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EA The Sand-Silt-Clay (SSC) Model: An Advanced Petrophysical Analysis and the Essential Applications to Lithology Computation, Permeability Estimation and Saturation Modeling*

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Abstract

The Sand-Silt-Clay petrophysical model is developed to solve the problems encountered in analysing most clastics reservoirs in Malaysia. This type of reservoir generally consists of fine- to very fine-grained sediments (silt) with low formation water salinity. In this model, the three main groups of particle sizes of lithological components (sand, silt and clay sized particles) are captured, based on core data acquired in the Malay Basin. The model has been developed from the Density-Neutron cross-plot to determine the lithology fractions and the porosity of the rocks. The cross-plot of Density-Neutron data, which is plotted through water-bearing sandstone, siltstone, and clay stone section in Malay Basin, shows a shape like a “boomerang”. In general, the data points that sit on the left limb of this boomerang are characterized as reservoirs and the ones on the right limb as non-reservoirs. A line called the “silt line” is drawn separating these two groups. The Density-Neutron cross-plot is a fundamental tool which is critical to the interpretation of shaly sands. The Density-Neutron cross-plot is used to determine the lithology fractions and the porosity of the rocks. In the past, the technique of selecting a clay point from the cross plot did not have a firm scientific foundation. The purpose of this article is to establish a robust procedure for petrophysical interpretation using the Density-Neutron cross-plot. Three sets of logs acquired in different reservoirs (gas, oil and heavy oil) and in very different geological environments were used to test the SSC model. The reservoirs were selected for geographical diversity and geological variability to demonstrate the robustness of the method.

The Sand-Silt-Clay Model

The Sand-Silt-Clay petrophysical model is developed to solve the problems encountered in analysing most of reservoirs in Malaysia. The Model defines the lithological components using three main groups of particle sizes which are so called Sand, Silt, and Clay sized particles (Bonnye, 2014). The model concept of particles and the fluids is presented in Figure 1.

The silt is accommodated at the expense of clay minerals, or shale. As a consequence, the locally used silty reservoir models have underestimated the amount of clay minerals associated with the silt-sized grains in the low-energy facies at the apex of the “boomerang” (Figure 2). All have defined the presence of clay minerals at the "silt" point (Heavysege, 2002).

Lithology from Neutron-Density Cross-Plots

Within the reservoir cluster, both porosity and permeability decrease from the upper most tip of the cluster to the apex of the boomerang. Core data suggests this trend is related to increasing clay and silt content associated with low energy sedimentary deposits. The distribution of data points on the cross-plot is therefore an important source of information about lithology (Bonnye, 2011).

Porosity and Lithology

The Total Porosity is calculated from Density log, using calculated grain density. Average grain density is a function of lithology fractions and their density:

$$\rho_g = V_{sand}\rho_{sand} + V_{silt}\rho_{silt} + V_{dcly}\rho_{dcly} \quad \text{(1)}$$

$$\phi_t = \frac{\rho_g - \rho_b}{\rho_g - \rho_f} \quad \text{(2)}$$

Figure 3 is an example of a Density-Neutron cross-plot through a sandstone (top), siltstone (center) and shale bottom sections from the Malay Basin for lithology volume calculation. In the top the point is located close to sand line (Vsand=1) resulting the projected Vsand is 0.85 v/v.

Permeability

A robust and inexpensive method using conventional well logs were envisaged by Chiew F. Choo in 2010. It utilizes the results from the Sand, Silt and Clay model which are currently used to predict permeability based on lithological compositions. Unlike others, this new technique has the capability to independently predict permeability in heterogeneous clastic formation which in turn can be used to determine water saturation on drainage capillarity (Choo, 2010).

