AN INTEGRATED APPROACH FOR REDUCING UNCERTAINTY IN THE ESTIMATION OF FORMATION WATER SATURATION AND FREE WATER LEVEL IN TIGHT GAS RESERVOIRS – CASE STUDIES

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ABSTRACT

To reduce the uncertainty in the estimation of hydrocarbon in place and fluid contact in tight gas reservoirs, it is essential to integrate core data and log analysis. A newly developed JMOD (an EXCEL-based saturation-height approach) has been successfully applied to calibrate log analysis to better define petrophysical properties such as formation water saturation and free water level in tight gas reservoirs. The application of this approach has played a critical role in exploration and development decision-making processes for tight gas reservoirs.

This approach is derived from capillary pressure and Leverett's "J-Function" concepts. The approach utilizes the constants that are obtained from curve-fitting "J-Function" from measured capillary pressure data. Unlike most of the models published in the literature, this approach accommodates different forms of J-Sw regressions, which is applicable to different pore geometries and very powerful in tight gas reservoirs. Using this approach, water saturation is calculated continuously from log porosity and free water level without formation resistivity and Archie exponents. This approach also estimates free water level by iterating on water saturations until matching those derived from log data.

In a tight gas "wild-cat" well where the porosity from most of the well logs is much larger than that from core analysis, this new approach was successfully utilized to reconcile the difference and predict the rock quality up-dip. The results are confirmed by the pressure transient analysis from the production test. Based on the integrated analysis, the decision to abandon the current well and up-dip drilling plan saved the company millions of dollars.

The reservoir simulation could not get a history match for a tight gas field. The parameters of this new approach were calibrated to several key wells with core data in this gas field. The results of the calibration were then used to populate water saturation throughout the field. Eventually, the history match was successfully achieved and the infill drilling opportunity was identified for this field.

In summary, this paper introduces a new integrated EXCEL-based saturation-height approach (JMOD) and its application to tight gas reservoirs. This paper also presents the

case studies that document the avoided failures and the captured opportunities by applying the proposed approach.

INTRODUCTION

There are significant uncertainties in log calculated water saturation (Sw), especially in tight gas, shaly, and heterogeneous reservoirs. Capillary pressure is an adhesive force caused by electro-static charges at the interface and is equal to the pressure difference between non-wetting and wetting phases at equilibrium condition**,** which is determined by pore throat size, wettability, and inter-phase tension in a pore system. The saturation profiles of virgin hydrocarbon reservoirs exemplify the balance between the opposing forces of gravity (buoyancy) and capillarity. The magnitude of those opposing forces is determined by the properties of a specific pore network and the fluids it contains. These opposing forces interact to produce a unique saturation profile that provides a core calibrated Sw calculation to "fine-tune" log analysis parameters so that uncertainties may be quantified and potentially mitigated. Free Water Level (FWL) is needed for volumetric calculations, well location determination, and reservoir producibility forecast for up-dip or down dip wells. The capillary pressure derived saturation-height function can be used to calculate FWL. Saturation-height function is recommended for geological model and reservoir simulation to normalize capillary pressure curves, especially for rocks with large transition zones in heterogeneous reservoirs.

The saturation-height function has taken many forms through previous decades by numerous authors [1-16]. Commonly used techniques are listed as follows:

$$J(Sw) = \frac{Pc}{\sigma \cos\theta}\sqrt{\left(\frac{k}{\Phi}\right)} \tag{1}$$

$$J = a\,(Sw)\hat{}\ b \tag{2}$$

$$\log(Sw) = b * Pc\ \hat{}\ (-c) - a * \log(k) \tag{3}$$

$$\log(\Phi * Sw) = a * \log(h) + b \tag{4}$$

$$Sw = 1 - a * \exp[-(\frac{b}{h+d})\hat{}\ c] \tag{5}$$

$$Sw = a + b\hat{}\,\Phi + c(d-\Phi)(d-owc) + (\frac{1}{1.068+gwc})\hat{}\,(-0.33) \tag{6}$$

$$Sw = Swirr + (1 - Swirr)e\hat{}\,(-gh) \tag{7}$$

$$Swirr = b\Phi + c\log(k) \tag{8}$$

$$Sw = \frac{a}{h\hat{}\,(b-\log(h))} + Swirr \tag{9}$$

$$Sw = a + b\Phi + c\log(h) + d\Phi\hat{}2 + f\log(h)\hat{}2 + g\Phi\log(h) \tag{10}$$

$$Sw = 1 + (a + b\Phi) + [1 - e\hat{}\,(c * gwc * \Phi(d + f\Phi))] \tag{11}$$

The majority of the saturation-height equations (2 -11) are based on curve-fitting with the observed data sets and labor intensive to implement. Equation 1 is based on both experimental tests and theoretical derivation [8], which is based on rock property physics and easiest to implement and apply [5].

