

Petrophysical characterization of carbonate formations for geothermal reservoir analysis

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ABSTRACT

As of today most of geothermal projects and the related feasibility studies have been realized on the basis of geological, 2D-seismic and hydrogeological data interpretation without considering the petrophysical and geomechanical properties at the micro scale.

In this paper we want to point out the primary role of petrophysics in the reservoir analysis for a right identification of the structural lineaments and flow lines, to optimize the thermal efficiency of a geothermal project finalized to decrease the risk and the costs.

1. INTRODUCTION

As far as the application of Archie's law is concerned, petrophysicists discriminate between Sand-Shale or Clastic and Complex Lithology or Carbonate formations.

While for pure homogeneous sands the simple Archie's law for standard values of the cementation exponent m and the constant a is often verified, complex lithologies with high heterogeneity need a detailed study for a detailed function description and parameters determination.

This paper describes a methodology for the petrophysical characterization of geothermal carbonate reservoirs.

The study has two main purposes.

- To analyze the type of porosity-permeability transforms, the porosity types and their spatial distribution as a first phase of the petrophysical characterization.
- To develop a system to apply carbonate classification for the identification of structural heterogeneities and main permeability features, identification of connectivity type, compartmentalization of petrophysical properties for possible correlation to other geophysical and seismic attributes.

2. BACKGROUND

A method was applied by Lucia for the Mansfield Field 1. We adapted some solutions to solve specific problems related to geothermal projects.

The most important aspect of these techniques concerns the application of the touching vugs porosity, permeability and fracture analysis. An extremely important factor for carbonate characterization is the determination of the

separate vuggy porosity (Phi-SV). Through the comparison of different methods we can establish the amount of separate and connected vuggy porosity. This permits to access a second step where we can calculate the cementation exponent that further characterizes the petrophysical and mechanical properties of the formation allowing further possibilities of correlation with other geophysical attributes.

3. THE PROCEDURE

Seven models are considered for the calculation of secondary porosity including separate vuggy porosity and total vuggy porosity ratio (VPR) from acoustic and resistivity logs with the neutron porosity plot and core measurements used as reference criteria.

The following models are considered: Secondary Porosity Index (SPI), Nurmi, Quadratic, Power law, Lucia, Phi-Acoustic Φ_v^{ac} , Phi-Resistivity Φ_v^{ei} .

From these models a few guidelines for the interpretation of geothermal associated problems are derived.

For the SPI Model the P waves of the sonic tool bypass the vuggy porosity therefore we can represent the secondary porosity with the equation 1:

$$\Phi_2 = \Phi_t - \Phi_s \quad (1)$$

where: Φ_2 is the secondary vuggy porosity, Φ_t is the total porosity and Φ_s is the porosity from the sonic tool.

The Nurmi Model considers that the acoustic waves bypass only half of the vuggy porosity and this can be represented by the following equation. Eq. 2:

$$\Phi_2 = 2 (\Phi_t - \Phi_s) \quad (2)$$

This model however was applied in formations where most of the secondary porosity was separate-vuggy porosity.

The Quadratic Model unifies the previous methods with the introduction of an empirical constant ρ and a quadratic dependence. Eq. 3:

$$\Phi_2 = (\Phi_t - \Phi_s) + \rho(\Phi_t - \Phi_s)^2 \quad (3)$$

The Power Law Model uses a scaling factor a as exponent of the ratio between the total porosity and the sonic porosity calculated from the Wyllie time-average equation. Eq. 4:

$$\Phi_2 = \frac{\Phi_t}{\Phi_s} (\Phi_t - \Phi_s) \quad (4)$$

Lucia and Conti calibrated the effect of separate-vug porosity on acoustic and resistivity logs using thin-section data in an upward-shoaling oomoldic sequence and used the point count method to measure Φ_{sv} . The equation that expresses such calibration is the following Eq. 5 :

$$\Phi_{sv} = 10^{4.09 - 0.1298 (\Delta t - 141.5 \Phi_t)} \quad (5)$$

After comparison of the results produced by the application of each method for the calculation of the separate vuggy porosity it was stated that the SPI method agrees with values derived from core data (point count analysis) for low vuggy porosity and can be applied in areas of low vuggy porosity representing the lower limit of the secondary porosity, while the Nurmi, Power Law and Quadratic models can represent a good approximation of the vuggy porosity in high vuggy porosity areas, representing therefore the upper limit of the secondary porosity. SPI is often similar to the resistivity porosity and the comparison of these methods can be often used as a diagnostic for the heterogeneity type. Fig. 1

