



Integration of advance logs to solve low resistivity contrast silty sand reservoirs and establish a unique saturation height equation

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Abstract

The petrophysical interpretation of silty sand reservoir is challenging and it is increased many folds in saturation estimation due to its low contrast resistivity nature. Many models are developed to address the issue for the sand-silt-clay reservoir but may not be applicable in all cases.

The present case study is from Upper Assam Basin where one of the silty sand reservoirs with resistivity in the range 10-12 ohm-m having very low contrast with adjacent shale produced huge amount of gas with condensate. The advance logs viz. NMR and image logs are integrated with conventional logs to reduce uncertainty in estimation of volumes, porosity and water saturation. Three different deterministic methods are applied to resolve for sand, silt and clay volumes. Two methods, i) the Sand-Silt-Clay (SSC) model from conventional logs and ii) NMR based volumes are used to solve the same. Thirdly, the image log average resistivity curve is extracted and used for demarcating sand, silt and clay. As adequate core data is not available, permeability is estimated using NMR porosity and permeability relation.

The saturation estimation in low resistivity contrast reservoir is complex and ends-up with underestimating hydrocarbon saturation with conventional methods. The Pseudo-Archie equation is used to estimate the pseudo values of Archie “m” and “n” in wells with NMR data and applied in other wells to estimate water saturation. Though this method shows substantial upsides in hydrocarbon saturation, still effected by surface conductivity/silty formation response. Therefore, Artificial Neural Network (ANN) is used to estimate the water saturation and is validated with production data.

An attempt has been made to estimate the saturation height equations from the relationship of height above Free Water Level (FWL) and ANN based water saturation. Three saturation height equations are established on the basis of porosity variations. By

using the petrophysical model presented in this paper, we are able to quantify the low-contrast pay which matches the production data and significantly improves the reserve.

Introduction

Water saturation is the key parameter in petrophysical evaluation, modelling and reserve estimation. The aim of the present case study is to fit a petrophysical model to solve the silty sand reservoirs of Upper Assam Shelf Basin, India. The study was initiated when a silty sand reservoir with low resistivity (10-12 ohm-m) compare to adjacent shale produced gas more than 0.1 MMSCMD with oil around 20 m³/day (Figure-1).

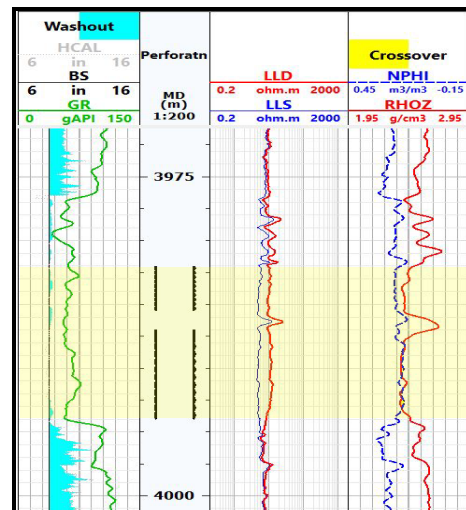


Figure 1: Well log motif of low resistivity contrast silty sand reservoir

The petrophysical evaluation of low salinity silty sand reservoir with relatively low resistivity is always challenging. Conventional petrophysical evaluation, in such reservoirs results in estimation of high-water saturation. Therefore, an approach has been made to estimate water saturation and is presented in this paper.



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The Sand-Silt-Clay petrophysical model is developed to address the issues arise due to grain size variation in some of the clastic reservoirs. This type of reservoirs generally consists of fine to very fine-grained sediments (silt) with low formation water salinity. In this model, the three main groups of particle size of lithological components (sand, silt and clay sized particles) are captured, based on core data acquired in the Malay Basin (Heavysege 2002). The same has been adopted in the study area to assign the endpoints for SSC modeling in the study area.

Sand-Silt-Clay Model

(i) The Sand-Silt-Clay (SSC) model from conventional logs

The SSC model is used in silty sand reservoirs of the study area to solve the uncertainty in estimation of volumes and porosity. The litho-porosity model based on the density-neutron cross-plot is illustrated in Figure-2.

