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PETROPHYSICAL ROCK TYPING OF COQUINAS FROM THE MORRO DO CHAVES FORMATION, SERGIPE-ALAGOAS BASIN (NORTHEAST BRAZIL)

José Leão de Luna1, Fabio Andre Perosi1, Mariléa Gomes dos Santos Ribeiro1, Andre Souza3, Austin Boyd3, Leonardo Fonseca Borghi de Almeida2 and Patrick William Michael Corbett2,4

ABSTRACT. This work has analyzed, considering the petrophysical point of view, samples of Coquinas obtained in the outcrop of the Morro do Chaves formation (Sergipe-Alagoas Basin). The complex sedimentological aspects for this study have been reduced by focusing on a single bed. The reservoirs found in this basin have the same age of the reservoirs of Campos, Santos and Espírito Santo Basins (Brazil) and Congo (Africa), from the end of Barremian to the beginning of Aptian ages, which can be considered analogs of those ones. The data were collected applying routine core analysis and special core analysis techniques in five samples taken vertically, reproducing the case in a single well through a bed of coquinas, with a spacing of approximately 20 cm between each one, to replicate what might be sampled in subsurface coring operations. Measurements of porosity and effective permeability by gas expansion, Nuclear Magnetic Resonance and resistivity were conducted. The analysis of the data revealed the heterogeneity of the porous space in terms of pore sizes and correlations between permeability and electrical formation factor. Along with this detailed analysis, a petrotyping classification of the samples was done using the Global Hydraulic Elements method, to compare with a larger poro-perm data set from a lateral profile. This work shows that the heterogeneity in these few samples from a single bed along a vertical profile is representative for heterogeneity over a much larger coquina data set from the same bed away from this single profile. This work has implications for the scaling and interpretation of NMR data from plug data to log data in these sequences and the resulting prediction of permeability from the latter.

Keywords: carbonate, porosity and permeability properties, NMR, electrical resistivity.

RESUMO. Esse trabalho analisa, considerando o ponto de vista petrofísico, amostras de Coquinas obtidas em afloramento da Formação Morro do Chaves (Bacia de Sergipe–Alagoas). Os aspectos sedimentológicos complexos envolvidos neste estudo foram reduzidos, focando em uma única camada. Os reservatórios encontrados nesta bacia têm a mesma idade dos reservatórios das Bacias de Campos, Santos e Espírito Santo (Brasil) e Congo (África), final do Barremiano no início do Aptiano, as quais podem ser consideradas análogas daquelas. Os dados foram obtidos por meio de técnicas de petrofísica básica e petrofísica especial em cinco amostras extradas verticalmente, reproduzindo o caso de um único poço através de uma camada de coquinas, com um espaçamento de aproximadamente 20 cm entre cada uma, de forma a replicar o que poderia ser amostrado em uma operação de retirada de plug em subsuperfície. Medidas de porosidade e permeabilidade efetiva por expansão de gás, Ressonância Magnética Nuclear e resistividade foram obtidas. A análise dos dados revelou a heterogeneidade do espaço poroso em termos de tamanho de poros e correlações entre permeabilidade e fator de formação elétrico. Junto a essa análise detalhada, foi realizada a classificação petrofísica das amostras pelo método de Elementos Hidráulicos Globais, para comparar com um conjunto maior de dados permo-porosos provenientes de um perfil lateral maior. Este trabalho mostra que a heterogeneidade nestas poucas amostras de uma única camada ao longo de um perfil vertical é representativa da heterogeneidade sobre um conjunto de dados de coquinas muito maior da mesma camada, afastados deste único perfil. Este trabalho tem implicações para a interpretação e escalonamento de dados de Ressonância Magnética Nuclear de plugar para dados de perfil de poço nesta sequência e para a predição da permeabilidade a partir destes.

Palavras-chave: carbonato, propriedades permporosas, RMN, resistividade elétrica.

