The Correct Shale-Volume Characterization Increases Hydrocarbon Reserves: Case Study of Cretaceous Formation, Lake Maracaibo, Venezuela

Rodolfo Soto B., SPE, Digitoil, and Duarry Arteaga, Cintia Martin, and Freddy Rodriguez, SPE, PDVSA Western Division

Abstract

Today, natural fracture and/or connected vuggy systems in carbonate reservoirs contribute significantly to hydrocarbon production. Combining concepts from normal distribution with normalization and soft computing techniques improves quantification of actual shale volumes for a reservoir with complex stratigraphy and natural fractures. This is especially important for cases when very few log curves are available to solve a high number of unknown lithologic variables. We applied our new methodology successfully in the Cretaceous formation, Lake Maracaibo, which is composed primarily of limestones with some dolomites and siliciclastics (glauconitic sandstones, siltstones, and shales).

It is common to use the standard gamma ray log (SGR) or total contribution from all three elements—uranium (U), potassium (K), thorium (Th)—as an indicator of shale content. The presence of highly radioactive black organic material and/or natural fractures in the formation results in a big difference from the X-ray diffraction data. This causes an overestimation of shale volume and therefore affects the original oil in place (OOIP) and reserves. We present a novel methodology that combines normal distribution and normalization to predict CGR from SGR and deep resistivity, Rt. We applied the cross correlation technique to validate our methodology, and the model CGR matches the actual CGR very well.

Next, we used the elemental capture spectroscopy (ECS) logs to quantify the actual clay volume (Vsh). Then, we used soft computing techniques to develop a shale volume model using CGR and Rt as independent variables and the Vsh from ECS as the dependent variable. Running the model for validation in three wells with ECS achieved a correlation coefficient of 0.9.

The average shale volume using our model is 12.5%, much lower than the former linear shale-volume model, which averaged 28.4%. This has had a great impact on the OOIP and reserves of our reservoir, as it would for other complex carbonate reservoirs.

Introduction

Carbonate reservoirs in western Venezuela have great potential for the production of hydrocarbons. However, the extreme heterogeneity because of their complex lithology and dual-porosity systems has limited their development; for these reasons, petrophysical evaluation is the key to predicting actual productivity and recovery of hydrocarbon reserves. This requires a large amount of data to develop models to predict the behavior of the reservoir, optimize their production, and give way to the characterization, development, analysis and monitoring of their productive lives.

An essential step in petrophysical evaluation is determining the amount of clay present in the formations to calculate the effective porosity and content of fluids. Normally, the clay content is estimated by laboratory analysis and X-ray diffraction. If these are not available, the shale volume can be predicted by conventional logs like gamma ray (GR), SP, neutron, resistivity or, thanks to a mineralogical special log, elemental capture spectroscopy (ECS). This tool measures the concentrations of minerals such as calcite, gypsum, anhydrite, quartz, and pyrite, and the amount of shale, regardless of gamma ray, SP, and porosity logs.

Spectral gamma ray (U, Th, K curves) and volume of shale (Vshale) curves from ECS and resistivity logs can be combined into a powerful tool to recognize clay zones or highly radioactive zones that contain the organic material characteristic of these formations.

The determination of reservoir quality in terms of petrophysical parameters, lithology identification, porosity, type and distribution of reservoir fluids, formation permeability, and anticipated water-cut estimates is based mainly on the evaluation of shale volume since these parameters are all of primary importance to the proper evaluation of reservoir potentiality. Therefore, quantitatively evaluating a formation requires an accurate estimate of the amount of shale to determine porosity and
water saturation. This paper discusses a new methodology to develop a confident shale volume model in this kind of formations and validate it.

**Development of a Model to Predict Gamma Ray Without Uranium Effect, CGRns**

The gamma ray log is a sum of three radioactive components: uranium (U), thorium (Th), potassium (K).

\[
\text{SGR} = a \times \text{U} + b \times \text{Th} + c \times \text{K} \quad \text{.................. (1)}
\]

where \(a\), \(b\), and \(c\) are the constants of each radioactive component of total GR or SGR.

It is possible with a spectral gamma ray log to discriminate the contributions of each of these components to get the total gamma ray, SGR.

Measures of concentrations of thorium (Th), uranium (U) and potassium (K) (Fig. 1) provide petrological information that helps improve reservoir characterization by:

1. Identifying types and volumes of clays
2. Identifying lithology (matrix components)
3. Identifying geological and sedimentary environments
4. Determining whether a formation is highly permeable, fractured, or with organic matter (separation of thorium and uranium curve) at high uranium concentrations observed with low concentrations of thorium and potassium.
5. Identifying producing areas, distinguishing a clean site (or radioactive producing zones) from shale.

