PS Carbonate Pore Type Identification Using Fuzzy Logic and Open-Hole Logs; Case of Study: Cretaceous Formation in Lake Maracaibo-Venezuela*

Rodolfo Soto[1], Duarry Arteaga[2], Cintia Martin[2], and Freddy Rodriguez[2]

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[1]DIGITOIL, Bogota, Columbia. (rodolfo.soto@digitoil.net)
[2]PDVSA, Maracaibo, Venezuela.

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Abstract

Today, natural fracture and/or connected vuggy systems in carbonate reservoirs contribute significantly to hydrocarbon production. If a carbonate reservoir has only intergranular porosity, the water saturation, Sw, can be calculated with high certainty using the Archie equation with a cementation factor, m, equal 2. But it is common to find in a carbonate reservoir a complex pore system that may be intergranular, vuggy, and fractured. If we use m equal 2 for vuggy or fractured porosities, the water saturation will be too low or too high respectively, leading engineers to easily make some incorrect decisions.

Despite its importance, one of the difficult tasks during the petrophysical evaluation of carbonates is to identify the multi-pore system present in each case. Engineers use data from cores, well-logs, and pressure transient tests to apply different techniques for this purpose. Unfortunately, core and pressure analyses are not always available and most of the techniques from well log analysis published in the literature do not manage imprecise data or factors that distort the data because of the pore complex systems in carbonates.

We present in this paper a new methodology for the reduction of uncertainty in pore type identification and characterization using soft computing technology with conventional well-log data. Membership functions were built for each conventional well log. Their outputs indicated the probability of fracture/vuggy/intercrystalline pores according to the logs analyzed. For each function, we determined a weight and a threshold parameter adjusted from core data and/or borehole images. Then we calculated the fracture or vuggy porosity from a resistivity-porosity model using the m variable determined from Pickett plots for each pore type. We found for our case that m = 2.46, 2.0 and 1.4 for vuggy, intercrystalline, and fractured formations respectively. The total and effective porosities were calculated from neutron-density-sonic logs.

Finally, we calculated Sw for each well and found that our models adjust with field results, explaining the behavior of each well with high certainty from the beginning of production. We have successfully applied our methodology to identify the complex pore types for the Cretaceous formation in Lagomar and Lagomedio fields in Venezuela.

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PDVSA Exploración y Producción

Rodolfo Soto B, Duarry Arteaga, Cintia Martin, Freddy Rodríguez

Abstract (AAPG-1072399)

Presenters contact: Rodolfo Soto/ Digitoil, Duarry Arteaga/PDVSA, 58-4265657063 rodolfo.soto@digitoil.net /4146493151 arteagada@pdvsa.com

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1-Introduction

In the analysis of logs of such reservoirs, it is very important for petrophysicists to know the types of pores. The reason for this importance of knowing is that changes in the type of pore, according to A. M. Borai and Asquith G. result in changes in the cementation exponent, m; and changes in the cementation exponent value can greatly affect water saturation calculated by the Archie equation.

Figure 1, It is remarkable to see how in systems of very low porosity, less than 5%, the uncertainty is much higher when using a wrong value in cementing factor, as is the case of the deposits under consideration.

