PETROPHYSICS, VOL. 61, NO. 6 (DECEMBER 2020); PAGES 623–632; 12 FIGURES. DOI: PJV61N6-2020a7

Multidetector Pulsed-Neutron Tool Application in a Low-Porosity Reservoir: A Case Study in Mutiara Field, Indonesia[1]

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ABSTRACT

In mature fields, pulsed-neutron logging (PNL) is commonly used to solve for the remaining saturation behind the casing. For years, sigma-based saturation has been used to calculate gas saturation behind casing; however, the high dependency of sigma-to-water salinity of the formation, especially the low-dynamic range at porosity near 12 p.u., has proven to be challenging in low-porosity gas rock. A new measurement from the third detector from a multidetector pulsed-neutron tool (MDPNT) is proposed to provide a better estimation of the gas saturation in a low-porosity reservoir.

Two sets of independently measured sigma and the third detector were taken in a casedhole well, with a dual-tubing system of a long string and short string. For the third-detector measurement, the measurement was based on the ratio of the slow capture gate and inelastic gate component from the decay curve created by the long detector. This ratio can be used to detect gas in a tight reservoir with a minimum salinity and lithology effect. This data will then be used to calculate the gas saturation from the third detector, and the result is compared to sigma-based gas saturation.

At an interval where the porosity is above 12 p.u., the sigma-based gas saturation and MDPNT-based gas saturation are very much in agreement. However, in a low-porosity reservoir near 12 p.u. or below, the sigma-based measurement starts to show its limitation. Meanwhile, the MDPNT-based gas saturation clearly shows the remaining gas saturation where sigma-based measurements failed to detect it. The subsequent decision was made based on the log analysis result, and perforation was done at a potential interval based on the MDPNT result. The results from the production test confirm the MDPNT-based gas saturation with 700-Mscf/d gas production added.

This study showcases a new technology to solve a low-porosity gas reservoir issue where a sigma-based measurement underestimates the remaining gas saturation. Using two different measurements in the same well, the results from the MDPNT measurement demonstrated a better result compared to the sigma-based measurement in low-porosity rock.

INTRODUCTION

Pulsed-neutron technology has been widely used for decades in formation evaluation in casedhole conditions. It is mainly used for determining the saturation in the reservoir. The classic technologies commonly known to be used are carbon-oxygen (C/O) and sigma (Σ).

The C/O method was introduced in the 1970s and widely used as a method to identify oil in an unknown water salinity formation. Unlike the sigma method, the C/O method is not affected by the salinity of water in the formation (Wijaya and Bagir, 2018).

The sigma method uses the intrinsic value of each element in the reservoir (matrix and fluid) in capturing thermal neutron (capture cross section or sigma). It computes hydrocarbon saturation by looking at the difference between water and hydrocarbon sigma values.

In this case study area, which is dominated by a freshwater reservoir, the low-contrast sigma value of fresh water and oil causes the use of the sigma method to be limited to gas saturation determination. However, the accuracy of the gas saturation calculation will depend heavily on the rock lithology (especially in shaly formations) and the porosity. In a low-porosity reservoir near 12 p.u. or lower,

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the sigma method gas saturation calculation starts to show its high uncertainty.

The third detector from the MDPNT produces a new measurement called SATG, a ratio between the slow and fast capture gate. It is less affected by the effect of lithology compared to the sigma method and has a better dynamic range in low-porosity reservoirs.

In the case study area, these two measurements are compared side by side to see the difference in determining the gas saturation across intervals near 12 p.u. or less.

FIELD HISTORY

The Mutiara Field is part of four major fields in the Sanga-Sanga block, located in East Kalimantan. Mutiara is the biggest gas and oil-producing field in the Sanga-Sanga PSC (Production Sharing Contract).

This field is located in the southern area of Sanga-Sanga PSC and is a 50-km distance from Balikpapan city. It covers a 68-km^2 measured area from north to south, as shown in Fig. 1.