The Choo permeability equation is derived based on five parameters, namely, m (cementation factor), porosity average, effective pore throat radius, grain size radius (rg) and net overburden. The results have yielded very convincing and reliable results where the permeability matched with the core data:

$$k = 0.125 \frac{rg^2 \phi^{m(\frac{2}{c}+1)+2}}{10^{(6V_{cl}+3V_{silt})}} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

Saturation Modeling

Core-derived capillary pressure measurements are normally analysed to create a set of saturation-height functions to predict water saturation anywhere in a reservoir. Handling capillary data from core is notoriously problematic. Core availability is usually limited; it is difficult and probably impossible in practice to assemble enough core plugs to represent the reservoir being studied. (Kyi and Ramli, 2011)
The Choo Saturation Height Function (Choo, 2010) is used in order to incorporate SSC petrophysical evaluation as written in Equation 4:

$$S_{w.cap} = \frac{10^{\left[(2b_o-1)\log\left(1+S_{wb}^{-1}\right)+\log(1+S_{wb})\right]}}{\left[0.2166 \frac{P_c}{\sigma\cos(\theta)}\sqrt{\frac{k}{\phi_t}}\right]^{b_o \frac{\log\left(1+S_{wb}^{-1}\right)}{3}}} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

The benefit of using the Sw equation above lies in its ability to accurately determine permeability. Then, the complex inter-relationship among reservoir rocks, water saturation, wettability and capillary or buoyancy pressure can be unravelled. Water saturation at the wellbore can be predicted without having access to a resistivity log (Figure 4). Given a column of hydrocarbon of known properties and knowledge of the characteristics of the reservoir rock, Sw can be uniquely calculated.

Summary and Conclusions

Porosity computed from logs, based on the lithological composition from the SSC model, matches very well with the porosity from core analysis. The Sand Silt Clay (SSC) model was tested successfully by evaluating well log data from a number of wells from Malaysian gas and oil fields.

The advantage of using Choo permeability is that it is a fast, robust and inexpensive method to predict permeability, a universal equation (not case by case study as with the current curve fittings practice), with no need for Swirr input, able to predict permeability with low uncertainty with limited amount of core data, all which lead to cost savings. Optimized reservoir characterisation by being able to populate permeability in models of poor rock leads to better facies type definition. The water saturation values, derived from the generic capillary pressure curves, were found to be in agreement with those computed using saturation height function based on core data.

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Nomenclature

k = permeability (mD)
m = formation cementation factor
Rw = formation water resistivity (ohm-m)
rg = dominant rock-grain radius (nm)
reff = effective pore-throat radius (nm)
c = natural reservoir compaction factor used in eq.
Vdcl = dry clay volume (v/v)
Vsand = sand volume (v/v)
Vsilt = silt volume (v/v)
ρg = grain density (gr/cc)
Ct = true formation conductivity (mho/m)
ϕt = total porosity (v/v)
ϕe = effective porosity (v/v)
Sw = generic water saturation, fraction of pore volume (v/v)
Swt = total water saturation (v/v)
n = saturation exponent
Cw = formation water conductivity (mho/m)
B = mobility constant (mho/m or meq/cm^3)
C = Qv response parameter (meq/cm^3)
Cwa = apparent formation water conductivity (mho/m)
Pc = capillary pressure (psi)
σ = interfacial tension (dynes/cm)
θ = interfacial tension contact angle
h = height above free water level (ft)
gw = water pressure gradient (psi/ft)
gh = hydrocarbon pressure gradient (psi/ft)
b = desaturation power exponent
bo = clean reservoir desaturation power exponent

Swb = clay bound water saturation (v/v)
Sw.cap = capillary water saturation (v/v)