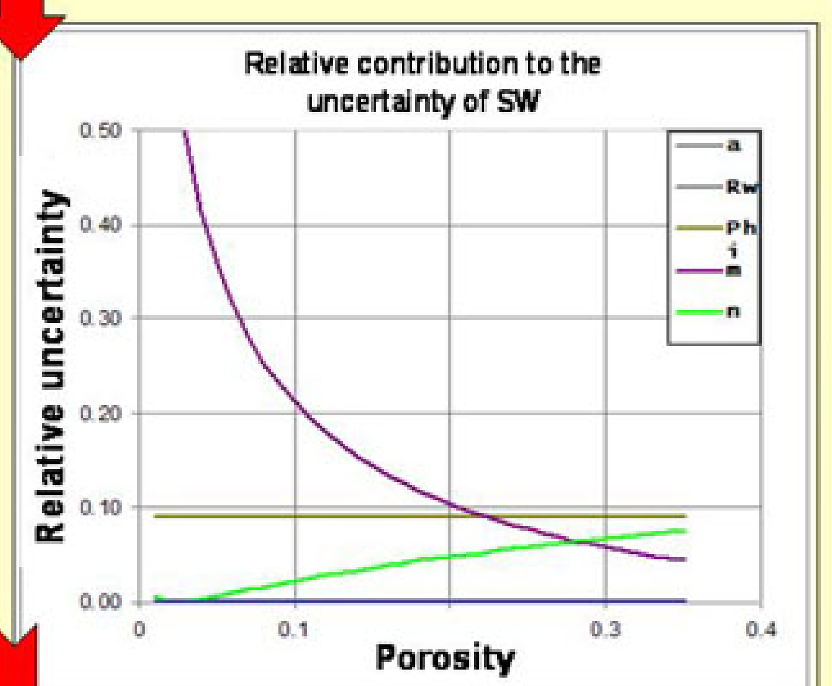

Figure 1. Relative Contribution to Uncertainty, Archie equation.

2- Identification and Characterization of Pore Type (Matrix, Fracture and Vugular): Applying Fuzzy Logic Concepts

It is of great importance to understand the effects of these complex systems on conventional well logs to attempt a better characterization of pore types. We discuss how to integrate the imprecise information from conventional well logs through fuzzy logic principles to identify the presence of fractures/vugs or only matrix. We used the following crossplots to identify the pore type: M – N lithology plot, Swarchie vs. Swratio, resistivity ratio (Rt-Rxo)/Rxo, Poisson ratio, and porosity from resistivity logs, ϕR, vs. total porosity, ϕt.

2.1- Identifying Pore Type Using M-N Lithology Plot

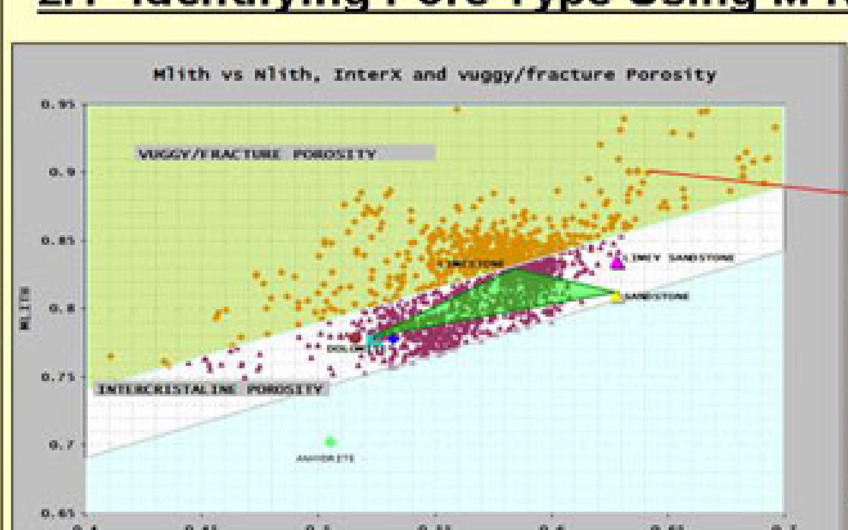

Figure 2. Mlith-Nlith crossplot to identify the pore type.

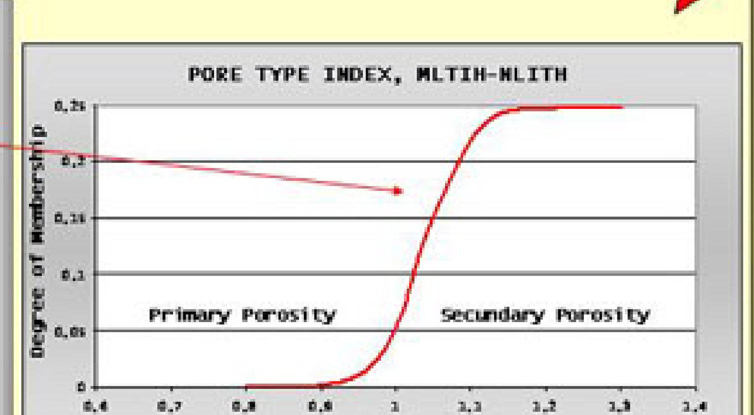

Figure 3. Mlith function vs. degree of membership to define two regions: primary or secondary porosity.

