

Specific Enthalpy Fractal Dimension for Characterizing Shajara Reservoirs of the Permo-Carboniferous Shajara Formation, Saudi Arabia

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Abstract

The quality and assessment of a reservoir can be documented in details by the application of specific enthalpy. This research aims to calculate fractal dimension from the relationship among specific enthalpy, maximum specific enthalpy and wetting phase saturation and to approve it by the fractal dimension derived from the relationship among capillary pressure and wetting phase saturation. Two equations for calculating the fractal dimensions have been employed. The first one describes the functional relationship between wetting phase saturation, specific enthalpy, maximum specific enthalpy 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 specific enthalpy and maximum specific enthalpy versus logarithm wetting phase saturation. The slope of the first procedure = $3 - D_f$ (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 = $D_f - 3$. 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.

Key words: Shajara Reservoirs; Shajara Formation; Specific enthalpy fractal dimension; Capillary Pressure fractal dimension.

Introduction

Seismo electric effects related to electro kinetic potential, dielectric permittivity, pressure gradient, fluid viscosity, and electric conductivity was first reported by [1]. Capillary pressure follows the scaling law at low wetting phase saturation was reported by [2]. Seismo electric phenomenon by considering electro kinetic coupling coefficient as a function of effective charge density, permeability, fluid viscosity and electric conductivity was reported by [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 [4]. The tangent of the ratio of converted electric field to pressure is approximately in inverse proportion to permeability was studied by [5]. Permeability inversion from seismo electric log at low frequency was studied by [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 and fluid density and Dracy permeability. A decrease of seismo electric frequencies with increasing water content was reported by [7]. An increase of seismo electric transfer function with increasing water saturation was studied by [8]. An increase of dynamic seismo

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electric transfer function with decreasing fluid conductivity was described by [9]. The 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 [10]. Seismo electric coupling is frequency dependent and decreases exponentially when frequency increases was demonstrated by [11]. An increase of permeability with increasing seismo magnetic moment and seismo diffusion coefficient fractal dimension was reported by [12, 13]. An increase of, molar enthalpy, work, electro kinetic, bubble pressure and pressure head fractal dimensions with permeability increasing and grain size was described by [14,15,16,17].

Material 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". (Figure1). 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 specific enthalpy 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 specific enthalpy to maximum specific enthalpy $\log(h^{1/4}/h_{\max}^{1/4})$ versus \log wetting phase saturation ($\log S_w$). Whereas the fractal dimension of the second procedure is determined from the negative slope of the plot of logarithm of \log capillary pressure ($\log P_c$) versus logarithm of wetting phase saturation ($\log S_w$).

The specific enthalpy can be scaled as

$$S_w = \left[\frac{1}{h_{\max}^{1/4}} \right]^{[3-D_f]} \quad 1$$

Where S_w the water saturation, h the specific enthalpy in Joule/kilo gram, h_{\max} the maximum specific enthalpy in Joule / kilo gram, and D_f the fractal dimension

Equation 1 can be proofed from

$$h = \left[\frac{E}{m} \right] \quad 2$$

Where h the specific enthalpy in Joule/kilo gram, E the enthalpy in Joule, and m the mass in kilo gram

The mass m can be scaled as

$$m = \rho * V \quad 3$$

Where m the mass in kilo gram, ρ the density in kilo gram/cubic meter, V the volume of the fluid in cubic meter

Insert equation 3 into equation 2

$$h = \left[\frac{E}{\rho * V} \right] \quad 4$$

The volume V can be scaled

$$V = \left[\frac{U}{P} \right] \quad 5$$

Where V the volume in cubic meter, U the energy in Joule, P the pressure in pascal

Insert equation 5 into equation 4

$$h = \left[\frac{E * P}{\rho * U} \right] \quad 6$$

The pressure P can be scaled as

$$P = \left[\frac{\mu}{t} \right] \quad 7$$

Where P the pressure in pascal, μ the viscosity of the fluid in pascal * second, t the time in second