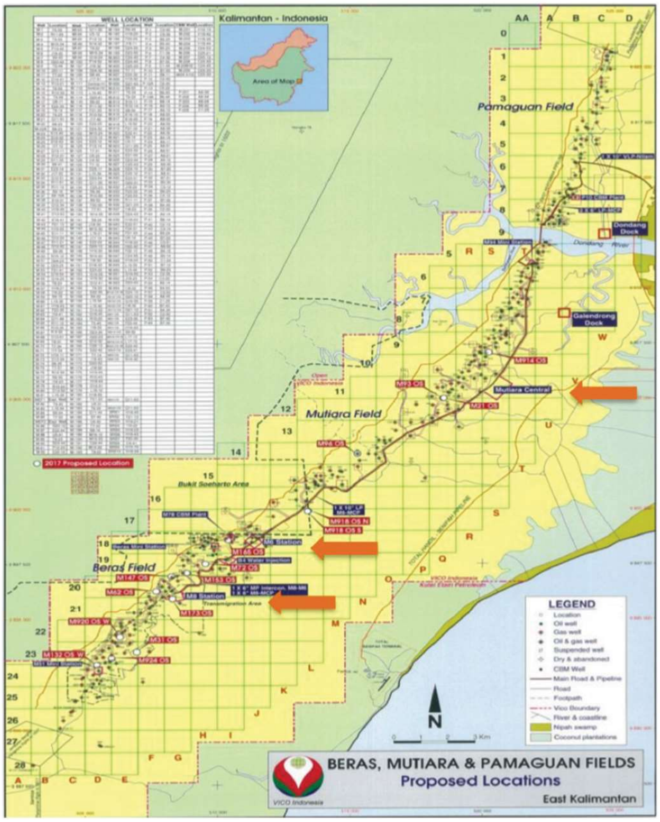


Fig. 1—Mutiara Field surface map (Kahfie et al., 2017).

The area around Mutiara is compartmentalized by normal faults, which trend relatively northwest to southeast perpendicular to the major thrust fault that is southwest to northeast. Its reservoir consists of siliciclastic channels and bars of middle Miocene deltaic (delta front to delta plain) with intraformational source rock that has been matured since 13 Ma. Later, this siliciclastic reservoir, composed of sand and shale intercalation, will introduce uncertainty in the sigma-based gas saturation.

Having over 50 years of active exploration and development, this field has reached its mature phase and requires some workover jobs to maintain its gas production.

SIGMA MEASUREMENT

A pulsed-neutron tool emits high-energy 14-MeV neutrons that "pulse" in a specifically designated time interval. The emitted neutrons travel from the neutron source through the casing to the formation. The interaction of neutrons with the element atoms in the borehole, casing, cement, and formation produces gamma ray particles. Depending on the interaction between neutrons and atoms in the formation, like background, inelastic, capture, and activation process, each interaction will produce a different type of gamma ray.

As shown in Fig. 2, the process starts with a burst from the initial firing of the tool. Shortly after the burst, the gamma ray count rate is predominantly affected by the near borehole. After several hundred microseconds, the formation component becomes the main contributor to the decay, and shortly after, it will return to the background rate (Imrie et al., 2019).

The sigma is defined as the capability of each mineral to capture thermal neutrons. This value is unique for each element. Figure 3 shows typical values of common minerals, rocks, and fluids.

Guo et al. (2012) emphasized the limitations of sigma-based saturation calculation. The uncertainty on saturation calculation is higher if the porosity (ϕ) is lower, and when the contrast between sigma water (Σ_w) and sigma gas (Σ_g) is low. In a clean reservoir with no shales, the gas saturation equation is shown in Eq. 1:

$$S_w = \frac{(\Sigma_{log} - \Sigma_{ma}) - \phi * (\Sigma_g - \Sigma_{ma})}{\phi * (\Sigma_w - \Sigma_g)} \quad (1)$$