In 1940, Leverett [8] introduced a dimensionless J-function or Equation (1) to convert all capillary data with similar pore geometry to a universal curve. The "cos θ" term was added later to include wettability effect. The $\sqrt{\frac{k}{\Phi}}$ term is the pore geometry factor and is used to normalize petrophysical properties such as capillary pressure, relative permeability, and residual saturations. The proposed approach in this paper has been built on Equation (1). The term Pc in Equation (1) is capillary pressure that can be expressed by:

$$Pc = (FWL - TVD) * 0.433 * \Delta SG \qquad (12)$$

Sw at each True Vertical Depth (TVD) can be solved by combining Equation (2) and (12):

$$Sw = \sqrt[b]{\frac{(FWL - TVD) * 0.433 * \Delta SG * \sqrt{\frac{k}{\Phi}}}{a * \sigma * \cos\theta}} \qquad (13)$$

Equation (2) does not seem to match core measurement in tight gas reservoirs. A new equation is proposed and seems to match core measurement much better:

$$J = a * e\hat{}(b * Sw) \qquad (14)$$

The proposed water saturation calculation is derived by combining Equation (12) and (14):

$$Sw = \frac{\ln\left(\frac{(FWL - TVD) * 0.433 * \Delta SG * \sqrt{\frac{k}{\Phi}})}{a * \sigma * \cos\theta}\right)}{b} \qquad (15)$$

Using Equation (15), Sw can be calculated for each TVD depth if FWL is known. If FWL is unknown, Sw and FWL can also be calculated iteratively by integrating core capillary pressure and log data.

PROCEDURES

An EXCEL program (JMOD) has been developed to integrate core and log data so that uncertainty in petrophysical parameters can be reduced and reservoir properties such as Sw and FWL can be calculated. The procedures of this integrated approach are outlined as follows:

Step.1 Convert Pc and J-function to reservoir condition:

$$P_{Cres} = P_{Clab} * \frac{(\sigma * \cos\theta)_{res}}{(\sigma * \cos\theta)_{lab}} \quad (16)$$

$$J_{res} = \frac{P_{Cres}}{(\sigma * \cos\theta)_{res}} \sqrt{\frac{k}{\Phi}} \quad (17)$$

Step.2 Fit J function from core data to obtain constants a and b in Equation (14) or Equation (2).

Step.3 Calculate Sw and FWL using Equation (15) or Equation (13). The program has a pull-down button for fitting function selection, which accommodate not only exponential and power functions but also any other form of J-function that fits the core data.

Step.4 Compare the calculated Sw using Equation (15) or (13) with that from log analysis.

Step.5 Predict Sw profile at different depth assuming constant porosity and permeability. Once a good match is achieved through Step.4, Sw profile can be predicted for drilling well location selection or producibility determination for up and down dip wells.

Step.6 Plot Sw versus depth to investigate Sw changes for up-dip and down-dip wells.

RESULTS

Case 1 – Estimate FWL and Calculate Sw for Reservoir Simulation Initialization

Case 1 is an example of using the integration of log and core data to calculate FWL and Sw for reservoir simulation initialization. Capillary pressure curves are available in wells W2, W11, and W6. Through J-function curve fitting with the core data, the constants a and b in Equation (14) and (15) were obtained. Using Equation (15), the FWL was calculated by iteratively matching the calculated Sw with log-derived Sw. Once FWL, a, and b are determined, water saturation is calculated using Equation (15) for all the wells that do not have capillary pressure data. The matches between calculated and log derived water saturation are reasonably good (Fig.1 and 2). The porosity and Sw were predicted for well W4 where there is neither log nor core data (Fig.2). Fig.3 is a water gas ratio map derived from Equation (15), which has been used for well location selection for infill drilling. Fig.4 effectively explain the reason that wells W6 and W7 are water producers, since they have poor rock quality and high water saturation.

Case 2 – Calibrate Density Log and Predict Sw up-dip

Case 2 is an application of JMOD to a tight gas exploration wildcat for porosity calibration and up-dip well Sw prediction. Fig.5 shows that the density porosity is up to 8% higher than core porosity. Sw calculated by JMOD does not match that estimated from density log (Fig.6) even after numerous FWL iterations. Thin section analysis also indicates that the density log derived porosity is too high (Fig.7). Since shear velocity tool is less borehole-fluid sensitive than density tool, porosity is calculated from shear DT. The porosity from shear DT matches very well with that from core measurement (Fig.8). The Sw derived from JMOD using shear DT derived porosity matches reasonably well with that from log analysis using the same porosity (Fig.9). The integrated approach resulted in a consistent story, which greatly reduces the uncertainty introduced by any single source of data. The reserve was re-calculated using the core calibrated shear DT porosity and the well result was not economical, so the well was abandoned.

The next issue to address was that if moving up-dip 200 feet (structure limitation), how much lower would Sw be? Sw profile was predicted by JMOD using the parameters such as a, b, and FWL obtained in the Wildcat well. The results show that there is only approximately 5% Sw improvement (Fig.10). The economics with 5% Sw improvement still could not save the project.

Case 3 – Prediction of FWL and Calibration of Log Analysis Parameters such as Vsh and Rw for Exploration Wells

There were some uncertainties of FWL and petrophysical properties such as Vsh and Rw in tight gas exploration wells. After applying the proposed approach (JMOD), the predicted FWL matches very well with that from the crossover depth by gas and water gradient lines determined by RFT pressures. The Sw predicted for up-dip well and that for down-dip well in the same sand falls nicely in the same predicted Sw profile (Fig.11). The down-dip well tested water with some gas, which fits very well with the predicted Sw profile in Fig.11. When inconsistent Vsh was applied in log analysis, there was no match between log derived Sw and JMOD predicted Sw (Fig.12). After correcting Vsh, the Sw from log analysis seems to match reasonably well with that from JMOD (Fig.13). When the incorrect Rw was used, there seemed to be no match between Sw from log analysis and that predicted by JMOD (Fig.14). After the right Rw was applied, the match is reasonably good (Fig.15). The Rw was later confirmed by water analysis results from the same well.