Two more models were considered for the calculation of the vuggy porosity from acoustic logs Φ_v^{ac} and

resistivity logs Φ_v^{ei} and the corresponding cementation exponent was derived with the equations of Brie, Johnson and Nurmi.

In this new example the vuggy porosities were calculated with five equations: SPI, Nurmi, Quadratic, Φ_v^{ac} and Φ_v^{ei} .

The results are exposed in Fig. 2 and show that the comparison of different methods and especially the difference between Φ_v^{ac} and Φ_v^{ei} can evidence the presence of fractures and structural discontinuity.

4. THE ARCHIE EQUATION APPLIED TO CARBONATIC FORMATIONS

The determination of the secondary vuggy porosity is fundamental for the characterization of carbonate formations. This influences the static, dynamic and mechanical properties.

This is the first step on the way to find a convenient form of the Archie equation and consequently to derive a realistic cementation exponent.

On the way to derive a generic Archie equation which takes into account the porosity type we refer to the Generalized Parallel Conductor Model (Lucia, Wang, Ballay).

We consider various forms of the Formation Factor **F** and Archie equation and refer to the end of the paper for the the parameter list. Eq. 6, 7, 8 :

The one conductor model will have the form of Eq. 9 :

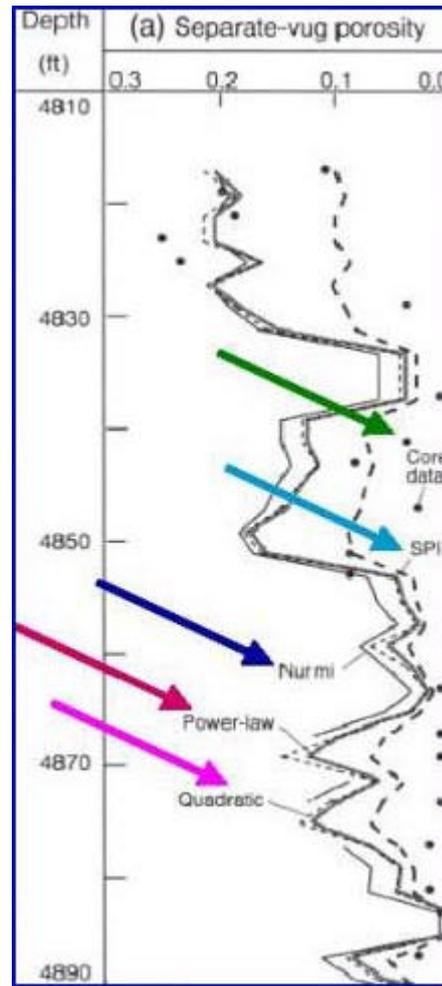


Fig. 1: Comparison of different models for the calculation of the vuggy porosity (Courtesy of F. Jerry Lucia, Rev. Robert E . Ballay)