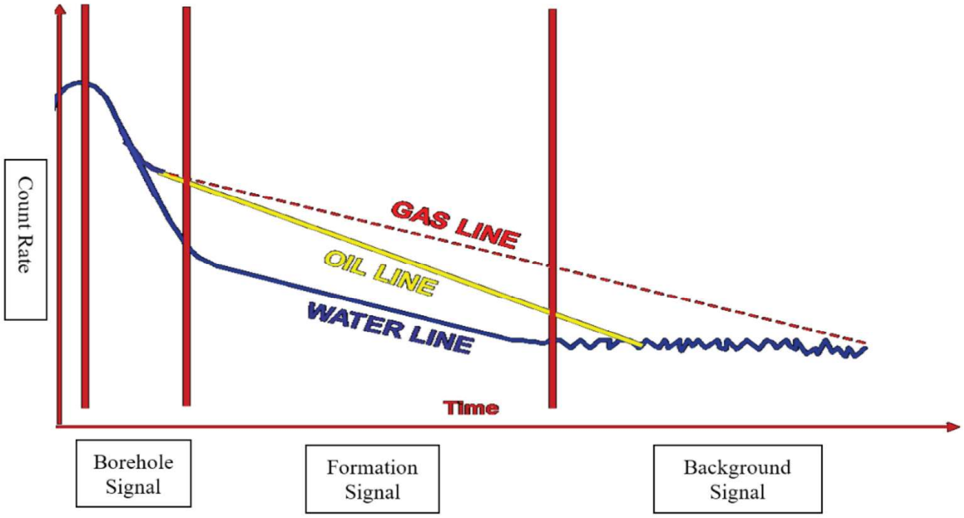


Fig. 2—Decay curve of count rates against time with different formation fluids.

TYPICAL Σ VALUES

MINERAL/FLUID	Σ VALUE	MINERAL/FLUID	Σ VALUE
SANDSTONE	4.6	SALT WATER (240 kppm NaCl)	118
LIMESTONE	7.5	OIL	18.2-22 **
DOLOMITE	4.7	GAS	UP TO 14 *
ANHYDRITE	12.6	QUARTZ	4.6
GYPSUM	18.6	CHALK	7.5
FRESH WATER	22	SHALE	20-50
SALT WATER (100 KPPM NaCl)	59	HALITE	761

* THE Σ VALUE IS DEPENDS UPON RESERVOIR PRESSURE, TEMPERATURE, GAS GRAVITY AND CONDENSATE RATIO.

** THE Σ VALUE DEPENDS UPON THE GAS OIL RATIO (GOR).

THE Σ VALUE FOR THE COMMON MINERALS IS SHOWN FOR PURE MATRIX. THE VALUE WILL VARY IN REALITY DEPENDING ON THE FORMATION CONDITION, i.e. TRACE IMPURITIES, CONNATE WATER SALINITY, ETC.

Fig. 3—Typical values of sigma for common minerals, rocks, and fluids.

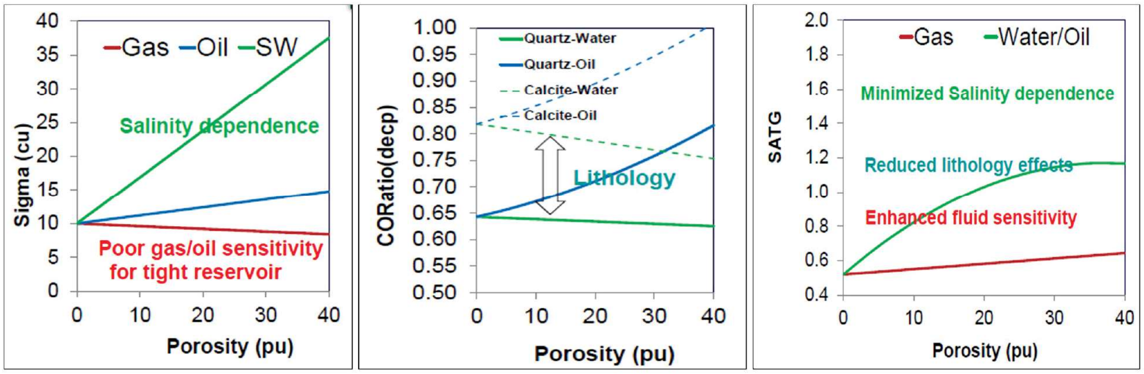
In the case study area, the reservoir consists of interbedded shale and sandstone. The following equation will be used in the reservoir with a shale component.

$$S_w = \frac{(\Sigma_{log} - \Sigma_{ma}) + V_{sh} * (\Sigma_{ma} - \Sigma_g) + Vsh * (\Sigma_{ma} - \Sigma_g)}{\phi_e * (\Sigma_w - \Sigma_g)} \qquad (2)$$

From the equation (Eq. 2), it was heavily affected by the contrast between sigma water and sigma gas, as well as the low porosity. It was also heavily affected by the volume and sigma of shale. The higher the sigma shale, the greater the effect on the water saturation calculation. This will later show the sigma-based gas saturation calculation to be highly sensitive to changes in shale volume.