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INTRODUCTION
Carbonate formations are responsible for about 50% of the petro-
liiferous reservoirs around the world (Ramakrishnan et al., 2001).
Many recent studies have been conducted to infer petrophysi-
cal properties of such reservoirs (examples include Al-Shahwan
& Al-Iessa, 2015; Goda et al., 2007; Taktak et al., 2011; Bal-
lay et al., 2007; Knackstedt et al., 2007; Sadeq & Yusoff, 2015;
Eberli et al., 2003) aiming to understand and describe the behav-
ior of those systems under oil production. Such reservoirs are
strongly marked by heterogeneity in their porous space, which
is strongly influenced by effects as dissolution, precipitation, re-
precipitation, dolomitization and fracturing that, differently from
siliciclastic reservoirs (e.g. sandstones), results in a space with
dimensions composed by two or three distinct modes. As
noted by Câmara (2013), most of these carbonate reservoirs, re-
sponsible for a large portion of world’s hydrocarbon production,
originated from carbonates deposited in marine environments.
In Brazil, the study of lacustrine carbonate depositional environ-
ments, mainly the Coquinas, has a long history with the disco-
very of Pampo, Badejo, Linguado and Trilha reservoirs in Campos
Basin during the 70’s, and are described by several authors with
respect to various sedimentological, stratigraphic and petrophys-
ical properties (Feijó & Pereira, 1994; Azambuja & Arienti, 1998;
Campos Neto et al., 2007; Câmara, 2013; Tavares et al., 2015).
With the discovery of additional high production capacity areas
from lacustrine carbonates (microbialites and Coquinas) in the Pre-
Salt interval of Santos Basin, the scenario has been
changed, and more effort and investment in research are being
done to characterize these rocks.
In comparative terms, Sergipe-Alagoas Basin, specifically the
Morro do Chaves formation, presents a thick and extensive co-
quina sequence with many geological characteristics, very simi-
lar to the producing Coquinas of the Pre-Salt (Kinoshita, 2010).
As a result the description and study of petrophysical param-
ters of these analogs at different scales can bring new and use-
ful information for the characterization of Pre-Salt extracts. This
represents a more detailed study at the bed scale to understand
the heterogeneity present at that scale.

MATERIAL
The object of this study consists on a group of five plugs obtained
from a layer of approximately one meter thick from an outcrop
section of Morro do Chaves formation (Sergipe-Alagoas Basin).
The measurements along a vertical profile were named as the 4A
series (Fig. 1). Besides the data from these samples, porosity and
permeability information were used from other series (horizontal
profiles), for comparison. The 4A series is similar in appear-
ance (Fig. 2) to other plugs from the same bed, presenting some
amounts of visible moldic or vuggy porosities.
Figure 1 presents the sample’s original layer, indicating the
positions of the 4A series and the stratigraphic layer delimita-
tion (Bed 2B layer), while Figure 2 shows the group of samples
studied.

SAMPLE PREPARATION AND DATA ACQUISITION
In an experimental procedure, the samples were subject to
cleaning by the Soxhlet method, i.e. a cycle of toluene to clean
hydrocarbons and a cycle of methanol to clean salts. After that,
they were dried in a moisture controlled oven (lab standard pro-
cedure), at 60°C for about 12 hours, and their weight measured
until constant mass was observed. After that, porosity and per-
meability by Helium gas expansion method were measured with
the application of 800 psi confining pressure, using a Coretest
Systems Inc. (USA) AP-608 equipment.
To perform various laboratory measurements (NMR and
electrical resistivity), the samples were fully saturated by apply-
ning isostatic pressure of 2,000 psi. The saturating fluid used was
brine of 30,000 ppm NaCl concentration, with 1.043 g/cc den-
sity at 21.5°C (lab standard). Mass values of the samples were
collected before and after saturation.
After saturation, the samples were wrapped in Teflon tape
to minimize fluid evaporation during the experiments, and the
NMR measurements carried out. Transversal relaxation time (T2)
was measured applying the CPMG pulse sequence (Coates et al.,
1999), using a Maran Ultra DRX F (Oxford Inc., UK) equipment
with resonance frequency of 2.6 MHz for the 1H nucleus. A total
of 16,834 echoes were acquired and signal averaging performed
to keep the signal-to-noise ratio always higher than 100. The main
parameters of the NMR acquisitions are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echo time</td>
<td>400μs</td>
</tr>
<tr>
<td>Number of averages</td>
<td>32</td>
</tr>
<tr>
<td>Waiting time between averages</td>
<td>10 s</td>
</tr>
<tr>
<td>90° pulse width</td>
<td>12.2μs</td>
</tr>
<tr>
<td>180° pulse width</td>
<td>24.4μs</td>
</tr>
<tr>
<td>Temperature</td>
<td>21°C</td>
</tr>
</tbody>
</table>

Electrical resistivity experiments were done using the Coretest
Systems Inc. (USA) AERS-702 equipment that operates at room
pressure and temperature of 22°C. The 2 terminal schedule, with
30 psi connection pressure (electrode-sample), was used, applying an alternating current of 1 KHz frequency (lab standard). The brine resistivity was obtained through an immersion conductivity cell Orion (Thermo Electron Co., USA), resulting in the brine resistivity value of $\rho_w = 0.128$ ohm-m, at 21°C. After the measurements, the electrical resistance obtained was normalized to 20°C to standardize ($R_t$), given by equation (1):

$$R_t = R \left(\frac{T + 6.77}{T_s + 6.77}\right)$$

where $R$ is the measured resistance, $T$ is sample’s temperature during measurements and $T_s$ is the temperature normalized to 20°C.