This plot is used to calculate the lithology dependent variables M (Mltih) and N (Nlith) requires the sonic log, neutron and density, but it can also be used to identify the pore type: vuggy/fracture or intercrystalline, correlating well with the description of VLA-978 in 76%.

For this case Figure 3, we used a sigmoidal function fuzzy logic representing the transition zone between intergranular porosity and secondary porosity.

2.2-Crossplot of Archie Water Saturation (Swa) – Resistivity Water Saturation (Swr):

This method defines the type of pores present in carbonate reservoirs. Swa is calculated assuming matrix porosity and cementation factor, m, equals 2:

$$Swa = \left(\frac{a * Rw}{\phi_e^{\,2} * Rt} \right)^{0.5}$$

and Eqs 2 Swr is computed as follows:

$$Swr = \left(\frac{(Rxo / Rt)}{(Rmf / Rw)} \right)^{0.625}$$

In Figure 4, we can observe the crossplot Swa vs Swr, the boundaries of each of the regions should be a transition zone, and the best way to be represented is through the basic concepts of fuzzy logic (See figure 5). To achieve this, the conditions are as follows, see summary table:

Pore Type	Value of m	Condition
Intergranular	m=2	Swa=Swr
Vugular (well connected)	m>2	Swa<Swr
Vugular (poor connection)	m>>2	Swa<<Sw
Fracture	m<2	Swa>Swr

Table 1. Values of m, and condictions of Swr and Swa for different pore types.

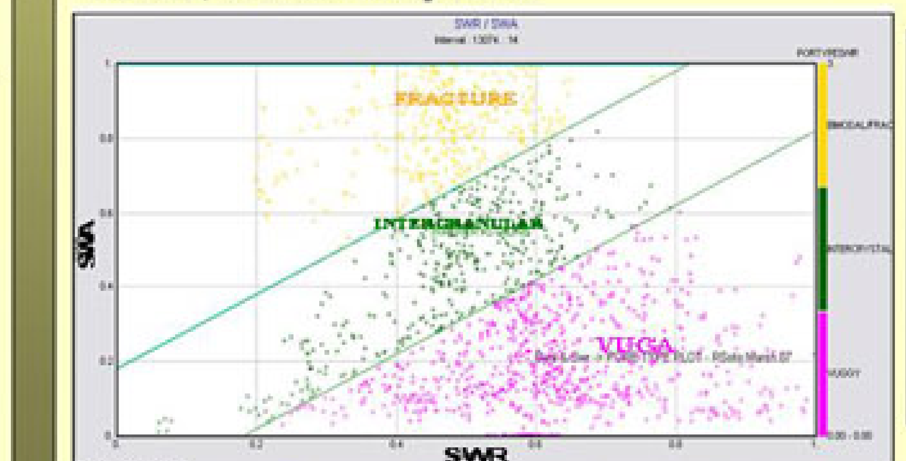

Figure 4. Figure Swratio vs Swarchie in Interactive Petrophysics.

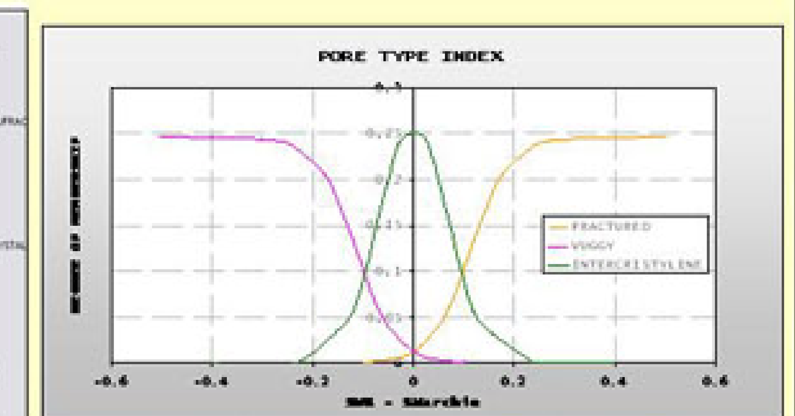

Figure 5. Membership degree functions of the pore type, Swr - Swa.