SATG MEASUREMENT

In low-porosity rock, sigma is not well suited to calculate an accurate gas saturation. Tight or low-porosity rock typically has a porosity less than 12 p.u. (Mekic et al., 2016). In such a low porosity, the dynamic range of 100% gas and 100% water is small, hence the low accuracy of sigma gas saturation. Figure 4 shows the different dynamic ranges between three products of PNL measurements (C/O, sigma, and SATG).



(a) (b) (c)

Fig. 4—(a) Sigma, (b) C/O, and (c) SATG fan charts.

SATG (saturation gate) is a newly introduced ratio also from the capture mode measurement from the MDPNT. The measurement comes from the long-spacing detector and was designed to overcome the shortcomings of sigma in low porosity. The SATG is a ratio between the inelastic gate and slow capture gate (Guo et al., 2012), as shown in Fig. 5.

The SATG measurement uses a fan chart to calculate gas saturation as a function of SATG vs. porosity. This fan chart is a function of borehole fluid and size, and casing size. Further study proves that the SATG method is independent of formation water salinity (Chen et al., 2015) and reduced lithology dependency, as shown in Fig. 6.

Although SATG has a reduced lithology dependency, the effect from lithology, especially shales, still needs correction. In the case study area, the SATG measurement is underestimating the gas saturation due to the high value of SATG shales. This effect is easily corrected by a linear relationship between SATG and volume of shales (V_{sh}) across the target interval (McIlroy et al., 2015), as shown in Fig. 7.

JOB PLANNING AND EXECUTION

The target interval consists of sandstone reservoirs with thick shales in between. The sandstone reservoir has porosity ranges from 8 to 12 p.u. and shales volume of 10 to 20%.

The well is a dual-monobore design, with a short-string and long-string combination. The executed logging plan was to log the target interval using capture mode in the short-string section.

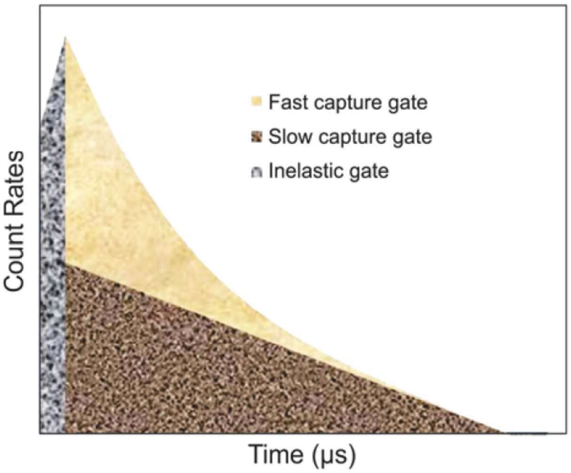


Fig. 5—SATG processing partitions of fast and slow capture gate and inelastic gate.

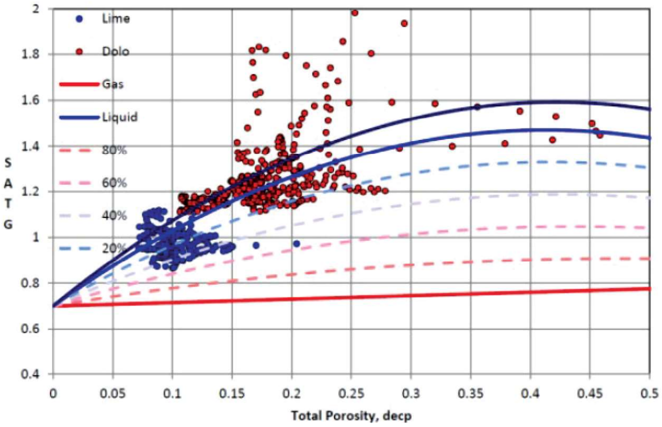


Fig. 6—Limestone and dolomite lithology plotted onto the SATG gas saturation fan chart (Kwong et al., 2013).