All data obtained was processed and analyzed to make possible the determination of the petrophysical parameters: effective porosity (gas, weight and NMR) and permeability, NMR $T_2$ relaxation time and pore size distributions, electrical formation factor (FF) and cementation exponent ($m$), which will be presented and discussed in the next section.

RESULTS AND DISCUSSION

Porosity, Pore Size Distribution and Partitioning

To determine porosity, techniques of NMR, Helium gas expansion and weight measurements were performed.

The porosity by weigh ($\phi_w$) is obtained through the ratio between sample’s mass before and after saturation process, together with brine’s density, through equation (2):

$$\phi_w = \frac{\text{saturated mass-dried mass}}{\text{brine density}} \times \frac{\text{sample total volume}}{\text{saturated mass-dried mass}}$$

The values of porosity obtained by the gas expansion ($\phi_G$) and weight ($\phi_W$) methods are showed in Table 2, together with the dried and saturated mass of the samples. To verify the quality of the saturation process, the saturation index (SI, in %) is calculated, given by the ratio between the weight to gas porosities. Gas expansion method is considered a more accurate result, since the application of the confining pressure assures that large pores located on the core’s surface will be efficiently filled by the probing gas. The values of saturation index obtained are also showed in Table 2. Values between 98% and 102% are considered good.
Differences on saturation index of about 3-10% were found, which can be explained by the inability to maintain the external large pore structures filled by the saturating fluid during the weight measurements. This textural characteristic of the samples will influence directly the NMR porosities as well, since these measurements are taken immediately after the weighting process.

The NMR signal is proportional to the total amount of fluid inside the porous space, and so, to extract porosity from this technique, a calibration measurement is necessary on a brine sample with a well-known volume in order to be compared with sample’s results. Knowing the mass of the calibration sample and its density, the NMR signal is linked to the volume of the filled porosity for each sample (Coates et al., 1999), whose results are showed in Table 3 together with \( \phi_W \) and \( \phi_C \) for comparison.

Table 3 – Porosity by NMR, weight and gas expansion methods.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \phi_W ) (%)</th>
<th>( \phi_C ) (%)</th>
<th>( \phi_{\text{NMR}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1A</td>
<td>12.5</td>
<td>13.6</td>
<td>12.6</td>
</tr>
<tr>
<td>4.2A</td>
<td>13.7</td>
<td>14.1</td>
<td>13.5</td>
</tr>
<tr>
<td>4.3A</td>
<td>15.2</td>
<td>15.7</td>
<td>15.3</td>
</tr>
<tr>
<td>4.4A</td>
<td>16.4</td>
<td>18.1</td>
<td>16.7</td>
</tr>
<tr>
<td>4.5A</td>
<td>10.5</td>
<td>11.8</td>
<td>10.6</td>
</tr>
</tbody>
</table>

NMR and weight porosities presented an excellent agreement. However, both results show lower values when compared to the gas one. This can be explained by the saturation issue state above, i.e. the lack of saturation of the external macro and moldic/vuggy porosities.

Beyond porosity, the NMR technique allows the estimation of the pore size distribution of a porous media (Coates et al., 1999). The NMR CPMG experiment measures the magnetization decay related to the nuclei spins that are filling the porous space, characterized by a decaying time constant called the transverse relaxation time \( T_{2} \). For the analysis of sedimentary rocks measured at room temperature, the acquired signal is converted to the \( T_{2} \) distribution via an Inverse Laplace Transformation method. For details on the procedure and signal processing to obtain the distribution of \( T_{2} \), see (Coates et al., 1999). In this application, each pore will generate a signal that decays with a single \( T_{2} \) relaxation time, given by equation (3):

\[
\frac{1}{T_2} = \frac{1}{T_{2,\text{Bulk}}} + \frac{1}{T_{2,\text{Surface}}} = \frac{1}{T_{2,\text{Bulk}}} + \frac{S}{V} \rho_2
\]

where \( T_2 \) is the measured transversal relaxation time, \( T_{2,\text{Bulk}} \) is the fluid’s bulk relaxation time (in this case brine, equals to 2.7 s), \( T_{2,\text{Surface}} \) is the relaxation time due to the rock/fluid interaction, \( S/V \) is the poré’s surface area-to-volume ratio and \( \rho_2 \) is the surface relaxivity parameter, associated to the rock/fluid interaction. An additional relaxation phenomenon can play a role on \( T_2 \) relaxation rate of porous materials, the so-called diffusion term, which depends on rock’s magnetic susceptibility, NMR experimental parameters (applied magnetic field strength and echo formation timing) and fluid’s translational diffusion coefficient. However, for carbonates inside a low magnetic field as the one applied in this study, this term can be neglected and so the \( T_2 \) relaxation time distribution obtained can be interpreted as proportional to the sample’s pore size distribution (since the presence of bulk relaxation will generate signals centered around a single value, the fluid’s \( T_{2,\text{Bulk}} \)). Figure 3 shows the \( T_2 \) distribution for all the 4A series samples. The area under each distribution reflects the NMR porosity.

