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Integrated Evaluation of Laminated Sand-Shale Gas-Bearing Reservoir Using Tensor Model. A Case Study Combining Data from Triaxial Resistivity, Image, Sonic, And Reservoir Testing in B-Field, Malaysia.

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ABSTRACT

In recent years, the development of frontier areas brings added challenges to formation evaluation, especially thinly bedded reservoirs. It is challenging to evaluate such reservoirs due to the low resistivity values and high shale volume, which masks the contrast between water and hydrocarbon zones. Using conventional approaches in these types of reservoirs will underestimate the hydrocarbon potential and reserves estimates. A study has been carried out of the thin-bed laminated reservoir in B-field using the tensor model technique to assess the hydrocarbon potential. Additional data from borehole imaging and sonic logs are critical for enhancing the evaluation of hydrocarbon potential and complements the result of the tensor model evaluation.

The study was conducted to calculate the sand resistivity and sand porosity using a combination of the tensor model and the Thomas-Stieber model. The tensor model uses acquired horizontal and vertical resistivities, while the Thomas-Stieber model uses the calculated shale volume and porosity. One of the main parameters in the tensor model is shale resistivity, which upon analysis, varies across many shale sections in the well. This uncertainty is reduced by picking multiple shale resistivity values based on borehole image facies analysis. The VPVS ratio technique and Brie's plot using compressional and shear travel time are used as a qualitative analysis that indicates the same gas-bearing interval.

The tensor model calculations improve hydrocarbon saturation by a range of 4-21%, depending on sand thickness and shale volume, which increases the net to gross by more than 20%. The borehole image facies analysis helps to objectively pick the shale resistivity parameters to avoid subjective interpretation and underestimating the pay. A qualitative approach using sonic data helps to identify the potential gas-bearing interval and complement the previous tensor model interpretation. Although all interpretation methods indicate a similar gas-bearing interval that correlates with the mudlog total gas reading, the combination of the tensor and Thomas-Stieber method with image constrained shale resistivities gives the most definitive gas saturation and net pay

The novelty of this study is to showcase two things. First is the application of combined tensor and Thomas-Stieber model in a laminated reservoir, with image constrained shale resistivity for improved gas saturation and net pay. The second is to highlight the use of gas-sensitive sonic data to confirm the gas saturated interval.

INTRODUCTION AND FIELD BACKGROUND

Identifying a potential hydrocarbon zone is always a challenge in a laminated sand-shale reservoir. Because of the nature of the reservoir and the low-resolution capability of conventional logging tools, this type of reservoir is often missed and calculated as a highly water-saturated reservoir or even water-bearing reservoir.

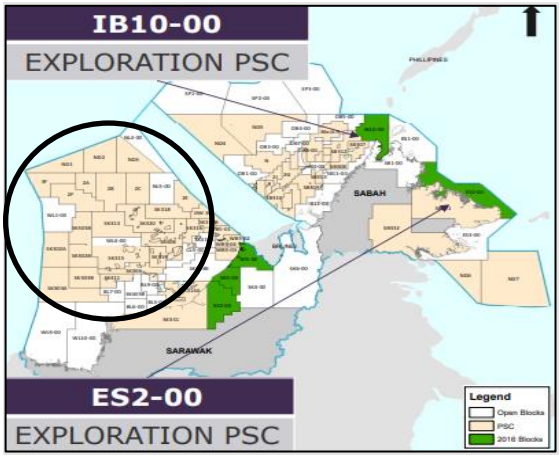

Figure 1: Location of the study (black circle).

This study focuses on the M1-well, located in the B-field, offshore Sarawak region, Malaysia (Figure 1). The M1-

well penetrates multiple formations, targeting a turbidite section where laminated reservoirs are encountered.

This paper will discuss the use of triaxial induction, sonic, image, and well test data to identify the gas-bearing interval. The combination of the Tensor and Thomas-Stieber model, with help from image facies analysis, has been used qualitatively to determine the tensor model parameters, hence improving the sand resistivity and porosity the ultimately increase the hydrocarbon saturation in this reservoir.