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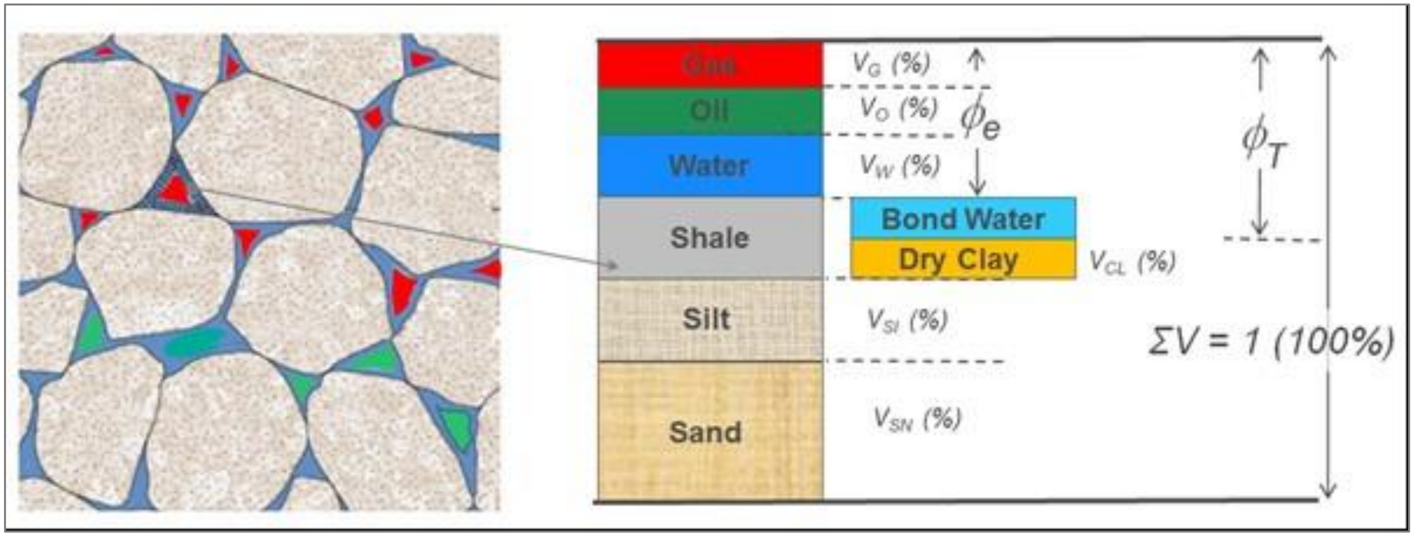

Figure 1. The concept of SSC fraction volume (after Anwar, 2011).