Figure 5 shows the functions that represent the degree of membership to each of the sets of pore types— fractured, vugular or intercrystalline—depending of the values of Swr and Swa.

2.3-Relationship of Resistivity Logs, RRES: (Rt-Rxo) / Rxo and Sonic dipole-Vp / Vs - Poisson ratio:

RRES relationship is based on the separation between the deep resistivity log, Rt and the short, Rxo. If the gap is growing there will be greater invasion, with a greater chance of having a fracture or zone of vuggy. **Poisson's ratio** is the relationship between normal stress and shear stress. In a fracture zone, reduces shear wave signal or energy, and Poisson values are high indicating fractures.

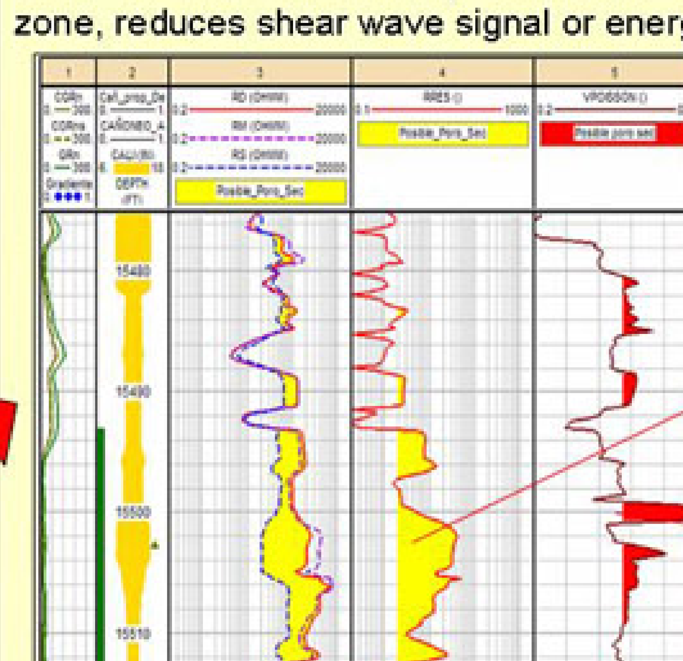

Figure 7. Example Application of the Poisson's ratio and RRES, well VLA-1562.

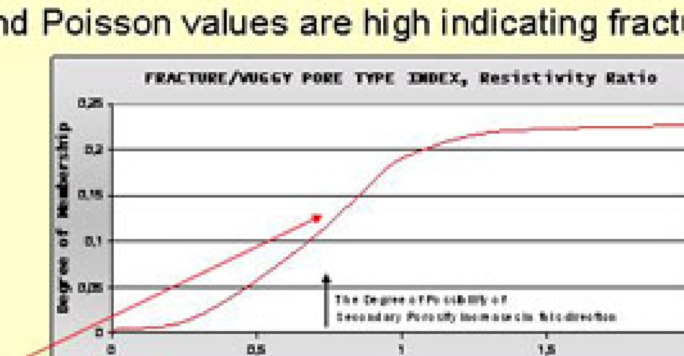

Figure 6. Poretype Index Function: RRES, Resistivity Ratio.