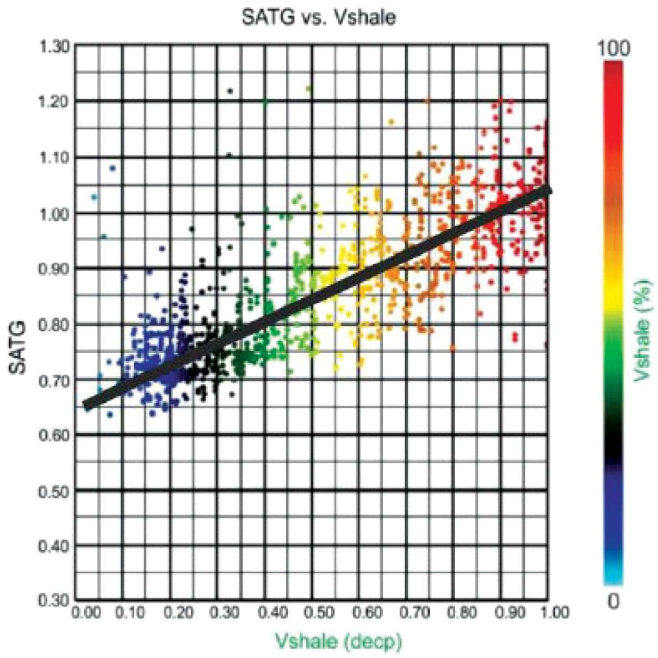


Fig. 7—Linear relationship between shale volume and SATG measurement vs. total porosity.

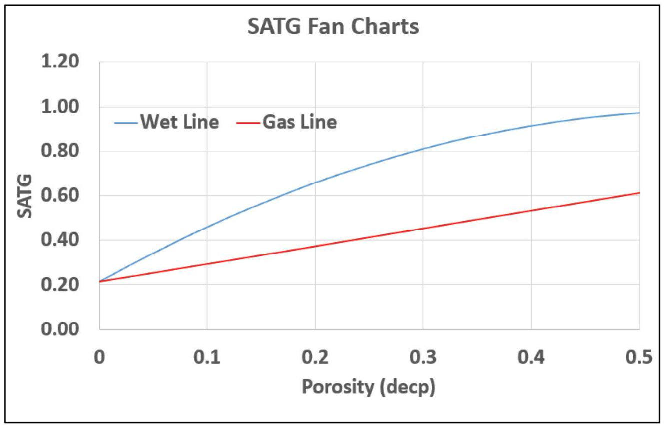


Fig. 8—SATG default fan chart.

Specifically, for the SATG measurement, a designated fan chart based on the casing, borehole size, and borehole fluid is created prior to the job to provide a fast turnaround time for quick perforation decisions. The fan chart designed for this job is shown in Fig. 8.

Supporting data for post-processing, such as openhole data and formation evaluation data (ϕ, ϕ_e, V_{sh}, and S_w), are provided prior to the job. Formation evaluation data like ϕ, ϕ_e, and V_{sh} are used as inputs in gas saturation calculation for both sigma and SATG-based measurements, while the rest is used for display purposes.

INTERPRETATION RESULT

Sigma-based gas saturation and SATG-based gas saturation are calculated independently across target intervals. The parameters for calculating the gas saturation from sigma consist of sigma water and sigma gas, which are obtained from information about the gas properties, reservoir pressure and temperature, and water salinity provided by the customer. The sigma matrix and sigma shales are estimated based on acquired sigma data, as shown in Fig. 9. The Sigsolidsapp is an apparent sigma matrix that gives an estimated value of sigma matrix at 0% shales volume and sigma shales at 100% shales volume. According to this crossplot, the sigma matrix is 7.5, and sigma shales are 27 c.u. The sigma water of 24 c.u. and sigma gas of 3 c.u. were estimated from given water salinity (5 kppm NaCl) and gas properties (gas gravity, formation temperature-pressure) from the customer.