![Fig. 1—Spectral gamma ray (SGR) and components K, U, and Th.](image)

According to Koizuml (1988), the normal values of uranium in formations vary from 2 to 6 ppm. However, in areas with high organic matter content, it is possible to find uranium values that reach 80 ppm, shooting the total gamma ray values, SGR, above 200ºAPI and misinterpreting them as clay zones. If we have a spectral gamma ray (SGR) log, it is possible to correct the gamma ray from the high uranium content. Then the corrected gamma ray curve is known as CGR. The carbonate Cretaceous formations are relatively clean formations, with low gamma ray. However, La Luna source rock and some specific zones of the Cogollo Group (Maraca, Lisure and Apón) display a significant increase radioactivity in the GR log, meaning high content of clay but not because of high resistivity (>800 ohm-m, Fig. 2).

From an analysis of the gamma ray, spectral components can be found because of anomalous uranium values (>40 ppm); this indicates organic matter that could be wrongly analyzed as clay. Hence the importance of running the spectral gamma ray log in each well to be drilled in the Cretaceous formation to determine when a high gamma ray value is associated with clay or organic matter. In this project, only 10 of the 53 wells have spectral gamma ray. The problem to be solved at this moment is how to get a CGR model in the wells where we do not have spectral gamma ray.
Fig. 2—Example of the high content of uranium (URANn), with high levels of radioactivity (GRn) and true resistivity (RD).

Fig. 3 shows a graph of SGR vs. RD (true resistivity from deep resistivity log) and CGR vs. RD represented by red and blue points respectively for the Cretaceous in Well UD-779. As you can see, the red dots indicate high values of gamma ray for high values of resistivity, indicating zones of high organic matter content as discussed above. The blue dots correspond to the same zones but corrected by uranium or organic material (the effect of uranium radioactivity is eliminated). Therefore, to use the gamma ray as a clay indicator, we should use the CGR, but not the SGR if we want to avoid overestimating the clay volumes, which would the OOIP and reserves.

To use the gamma rays log as an indicator, we should use Vshale to predict the gamma ray curve without the effect of uranium, CGRns. This means that data of normalized total gamma ray, SGRn (region of red dots in Fig. 3), should be moved to the region of blue dots that correspond to normalized gamma ray without the effect of uranium or organic material, CGRn. It means for clean zones we should have low gamma ray values with high resistivity values.

If we make a graph of SGRN vs. RD with uranium in the z axis (Fig. 4) using a threshold of 6 ppm of uranium, we can determine the region, with upper and lower limits, of normal behavior not affected by organic matter. We applied this concept to a well that has a spectral gamma ray log and plotted SGRN and CGRn against RD using the uranium in the z axis for the
UD-779 well. The CGRn data (in blue) exactly fall into the region bounded by the upper and lower limits of Fig. 4. This chart could be used to reliably predict uranium in wells where there is no spectral gamma ray.

![Fig. 4—Upper and lower limits of normal gamma ray (between curves) without effect of organic material.](image)

Another way to eliminate the effect of organic material on uranium is to make a normalization of total gamma ray logs, SGR, for the wells where we do not have spectral gamma ray curves. That entails using CGRn as a reference curve from one of the wells with spectral gamma ray and making a normalization of the SGR curves from the other wells that do not have spectral gamma ray. The obtained curves are called synthetic normalized gamma ray, CGRns. To demonstrate the validity of this method, we used the CGRn curve for Well UD-779 as reference curve. We took the SGR curve for the same well and normalized this one with respect to the reference curve, CGRn, to obtain CGRns. Fig. 5 shows how the generated curve, CGRns, fits perfectly with respect to the reference curve CGRn.

![Fig. 5 Normalization of CGRn using CGRn as a reference matches CGRns.](image)

The same procedure was applied first to the rest of the wells that do not have spectral gamma ray, using for all of them the same reference curve, CGRn from Well UD-779. The correlation coefficient in each case was higher than 0.84. Subsequently, we plotted the CGRns for each well with respect to RD (Fig. 6). The data fall in the blue region developed in Fig. 4 and the effects of organic matter on uranium have been eliminated.
Vshale Model Applying Fuzzy Logic

The best way to get a clay model, Vshale, is as follows: Perform petrographic analysis (XRD) of cores; place data obtained from these tests in depth with the well logs; use the clay indicator logs, such as gamma ray, to develop a nonlinear model. If x-ray diffraction data are not available, models found in the literature could be used to determine the Vshale from gamma ray log, but the uncertainty is too high. In our case, we used the mineralogical record of ECS (elemental capture spectroscopy) because no available petrographic analysis of XRD was available. We generated a graph of Vshale (ECS) vs. normalized gamma ray without uranium (CGRn), discriminated by the deep resistivity log (RD), using confidence ellipses. This graph allows visualizing the correspondence between these variables in the multivariate analysis (Fig. 7). In Fig. 7, we can see that the clay volume, Vshale, applied for this type of complex reservoir carbonate lithology is a nonlinear model, and we applied fuzzy logic, described in the following section, to develop a confident model.

