Seismo Magnetic Field Fractal Dimension for Characterizing Shajara Reservoirs of the Permo-Carboniferous Shajara Formation, Saudi Arabia

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Received February 03, 2019; Accepted February 20, 2019; Published December 22, 2019

ABSTRACT

The quality and assessment of a reservoir can be documented in details by the application of Seismo magnetic field. This research aims to calculate fractal dimension from the relationship among Seismo magnetic field, maximum Seismo magnetic field and wetting phase saturation and to approve it by the fractal dimension derived from the relationship among capillary pressure and wetting phase saturation. In this research, porosity was measured on real collected sandstone samples and permeability was calculated theoretically from capillary pressure profile measured by mercury intrusion contaminating the pores of sandstone samples in consideration. Two equations for calculating the fractal dimensions have been employed. The first one describes the functional relationship between wetting phase saturation, Seismo magnetic field, maximum Seismo magnetic field and fractal dimension. The second equation implies to the wetting phase saturation as a function of capillary pressure and the fractal dimension. Two procedures for obtaining the fractal dimension have been utilized. The first procedure was done by plotting the logarithm of the ratio between Seismo magnetic field and maximum Seismo magnetic field versus logarithm wetting phase saturation. The slope of the first procedure=3 - Df (fractal dimension). The second procedure for obtaining the fractal dimension was determined by plotting the logarithm of capillary pressure versus the logarithm of wetting phase saturation. The slope of the second procedure=Df - 3. On the basis of the obtained results of the fabricated stratigraphic column and the attained values of the fractal dimension, the sandstones of the Shajara reservoirs of the Shajara Formation were divided here into three units. The obtained units from bottom to top are: Lower, Middle and Upper Shajara Seismo magnetic field Fractal Dimension Units. It was found that fractal dimension increases with increasing grain size and permeability.

Keywords: Shajara reservoirs, Shajara formation, Seismo magnetic field fractal dimension

INTRODUCTION

Seismo electric effects related to electro kinetic potential, dielectric permittivity, pressure gradient, fluid viscosity and electric conductivity was first reported by Frenkel [1]. Capillary pressure follows the scaling law at low wetting phase saturation was reported by Li and Williams [2]. Seismo electric phenomenon by considering electro kinetic coupling coefficient as a function of effective charge density, porosity, fluid viscosity and electric conductivity was reported by Revil and Jardani [3]. The magnitude of seismo electric current depends on porosity, pore size, zeta potential of the pore surfaces and elastic properties of the matrix was investigated by Dukhin et al. [4]. The tangent of the ratio of converted electric field to pressure is approximately in inverse proportion to permeability was studied by Guan et al. [5]. Permeability inversion from seismolectric log at low frequency was studied by Hu et al. [6]. They reported that, the tangent of the ratio among electric excitation intensity and pressure field is a function of porosity, fluid viscosity, frequency, tortuosity, fluid density and Dracy permeability. A decrease of seismo electric frequencies with increasing water content was reported by Borde et al. [7]. An increase of seismo electric transfer function with increasing water saturation was studied by Jardani and Revil [8]. An increase of dynamic seismo electric transfer function with decreasing fluid conductivity was described by Holzhauer et al. [9].

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amplitude of seismo electric signal increases with increasing permeability which means that the seismo electric effects are directly related to the permeability and can be used to study the permeability of the reservoir was illustrated by Rong et al. [10]. Seismo electric coupling is frequency dependent and decreases exponentially when frequency increases was demonstrated by Djuraev et al. [11]. An increase of permeability with increasing pressure head and bubble pressure fractal dimension was reported by Alkhidir [12,13]. An increase of geometric and arithmetic relaxation time of induced polarization fractal dimension with permeability increasing and grain size was described by Alkhidir [14-16]. An increase of seismo electric field fractal dimension with increasing permeability and grain size was described by Alkhidir [17]. An increase of resistivity fractal dimension with increasing permeability and grain size was illustrated by Alkhidir [18]. An increase of electro kinetic fractal dimension with increasing permeability and grain size was demonstrated by Alkhidir [19]. An increase of electric potential energy with increasing permeability and grain size was defined by Alkhidir [20]. An increase of electric potential gradient fractal dimension with increasing permeability and grain size was defined by Alkhidir [21]. An increase of differential capacity fractal dimension with increasing permeability and grain size was described by Alkhidir [22].