Insert equation 7 into equation 6

$$h = \left[\frac{E * \mu}{\rho * U * t} \right] \quad 8$$

Equation 8 after rearrange will become

$$h * \rho * U * t = E * \mu \quad 9$$

The time t can be scaled as

$$t = \left[\frac{V}{Q} \right] \quad 10$$

Where t the time in second, V the volume in cubic meter, Q the flow rate in cubic meter/second

Insert equation 10 into equation 9

$$h * \rho * U * \frac{V}{Q} = E * \mu \quad 11$$

The flow rate Q can be scaled as

$$Q = \left[\frac{3.14 * r^4 * \Delta P}{8 * \mu * L} \right] \quad 12$$

Where Q the flow rate in cubic meter/second, r the pore radius in meter, ΔP the differential pressure in pascal, μ the fluid viscosity in pascal * second, and L the capillary length in meter

Insert equation 12 into equation 11

$$h * \rho * U * \frac{V * 8 * \mu * L}{3.14 * r^4 * \Delta P} = E * \mu \quad 13$$

Equation 13 after rearrange will become

$$h * \rho * U * V * 8 * \mu * L = E * \mu * 3.14 * r^4 * \Delta P \quad 14$$

The maximum pore radius rmax can be scaled as

$$h_{\max} * \rho * U * V * 8 * \mu * L = E * \mu * 3.14 * r_{\max}^4 * \Delta P \quad 15$$

Divide equation 14 by equation 15

$$\left[\frac{h * \rho * U * V * 8 * \mu * L}{h_{\max} * \rho * U * V * 8 * \mu * L} \right] = \left[\frac{E * \mu * 3.14 * r^4 * \Delta P}{E * \mu * 3.14 * r_{\max}^4 * \Delta P} \right] \quad 16$$

Equation 16 after simplification will become

$$\left[\frac{h}{h_{\max}} \right] = \left[\frac{r^4}{r_{\max}^4} \right] \quad 17$$

Take the fourth root of equation 17

$$\sqrt[4]{\left[\frac{h}{h_{\max}} \right]} = \sqrt[4]{\left[\frac{r^4}{r_{\max}^4} \right]} \quad 18$$

Equation 18 after simplification will become

$$\left[\frac{\frac{1}{h_{\max}^{\frac{1}{4}}}}{\frac{1}{h^{\frac{1}{4}}}} \right] = \left[\frac{r}{r_{\max}} \right] \quad 19$$

Take the logarithm of equation 19

$$\log \left[\frac{\frac{1}{h_{\max}^{\frac{1}{4}}}}{\frac{1}{h^{\frac{1}{4}}}} \right] = \log \left[\frac{r}{r_{\max}} \right] \quad 20$$

$$\text{But; } \log \left[\frac{r}{r_{\max}} \right] = \frac{\log Sw}{[3 - Df]} \quad 21$$

Insert equation 21 into equation 20

$$\frac{\log Sw}{[3 - Df]} = \log \left[\frac{\frac{1}{h^{\frac{1}{4}}}}{\frac{1}{h_{\max}^{\frac{1}{4}}}} \right] \quad 22$$

Equation 22 after log removal will become

$$Sw = \left[\frac{\frac{1}{h^{\frac{1}{4}}}}{\frac{1}{h_{\max}^{\frac{1}{4}}}} \right]^{[3-Df]} \quad 23$$

Equation 23 the proof of equation 1 which relates the water saturation, specific enthalpy, maximum specific enthalpy, and the fractal dimension

The capillary pressure can be scaled as

$$\log Sw = [Df - 3] * \log(Pc) + \text{constant} \quad 24$$

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 Permo-Carboniferous Shajara Formation were divided here into three units as described in Figure1. These units from bottom to top are: Lower Shajara Reservoir, Middle Shajara reservoir, and Upper Shajara Reservoir. Their attained results of the specific enthalpy fractal dimension and capillary pressure fractal dimension are shown in Table 1. Based on the achieved results it was found that the specific enthalpy fractal dimension is equal to the capillary pressure fractal dimension. The maximum value of the fractal dimension was found to be 2.7872 allocated 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 shown in Table1. The Specific enthalpy fractal dimension and capillary pressure fractal dimension were detected to increase with increasing permeability as proofed in Table1 owing to the possibility of having interconnected channels.