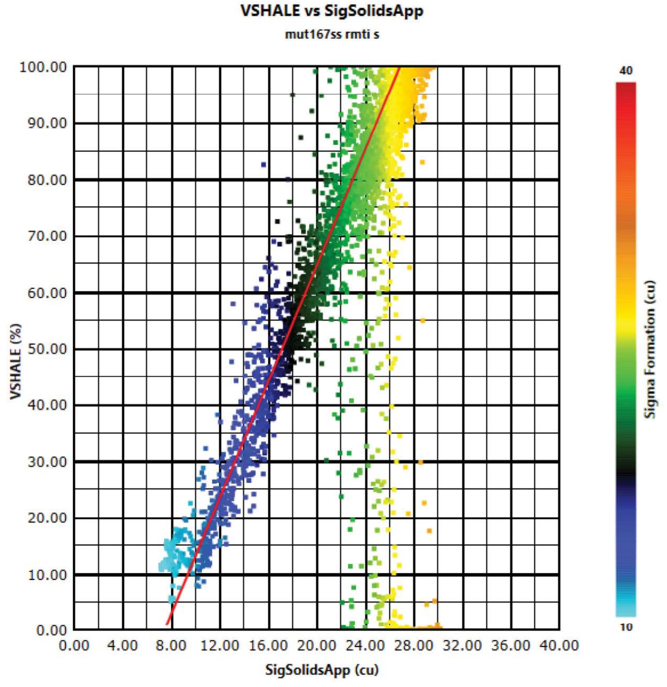


Fig. 9—Sigma matrix and sigma shale determination.

The sigma-based gas saturation is calculated based on a fan chart created by these sigma parameters. In a water zone, the crossplot between sigma intrinsic and total porosity will fall into the sigma wet line. However, due to the low porosity of this water zone interval (2 to 7 p.u.), the distribution of the data points is not conclusive and shows a high uncertainty (Fig. 10). Looking closely, when porosity is close to 6 p.u., the data become better aligned with the sigma wet line.

The SATG-based gas saturation is calculated based on the specific fan chart. Across the water zone, the distribution between SATG vs. porosity should be close to the wet line (blue line) in the fan chart. Figure 11 shows the SATG fan chart across the water zone. The SATG fan matrix value has been adjusted from the default (0.22) to 0.39. This offset was applied to better fit the wet line in the fan chart. A linear shale correction to SATG was also applied prior to calculating the gas saturation.

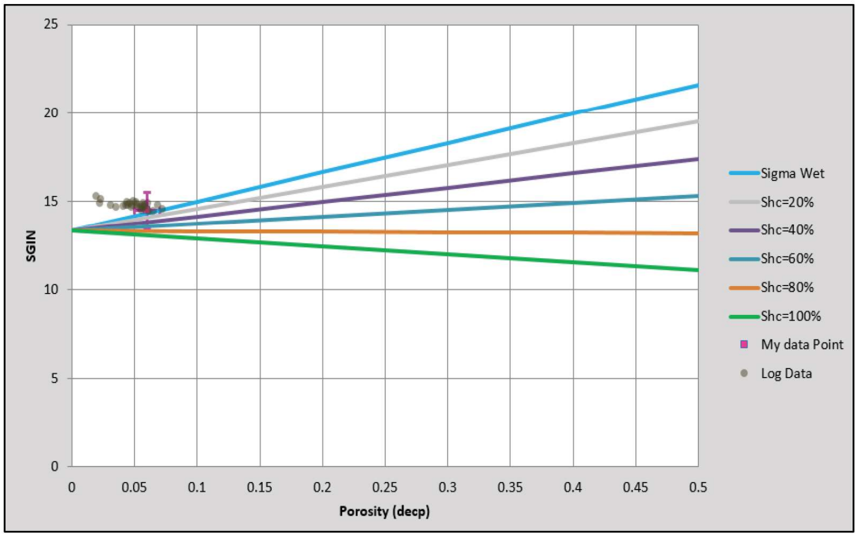


Fig. 10—Sigma fan chart across the water zone.

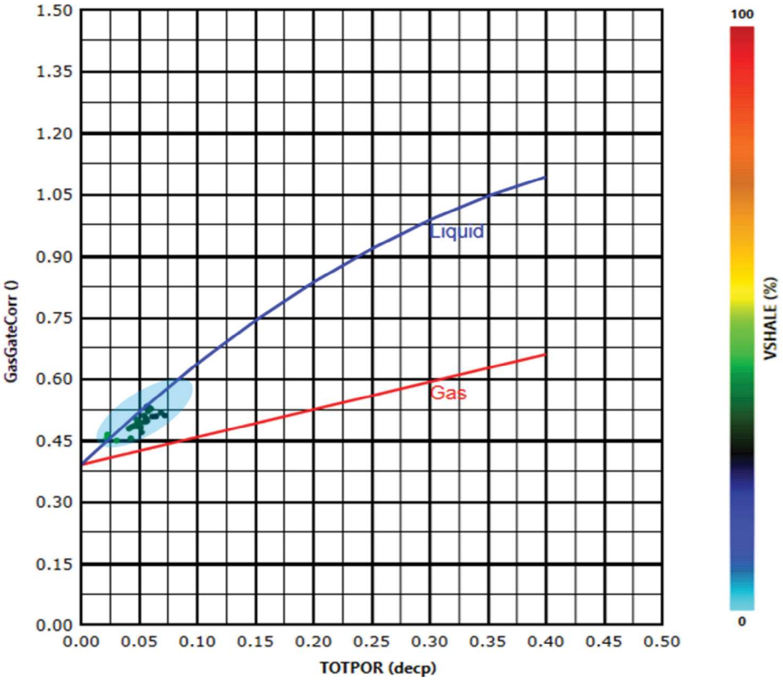


Fig. 11—SATG fan chart across the water zone.