Additionally, the qualitative interpretation using compressional and shear data is used to support the presence of a gas-bearing reservoir in this well.

LAMINATED SAND-SHALE RESERVOIR

A laminated sand-shale reservoir is known for its low resistivity log reading and high shale volume. Consequently, the calculated hydrocarbon saturation will be too low, missed, and potentially not considered a pay zone.

A lamination is defined as a thickness less than the tool vertical resolution, typically 2-ft or less from a petrophysics point of view. This will induce a macroscopic anisotropy effect on resistivity and lower the resistivity (R_h) reading (Figure 2).

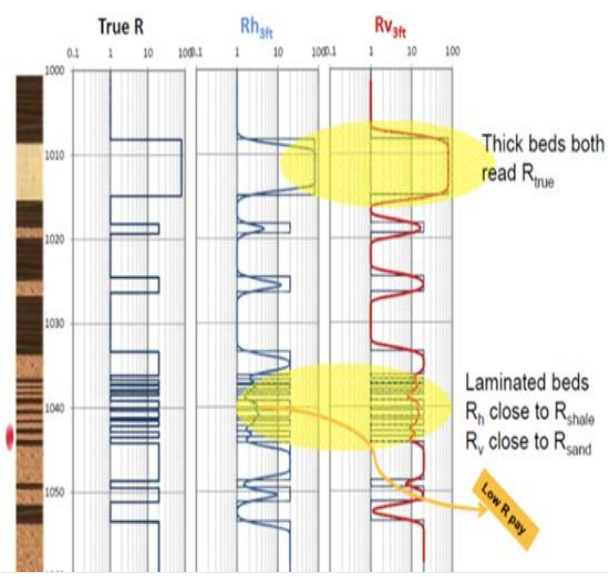

Figure 2: - Thin laminated sand-shale effect on conventional resistivity reading-Rh (Quirein et al., 2012).

The density-neutron log will also be affected by the presence of shale (Figure 3) and will induce a high shale volume. If not corrected using the Thomas-Stieber model, it will give a low sand porosity and lower the hydrocarbon saturation.

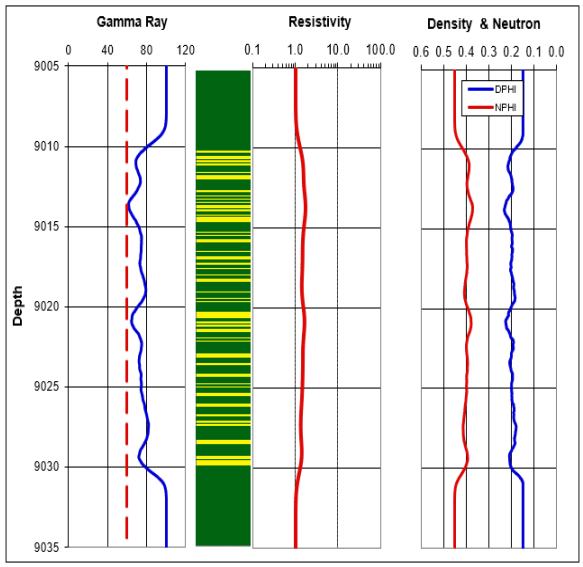

Figure 3: - Simulated conventional log response over 40% Net to Gross in a laminated sand-shale reservoir (Passey, Q.R. et al., 2006)

Apart from the macroscopic anisotropy effect, the shales may inherently introduce intrinsic electrical anisotropy called microscopic anisotropy, caused by a stratified grain of minerals or elongated micas in shales.

Not accounting this, the intrinsic shale resistivity anisotropy may introduce an error up to 30% on the sand resistivity calculation at laminated shale volume as low as 10% (Wijaya, 2019).