MATERIALS AND METHOD
Sandstone samples were collected from the surface type section of the Permo-Carboniferous Shajara Formation, latitude 26°52'17.4", longitude 43°36'18" (Figure 1). Porosity was measured on collected samples using mercury intrusion Porosimetry and permeability was derived from capillary pressure data. The purpose of this paper is to obtain seismo magnetic field fractal dimension and to confirm it by capillary pressure fractal dimension. The fractal dimension of the first procedure is determined from the positive slope of the plot of logarithm of the ratio of seismo magnetic field to maximum seismo magnetic field log (H_{1/2}/H_{max}) versus log wetting phase saturation (log Sw). Whereas the fractal dimension of the second procedure is determined from the negative slope of the plot of logarithm of log capillary pressure (log Pc) versus logarithm of wetting phase saturation (log Sw).

Figure 1. Surface type section of the Shajara Reservoirs of the permo-carboniferous Shajara Formation at latitude 26°52'17.4", longitude 43°36'18".
The seismo magnetic field can be scaled as:

\[
Sw = \left( \frac{H_{s,r}^2}{H_{s,r,\text{max}}} \right)^{3-Df}
\]  (1)

Where \( Sw \) the water saturation, \( H \) the seismo magnetic field in ampere/meter generated from the shear wave velocity, \( H_{s,r,\text{max}} \) the maximum seismo magnetic field in ampere/meter generated from the shear wave velocity and \( Df \) the fractal dimension.

“Eq. (1)” can be proofed from:

\[
H_{s,0} = \frac{\Phi \cdot \varepsilon_0 \cdot k f \cdot \zeta \cdot \rho f \cdot \frac{dU_s}{dt}}{\alpha_{\infty} \cdot \eta} \]  (2)

Where \( H_{s,0} \) the seismo magnetic field generated from shear wave velocity in ampere/meter, \( \Phi \) the porosity, \( \varepsilon_0 \) permittivity of free scape in Faraday/meter, \( k_f \) dielectric constant of the fluid, \( \zeta \) the zeta potential in volt, \( \rho \) the fluid density in kilogram/meter, \( G \) the shear modulus in pascal, \( \rho \) bulk density in kilogram/meter, \( dU_s/dt \) the radial grain velocity in meter/second, \( \alpha_{\infty} \) the tortuosity and \( \eta \) the fluid viscosity in pascal * second.

The zeta potential can be scaled as:

\[
\zeta = \left[ C_S \cdot \sigma f \cdot \eta \right] \]  (3)

Where \( \zeta \) the zeta potential in volt, \( C_S \) streaming potential coefficient in volt/pascal, \( \sigma_f \) the fluid electric conductivity in Siemens/meter, \( \eta \) the fluid viscosity in pascal * second, \( C_E \) the fluid permittivity in Faraday/meter.

Insert “Eq. (3)” in “Eq. (2)”: \[
H_{s,0} = \frac{\Phi \cdot \varepsilon_0 \cdot k f \cdot \frac{dU_s}{dt}}{\alpha_{\infty} \cdot \eta} \]  (4)

The streaming potential coefficient can be scaled as:

\[
C_S = \left( \frac{r_{\text{eff}}^2 \cdot C_E}{8 \cdot \sigma f \cdot \eta} \right) \]  (5)

Where \( C_S \) the streaming potential coefficient in volt/pascal, \( r_{\text{eff}} \) the effective pore radius in meter, \( C_E \) the electro osmosis coefficient in pascal/volt, \( \sigma_f \) the fluid conductivity in Siemens/meter and \( \eta \) the fluid viscosity in pascal * second.

Insert “Eq. (5)” into “Eq. (4)”: \[
H_{s,0} = \frac{\Phi \cdot \varepsilon_0 \cdot k f \cdot r_{\text{eff}}^2 \cdot C_E \cdot \sigma f \cdot \eta \cdot \rho f \cdot \frac{dU_s}{dt}}{\alpha_{\infty} \cdot \eta \cdot 8 \cdot \sigma f \cdot \eta} \]  (6)

If the pore radius is introduced equation 6 will become, \[
H_{s,0} = \frac{\Phi \cdot \varepsilon_0 \cdot k f \cdot r^2 \cdot C_E \cdot \sigma f \cdot \eta \cdot \rho f \cdot \frac{dU_s}{dt}}{\alpha_{\infty} \cdot \eta \cdot 8 \cdot \sigma f \cdot \eta} \]  (7)

The maximum pore radius can be scaled as:

\[
H_{s,r,\text{max}} = \frac{\Phi \cdot \varepsilon_0 \cdot k f \cdot r_{\text{max}}^2 \cdot C_E \cdot \sigma f \cdot \eta \cdot \rho f \cdot \frac{dU_s}{dt}}{\alpha_{\infty} \cdot \eta \cdot 8 \cdot \sigma f \cdot \eta} \]  (8)

Divide “Eq. (7)” by “Eq. (8)”: \[
\frac{H_{s,0}}{H_{s,r,\text{max}}} = \left[ \frac{r^2}{r_{\text{max}}^2} \right] \]  (9)