The distributions obtained span over 3 orders of magnitude, a broad range that reflects the complexity and heterogeneity of the Coquinas samples from this single bed. A small influence of \( T_{2,\text{Bulk}} \) term is seeing (signals around 2 to 3 seconds), and so this relaxation rate can be neglected. This allows the interpretation of the obtained distributions as a reflection of core’s pore size distribution, given by the \( T_{2,\text{Surface}} \) term of equation (3).

To convert \( T_2 \) distributions to pore size distributions, as described by the surface term of equation (3), the surface relaxivity parameter \( \rho_2 \) which characterizes the relaxation phenomenon due to the rock/fluid interaction must be determined. This was done through the acquisition of the bi-dimensional Diffusion-\( T_{2} \) map (not shown), whose experimental details are described in (Souza et al., 2013). Table 4 shows the obtained values.

Applying equation (3) and calculating \( S/V \) as a function of pore radius, the conversion of the \( T_2 \) distribution to pore radius distribution can be described by equation (4):

\[
r(T_2) = C \cdot \rho_2 \cdot T_2
\]

Table 2 – Dried and saturated masses, porosity by weight and gas expansion methods, and saturation index (SI) calculated by the percentage between weight and gas porosity results.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dried Mass (g)</th>
<th>Saturated Mass (g)</th>
<th>( \phi_W ) (%)</th>
<th>( \phi_C ) (%)</th>
<th>SI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1A</td>
<td>127.315</td>
<td>134.573</td>
<td>12.5</td>
<td>13.6</td>
<td>92.9</td>
</tr>
<tr>
<td>4.2A</td>
<td>123.732</td>
<td>131.310</td>
<td>13.5</td>
<td>14.1</td>
<td>95.7</td>
</tr>
<tr>
<td>4.3A</td>
<td>131.067</td>
<td>140.354</td>
<td>15.3</td>
<td>15.7</td>
<td>97.7</td>
</tr>
<tr>
<td>4.4A</td>
<td>123.393</td>
<td>133.146</td>
<td>16.7</td>
<td>18.1</td>
<td>91.9</td>
</tr>
<tr>
<td>4.5A</td>
<td>138.461</td>
<td>144.960</td>
<td>10.6</td>
<td>11.8</td>
<td>90.2</td>
</tr>
</tbody>
</table>
where $T_2$ is the measured relaxation time, $\rho_2$ is the surface relaxivity and $C$ is the geometrical factor that models the pores as spheres (3), cylinders (2) or parallel plates (1).

Table 4 – Surface relaxivity parameters ($\rho_2$) obtained.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\rho_2$ (μm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1A</td>
<td>38.7</td>
</tr>
<tr>
<td>4.2A</td>
<td>37.1</td>
</tr>
<tr>
<td>4.3A</td>
<td>29.8</td>
</tr>
<tr>
<td>4.4A</td>
<td>33.5</td>
</tr>
<tr>
<td>4.5A</td>
<td>39.7</td>
</tr>
</tbody>
</table>

Using those $\rho_2$ values and $C = 3$, that considers the spherical geometry to the pores, the transversal relaxation time distributions of Figure 3 can be converted to pore sizes, making possible the partitioning of the distributions into micro, meso and macroporosities as used by Machado et al. (2011) and depicted in Figure 4.

Figure 5 shows the distributions of pore sizes for the samples, with the resulting porosity partitioning. At this point, it is clearly seen that even if one consider a larger $T_2$ range for the bulk relaxation influence (e.g. 1 to 3 seconds) (Machado et al., 2011), the resulting macroporosity fractions would not be affected since these signals are located far above the respective cutoff applied.

From pore size distributions shown in Figure 5 and the cutoffs assumed, the relative porosities for the adopted partitioning were calculated to quantify micro, meso and macroporosity fractions. Table 5 lists the findings, whose sum must be equal to total NMR porosity, and also the percentage of each partition relative to total $\rho_{NMR}$.

The proportions found clearly indicate that macroporosity is the predominant porosity fraction, responding in average for approximately 82% of total porosity, while mesoporosity responds to approximately 17%. Microporosity is very small, responding for approximately 2.2% of total porosity in average. Samples 4.3A and 4.4A presented the highest amount of macroporosity, together with the lowest amount of mesoporosity, 1.7 and 1.3%. Considering the relatively constant values found for their surface relaxivity parameter (see Table 4), one can affirm that the differences observed on the $T_2$ distributions would be mostly caused by differences related to the size of the pores.