AGE	Fm.	Mbr.	unit	LITHO-LOGY	DESCRIPTION		
Late Permian	Khuff Formation	Huqayf Member			Limestone : Cream, dense, burrowed, thickness 6.56'		
					Sub-Khuff unconformity.		
Late Carboniferous - Permian	Shajara Formation	Upper Shajara Member	Upper Shajara mudstone		Mudstone : Yellow, thickness 17.7'		
				Upper Shajar Reservoir	SJ13▲ SJ12▲	Sandstone : Light brown, cross-bedded, coarse-grained, poorly sorted, porous, friable, thickness 6.5'	
			Middle Shajara Member	Upper Shajar Reservoir	SJ11▲	Sandstone : Yellow, medium-grained, very coarse-grained, poorly, moderately sorted, porous, friable, thickness 13.1'	
					Middle Shajara mudstone		Mudstone : Yellow-green, thickness 11.8'
				Middle Shajara Reservoir	Middle Shajara mudstone		Mudstone : Yellow, thickness 1.3'
					Middle Shajara mudstone		Mudstone : Brown, thickness 4.5'
		Middle Shajara Reservoir	SJ10▲ SJ9▲ SJ8▲		Sandstone : Light brown, medium-grained, moderately sorted, porous, friable, thickness 3.6'		
		Middle Shajara Reservoir	SJ7▲		Sandstone : Yellow, medium-grained, moderately well sorted, porous, friable, thickness 0.9'		
		Lower Shajara Member	Lower Shajara Reservoir	SJ6▲	Sandstone : Red, coarse-grained, medium-grained, moderately well sorted, porous, friable, thickness 13.4'		
				SJ5▲	Sandstone : White with yellow spots, fine-grained, hard, thickness 2.6'		
				SJ4▲	Sandstone : Limonite, thickness 1.3'		
				SJ3▲	Sandstone : White, coarse-grained, very poorly sorted, thickness 4.5'		
				SJ2▲	Sandstone : White-pink, poorly sorted, thickness 1.6'		
				SJ1▲	Sandstone : Yellow, medium-grained, well sorted, porous, friable, thickness 3.9'		
		Early Devonian	Tafil Formation				Sandstone : Red, medium-grained, moderately well sorted, porous, friable, thickness 11.8'
							Sub-Unayzah unconformity. Sandstone : White, fine-grained.

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"

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

Table 1: Petrophysical model showing the three Shajara Reservoir Units with their corresponding values of specific enthalpy fractal dimension and capillary pressure fractal dimension

The Lower Shajara reservoir was symbolized by six sandstone samples (Figure 1), four of which label as SJ1, SJ2, SJ3 and SJ4 were carefully chosen for capillary pressure measurement as proven in Table1. Their positive slopes of the first procedure log of the specific enthalpy to maximum specific enthalpy versus log wetting phase saturation (Sw) and negative slopes of the second procedure log capillary pressure (Pc) versus log wetting phase saturation (Sw) are clarified in Figure 2, Figure 3, Figure 4, Figure 5 and Table 1. Their Specific enthalpy 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 Specific enthalpy 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 specific enthalpy fractal dimension and capillary pressure fractal dimension was found to be 2.6843 as described in Table 1.

In contrast, the Middle Shajara reservoir which is separated from the Lower Shajara reservoir by an unconformity surface as revealed in Figure 1. It was nominated by four samples (Figure 1), three of which named as SJ7, SJ8, and SJ9 as illuminated in Table1 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 Figure 6, Figure 7 and Figure 8 and Table 1. Furthermore, their Specific enthalpy 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.

