit Bay well location map to construct the iso-gas level contour map ([Fig. 10 \[88,880 bytes\]](#)).

The well locations for three new infill wells in the western flank of the Zeit Bay field were determined based on the iso-gas level contour map (Fig. 10).

Open-hole logging in these wells verified the expected gas/oil contact.

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The Authors



Gharib M. Hamada is an associate professor with King Saud University, Saudi Arabia. He is a professor of well logging and applied geophysics. He previously was with the Technical University of Denmark and the College of Engineering, Sultan Qaboos University, Oman. Hamada has a BS and MS from Cairo University and a DEA and Doc D'Ing degrees from Bordeaux University in France. He is a member of SPE SPWLA, SCA, and SEG.



Musaed N.J. Al-Awad is an assistant professor with King Saud University in Saudi Arabia. He is a professor of oil and gas well drilling engineering and petroleum-related rock mechanics. Al-Awad has a BS and MS from King Saud University, and a PhD from Heriot-Watt University, Edinburgh.

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1455 West Loop South
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(713) 621-9720

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