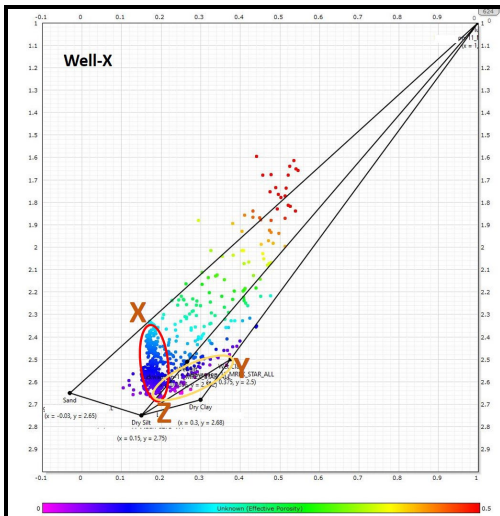


Figure 2: Neutron-Density Cross-plot representing sand-silt-clay Boomerang shape in study area

The data points, which forms a boomerang type of distribution are used to define the end points. Thus, the point X represents a clean, wet, quartz sandstone; point Y represents a wet clay and Z represents a wet siltstone. These end members are referred to as sand, clay, and silt respectively. Thus, any rock (matrix and porosity components) can be described in terms of these end members.

The SSC model output is presented in Figure-3. Porosity computed from logs, based on the lithological composition from the SSC model, matches very well with the NMR porosity (track-6).

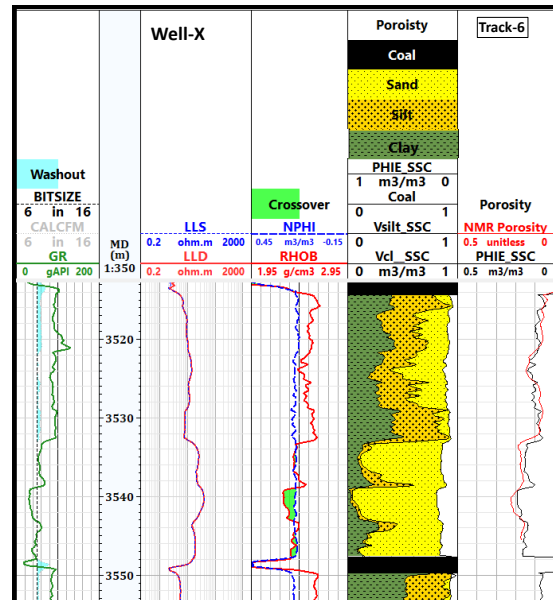


Figure 3: Sand Silt Clay (SSC) model output

The SSC model is applied in another silty sand reservoir and validated the porosity output with conventional core porosity data (Figure-4).

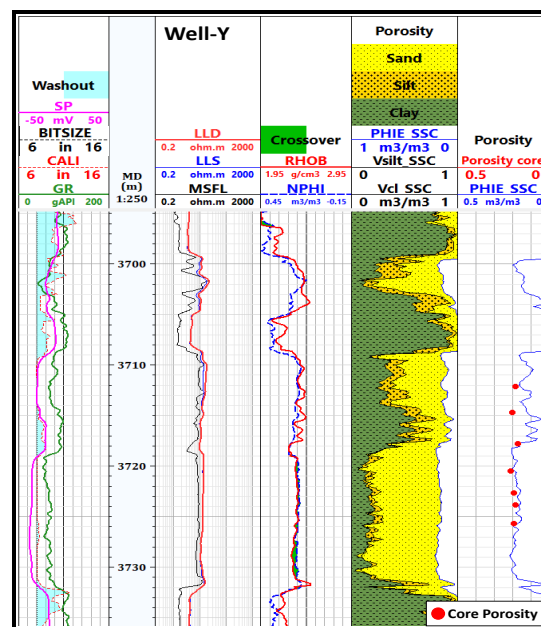


Figure 4: Sand Silt Clay (SSC) model output



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(ii) NMR based sand, silt and clay volumes

NMR total porosity, CBW (Clay Bound Water) and BVI (Bulk Volume Irreducible) obtained from T2 relaxation can be used to calculate effective porosity (Φ_e), volumes of sand, silt and clay in the reservoir. The total bound fluid volume BFV is split between clay-bound (Φ_{clay}) and capillary-bound (Φ_{silt}) volumes with a clay cut-off (Claverie et al. 2007). The volumes of clay, silt and the effective porosity can then be calculated with the following equations:

$$\Phi_e = \Phi_T - \Phi_{Clay}$$

$$V_{Clay} = \Phi_{CBW} / \Phi_{Clay_wet}$$

$$V_{Silt} = [(1 - V_{Clay} - \Phi_e) / \Phi_e] * \Phi_{BVI}$$

$$V_{Sand} = 1 - V_{Silt} - V_{Clay} - \Phi_T$$

This method can provide a robust and fast volumetric analysis, results are plotted in Figure-5

(iii) Image log for demarcating sand, silt and clay

The average resistivity curve is extracted from image log. The borehole image in this well clearly defines numerous conductive silt and clay laminations in a resistive sand matrix. Cut-offs are selected to demarcate the sandstone, silt, clay and coal are plotted in Figure-5.