TENSOR MODEL IN LAMINATED RESERVOIR

The tensor model solves the true sand resistivity as a function of horizontal and vertical resistivities available in the laminated reservoir, both macroscopic and microscopically.

The horizontal resistivity (R_h) is a resistivity reading parallel to the bedding dip. The vertical resistivity (R_v) is a resistivity reading perpendicular to bedding dip/ parallel to the tool axis. Both values are acquired simultaneously using a triaxial induction logging tool (Figure 4).

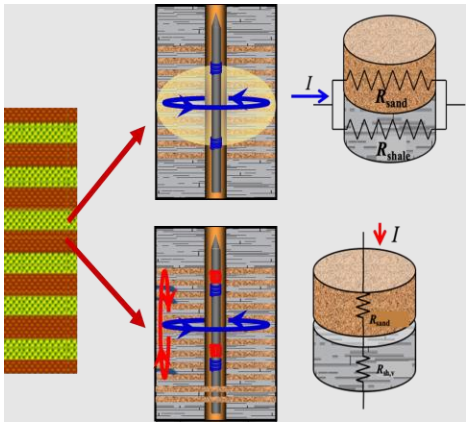

Figure 4: - Horizontal and vertical resistivity measurements in laminated sand-shale reservoir

The tensor model is a function of laminated shale volume (V_{Lam}), sand resistivity (R_{Sd}), and anisotropic resistivity from resistivity measurements (R_v, R_H) and shale (R_{shH}, R_{shV}).

$$\frac{1}{R_h} = \frac{(1 - V_{Lam})}{R_{Sd}} + \frac{V_{Lam}}{R_{shH}}$$

$$R_V = R_{Sd} * (1 - V_{Lam}) + R_{shV} * V_{Lam}$$

The acquired R_V and R_H are used as inputs, and the V_{Lam} was obtained from the interpretation of quad combo data using Thomas-Stieber crossplot.

GAS-BEARING IDENTIFICATION USING SONIC SLOWNESS INTERPRETATION

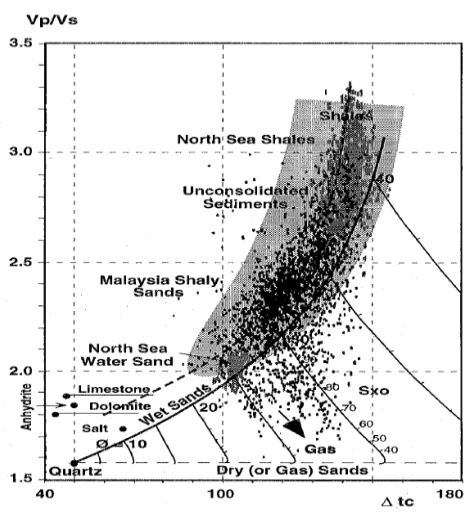

Figure 5: - Brie's plot (Brie et al., 1995). Vp/Vs ratio against DTC.

Brie et al. (1995) introduced an approach using acoustic slowness to determine the presence of gas. By using a crossplot of VP (P-wave velocity) to VS (S-wave velocity) ratio against DTC (compressional), Brie et al. established a trend of wet sand and gas sand. The original crossplot, as shown in Figure 5, has been used, modified, and tested for its reliability in multiple basins.

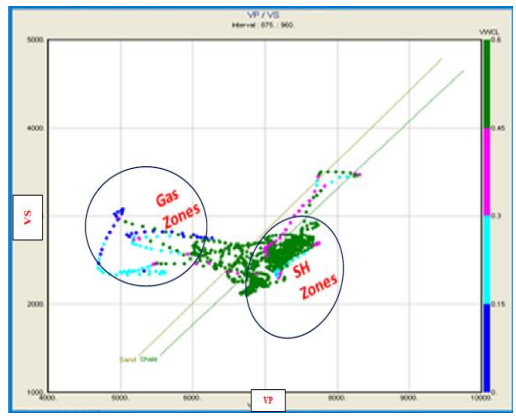

Figure 6: - VP vs. VS crossplot (Wazery et al., 2011). X-axis and y-axis are the P-wave and S-wave velocity plotted in Km/s. Showed the effect of gas presence compared to shale (SH) zone.