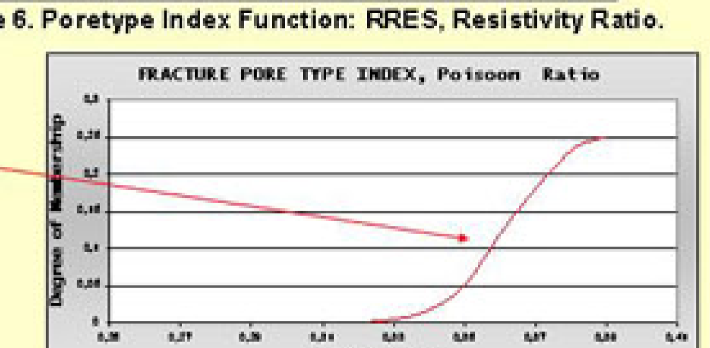

Figure 8. Degree of membership to pore type set using Poisson´s ratio as independent variable.

Figure 7 shows an example of the well VLA-1562, high Poisson ratio of areas with high potential for secondary porosity according to RRES function. Figure 6 and 8 shows the sigmoid function to calculate the degree of membership of belonging to a type of pores.

		PI: POROSITY INDEX: INDICE DE PROBABILIDAD DE FRACTURA/VUGULAR/INTERCRISTALINE
✓	PIfracture	IF(VSH<VSHcut, 0.8*PIswrf+0.8*PIrrf+.8*PIpoisson+0.4*PIcaliper+0.8*PIcrossDN+0.8*PImlith+0.8*PIres,0)
	PIfracture	IF(VSH<VSHcut,0.8*PIswrf+ 0.8*PIrrf +0.4*PIcaliper+0.8*PIcrossDN+0.8*PImlith+ PIres,0)
✓	PIfracture	IF(PIfracture>1,0,1,PIfracture)
	VUGGY	IF(AND(PIswrv>0.23, PIrrv>0.23),1,0)
✓	PIvuggy	IF(VSH<VSHcut, 0.8*PIswrv + 0.8*PIrrv + .4*PIcaliper + PImlith+ 0.4*PIres+0.4*PIcrossDN,0)
✓	PIvuggy	IF(AND(VUGGY=1,PIvuggy>PIfracture), 0.8*PIswrv + 0.8*PIrrv + .4*PIcaliper + PImlith+0.5*PIres+0.4*PIcrossDN,PIvuggy))
✓	PIvuggy	IF(PIvuggy>1,0,1,PIvuggy)

Figure 9. Programming in Visual Basic of fractured and vuggy pore type index.

According to the sigmoidal functions developed for each of the techniques discussed above, where we obtain some index of pore type, PI (See Figure 9). We developed a multilinear function. Its coefficients or weights were adjusted to achieve a good (r2, 0,86) match with pore types present in the cores and image logs.

3-Triple Porosity Model: PHImatrix, PHIfracture and PHIvuggy:

Carbonate rocks (limestone and dolomite) are important oil and gas reservoirs. According to Choquette and Pray (1970), the porosity in carbonates can be subdivided into the following two types: primary porosity (such pores may be present between the particles or crystals) and secondary porosity (formed as result of a dissolution or fracturing). To quantify the values of porosity present after each type of pore characterized by fuzzy logic functions, we use Eqs. 3 and 4. In this case, the cementing factor to be used is not equal to 2, but one variable, mvariable, calculated from Pickett plot:

$$\phi_{efracture} = \left(\frac{R_{mf}}{R_{xo}} \right)^{1/1.6}$$

and Eqs 4 PHIvuggy is computed as follows:

$$\phi_{evuggy} = \left(\frac{R_{mf}}{R_{xo}} \right)^{1/2.54}$$

In the case of the Cretaceous-Lago, from the core analysis and image logs, we can say that at least three types of pore are present: intergranular, fractured and/or vugular. As discussed above, density and neutron logs are affected by the type of pore—fractures or vugs—while sonic log readings are not affected by the secondary porosity, with an indicator to estimate the porosity of the matrix. So the effective porosity, ϕe, is a sum of fracture/vugs and/or intercrystalline porosity. Subsequently, we determine whether ϕe > ϕefracture or ϕe > ϕevuggy:

✓ If ϕe > ϕefracture Eqs 5 is used to calculate ϕematrix

$$\phi_{matrix} = \left(\frac{\phi_e - \phi_{efracture}}{1 - \phi_{efracture}} \right)$$

✓ If ϕe > ϕevuggy Eqs 6 is used to calculate ϕematrix

$$\phi_{matrix} = \left(\frac{\phi_e - \phi_{evuggy}}{1 - \phi_{evuggy}} \right)$$

3.1-Calculation and Validation of the Cementation Exponent, mvariable with the Pickett-Plots:

The Pickett plot is a graphical solution of the Archie equation and is commonly used to estimate the value of Rw and cementation factor, m (See Figure 10). In zones where water saturation is equal to 1.0, the term of the equation Archie becomes zero, and then we have:

$$\mathrm{Log}\,(Rt) = -\,m \times \log\,(\phi_e) + \log\,(a \times Rw)$$

Table 2 shows the summary of average results achieved by the mvariable Pickett method and validated with literature data

Pore Type	Literature Value of m	Pickett Plot Value of m
Intergranular	1.8 - 2.2	1.98 - 2
Fracture	1 - 1.8	1.42 - 1.6
Vugular	2.2 - 3.4	2.44 - 2.50

Table 2 Comparison of values of the Pickett plot & mvariable with literature values

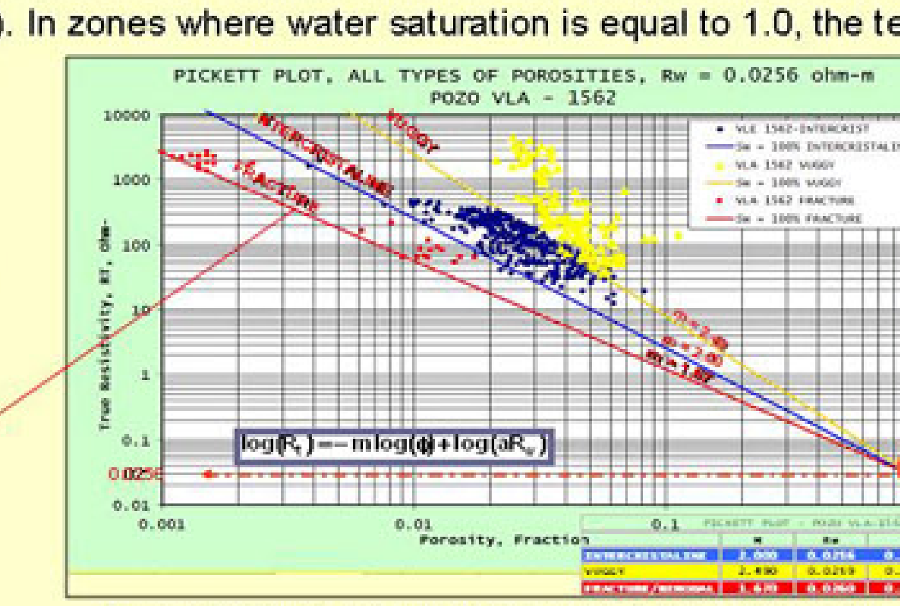

Figure 10. Pickett plot, calculation, and validation of m variable.

3.2 Running the Porosity Model, Pore Type and Validation with Cores and Image Logs:

Figure 11 shows the comparison of the prediction models of PHIfracture and PHIvuggy with the fractures and vugs seen by the FMI log images in the VLA-1562 well. We found that our model predicted the actual fractures with 76% accuracy and vugs with 84%. The open fractures are red dots and the vugs, blue. The blue color is the matrix porosity; violet, the fractures; and blue, vugs.