➡ Quadratic,
 ➡ Power-Law,
 ➡ Nurmi,
 ➡ SPI,
 ➡ Core Data

$$F = \frac{a}{\Phi^m} \quad (6)$$

$$F = \frac{R_o}{R_w} \quad (7)$$

$$F = \frac{C_w}{C_o} \quad (8)$$

$$C_o = \frac{\Phi^m}{a} C_w \quad (9)$$

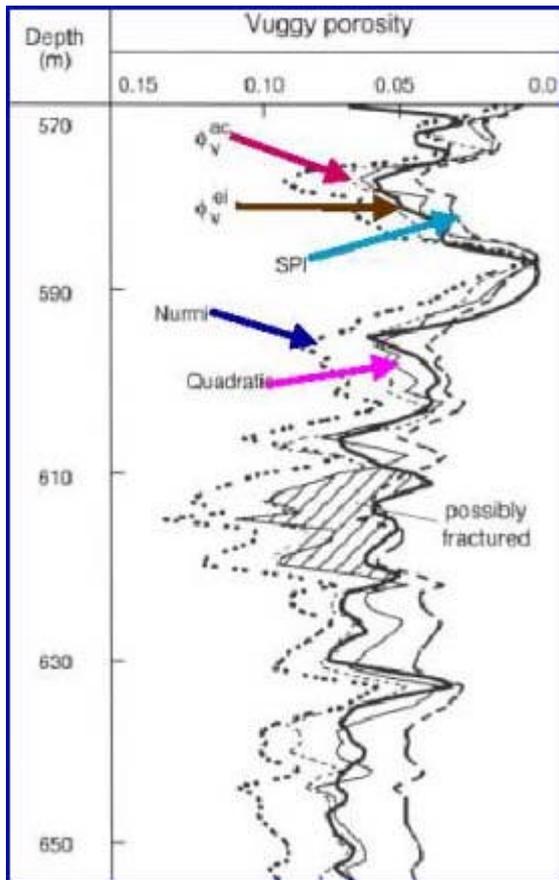


Fig. 2. Heterogeneity and structural interpretation from vuggy porosity models (Courtesy of F. Jerry Lucia, Rev. Robert E. Ballay)

- Quadratic, → Nurmi, → SPI,
- Φ_v^{ei} , → Φ_v^{ac}

The i conductors model has the form of Eq. 10 :

$$C_o = C_w \sum \frac{1}{F_i} \quad (10)$$

The Parallel Conductor Model is derived from the review of various models for separate vug systems, touching-vug systems and fractured systems (Wang, Lucia, Ballay) and assumes that conductivities related to different pore types are linearly additive. Linearly additive in the conductivity domain means that also the factor $1 / F_i$ and its components are linearly additive. For this reason we can consider a model where C_o accounts for the intercrystalline porosity and the vuggy porosity components. Eq. 11:

$$C_o = C_w \left[\frac{\Phi_{ip}^{m_{ip}}}{a_{ip}} + \frac{\Phi_v^{m_v}}{a_v} \right] \quad (11)$$

a_v characterizes the vuggy porosity type and is a fundamental parameter for the classification of carbonatic formations. This parameter could be used as an aid for facies characterization purposes as source of correlation with seismic attributes to identify the spatial porosity and facies distribution.

In practical log analysis the Dual-Porosity model finds a more flexible application and can be applied for vuggy and fractured reservoirs. The Dual-Porosity Model is derived from the Parallel Conductor Model.

We can set $a_{ip} = 1$ for well connected intercrystalline porosity.

Therefore the Dual-Porosity Model can be expressed from the following equation. Eq.12 :

$$C_o = C_w \left[\Phi_{ip}^{m_{ip}} + \frac{\Phi_v^{m_v}}{a_v} \right] \quad (12)$$

The parameter a_v describes the characterization of the porosity type and its connectivity.

The sensitivity of the the cementation exponent m is dependent upon the value of a_v Fig. 3 .