Similarly, several studies (Wazery et al., 2011 and Fadjarijanto et al., 2018) have published the application of sonic data in determining the gas-bearing reservoir. Although using a different crossplot, the premise is the same. By using a known shale zone as a baseline (high gamma ray, density-neutron separation), any DTC value higher than shale can be regarded as a gas-bearing zone or high-organic lithologies such as organic shales or coal (Figure 6 & 7).

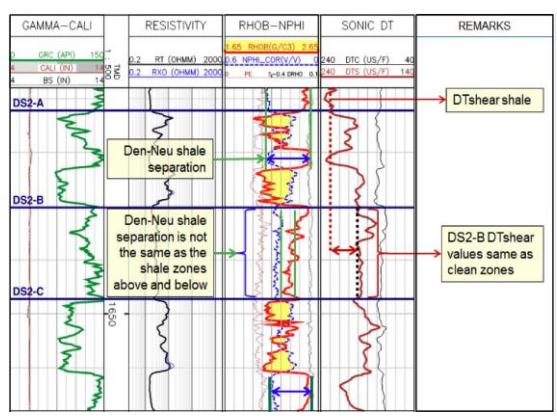

Figure 7: - DTC-DTS quick look (Fadjarijanto et al., 2011). New gas zone is identified based on acoustic wave travel time (DTC, DTS).

CONVENTIONAL INTERPRETATION

Quad combo data is used for a quick look to identify possible thin beds and the presence of a gas-bearing reservoir.

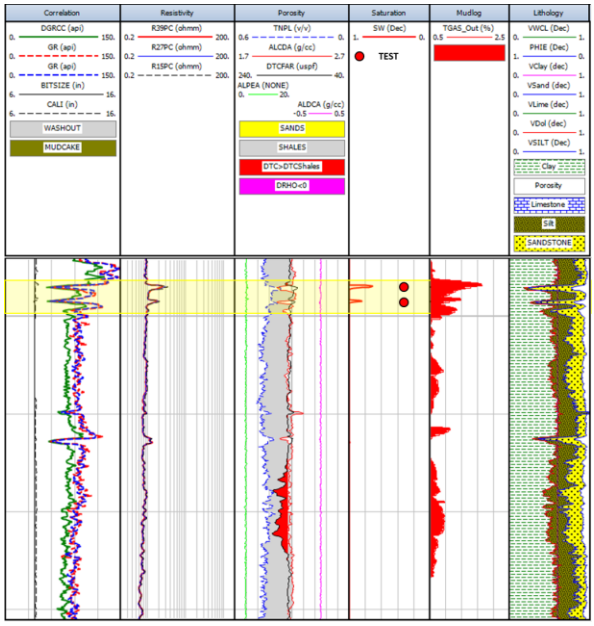

Figure 8: - Conventional interpretation (full interval)

From a quick interpretation, the entire section has a high shale volume (V_{sh}) with only a thin carbonate in the middle section. The shale volume is calculated from a combination of gamma-ray and density neutron.

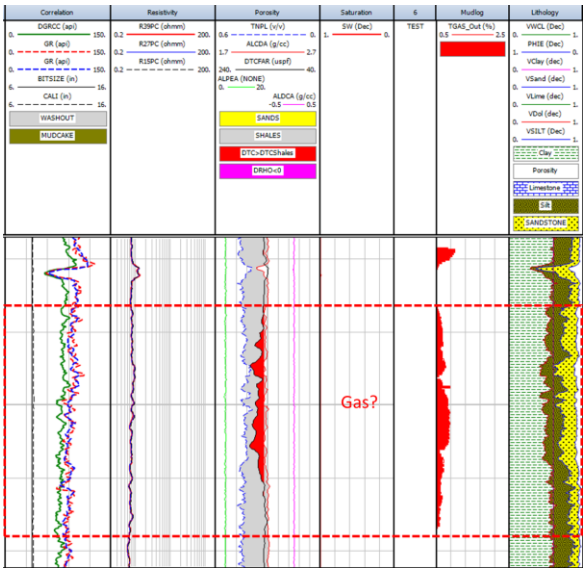

Figure 9: - Potential gas-bearing interval.