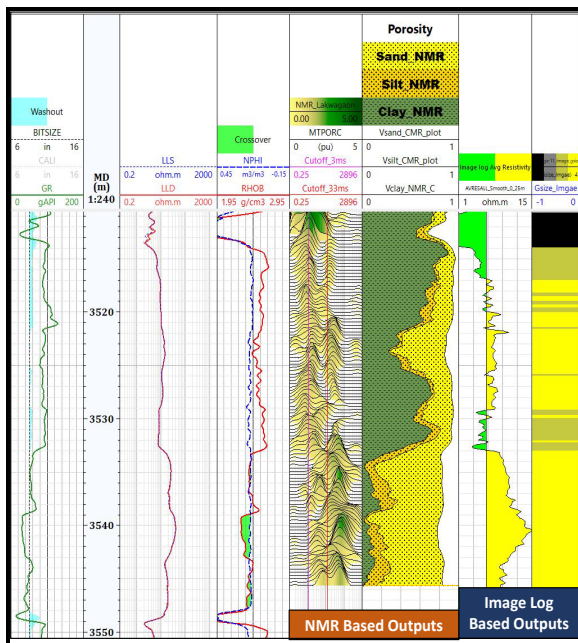


Figure 5: NMR & Image based volume estimations

Permeability Estimation

Though the core data is available for one well but data is not enough to make a relationship between porosity and permeability. Therefore, the permeability is estimated using modified Coates equation and NMR data.

The permeability is computed using following modified Coates equation and is validated with NMR permeability (Figure-6).

$$k = 1014 \times ((\Phi_e^3) / (1 - \Phi_e)^2) \times (((1 - V_{cl}) / (2 \times V_{cl} + \Phi_e))^2)$$

where Φ_e is effective porosity and V_{cl} is volume of clay.

A regression line has been fit into a NMR porosity-permeability cross-plot and the regression equation is utilized to estimate permeability in the study area. The NMR permeability (33 ms cut-off), NMR regression equation permeability and modified Coates permeability are plotted in Figure-6

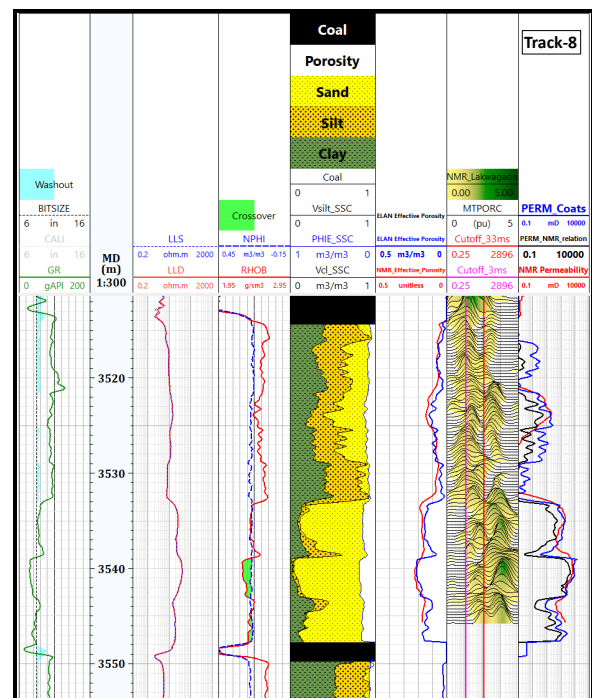


Figure 6: Well composite showing NMR and modified Coates permeability in track-8

The NMR porosity & permeability regression equation is found to be more suitable and showing a reasonable match with NMR permeability and core permeability range.

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Saturation Estimation

Conventional petrophysical evaluation in low salinity silty sand reservoir with relatively low resistivity resulted in estimation of high-water saturation (60-75%) which is not able to justify the present water free production. In addition to that the available core data shows an irreducible water saturation of 30-40% which also contradicts the same. Therefore, various approaches have been made to estimate water saturation in the study area.