DISCUSSION

This proposed approach (JMOD) is similar to the previous work [2,8], but it distinguishes itself in being capable of accommodating different J-Sw fitting functions and being able to integrate/reconcile log and core data in an efficient manner. JMOD can be easily applied to FWL calculation, Sw profile prediction, and log analysis parameter calibration. FWL is recommended rather than GWC, because FWL unifies fluid contact determined from logs, RFT pressure gradients, and capillary pressure data [2]. In addition, GWC is often unclear and needs agreed Sw convention, since gas column may be considered to be a continuous transition zone [2].

The limitation of this approach is that it is only applicable to similar pore geometry, although more than one saturation-height functions may be determined for different pore geometries.

CONCLUSIONS

An EXCEL-based integrated saturation-height approach (JMOD) has been developed and applied to tight gas formations for exploration and development decisions. Case studies of FWL determination and log analysis parameter calibration have been presented. The application of this proposed approach have greatly reduced the uncertainty in hydrocarbon in place estimation, avoided some failures, and captured opportunities in exploration and development processes.

NOMENCLATURE

Sw: Water saturation, frac.
Swirr: Irreducible water saturation, frac.
Φ: Porosity, frac.
k: Permeability, md
h: Height above FWL, ft.
gwc: Gas water contact, ft
a,b,c,d,f,g: Constants
Pc: Capillary pressure, psi
J (Sw): Leverett's J-function, dimensionless
σ: Interfacial tension, dyn/cm
θ: Contact angle
ΔSG: Specific gravity difference between wetting and non-wetting phases
TVD: True vertical depth, ft
DT: Acoustic transit time, us/ft

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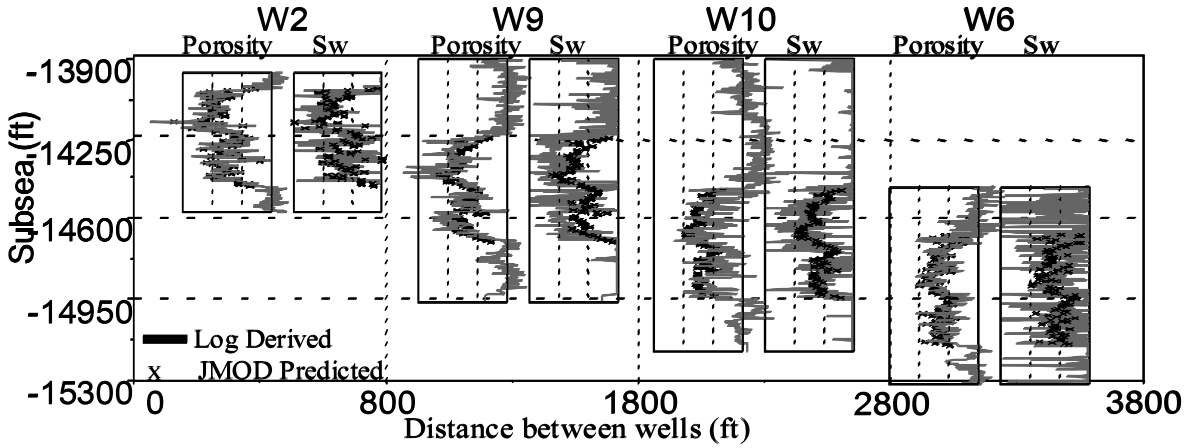