A conventional saturation (Figure 8) calculation using the Indonesian equation gives a high-water saturation ranging from 75-85%, which only appears over the highlighted of a relatively cleaner reservoir section.

Despite the high-water saturation, the gas sampling was taken from the highlighted interval and considered as gas bearing interval. The conventional interpretation is not optimized in this kind of reservoir.

Furthermore, from adding sonic slowness data (DTC) comparison, some intervals indicate gas-bearing potential. Figure 9 is an expanded section where the zone below the gas bearing interval indicates slowness slower than the shale above and below it. Across this zone, gas reading indicates an increase compared to background reading, while the conventional saturation calculated a 100% water saturation.

Across this identified interval, the shaliness is slightly reduced, however, the slowness is increased instead. This slowness signature and increased gas reading are indicating a presence of a gas-bearing interval that was not captured in the conventional interpretation.

GEOLOGICAL INTERPRETATION

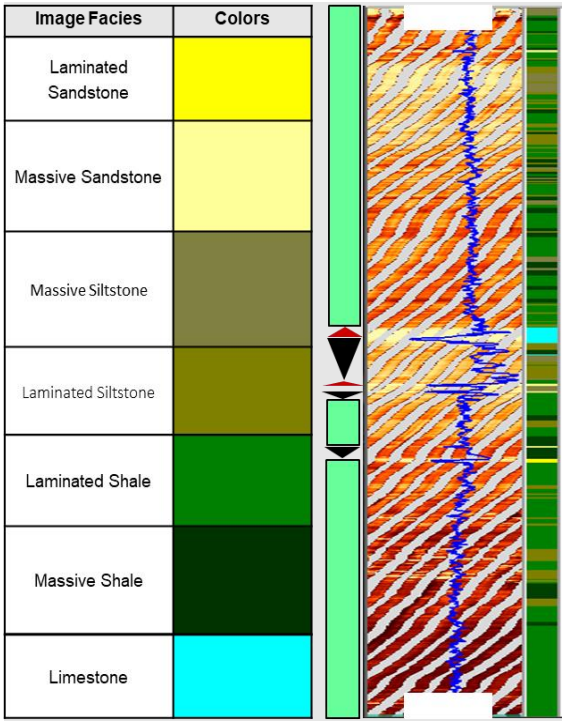

Figure 10: - Facies analysis from Image data. Later, this facies image analysis will be used to define the zone at which the anisotropic shale resistivity value was taken.

Image data was acquired in the present well. The data was processed and interpreted which verified the presence of a laminated sand-shale reservoir. From image data, the entire section is believed to be predominantly laminated siltstone and laminated shale facies shown in Figure 10.

TENSOR MODEL ANALYSIS

The acquired triaxial resistivity is corrected for borehole effects and subsequently V1D (vertically 1-dimensional inversion) for shoulder bed effects (Hou et al., 2013). The corrected data is then used in combination with V_{Lam} to calculate the R_{Sd}. Using the interpreted V_{Sh} from quad combo data, the V_{Lam} then calculated from the crossplot between total porosity (PHIT) and V_{Sh} using the Thomas-Stieber method, as shown in Figure 11.