**Electrical Resistivity, Formation Factor and Cementation Exponent**

The classical model of electrical resistivity ($\rho_a$) for homogenous samples will be considered here, expressed by equation (5):

$$\rho_a = RA \frac{A}{l}$$  \hfill (5)$$

where $R$ is the electrical resistance measured, $A$ the area of the transversal section of the samples and $l$ their lengths. Table 6 shows the $\rho_a$ obtained.

As the brine resistivity ($\rho_w$) is known, the Formation Factor (FF) can be calculated through equation (6):

$$FF = \frac{\rho_a}{\rho_w}$$  \hfill (6)$$
Figure 4 – Scheme of the carbonate porous space partitioning used, adapted from Machado et al. (2011).

Figure 5 – Pore size distributions obtained by NMR, with carbonate porosity partitioning proposed by Machado et al. (2011).

Table 5 – Porosity partitioning according to the classification by porosity type (micro, meso and macroporosity), and their percentage of total NMR porosity ($\phi_{NMR}$).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Porosity Partitioning</th>
<th>% of total $\phi_{NMR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Micro (%)</td>
<td>Meso (%)</td>
</tr>
<tr>
<td>4.1A</td>
<td>0.2</td>
<td>2.0</td>
</tr>
<tr>
<td>4.2A</td>
<td>0.5</td>
<td>3.4</td>
</tr>
<tr>
<td>4.3A</td>
<td>0.2</td>
<td>1.7</td>
</tr>
<tr>
<td>4.4A</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>4.5A</td>
<td>0.4</td>
<td>2.3</td>
</tr>
</tbody>
</table>
where $\rho_m$ is the resistivity obtained through equation 5. The FF values found are also listed in Table 6.

Considering the Archie equation (Doveton, 2014), the Formation Factor (FF) can be expressed as a relation between porosity and cementation exponent ($m$) through equation (7):

$$ FF = \frac{1}{\phi^m} \quad (7) $$

The porosity used to calculate FF was the NMR derived one, since resistivity measurements were done without confining pressure. Thus, as observed for the NMR experiments, the external macropores were empty during acquisition of plug's resistances. Table 6 shows the FF obtained for the 4A series.

The so-called “generalized Archie equation” substitutes the unitary numerator in equation (7) by a parameter commonly called “electrical tortuosity” (Doveton, 2014). However, the original Archie formulation (given by Eq. (7)) is more appropriate for heterogeneous samples, like the Coquinas studied here, since it is not expected all samples to have the same electrical tortuosity. Data of NMR distributions shown in the previous section and Helium gas expansion permeability (presented and discussed in the next section) show high variability, confirming this assumption. An appropriate method to calculate this constant would be the determination of FF for several saturation states of a core. The estimation of a unique electrical tortuosity for a set of cores, however, can be done for a highly homogeneous, constant lithology formation.

The exponent $m$ is often referred as a parameter that depends on the degree of the inter-particle porous space that are cemented, i.e. blocked by a substance, and so is a major obstacle to the electrical current’s flow. Recent discussions are tending to redefine it, recognizing that a multiplicity of depositional and diagenetic processes must play a crucial role on $m$ (Doveton, 2014). For this reason, a modern and more accurate name for cementation coefficient is “porosity exponent”. The $m$ results found here for the 4A series will be interpreted based on this modern definition, where different and specific porosity types explain its variation.

Figure 6 shows a log-log plot of FF versus $\phi_{NMR}$, following Archie’s model of equation (7). The correlation reveals a fairly linear dependence, with a $R^2$ of 94.7%. Despite such good correlation, no numerical estimates were based on that fitting due to the heterogeneity of the samples and lack of knowledge about their tortuosities. The purpose of this plot is to show the strong dependence of FF with $\phi_{NMR}$, revealing the importance of such analysis.

For each sample, $m$ was calculated based on the log-log linearization of equation (7), given by equation (8):