Fig.1- Porosity and Permeability Match and Prediction

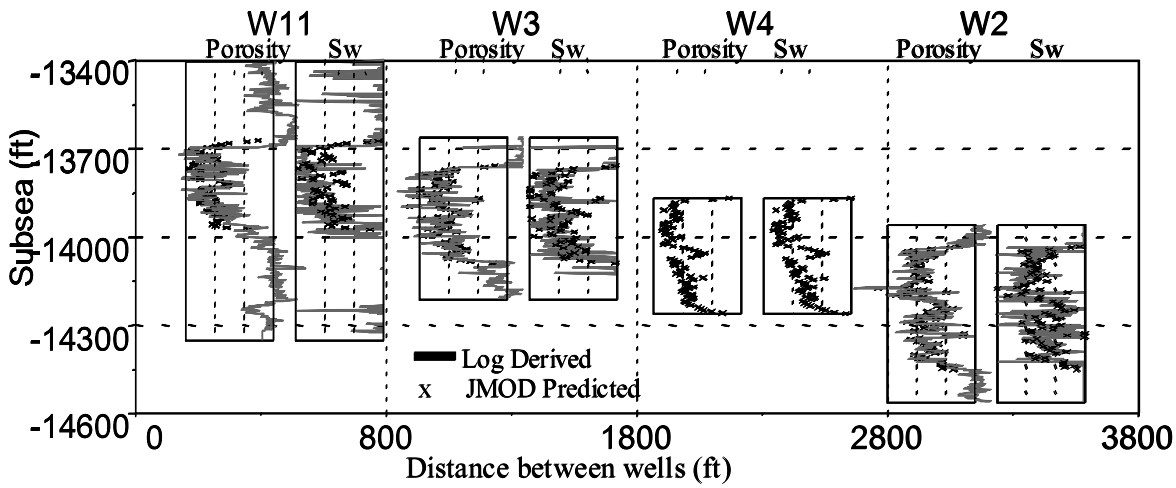

Fig.2 - Porosity and Permeability Match and Prediction

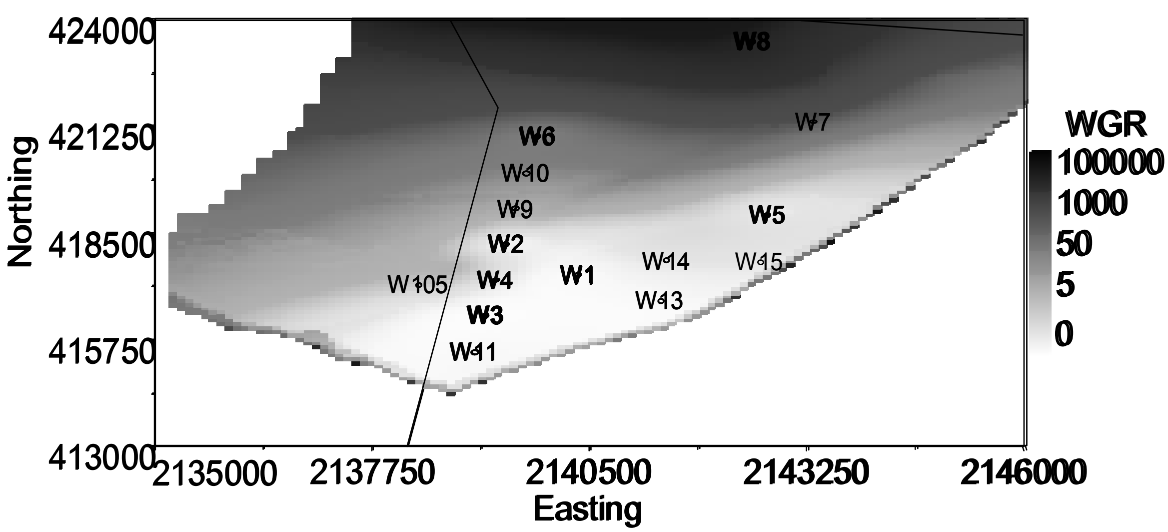

Fig.3 – Water Gas Ratio (STB/MMCF)