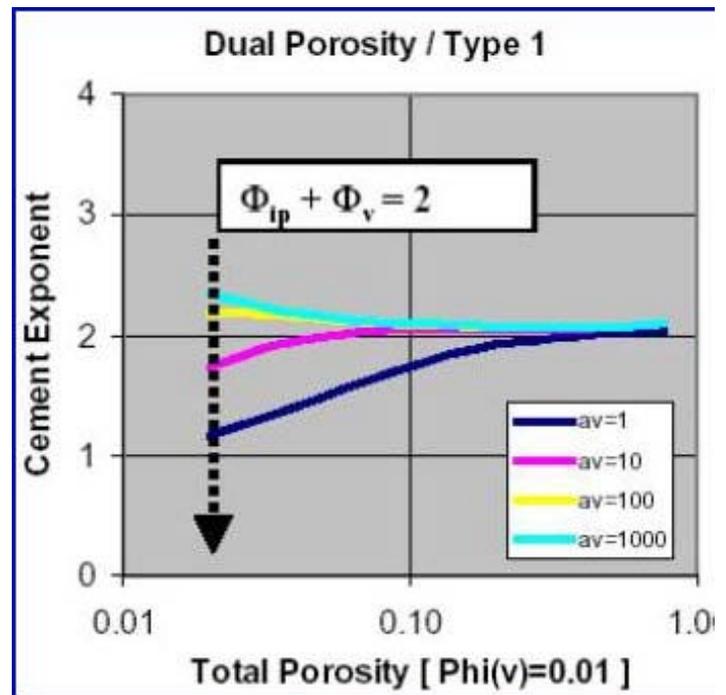


Fig. 3. Dependence of the cementation exponent m from a_v

If we consider the Dual Porosity model we can characterize the Phi-SV on the basis of the parameter a_v .

For $a_v > 100$: we can recognize separate vugs.

For $a_v < 20$: touching vugs porosity and

for $a_v = 1$: well connected planar fractures.

This is a very important result for the target identification in the geothermal exploration.

5. DERIVATION OF THE CEMENTATION EXPONENT m

The calculation of m represents a critical phase of the petrophysical analysis.

The modeling of the cementation exponent m takes into account the above performed porosity analysis.

For this new interpretation step we consider six models for the calculation of m from acoustic and resistivity measurements. The models differ as a function of the weight given to the VPR for such calculation.

The following models are considered: SPI/Nugent, Lucia, Nurmi/Asquith, Modified Myers, Dual Porosity, Archie.

For the One-Conductor model where the a effect is already contained in the conductivity equation, m can be calculated as Eq. 13 and 14 :

$$C_o = \Phi^m C_w \tag{13}$$

$$m \text{ Log } \Phi = \text{Log} \left(\frac{C_o}{C_w} \right) \tag{14}$$

Here we introduce the parallel conductor model, Eq. 15, 16:

$$m \text{ Log } \Phi = \text{Log} \left(\frac{\Phi_{ip}^{m_{ip}}}{a_{ip}} + \frac{\Phi_v^{m_v}}{a_v} \right) \tag{15}$$

The parameter m is a fundamental property for the carbonate petrophysical evaluation:

$$m = \frac{\text{Log} \left(\frac{\Phi_{ip}^{m_{ip}}}{a_{ip}} + \frac{\Phi_v^{m_v}}{a_v} \right)}{\text{Log } \Phi} \tag{16}$$

We state that for high values of the cementation exponent the SPI/Nugent method sets a lower limit of m while Nurmi/Asquith sets the upper limit. The Archie and Lucia

equations set a benchmark. The Dual Porosity model also matches Archie's m for high m values but overestimates m for lower m values.

Fig. 4 .