$$ m = \frac{\log_{10} FF}{\log_{10} \phi_{NMR}} \quad (8) $$

According to Schön (2004), Tiab & Donaldson (2012) and Doveton (2014), carbonates with $m$ higher than 2 presents a significant amount of vuggy porosity, while values lower than 2 are presented by carbonates with predominance of inter-particle and fractured porosities. The term vuggy porosity is synonymous with macro pore for the purpose of this study. Definition of inter-particle porosity for carbonates takes a very comprehensive meaning, aiming to consider several types of inter-crystalline and intergranular spaces (Doveton, 2014). Vuggy porosity incorporates large spaces mostly caused by particle and matrix dissolution, here it is often the shells alone that dissolve (i.e., moldic porosity), while fractured ones can be generated by other processes that are difficult to interpret based only on indirect exploratory methods (Doveton, 2014). Table 6 lists the $m$ values extracted from the electrical resistivity measurements by equation (8).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\rho_m$ (ohm-m)</th>
<th>FF</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1A</td>
<td>6.75</td>
<td>52.70</td>
<td>1.91</td>
</tr>
<tr>
<td>4.2A</td>
<td>6.19</td>
<td>48.32</td>
<td>1.95</td>
</tr>
<tr>
<td>4.3A</td>
<td>4.88</td>
<td>37.74</td>
<td>1.93</td>
</tr>
<tr>
<td>4.4A</td>
<td>4.91</td>
<td>38.96</td>
<td>2.02</td>
</tr>
<tr>
<td>4.5A</td>
<td>9.62</td>
<td>75.09</td>
<td>1.92</td>
</tr>
</tbody>
</table>

All the samples presented $m$ values ranging between 1.91 and 2.02, which means that disconnected vuggy porosity should be very low with a predominance of inter-particle porosity. FF values were lowest for samples 4.3A and 4.4A, and increasing values were found for samples 4.2A, 4.1A and 4.5A, respectively. Also, FF data did not correlate well with $m$ parameter, which can be explained as a consequence of a significant variation of porosity. $\phi_{NMR}$ have shown to vary between 10.5% and 15.2%, a difference of about 50% considering the lowest $\phi_{NMR}$ value of sample 4.5A. In conclusion, despite the high linearity seen on Figure 6, the derived $m$ values have demonstrated to be a complex function of porosity fractions and types that characterize the studied samples.

Next sections will present and discuss permeability data that will lead, together with porosity results, to the development of a...
“petrotype” classification inspired by the work of Corbett & Potter (2004). This is a petrophysical rock typing method that will then be supported by the NMR and electrical resistivity findings.

Permeability and Global Hydraulic Elements Classification

Permeability ($k$) measures the flow capacity of a porous media related to a specific percolating fluid. Therefore, it is dependent on the porosity (primary and secondary), wettability, tortuosity and the connectivity of the pores, besides the environmental pressure conditions. Due to the high heterogeneity of Coquinas, one can observe a high variety in permeability of 4A series, ranging from about 20 to 600 mD. Table 7 presents the values of porosity and permeability obtained by the Helium gas expansion method.

![Figure 6](image)

Figure 6 – Electrical formation factor (FF) versus $\phi_{NMR}$ correlation for the 4A series samples. The red solid line represents the fitting of the data, showing a very good linear correlation with a $R^2$ of 94.67%.

The understanding of the relations between porosity and permeability becomes necessary for the assessment of the system behavior as a possible reservoir. According to Akbas (2005), the correlation between permeability and porosity are usually linear models, expressed as equation (9):

$$\log_{10}(k) = a \cdot \log_{10}(\phi) + b \quad (9)$$

where $a$ and $b$ are constant. This analysis is generally called poro-perm correlation. Figure 7 shows the correlation plot of both properties, called the $k$-$\phi$ plot, where the model given by equation (9) were applied for the 4A series. The linear fitting applied have resulted in a fairly good adjustment, presenting a $R^2$ of 44.6%.

Considering the limited number of samples studied, data from 32 plugs extracted from the horizontally delimited Bed 2B layer (white dashed lines shown in Fig. 1) were studied, to check the $k$-$\phi$ properties along the formation. The obtained $k$-$\phi$ plot is shown in Figure 8, with the adjustment to the proposed linear model (red solid line) resulting in a $R^2$ of 72.9%. The equation and exponents that best adjusted the model were given by equation (10):

$$\log_{10}(k) = 8.29 \cdot \log_{10}(\phi) - 7.59 \quad (10)$$

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\phi$ (%)</th>
<th>$k$ (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1A</td>
<td>13.6</td>
<td>80.50</td>
</tr>
<tr>
<td>4.2A</td>
<td>14.1</td>
<td>20.62</td>
</tr>
<tr>
<td>4.3A</td>
<td>15.7</td>
<td>597.62</td>
</tr>
<tr>
<td>4.4A</td>
<td>18.1</td>
<td>393.75</td>
</tr>
<tr>
<td>4.5A</td>
<td>11.8</td>
<td>24.13</td>
</tr>
</tbody>
</table>

![Table 7](image)
Figure 7 – $k$-$\phi$ plot of gas expansion method results, with linear fitting given by equation (9) (red solid line) for the poro-perm pairs of 4A series samples.