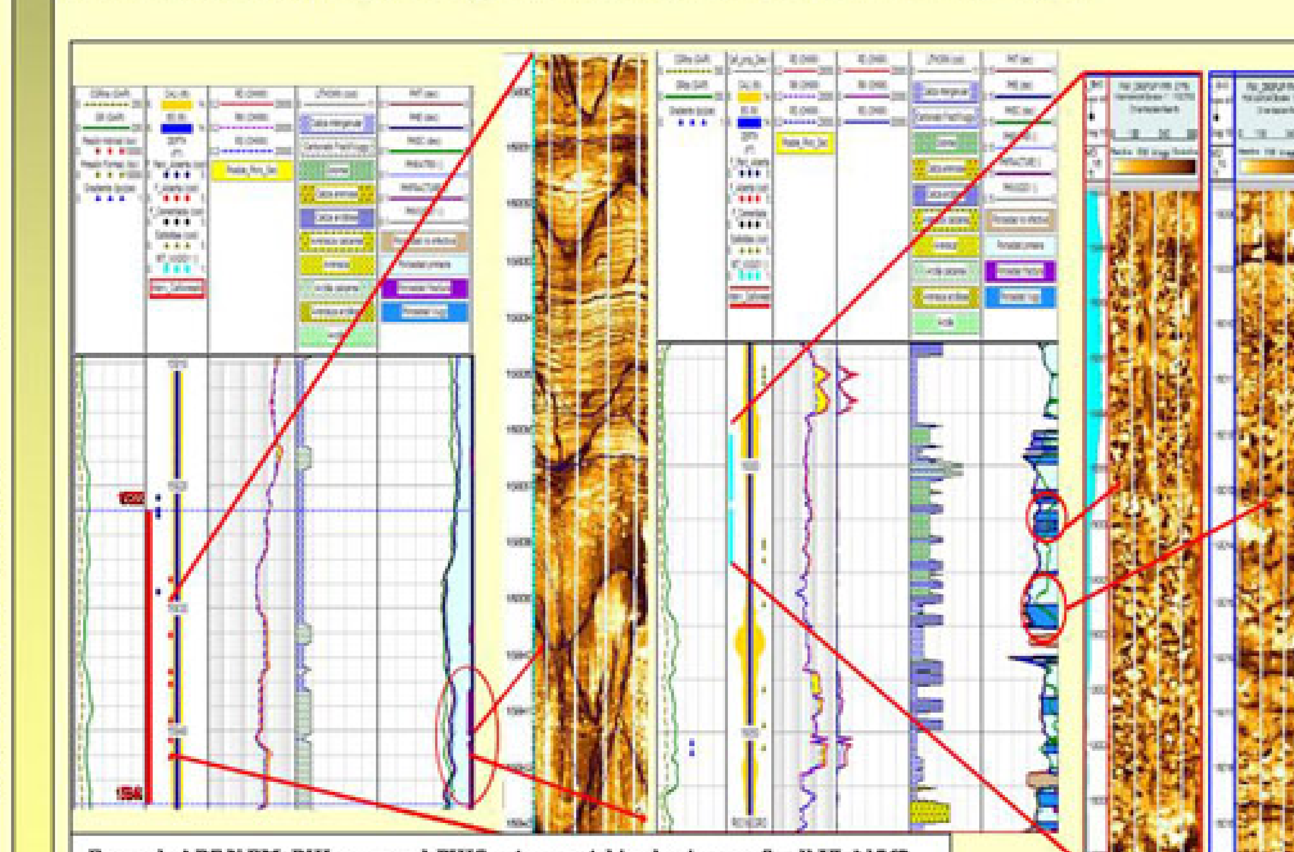

Figure 11. Prediction of PHIfracture-PHIvuggy compared with the Image FMI Log in the well VLA-1562.

4- Conclusions:

- We have characterized the type of pore (matrix, fracture, and vugs) in the Cretaceous Formation using fuzzy logic and the following indicators: Mlith-Nlith; Swa vs Swr; RRES and Poisson'.
- We determined that the value of m for intergranular porosity ranges from 1.98 to 2; fractures, 1.42 and 1.6; and for vugs, m varies between 2.44 and 2.5.
- The correlation coefficient, r2, between the developed porosity model and core porosity is 0.87 for all key wells of Lagomar and Lagomedio areas.
- The new model to predict the pore types was validated with the FMI image logs of the VLA-1562 well, Lagomar Area. Our model fits 76% with fractures and 84% with vugs.