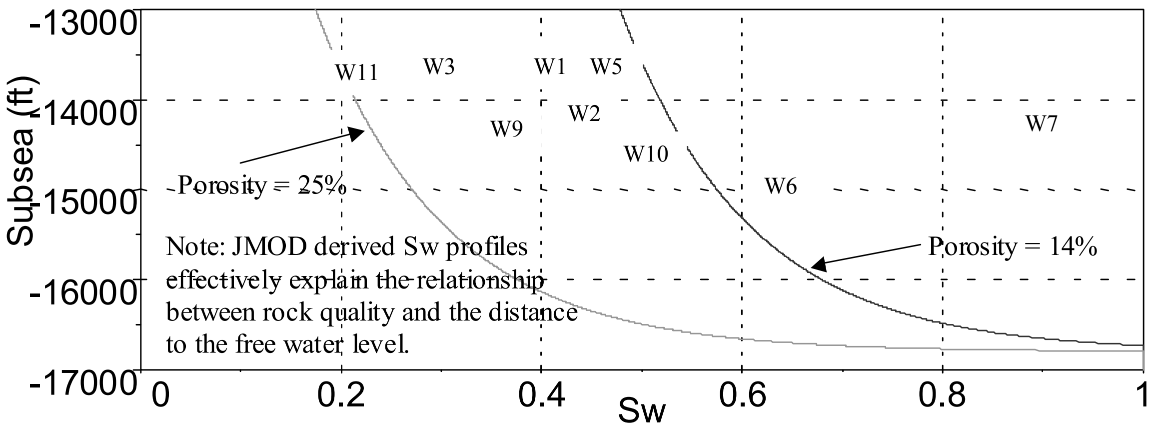

Fig.4 – JMOD Derived Sw Profile for Different Porosity

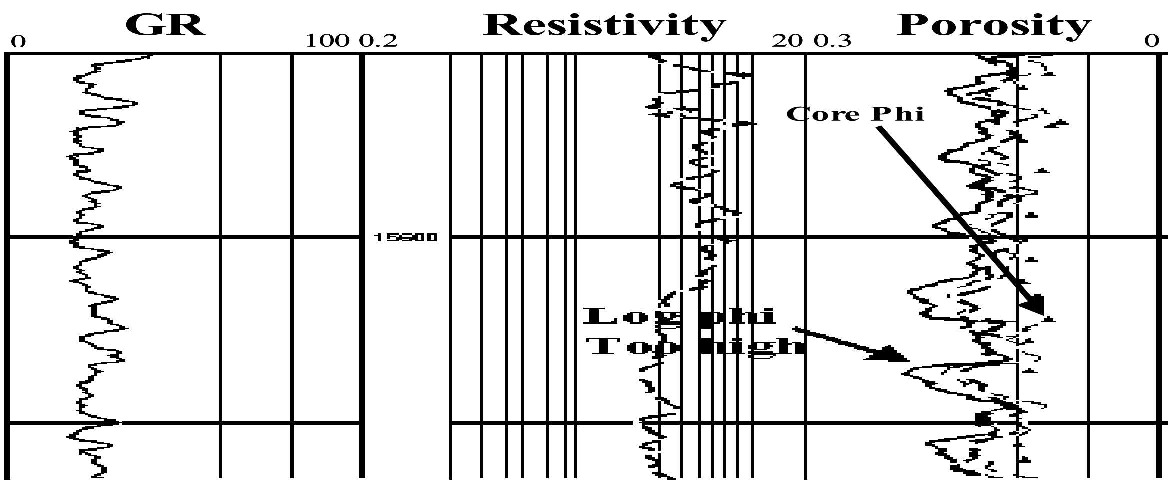

Fig.5 – Density Porosity Does not Match Core Porosity

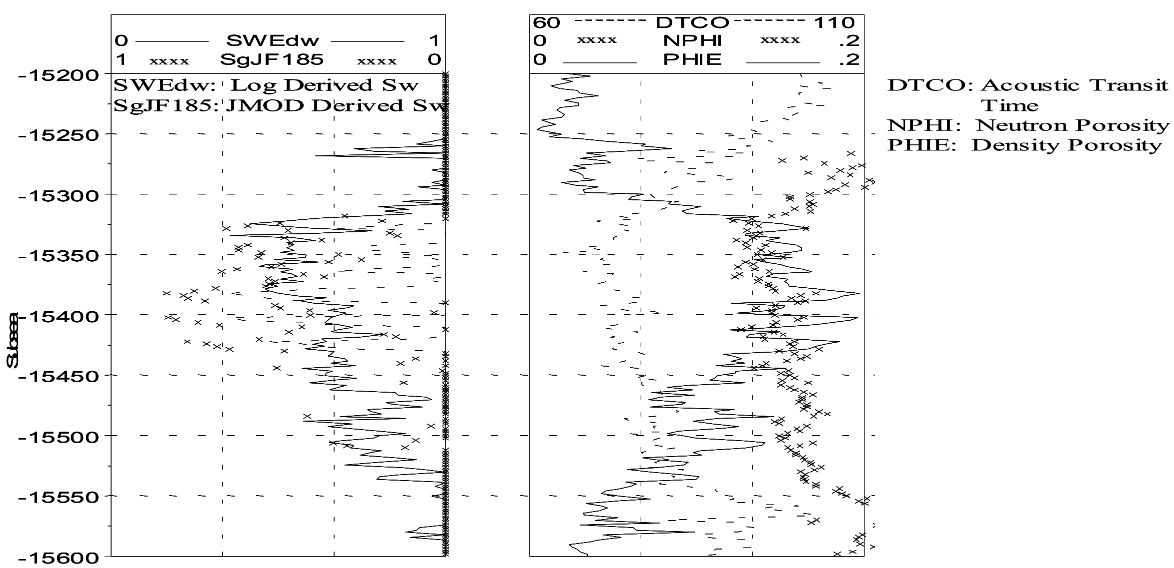

Fig.6 – No Sw Match When Using Density Porosity

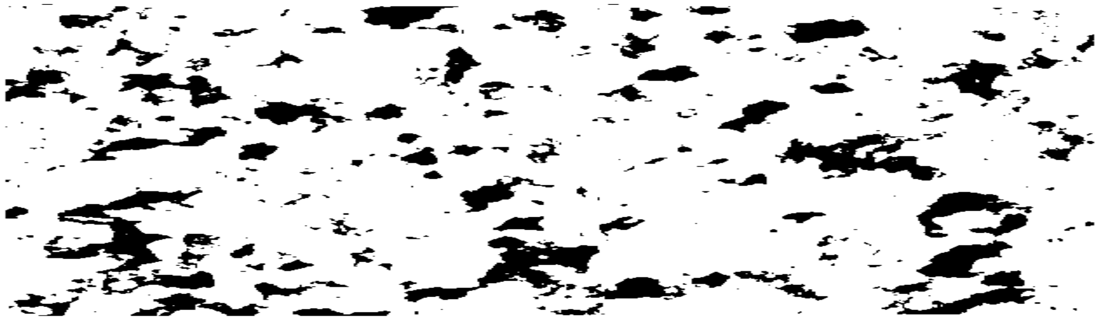