Figure 8 – $k$-$\phi$ plot with linear fitting for the poro-perm data considering all the samples obtained from the Morro do Chaves Formation: 4A series (blue circles) and horizontal Bed 2B layer (black circles). Note that the fit (red full line), whilst statistically reasonable, exhibits a significant variability not captured by the regression. Consequently, the resulting fitting will lead to poor permeability prediction if used for that purpose.
From the plot, it is clear that the 4A series samples are good representatives of the $k$-$\phi$ properties for the whole Bed 2B, no matter if horizontal or vertically sampled, justifying their choice for the detailed petrophysical analysis done.

Another important application of the poro-perm correlation is the classification of the system in terms of Hydraulic Units (HU), defined as a classification method that aggregates representative elementary volumes by similar poro-perm petrophysical and geological properties of a reservoir (Câmara, 2013). The obtained HU must be internally consistent and sufficiently distinct from other units that affects the hydraulic flow of such formation (Câmara, 2013). These units are obtained through the porosity and permeability analysis, generating groups by the calculation of the Flow Zone Index (FZI) parameter, expressed by equation (11):

$$F_{ZI} = \frac{0.0314}{(\frac{G}{N})^{0.5}}$$

Defining constant FZI zones, it is possible to locate the $k$-$\phi$ pairs inside different zones, allowing the classification of the samples in terms of consistent Global Hydraulic Elements (GHE) (Corbett & Potter, 2004). The resulting GHE zones and sample’s classification are presented in Figure 9.

The advantage on the GHE classification is that it allows the identification of trends on the $k$-$\phi$ properties, through the regular progression of FZI (Corbett & Potter, 2004), and also a fairer comparison among samples of different origins.

The results show the presence of 3 GHE’s (5, 6 and 7) with different hydraulic flow behaviors in the vertically sampled 4A series. The 32 $k$-$\phi$ pairs of the whole Bed 2B were also applied to the GHE classification, whose results are shown in Figure 9.

It is remarkable the fact that for all the samples, as shown by Figure 10, the same 3 distinct GHE’s (5, 6 and 7) were found; those are exactly the ones found for the vertical 4A series. This fact encourages the correlations and discussions about the 4A samples, even considering it as a limited sample space case. It suggests that samples along a vertical profile (as the ones extracted by subsurface coring operations) can be extended laterally into the reservoir.

Petrophysical Rock Typing by GHE and Data Correlation

To facilitate the correlation of the acquired and discussed data, Table 8 presents a chart that resumes the key results obtained for the 4A series.

Table 8 – Porosity ($\phi_{MACRO}$) and permeability ($k_{MACRO}$) by gas expansion method.

<table>
<thead>
<tr>
<th>Sample</th>
<th>4.1A</th>
<th>4.2A</th>
<th>4.3A</th>
<th>4.4A</th>
<th>4.5A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{MACRO}$ (%)</td>
<td>14.1</td>
<td>14.1</td>
<td>15.7</td>
<td>18.1</td>
<td>11.9</td>
</tr>
<tr>
<td>$\phi_{NMR}$ (%)</td>
<td>12.5</td>
<td>13.7</td>
<td>15.2</td>
<td>16.4</td>
<td>10.5</td>
</tr>
<tr>
<td>$\phi_{MACRO}$ (%)</td>
<td>0.05</td>
<td>0.2</td>
<td>0.1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>$\phi_{NMR}$ (%)</td>
<td>2.0</td>
<td>3.4</td>
<td>1.7</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td>$\phi_{MACRO}$ (%)</td>
<td>10.3</td>
<td>9.8</td>
<td>13.3</td>
<td>15.0</td>
<td>7.8</td>
</tr>
<tr>
<td>$k_{MACRO}$ (mD)</td>
<td>80.50</td>
<td>20.62</td>
<td>597.62</td>
<td>393.75</td>
<td>34.13</td>
</tr>
<tr>
<td>FF</td>
<td>52.70</td>
<td>48.32</td>
<td>37.74</td>
<td>38.36</td>
<td>75.09</td>
</tr>
<tr>
<td>$m$</td>
<td>1.91</td>
<td>1.95</td>
<td>1.93</td>
<td>2.02</td>
<td>1.92</td>
</tr>
<tr>
<td>GHE</td>
<td>GHE5</td>
<td>GHE6</td>
<td>GHE5</td>
<td>GHE7</td>
<td>GHE7</td>
</tr>
</tbody>
</table>

It was surprisingly noted that $m$ does not look to correlate well with FF and also with the NMR porosity partitioning proposed. According to Doveton (2014), the electrical properties of carbonates must depend on porosity differently from what is commonly seen in sandstones, in a way that not all the porosity fractions play a significant role in electrical conductivity through a complex carbonate rock sample. As $m$ takes into account the total porosity, its value can be inaccurate and so FF looks to correlate better with NMR porosities and GHE zones. It is possible that the macropores are relatively uniformly distributed through these samples, hence the ‘interparticle’ $m$ exponents. These macropores are therefore not connected vugs in the petrophysical sense.