“Eq. (9)” after simplification will become, \[
\frac{H_{s,0}}{H_{s,r,\text{max}}} = \left[ \frac{r}{r_{\text{max}}} \right] \]  (10)

Take the square root of “Eq. (10)”: \[
H_{s,0} = \left[ \frac{r}{r_{\text{max}}} \right] \]  (11)

“Eq. (11)” after simplification will become, \[
H_{s,0} = \left[ \frac{r}{r_{\text{max}}} \right] \]  (12)

Take the logarithm of “Eq. (12)”: \[
\log \left[ \frac{H_{s,0}}{H_{s,r,\text{max}}} \right] = \frac{r}{r_{\text{max}}} \]  (13)

But; \[
\log \left[ \frac{r}{r_{\text{max}}} \right] = \log \left[ \frac{Sw}{3-Df} \right] \]  (14)

Insert “Eq. (14)” into “Eq. (13)”: \[
\log \left[ \frac{Sw}{3-Df} \right] = \log \left[ \frac{H_{s,0}}{H_{s,r,\text{max}}} \right] \]  (15)

After log removal “Eq. (15)” will become, \[
Sw = \left[ \frac{H_{s,0}}{H_{s,r,\text{max}}} \right]^{3-Df} \]  (16)
“Eq. (16)” the proof of equation 1 which relates the water saturation, seismo magnetic field, maximum seismo magnetic field generated from the shear wave and the fractal dimension.

The capillary pressure can be scaled as:

\[ Sw = [Df - 3] \times Pc \times \text{constant} \]  

(17)

Where \( Sw \) the water saturation, \( Pc \) the capillary pressure and \( Df \) the fractal dimension.

**RESULTS AND DISCUSSION**

Based on field observation the Shajara Reservoirs of the Permocarboniferous Shajara Formation were divided here into three units as described in Figure 1. These units from bottom to top are: Lower Shajara Reservoir, Middle Shajara reservoir and Upper Shajara Reservoir. Their acquired Table 1. Petrophysical model showing the three Shajara reservoir units with their corresponding values of seismo magnetic field fractal dimension and capillary pressure fractal dimension.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Reservoir</th>
<th>Sample</th>
<th>Porosity %</th>
<th>( k ) (md)</th>
<th>Positive slope of the first procedure Slope=3-Df</th>
<th>Negative slope of the second procedure Slope=Df-3</th>
<th>Seismo magnetic field fractal dimension</th>
<th>Capillary pressure fractal dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permo-Carboniferous Shajara Formations</td>
<td>Upper Shajara Reservoir</td>
<td>SJ13</td>
<td>25</td>
<td>973</td>
<td>0.2128</td>
<td>-0.2128</td>
<td>2.7872</td>
<td>2.7872</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SJ12</td>
<td>28</td>
<td>1440</td>
<td>0.2141</td>
<td>-0.2141</td>
<td>2.7859</td>
<td>2.7859</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SJ11</td>
<td>36</td>
<td>1197</td>
<td>0.2414</td>
<td>-0.2414</td>
<td>2.7586</td>
<td>2.7586</td>
</tr>
<tr>
<td></td>
<td>Middle Shajara Reservoir</td>
<td>SJ9</td>
<td>31</td>
<td>1394</td>
<td>0.2214</td>
<td>-0.2214</td>
<td>2.7786</td>
<td>2.7786</td>
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<tr>
<td></td>
<td></td>
<td>SJ8</td>
<td>32</td>
<td>1344</td>
<td>0.2248</td>
<td>-0.2248</td>
<td>2.7752</td>
<td>2.7752</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SJ7</td>
<td>35</td>
<td>1472</td>
<td>0.2317</td>
<td>-0.2317</td>
<td>2.7683</td>
<td>2.7683</td>
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<td></td>
<td>Lower Shajara Reservoir</td>
<td>SJ4</td>
<td>30</td>
<td>176</td>
<td>0.3157</td>
<td>-0.3157</td>
<td>2.6843</td>
<td>2.6843</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SJ3</td>
<td>34</td>
<td>56</td>
<td>0.5621</td>
<td>-0.5621</td>
<td>2.4379</td>
<td>2.4379</td>
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<td></td>
<td></td>
<td>SJ2</td>
<td>35</td>
<td>1955</td>
<td>0.2252</td>
<td>-0.2252</td>
<td>2.7748</td>
<td>2.7748</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SJ1</td>
<td>29</td>
<td>1680</td>
<td>0.2141</td>
<td>-0.2141</td>
<td>2.7859</td>
<td>2.7859</td>
</tr>
</tbody>
</table>