Though the NMR based saturation methods found to be more accurate, all the wells don't have NMR data. An alternative approach is required to get saturation in other wells which is correlatable with NMR saturation. The Pseudo-Archie method is attempted in the study area to estimate "m" and "n" value which is further used for water saturation estimation.

Pseudo-Archie Method

The foundation of the petrophysical evaluation of freshwater reservoirs is the pseudo-Archie approach (Paul F. Worthington, 2011). This method is long been using in problematic reservoirs and its appropriate for low-salinity formations.

Estimation of "m" and "n" are challenging for hydrocarbon saturations estimation in low salinity shaly sand/silty reservoirs. The method ideally requires core measurements of F and I_r using simulated formation water so that pseudo-values of "m" and "n" can be determined directly. In absence of core, the pseudo-Archie exponents can be evaluated with the pseudo-Archie approach (Paul F. Worthington, 2010) using standard logs. The pseudo-Archie workflow as presented in Figure-7.

The "m" and "n" values were estimated using pseudo-Archie approach in the NMR wells and the average "m" & "n" values found to be 1.7 and 1.8 respectively. Those parameters were applied in other non-NMR wells to estimate water saturations. The application of this work flow in the present case study has shown that the pseudo-Archie method can indicate substantial upsides in hydrocarbon saturation but still effected by surface conductivity/silty formation response.

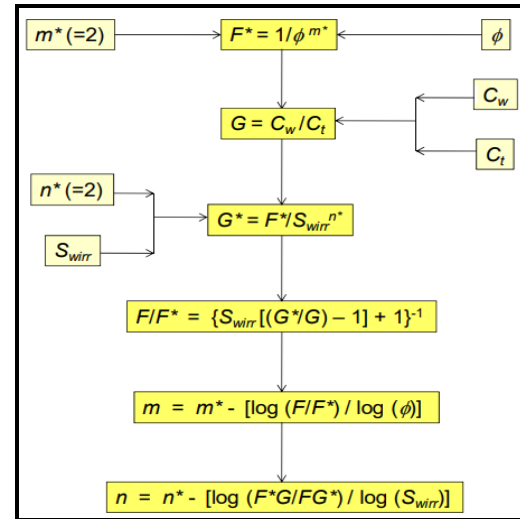


Figure-7: Pseudo-Archie workflow

Artificial Neural Networks (ANN)

The application of ANN in the field of petrophysical properties prediction has received increasing attentions. ANN is a computer model that attempts to mimic some workings of the human brain (Dayoff, 1990), analogous to biological nervous systems and consist of input layer, hidden layers and output layer (Fausett, 1994; Haykin, 1999). A neural network can learn from examples or experiences and is useful in solving pattern classification problems.

ANN process requires training data, which consist of input signals paired with target signals. The total sum of differences between the output and target values (i.e. error) for all the training pairs is minimized within the network through an iteration method. Thus, the developed ANN is a three-layer (i.e., input, hidden and output layers) model. After training, a set of parameters is determined and can be used for predicting values in situations where the actual output is unknown.

In the ANN model, effective porosity and permeability are considered as input curve and NMR based saturation is considered as curve to predict. The ANN trained in the NMR wells and applied the outcome in non-NMR wells to estimate water saturation (Figure-8).



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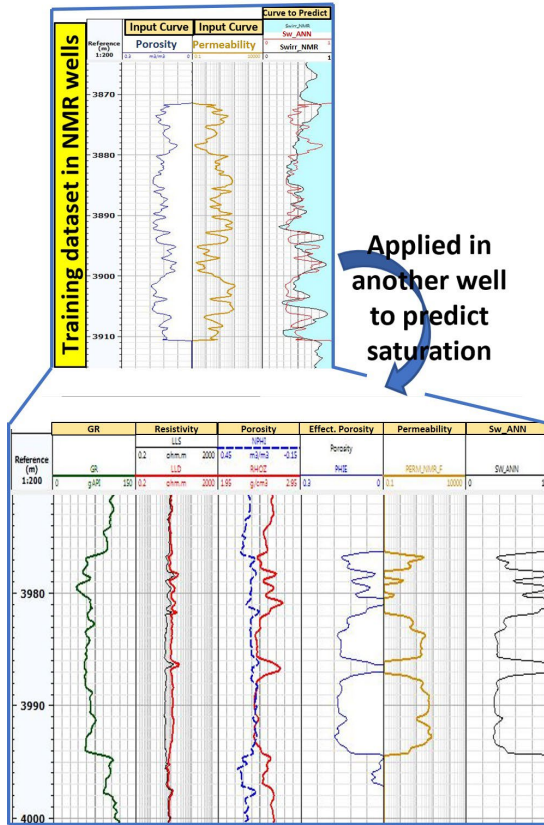