Permeability data were grouped by the GHE method applied. Samples 4.3A and 4.4A, the most permeable ones, were grouped as GHE7. This element has shown to represent the best quality reservoir among the samples. This is corroborated by the good porosities (15% and 18%, approximately) found for this element, and permeabilities of approximately 600 and 400 mD. Samples 4.1A and 4.5A were grouped as GHE5, presenting porosities of approximately 14% and 12%, and permeabilities around 80 and 34 mD, respectively. Sample 4.1A was classified as belonging to GHE5, presenting the lowest permeability (20 mD) and an approximate porosity of 14%.

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Figure 9 – GHE classification of the 4A series samples based on the porosity and permeability data. The limits of the GHE’s are defined by the FZI parameter.

Figure 10 – GHE classification of the 4A series and the 32 Coquinas samples from the whole Bed 2B horizontal layer, based on the porosity and permeability data. The limits of the GHE’s are defined by the FZI parameter.
PETROPHYSICAL ROCK TYPING OF COQUINAS FROM THE MORRO DO CHAVES FORMATION

As already described, FF was able to correlate with porosity, but \( \Phi \) does not. At the same time, NMR \( \Phi_{\text{MESO}} \) porosity also correlated very well with permeability and FF (higher for the lowest permeable core – sample 4.2A, and lower for the highest ones – samples 4.3A and 4.4A). Meanwhile, the \( \Phi_{\text{MACRO}} \) porosity fails in predicting permeability, which can be understood in terms of the well-established concept that permeability is a property of pore throats, or the constrictions to the fluid’s flow, most likely represented by \( \Phi_{\text{MESO}} \).

With these conclusions in mind, it is feasible the proposition of a “petrotype” classification (an alternative name for the idea of petrophysical rock typing) (Corbett & Potter, 2014), that is able to predict petrophysical features of Coquinas based on the \( k-\Phi \) plots associated with the GHE zones. It was shown that the findings are strongly dependent on the amount of mesoporosity, defined as pores with sizes between 0.5 and 5.0 \( \mu m \). Macroporosity, defined as pores with sizes longer than 5 \( \mu m \), can play a role on the electrical resistivity properties, but a less important role on fluid transport properties. Microporosity, as defined, is very low in quantity, and so does not play an important role on permeability for these samples.

As a main conclusion of this work, NMR and electrical resistivity were able to support the GHE zones found that were, in turn, able to predict pore-perm properties. Moreover, the prediction of the petrophysical properties studied were proposed with a minimum of time (in data acquisition) and data availability.

To further corroborate and to provide a deep understanding of those findings, it would be necessary the acquisition of more data, able to elucidate key properties of Coquinas’ geological aspects, like thin section and micro-computed Tomography (\( \mu \)-CT) images (Corbett et al., 2017). Further correlation of those data will enlighten the role of important characteristics as cementation degree, pore types, sizes and their associated aspect ratios, and grain conservation. Besides, effects from physical-chemical processes that happened during their lithification processes will enlighten the role of important characteristics as cementation degree, pore types, sizes and their associated aspect ratios, and grain conservation. Besides, effects from physical-chemical processes that happened during their lithification processes will be very valuable to the consolidation of the discussions and conclusions made.

CONCLUSIONS

The Coquinas carbonate samples studied, extracted from a vertical profile in a single bed of the Morro do Chaves Formation, were characterized by a high degree of heterogeneity in their spatial petrophysical properties, especially regarding to their characteristic porous space. The significant presence of mesoporosity and a predominance of macroporosity were found by an adapted NMR pore size distribution partitioning method. A consequence of this fact is reflected in the cementation coefficient, which were observed to lie between 1.91 to 2.02, the lower limit of carbonates with high amounts of vuggy porosity. Electrical resistivity formation factor parameter shows a strong dependence with the macroporosity fraction and a small effect on the poro-perm properties of the studied Coquina samples.

A “petrotype” classification was proposed, that uses the Global Hydraulic Elements method based on the \( k-\Phi \) pilot. Three distinct GHE elements were successfully observed, corroborated by additional 32 samples extracted from the same formation along a horizontal profile. The resulting petrotyping definition revealed that all the samples have the same pore space characteristics: strong predominance of macroporosity, always higher than 70% of total porosity, medium mesoporosity fraction (about 16% of total porosity) and very low microporosity fractions (about 2-3% of the total porosity); and that even considering the high amounts of macroporosities found, the mesoporosity fractions were more successful in prediction the GHE zones and associated permeabilities.

The presented results and their inter-correlations will be further studied and refined in ongoing studies, with the addition of more petrophysical data from samples of the same formation, and also a comprehensive analysis of their geological characteristics.

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REFERENCES


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