Each result is presented in the plot (Fig. 12) to show the difference in terms of calculated gas saturation across the target interval. The gas saturation by sigma is shown as a blue line, and the gas saturation from SATG is shown as a red line/red shading in the Track-9 (saturation track). Detail on each track on the plot is explained as follows:

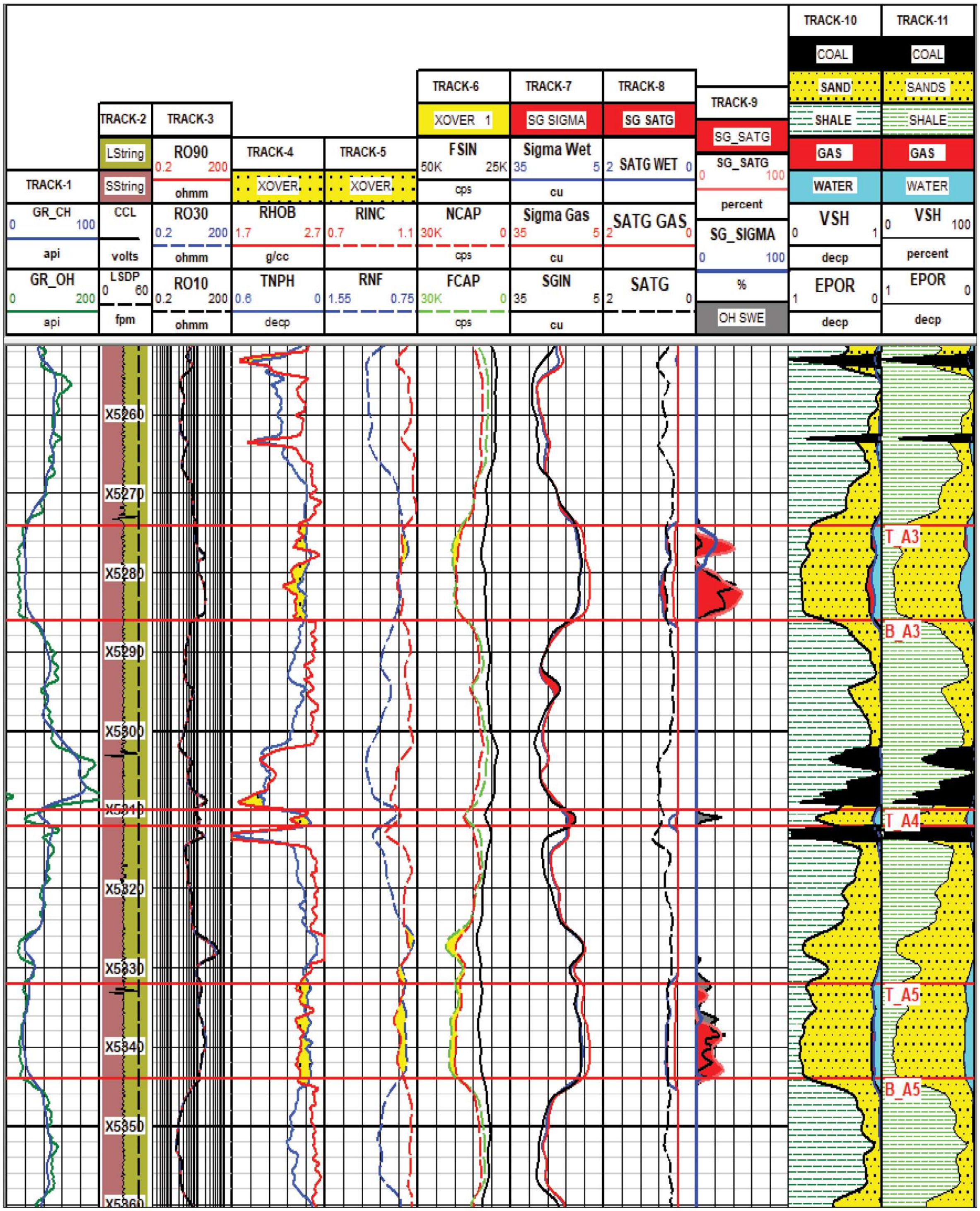


Fig. 12—Sigma vs. SATG-based gas saturation.