The Lower Shajara reservoir was denoted by six sandstone samples (Figure 1), four of which label as SJ1, SJ2, SJ3 and SJ4 were carefully chosen for capillary pressure measurement as established in Table 1. Their positive slopes of the first procedure log of the seismo magnetic field (H) to maximum seismo magnetic field (\( H_{max} \)) versus log wetting phase saturation (Sw) and negative slopes of the second procedure log capillary pressure (Pc) versus log wetting phase saturation (Sw) are explained in Figures 2-5 and Table 1. Their seismo magnetic field fractal dimension and capillary pressure fractal dimension values are revealed in Table 1. As we proceed from sample SJ2 to SJ3 a pronounced reduction in permeability due to compaction results of the seismo magnetic field fractal dimension and capillary pressure fractal dimension are displayed in Table 1. Based on the attained results it was found that the seismo magnetic field fractal dimension is equal to the capillary pressure fractal dimension. The maximum value of the fractal dimension was found to be 2.7872 assigned to sample SJ13 from the Upper Shajara Reservoir as verified in Table 1. Whereas the minimum value of the fractal dimension 2.4379 was reported from sample SJ3 from the Lower Shajara reservoir as displayed in Table 1. The seismo magnetic field fractal dimension and capillary pressure fractional dimension were observed to increase with increasing permeability as proofed in Table 1 owing to the possibility of having interconnected channels.

The Lower Shajara reservoir was denoted by six sandstone samples (Figure 1), four of which label as SJ1, SJ2, SJ3 and SJ4 were carefully chosen for capillary pressure measurement as established in Table 1. Their positive slopes of the first procedure log of the seismo magnetic field (H) to maximum seismo magnetic field (\( H_{max} \)) versus log wetting phase saturation (Sw) and negative slopes of the second procedure log capillary pressure (Pc) versus log wetting phase saturation (Sw) are explained in Figures 2-5 and Table 1. Their seismo magnetic field fractal dimension and capillary pressure fractal dimension values are revealed in Table 1. As we proceed from sample SJ2 to SJ3 a pronounced reduction in permeability due to compaction was described from 1955 md to 56 md which reflects decrease in seismo magnetic field fractal dimension from 2.7748 to 2.4379 as quantified in Table 1. Again, an increase in grain size and permeability was proved from sample SJ4 whose seismo magnetic field fractal dimension and capillary pressure fractal dimension was found to be 2.6843 as pronounced in Table 1.
In contrast, the Middle Shajara reservoir which is separated from the Lower Shajara reservoir by an unconformity surface as shown in Figure 1. It was nominated by four samples (Figure 1), three of which named as SJ7, SJ8 and SJ9 as clarified in Table 1 were chosen for capillary measurements as described in Table 1. Their positive slopes of the first procedure and negative slopes of the second procedure are shown in Figures 6-8 and Table 1. Furthermore, their seismo magnetic field fractal dimensions and capillary pressure fractal dimensions show similarities as defined in Table 1. Their fractal dimensions are higher than those of samples SJ3 and SJ4 from the Lower Shajara Reservoir due to an increase in their permeability as explained in Table 1.
On the other hand, the Upper Shajara reservoir was separated from the Middle Shajara reservoir by yellow green mudstone as shown in Figure 1. It is defined by three samples so called SJ11, SJ12, SJ13 as explained in Table 1. Their positive slopes of the first procedure and negative slopes of the second procedure are displayed in Figures 9-11 and Table 1. Moreover, their seismo magnetic field fractal dimension and capillary pressure fractal dimension are also higher than those of sample SJ3 and SJ4 from the Lower Shajara Reservoir due to an increase in their permeability as simplified in Table 1.
Overall a plot of positive slope of the first procedure versus negative slope of the second procedure as described in Figure 12 reveals three permeable zones of varying Petrophysical properties. These reservoir zones were also confirmed by plotting seismo magnetic field fractal dimension versus capillary pressure fractal dimension as described in Figure 13. Such variation in fractal dimension can account for heterogeneity which is a key parameter in reservoir quality assessment.

CONCLUSION

- The Units from base to top are: Lower Shajara seismo magnetic field Fractal dimension Unit, Middle Shajara Seismo Magnetic Field Fractal Dimension Unit and Upper Shajara Seismo Magnetic Field Fractal Dimension Unit.
- These units were also proved by capillary pressure fractal dimension.
- The fractal dimension was found to increase with increasing grain size and permeability owing to possibility of having interconnected channels.

ACKNOWLEDGEMENT

The author would to thank King Saud University, college of Engineering, Department of Petroleum and Natural Gas Engineering, Department of Chemical Engineering, Research Centre at College of Engineering and King Abdullah Institute for research and Consulting Studies for their supports.

REFERENCES