Figure 8: ANN to training data set in one well and outcome applied in other wells

A comparison of water saturations estimated from three different methods viz. conventional, Pseudo-Archie & ANN are showed in Figure-9

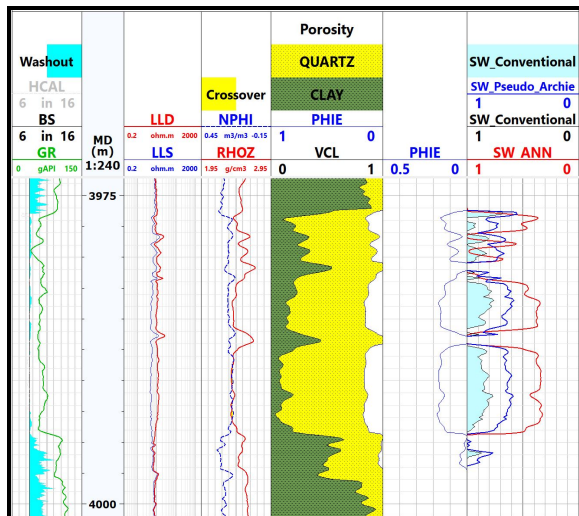


Figure 9: Saturation comparison plot

Saturation Height Equation

The ANN based water saturation vs Height above FWL is plotted with porosity in third axis in Figure 10.

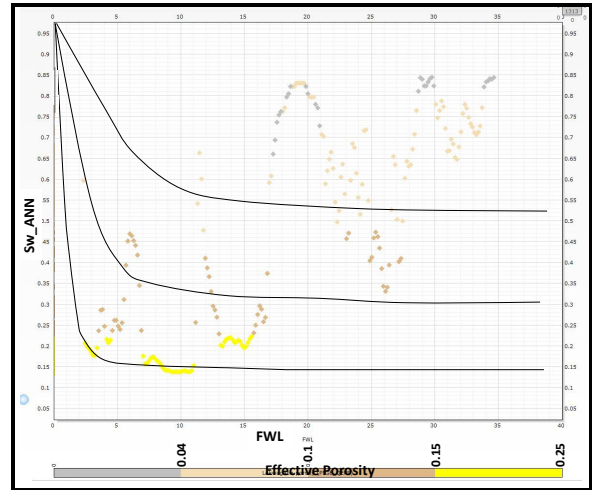


Figure 10: The ANN based saturation vs FWL

The water saturation estimated from ANN method showing a trend with porosity variation and based on these, three saturation height functions are constructed. Those equations can be further applied in static model to generate the saturation model for volume estimation.

Conclusions

Identifying, evaluating and commercializing low-resistivity contrast silty sand reservoir is a challenge. In such non-Archie cases, conventional petrophysical evaluation procedure goes wrong and the actual hydrocarbon saturation becomes very difficult to determine. Many productive silty sand reservoirs have low apparent resistivity values, and remapping these intervals using advance petrophysical techniques can get significant production and reserve implications.

In the present study, the advance logs like NMR and image log are integrated to solve the issues with low resistivity contrast silty sand reservoir and to establish a unique saturation height equation. Sand, silt and clay are quantified using neutron-density cross-plot (Sand-Silt-Clay Model) and NMR data. Both the methods work on different principles and improve the effective porosity than conventional



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method. The pseudo-Archie method is showing good result with pseudo “m” and “n” values but still it is dependent on resistivity variation caused by the grain size/ excess clay conductivity. Artificial Neural Network (ANN) technique is applied to estimate saturation in this study showing a satisfactory result and is able to make log-based saturation height equations successfully. The petrophysical model adopted, also justify the production behavior of the wells.

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Nomenclature

NMR	nuclear magnetic resonance
Ir	resistivity index
F*	intrinsic formation factor
Φ	porosity
m*	intrinsic porosity exponent
G	generalized formation factor
Cw	conductivity of formation water
Ct	conductivity of fluid fill reservoir rock
G*	intrinsic generalized formation factor
Swirr	irreducible water saturation
n*	intrinsic saturation exponent
F	formation factor
Sw	water saturation
m	porosity exponent
n	saturation exponent
FWL	Free Water Level
Vsand	Volume of sand
Vsilt	Volume of silt
Vclay	Volume of clay

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