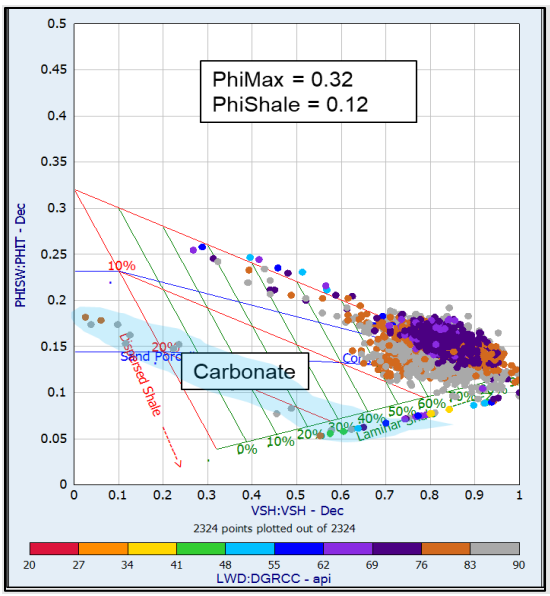

Figure 11: - Thomas-Stieber crossplot across target interval.

One of the most critical parameters in the tensor model is anisotropic shale resistivity (R_{shH} and R_{shV}), which if left unchecked, can introduce an error up to 30% in calculated R_{Sd}. Typically, the determination of anisotropic shale resistivity is using a Klein's plot against a 100% shale (Figure 12).

However, from the RV and RH data distribution in this well, a single anisotropic shale resistivity will not give the best result in representing the reservoir condition. With more than 70% V_{sh}, there is no single cloud used as a reference for anisotropic shale resistivity.

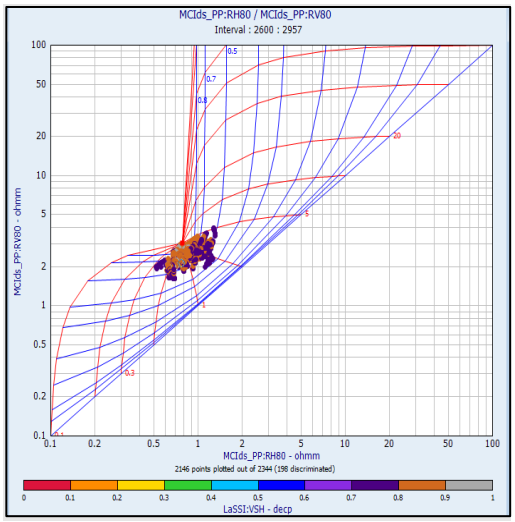

Figure 12: - Klein's Plot distribution at of Rv and Rh at V_{sh} > 70%.

Instead of using a single value for R_{shH} and R_{shV} due to varying shale properties, multiple values for anisotropic shale resistivity is used. From the facies image analysis, multiple massive shale points are picked based on proximity to the potential laminated gas-bearing reservoir, as the best representation of the shale in the laminated reservoir section. This approach will reduce the uncertainty of anisotropic shale resistivity in calculating R_{Sd}.

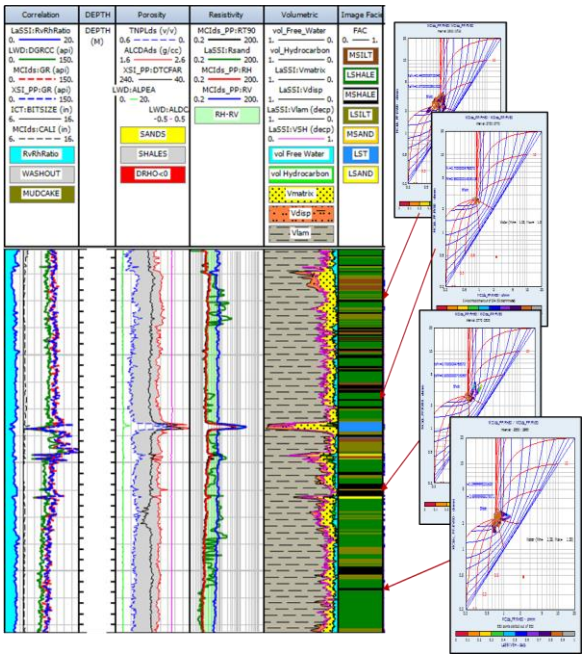

Figure 13: - Variation in anisotropic shale resistivity across the whole log interval.