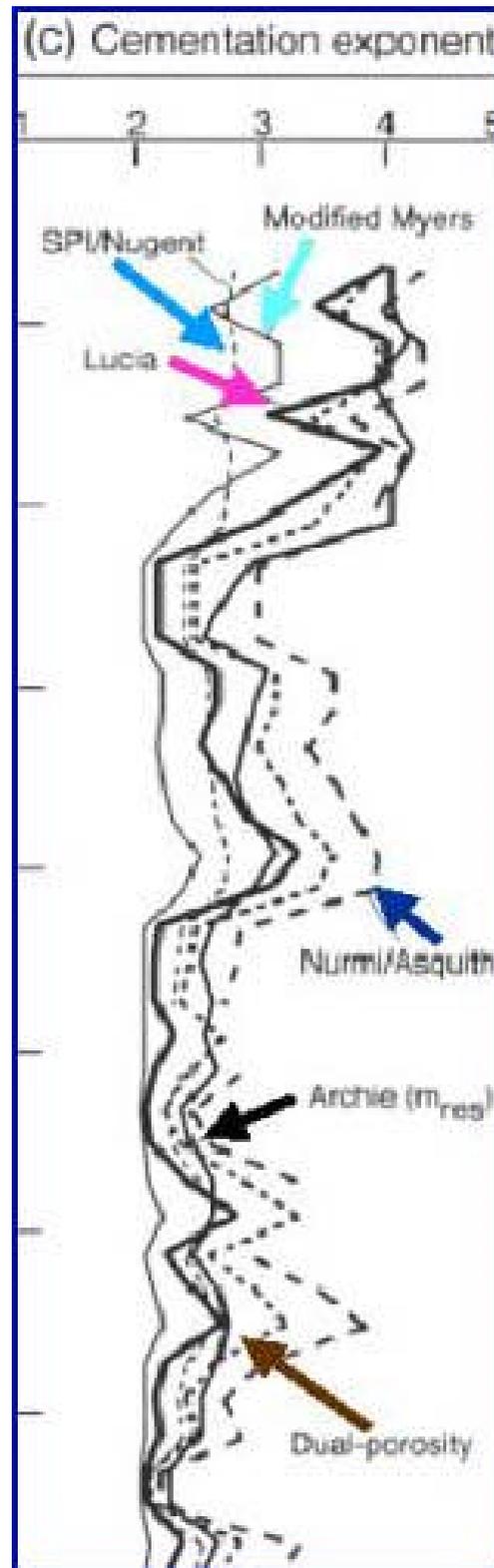


Fig. 4. Variability of m as a function of the model used which shows the dependence from the vuggy porosity type (Courtesy of F. Jerry Lucia, Rev. Robert E. Ballay)

→ Dual -Porosity,
 → Archie m_{res} ,
 → M. Myers
→ Nurmi/Asquith,
 → Lucia,
 → SPI/Nugent

For reservoirs with well connected planar fractures the coefficient of the vuggy porosity coefficients reduce to Φ_f (fracture porosity). Eq. 17 :

$$m = \frac{\text{Log} \left[\frac{\Phi_{ip}^m}{a_{ip}} + \Phi_f \right]}{\text{Log} \Phi} \quad (17)$$

6. CONCLUSIONS

With these models we can also characterize carbonates on the base of permeability and can use the parameters m and a_v as mapping attributes to verify geostatistical cross-covariance relations with other petrophysical, geomechanical and/or complex, amplitude or time seismic attributes. This technique is a remarkable step to be integrated with other disciplines for a detailed reservoir analysis on the way to construct a static geological model with enhancement of the most important reservoir architecture's structural features that help to identify the right target for the optimization of the geothermal project efficiency.

ACKNOWLEDGEMENTS

The author would like to acknowledge the feedback received from the literature and the fundamental research of F. Jerry Lucia, Fred P. Wang and Robert E. Ballay on which works this paper is based.

NOMENCLATURE

m = cementation exponent
 a = structural constant
 VPR = vuggy porosity ratio = Φ_{sv} / Φ_t
 Φ = effective porosity
 Φ_t = total porosity from Neutron-Density logs
 Φ_{sv} = Phi-SV = separate vuggy porosity
 Φ_2 = secondary porosity (separate and connected)
 Φ_s = sonic porosity (Wyllie time-average equation)
 ρ = quadratic model constant
 Δt = p wave sonic arrival time
 Φ_v^{ac} = vuggy porosity from sonic logs
 Φ_v^{ei} = vuggy porosity from resistivity logs
 Φ_{ip} = intercrystalline (interparticle) porosity

a = power law model scaling factor
 F = formation factor
 R_o = resistivity of the brine saturated formation
 R_w = formation water (brine) resistivity
 C_o = conductivity of the brine saturated formation
 C_w = formation water (brine) conductivity
 F_i = formation factor of the conductor i
 m_{ip} = cementation exponent of the intercrystalline porosity
 m_v = cementation exponent of the vuggy porosity
 a_v = structural constant of the vuggy porosity component
 a_{ip} = structural constant of the intercrystalline porosity component

Subscripts

t = total
 sv = separate vuggy
 2 = secondary
 s = sonic
 v = vuggy
 ip = intercrystalline (interparticle)
 o = 100 % brine saturated formation
 w = formation water (brine)
 i = conductor i

Superscripts

ac = acoustic (sonic)
 ei = resistivity (electrical)

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