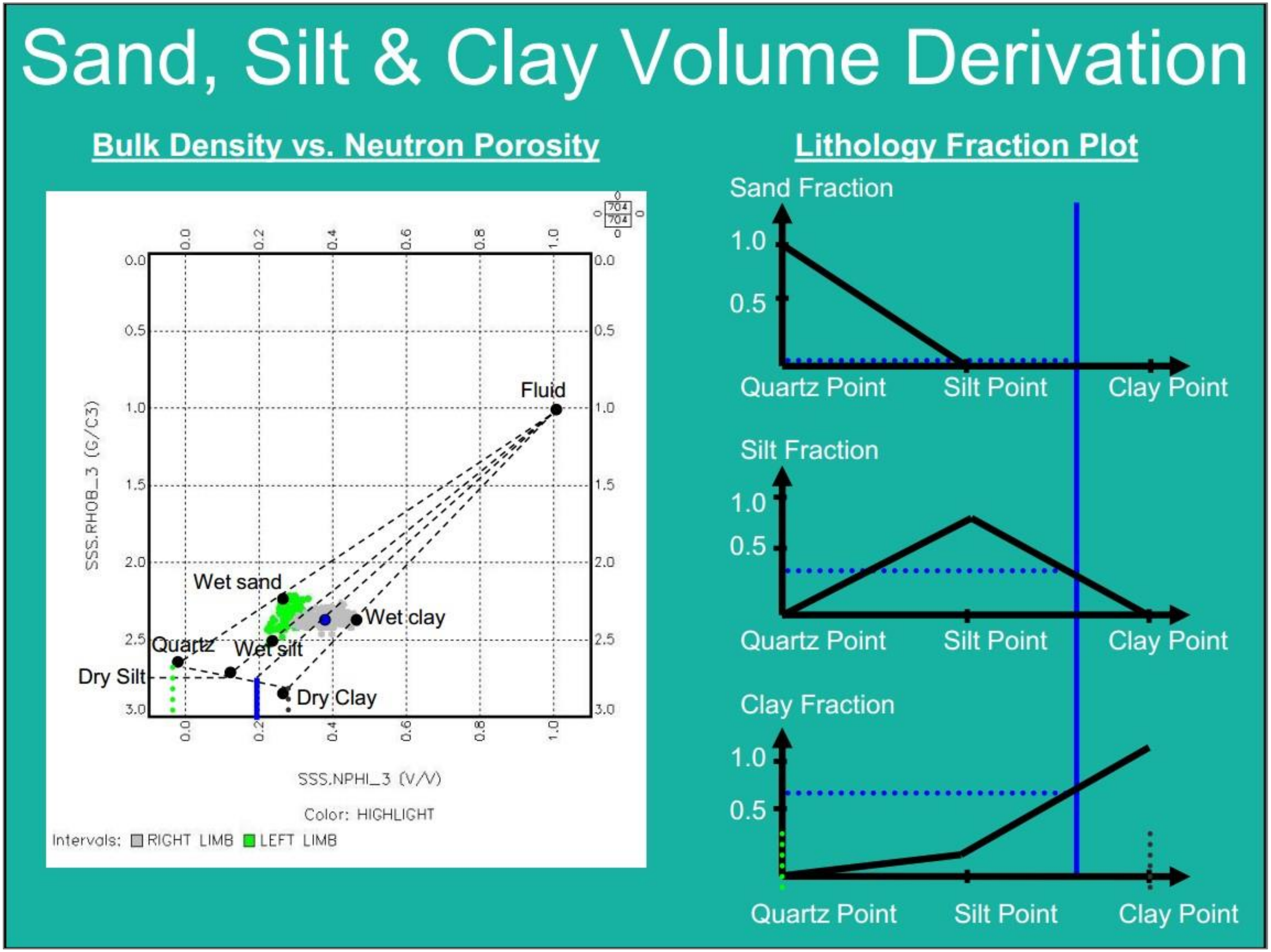

Figure 2. Sand-Silt-Clay Model volume derivation (Kyi et al., 2008).

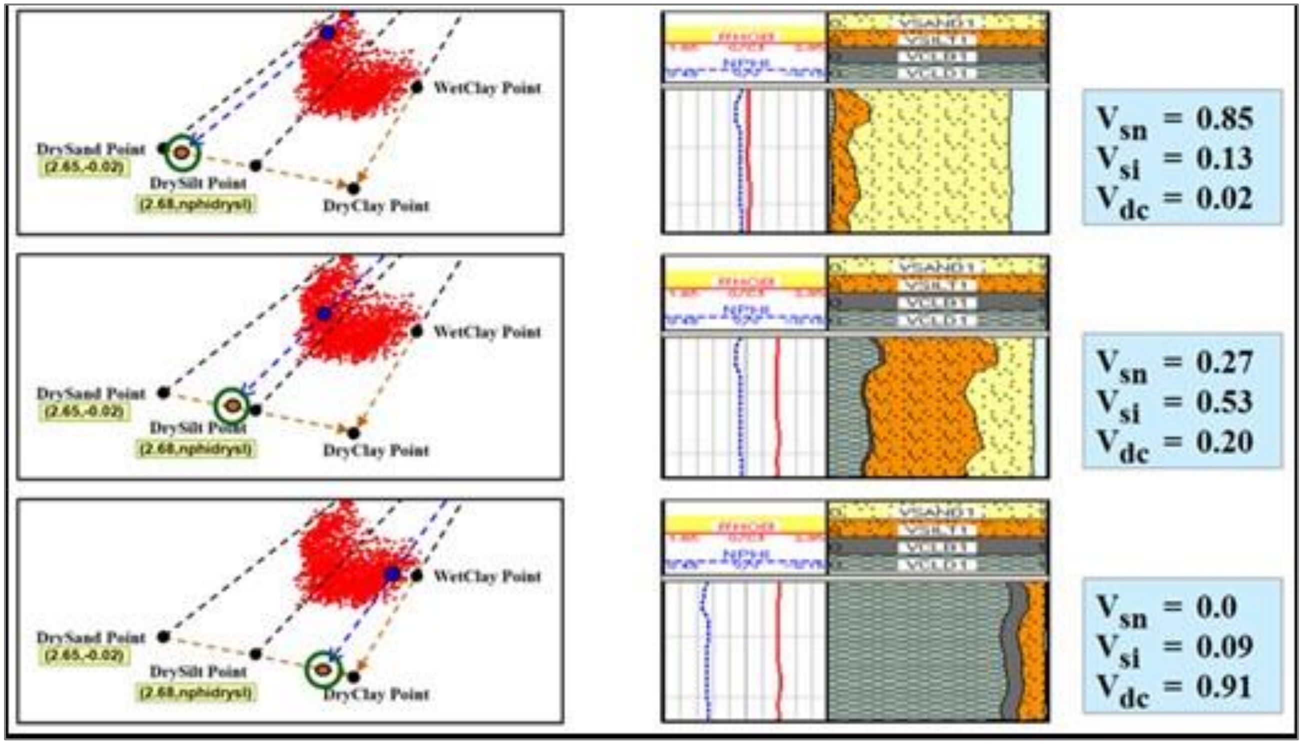

Figure 3. Example of Lithology volume determination using SSC ternary diagram.