GAS-BEARING IDENTIFICATION USING SLOWNESS SONIC DATA

Using the deeper section of the well, where there are multiple clean water-bearing sands, a modeled DTC at water-bearing sand ($DTC_{wetsand}$) as a function of DTS is created. This method is chosen because DTS is less affected by the type of fluid in the reservoir. The correlation between DTS and DTC at water-bearing sand indicates a good correlation, with a regression coefficient of about 94%.

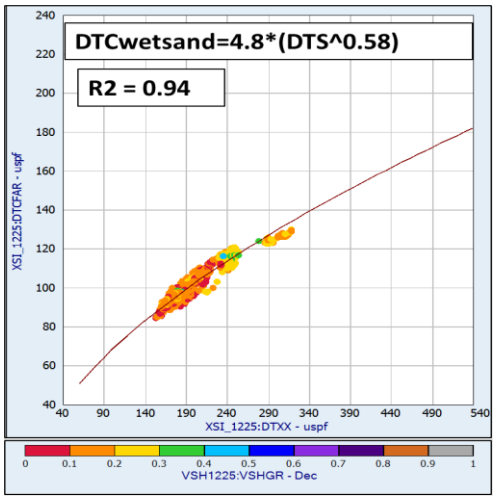

Figure 14: - DTC vs. DTS at clean water-bearing sands

This modeled DTC will be used to calculate DTC at target interval and will be compared to measured DTC to identify the presence of a gas-bearing reservoir. The VPVS ratio was also calculated from the modeled DTC as $VPVS_{wetsand}$ against the measured VPVS. DTC baseline using shale DTC, $DTC_{wetsand}$ vs. DTC, and $VPVS_{wetsand}$ vs. VPVS will all be used to support the interpretation of gas-bearing reservoir with relation to the tensor model result.

INTERPRETATION RESULT (TENSOR MODEL AND GAS-ID USING SONIC)

The full interpretation of this well is made by combining the saturation result from the Tensor model and qualitative Gas-ID from sonic. The result is also plotted alongside gas reading from mudlog to help compliment the interpretation.

The target intervals are indicated by the red shadings numbered from 1 at the top to 3 at the bottom (Figure 15). These zones are focusing on the shaly sand reservoir only.

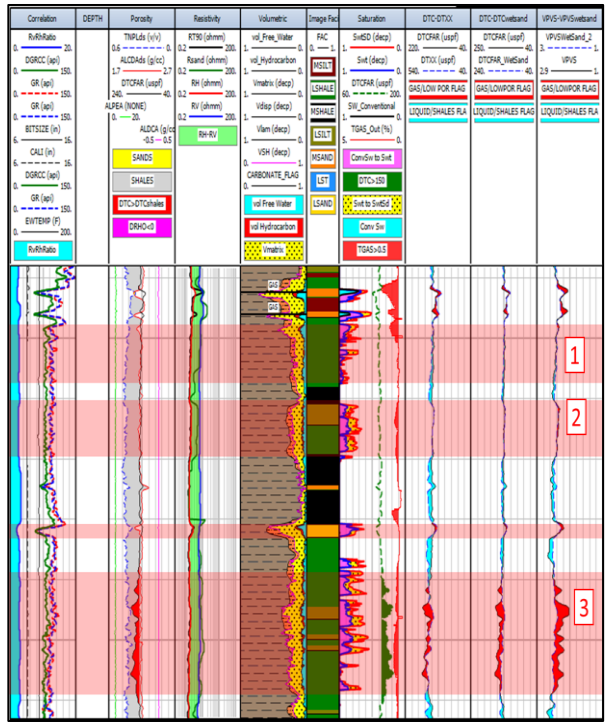

Figure 15: - Integrated plot across target intervals.

