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 $\Phi_{V^{ac}}$, Phi-Resistivity $\Phi_{V^{ei}}$.
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:

$$\phi_2 = \phi_t - \phi_s$$  \hspace{1cm} (1)

where: $\phi_2$ is the secondary vuggy porosity, $\phi_t$ is the total porosity and $\phi_s$ 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:

$$\phi_2 = 2 (\phi_t - \phi_s)$$  \hspace{1cm} (2)

This model however was applied in formations where most of the secondary porosity was separate-vuggy porosity.
The Quadratic Model unify the previous methods with the introduction of an empirical constant $\rho$ and a quadratic dependence. Eq. 3:

$$\phi_2 = (\phi_t - \phi_s)^2 + \rho(\phi_t - \phi_s)^2$$  \hspace{1cm} (3)

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

\[
\frac{2}{s} = \left( \frac{t - s}{s} \right)
\]

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 \(\phi_{sv}\).
The equation that expresses such calibration is the following
Eq. 5:

\[
\phi_{sv} = 10^{4.09 - 0.1298 (t - 141.5 \phi_t)}
\]

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.

Two more models were considered for the calculation of the
vuggy porosity from acoustic logs \(\phi_{vac}\) and
resistivity logs \(\phi_{vei}\) 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, \(\phi_{vac}\)
and \(\phi_{vei}\).

The results are exposed in Fig. 2 and show that the
comparison of different methods and especially the
difference between \(\phi_{vac}\) and \(\phi_{vei}\) 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 $i$ conductors model has the form of Eq. 10:

$$ C_o = \frac{1}{F_i} $$  (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:

$$ C_o = C_w \frac{a_{ip}}{a} + \frac{a_v}{a} $$  (11)

The parameter $a_v$ 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:

$$ C_o = C_w \left( \frac{m_{ip}}{a_{ip}} + \frac{m_v}{a_v} \right) $$  (12)

The parameter $a_v$ describes the characterization of the porosity type and its connectivity. The sensitivity of the cementation exponent $m$ is dependent upon the value of $a_v$. Fig. 3.
Fig. 3. Dependence of the cementation exponent $m$ from $
abla v$

If we consider the Dual Porosity model we can characterize the Phi-SV on the basis of the parameter $\nabla v$.

For $\nabla v > 100$ : we can recognize separate vugs.
For $\nabla v < 20$ : touching vugs porosity and for $\nabla v = 1$ : 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 $\nabla$ effect is already contained in the conductivity equation, $m$ can be calculated as Eq. 13 and 14 :

$$m = \frac{m}{C_w} C_0$$

(13)

$$m \log \frac{m}{C_w} = \log \frac{C_0}{C_w}$$

(14)

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

$$m \log \frac{m}{C_w} = \log \left( \frac{m}{m_{ip}} \frac{m_{ip}}{a_{ip}} + \frac{m_{v}}{a_{v}} \right)$$

(15)

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

$$\log \left( \frac{m_{ip}}{a_{ip}} + \frac{m_{v}}{a_{v}} \right)$$

(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)

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

$$
\begin{align*}
\log [m_{ip} - \phi_{ip} a_{ip} + \phi_f] &= \log [\phi_f] \\
m &= \frac{\phi_f}{\log [\phi_f]}
\end{align*}
$$

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.

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NOMENCLATURE

$m$ = cementation exponent
$a$ = structural constant
$VPR = \text{vuggy porosity ratio} = \phi_{sv} / \phi_t$
$\phi = \text{effective porosity}$
$\phi_t = \text{total porosity from Neutron-Density logs}$
$\phi_{sv} = \text{Phi-SV = separate vuggy porosity}$
$\phi_2 = \text{secondary porosity (separate and connected)}$
$\phi_s = \text{sonic porosity (Wyllie time-average equation)}$
$p = \text{quadratic model constant}$
$\tau = \text{p wave sonic arrival time}$
$\phi_v^{ac} = \text{vuggy porosity from sonic logs}$
$\phi_v^{ei} = \text{vuggy porosity from resistivity logs}$
$\phi_{ip} = \text{intercrystalline (interparticle) porosity}$
$\phi_f = \text{fracture porosity}$
$F = \text{formation factor}$
$R_o = \text{resistivity of the brine saturated formation}$
$R_w = \text{formation water (brine) resistivity}$
\( C_0 \) = 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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Cementation Exponent ranges from 2 to 5, dependant upon Vuggy / Total Porosity Ratio Laboratory data interpreted within context of pore geometry illustrations


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Serra, 0., 1989, Formation MicroScanner image
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Wang & Lucia classic review, including theory and applications to actual data, Estimation of vuggy Porosity Fraction, Secondary Porosity Index (Generalized, Sonic vs Total Porosity), Nurmis Model (Originally developed for oomoldic grainstones in the Smackover), Quadratic Model (Combination of SPI & Nurmi), Power Law (Combination of SPI & Nurmi), Estimation of Cementation Exponent, Lucia Model, Nugent Model, Asquith Model