Developing a Vshale Model using Fuzzy Logic in Conjunction with Spectral Gamma Ray, X-Ray Diffraction, ECS Log (Mineralogy) and Deep Resistivity (RD)

Conventional (Clavier and Steib) models were calculated according to literature and found an average absolute greater than 300% when compared to Vshale calculated from the ECS logs for each model. We used as input variable CGRns, the gamma ray corrected by uranium and normalized as discussed above (see Fig. 8). These models predict higher clay content than the real Vshale, affecting the calculation of porosity and therefore the OOIP and the reserves estimates. To obtain a more reliable model, we used multivariate statistical techniques and fuzzy logic. For this case the variables were RD and CGRn as independent variables and Vshale from ECS as the dependent variable. As shown in Fig. 8, the Vshale from the model (VCLMODEL) developed using fuzzy logic correlated in a remarkable way with real Vshale (ECS). Then we ran the model in all the wells to calculate the Vshale. The development of this model had a positive impact on the calculation of OOIP and recovery factor by a factor of 1.25
Predominant Clay Type Based on Core Gamma and Gamma Ray Spectral

A thorium-potassium methodology using a core gamma or gamma ray spectral log is available for determining the predominant clay. With this analysis, we can use the parameters measured by the gamma ray spectral tool in the identification of clay minerals (classification, types, and volume). From those results and the application of the appropriate techniques, we can obtain reliable models of effective and total porosity. This technique is used when there is limited petrographic analysis information as such SEM, thin sections (FS), and X-ray diffraction (XRD).

We generated Th (%) vs K (ppm) crossplots to determine the different types of clay; then we coded each one by the lines of separation of each type of clay to quantify them and see their percentage of contribution. Finally, we found that the predominant clays are as follows: Lagomar area: kaolinite in 100% clay zones and chlorite in carbonate/sandstones zones; and Lagomedio area: kaolinite in 100% clay zones and smectite in carbonate/sandstone zones.

Fig. 9 shows the distribution of K and Th from the spectral gamma ray and the percentage of each type of clay for the VLA-1453_ST well (Lagomar area). Fig. 10 shows that the predominant clay is kaolinite for a zone containing 100% clay (CGRn> 70 API), while for a clean zone (CGRn <70 API), it is chlorite. The Th is often associated with detrital sediments, never chemical sediments (limestone and dolomite), so in carbonate reservoirs the Th is an important indicator of clay, and a graph of K vs Th identifies the predominant type of clay and quantifies the clay volume.
Running and Validating the Vshale Model
We ran the developed model was run in all wells in the pilot area of the Cretaceous lake and validated it with the mineralogy log, ECS, from the UD-791 well. Fig. 11 shows how the Vclay or Vshale from the ECS compares with the Vshale from our model, VCLCRETACEO. There is a very good match (the green and red curves). The correlation coefficient, $R^2$, of the model is 0.71 (Fig. 12).
Fig. 12—VCLMODEL (fuzzy model) matches closely with VCL (ECS) of the well UD-791.

Moreover, excellent results were observed in the Vshale from comparing our model with the ECS Vshale in the recently drilled VLA-1562 well, Lisure formation (see Fig. 13), where despite not having spectral gamma ray, we built a synthetic gamma ray corrected by uranium (CGRns), getting reliable results. Running the model for validation in wells with ECS achieved a correlation coefficient of 0.9.

Fig. 13—VCLMODEL (VCLCRETACEO of fuzzy logic) captures VCL_ECS in the VLA-1562 well.
Conclusions
We developed a procedure and a confident Vshale that will have a great impact on estimating the original oil in place (OOIP) and the reserves in the Cretaceous formation at Lake of Maracaibo. To develop the Vshale model we used the ECS logs as the dependent variable and gamma ray, CGRn, and deep resistivity, RD as independent variables. We applied concepts of fuzzy logic and neural networks to get a nonlinear and multivariable model. The correlation coefficient, $R^2$, obtained was 0.9 with an error of 15%, compared with the error of the conventional linear model from gamma ray that it is greater than 300%.

The new methodology developed in this project lets us reduce the uncertainty of Vshale calculation and increase the OOIP and reserves by a factor of 1.25.

We generated Th (%) vs K (ppm) crossplots from the spectral gamma ray logs to determine the different types of clay; we found that for the Lagomar area, kaolinite is predominant in 100% clay zones and chlorite in carbonate/sandstones zones; and for the Lagomedio area, kaolinite is predominant in 100% clay zones and smectite in carbonate/sandstone zones.

If engineers want to reduce uncertainty in the calculation of Vshale, the spectral gamma ray log should be run in any future wells to be drilled in the Cretaceous Lake Maracaibo.

References