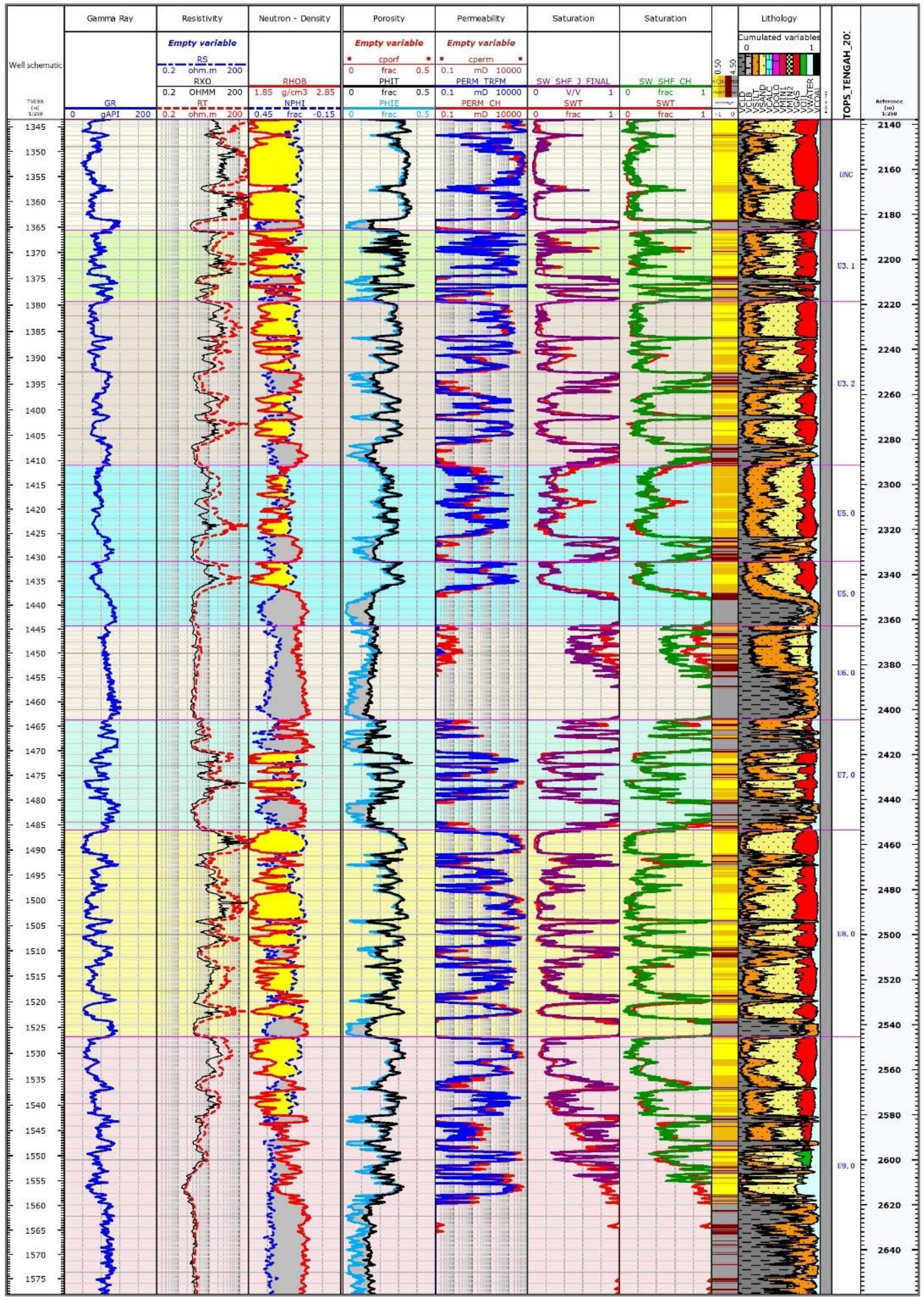

Figure 4. Example of predicted permeability and modeled water saturation.