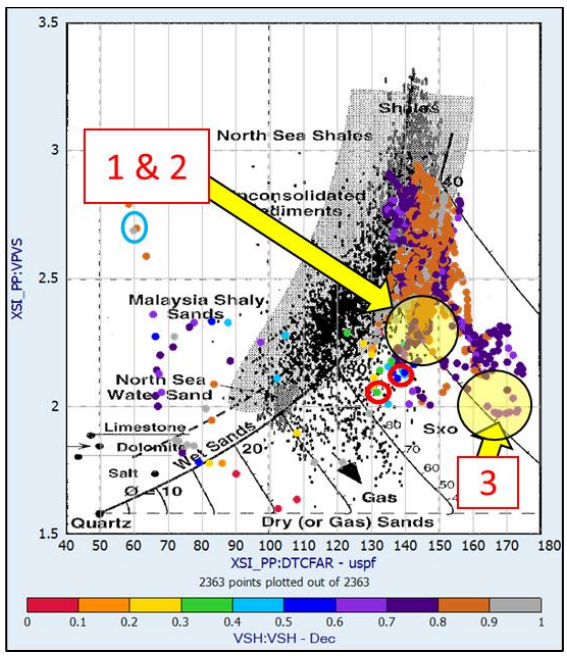

Figure 16: - Brie's plot across target intervals.

The Brie's plot is shown (Figure 16), with water and tested gas marked as blue and red circles, respectively. The target intervals distribution is marked with the yellow-shaded circles.

Zone 1 and 2 indicate about 10-20% total gas saturation from the tensor model, while zone 3 indicates about 20-40% total gas saturation from.

The result from tensor model analysis improves the gas saturation up to 20% over conventional saturation analysis. (Figure 17).

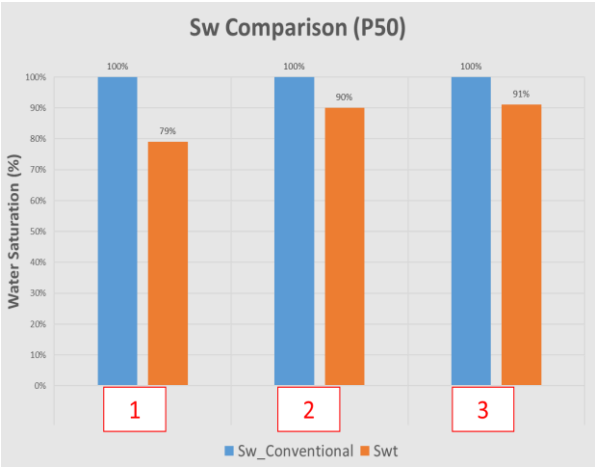

Figure 17: - Saturation improvement after Tensor Model

The combination of the tensor model and Brie's plot provide supporting evidence of the gas-bearing presence. Total gas reading supports the interpretation with high reading across target intervals.

The first and second zones indicate a small amount of gas saturation, which may produce gas with zero water cut depending on the reservoir flowing properties. Additional information from NMR log may help understanding the reservoir flowing properties.

The third zone indicates a higher gas saturation, supported by the other data (sonic interpretation and total gas reading). Among all zones in the target intervals, this zone is the most promising zone to develop further.

CONCLUSION

The tensor model improved the gas saturation by 4-21%, depending on sand thickness and shale volume, which increased the net to gross by more than 20%.

The gas saturation improvement after the tensor model is supported by the sonic slowness qualitative interpretation (Brie's plot).

The borehole image facies analysis helps to objectively select the anisotropic shale resistivity parameters to minimize R_{Sd} uncertainty.

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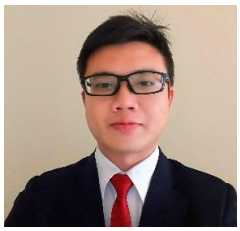

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