Fig.7 – Point count porosity=9%, Log porosity=18%

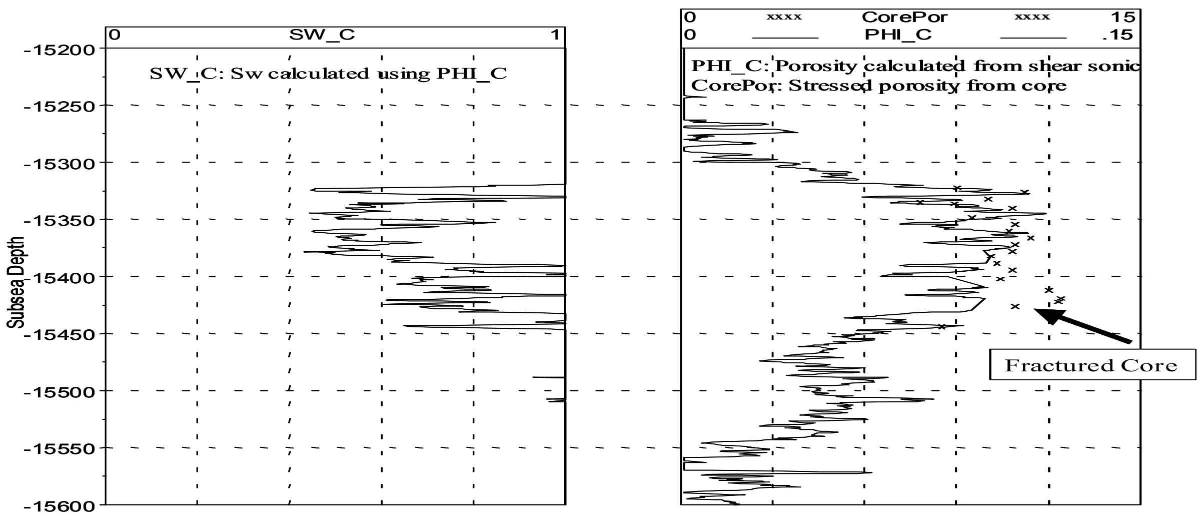

Fig.8 – Shear DT Derived Phi Matches Core PHI

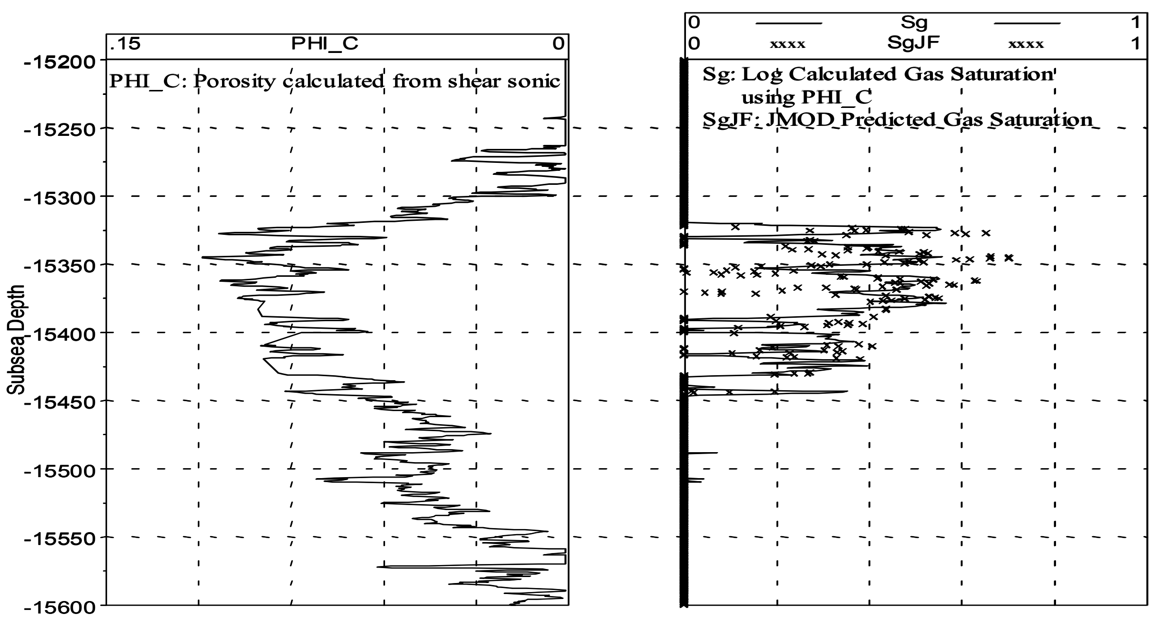

Fig.9 – JMOD Predicted Gas Saturation Matches that calculated by Log

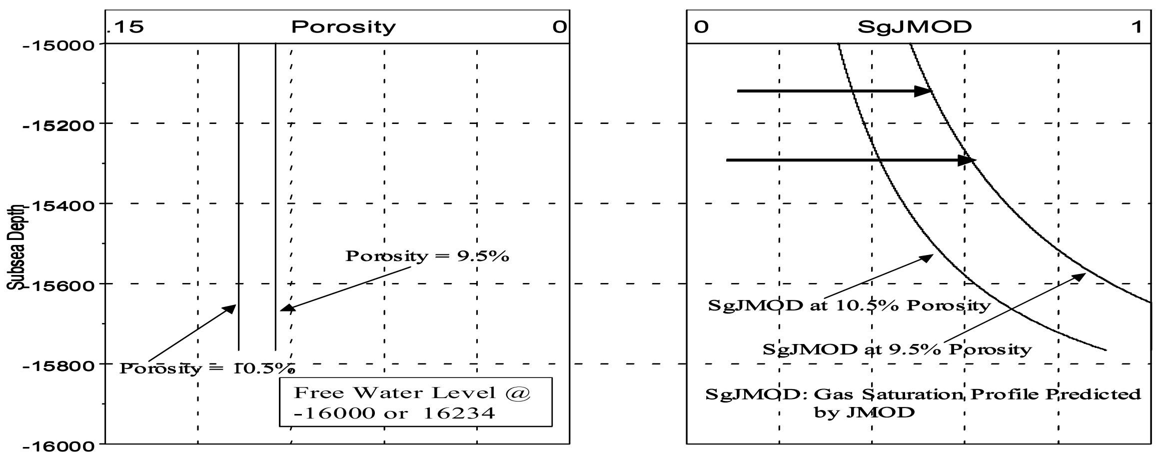