Track-1: Correlation track, consists of GR from open hole (GR_OH) and cased hole (GR_CH).

Track-2: Depth track with dual-monobore diagram.

Track-3: Deep (RO90), medium (RO30), and shallow (RO10) resistivity from open hole.

Track-4: Density (RHOB) and neutron (TNPH) from open hole.

Track-5: Inelastic (RINC) and capture ratio (RNF) from cased hole.

Track-6: Far- (FCAP) and near-count rates (NCAP) from cased hole.

Track-7: Sigma intrinsic/formation (SGIN), sigma at 100% wet (Sigma Wet), and sigma at 100% gas saturation (Sigma Gas).

Track-8: SATG formation (SATG), SATG at 100% wet (SATG WET), and SATG at 100% gas (SATG GAS).

Track-9: Saturation track showing SATG-based gas saturation (SG_SATG) and sigma-based gas saturation (SG_SIGMA). Openhole saturation is also plotted for display purposes.

Track-10: Volumetric track of shale, sand, and bulk volume of fluid, based on SATG.

Track-11: Volumetric track of shale, sand, and bulk volume of fluid, based on sigma.

Zone A3

This interval shows gas saturation from sigma at the top, around 10 to 20% (blue line), whereas the SATG-based gas saturation shows around 40 to 50% gas saturation.

In the A3 top section where the porosity is around 10 to 11 p.u., the SATG gives much higher saturation (around 40%) compared to sigma saturation (around 20%).

Interestingly, the A3 second peak of gas has a porosity of 12 to 15 p.u.; however, the sigma was not able to calculate any gas saturation, whereas the SATG gives high saturation of gas.

Zone A5

This interval shows no gas saturation from sigma, whereas the SATG-based gas saturation shows 10 to 27% gas saturation. Across this zone, the porosity is 8 to 11 p.u.; therefore, sigma is not suitable for this kind of reservoir.

In this low-porosity reservoir, SATG was able to detect the presence of gas missed or underestimated by traditional sigma saturation methods. This was confirmed by gas production of 700 Mscf/d from the A3 and A5 zones (commingled production).

CONCLUSIONS

In this case study, where the lithology consists of sandstone and shales, the sigma-based gas saturation is affected by shale volume, especially when sigma shale value is high.

This interval is dominated by relatively low porosity (A5 zone), where due to sigma low-dynamic range in low-porosity rock, the gas saturation uncertainty using sigma will be quite high.

The qualitative curves, which usually can be used to indicate the presence of gas, also suffer from low-porosity rock, and the crossover will not be able to differentiate between gas or low-porosity rock with liquid, since the response is the same.

The results using SATG demonstrated that the SATG gas saturation has reduced dependency on lithology and water salinity, and overall better dynamic range. This brings an additional value to evaluating low-porosity reservoirs by identifying previously overlooked zones, rejuvenating production in the mature field phase.

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NOMENCLATURE

Abbreviations

Sigsolidsapp = apparent sigma matrix
GR_OH, CH = open hole (OH), cased hole (CH) gamma ray
RO90, 30, 10 = openhole deep, medium, shallow resistivity
RHOB = openhole density
TNPH = openhole neutron porosity
RINC = casedhole inelastic ratio

RNF = casedhole capture ratio
FCAP = far-capture count rates
NCAP = near-capture count rates
SGIN = intrinsic sigma formation
SATG = long-detector gas ratio
SG_SATG = SATG-based gas saturation
SG_SIGMA = sigma-based gas saturation

Symbols

C/O = carbon-oxygen
$\Sigma_{w,ma,log,sh,g}$ = sigma water (*w*), matrix (*ma*), measured (*log*), shales (*sh*) and gas (*g*)
ϕ, ϕ_e = total porosity, effective porosity
V_{sh} = volume of shales
S_w = water saturation

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