Fig.10 – 5% Gas Saturation Improvement Moving 200' Up-dip

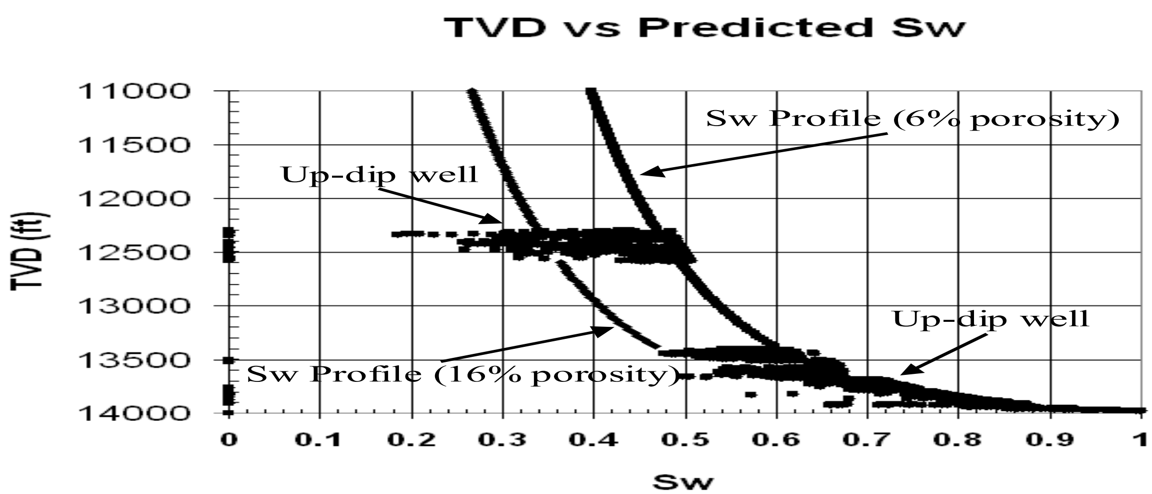

Fig.11 – The Log Sw from Both Up and Down-dip Falls in Predicted Sw Profile

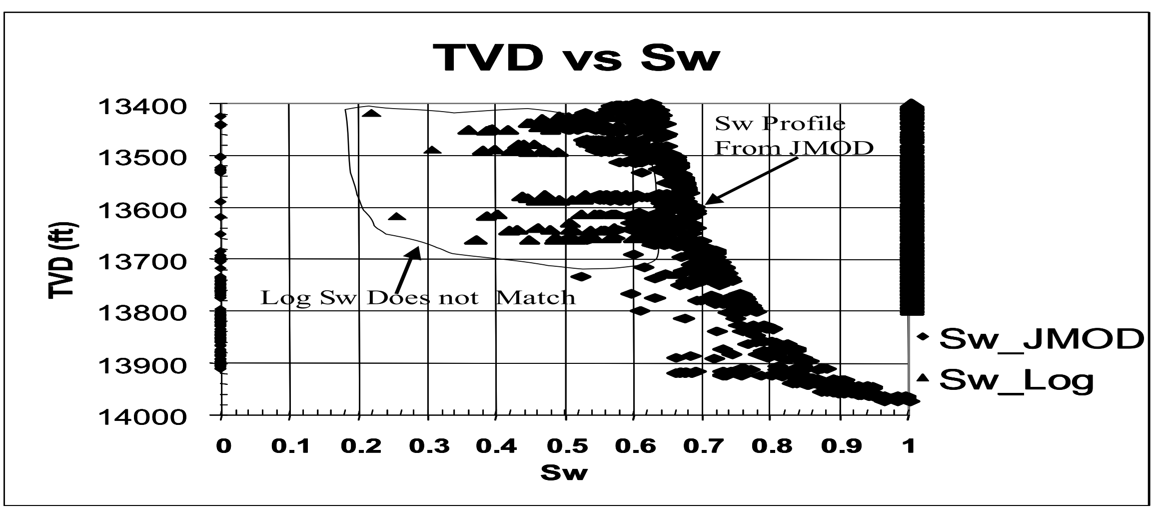

Fig.12 - Cap. Derived Sw Does **NOT** Match with Log Sw using too low Vsh

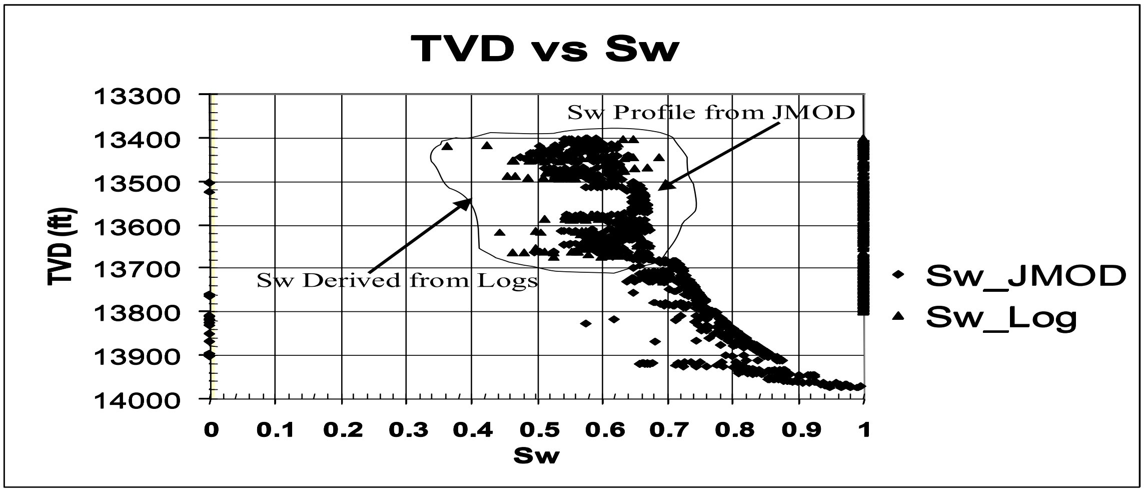

Fig.13 - Cap. Derived Sw Matches Reasonably Well with Log Sw using Consistent Vsh

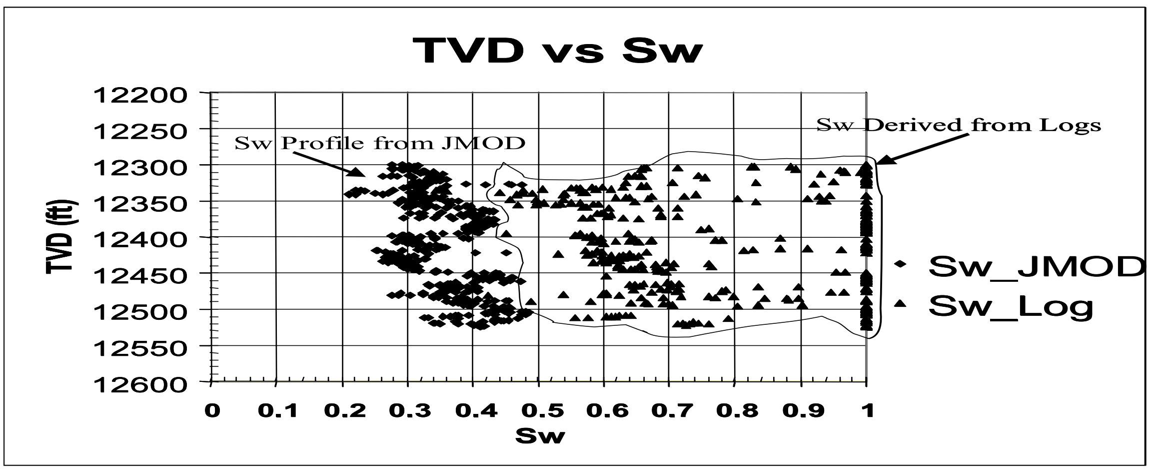

Fig.14 - Cap. Derived Sw Does **NOT** Match with Log Sw using Rw = 0.05 ohmm

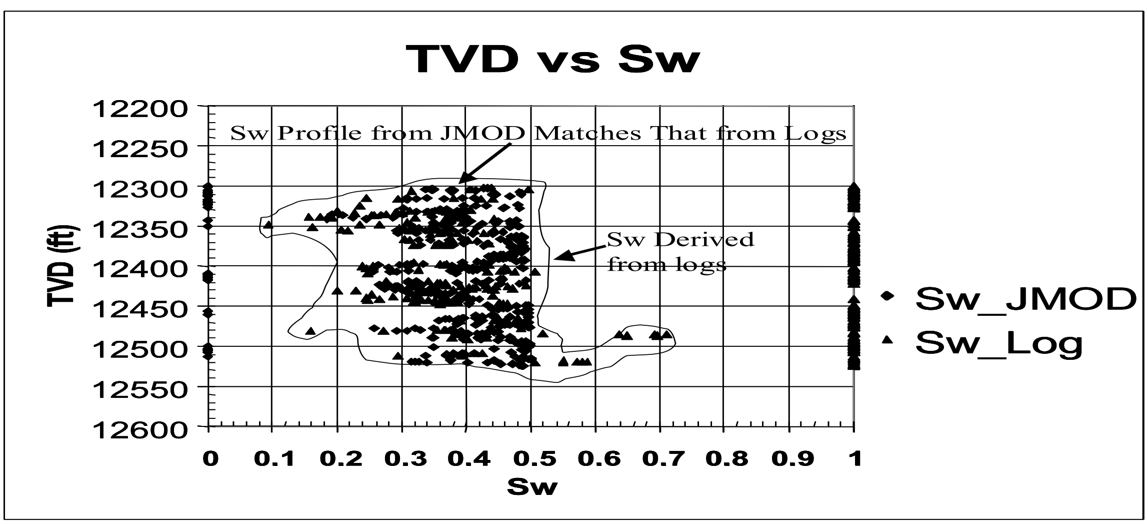

Fig.15 - Cap. Derived Sw Matches Reasonably Well with Log Sw using Rw=0.02ohmm