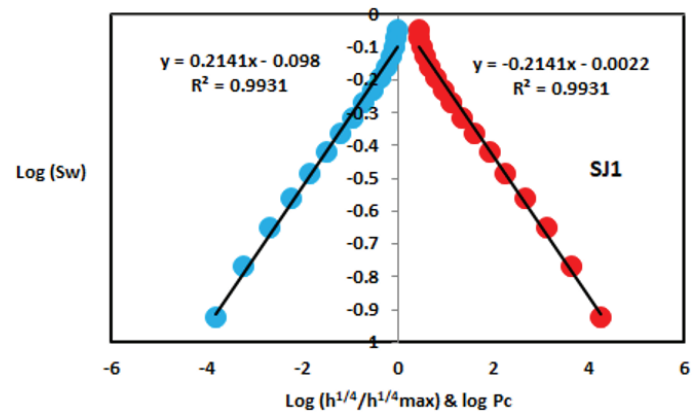


Figure 2: Log ($h^{1/4}/h^{1/4}_{max}$) & log (Pc) versus log Sw for sample SJ1.

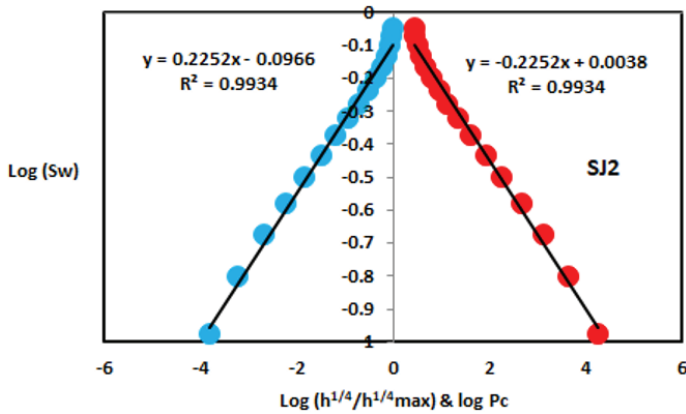


Figure 3: $\log (h^{1/4}/h^{1/4}_{max})$ & $\log (Pc)$ versus $\log Sw$ for sample SJ2.

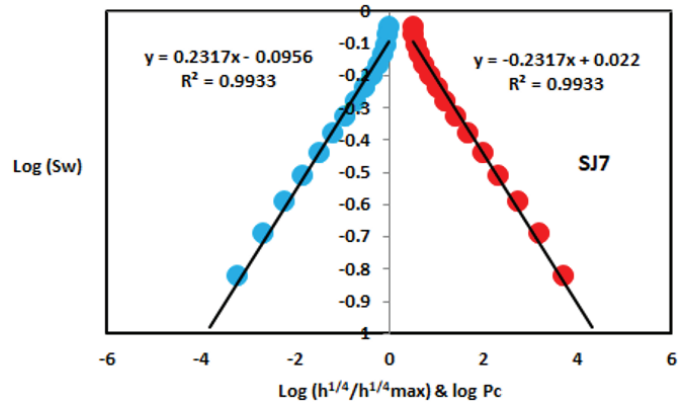


Figure 6: $\log (h^{1/4}/h^{1/4}_{max})$ & $\log (Pc)$ versus $\log Sw$ for sample SJ7.

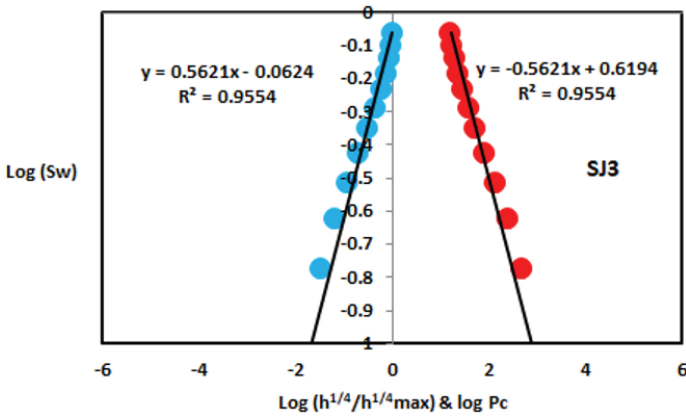


Figure 4: $\log (h^{1/4}/h^{1/4}_{max})$ & $\log (Pc)$ versus $\log Sw$ for sample SJ3.

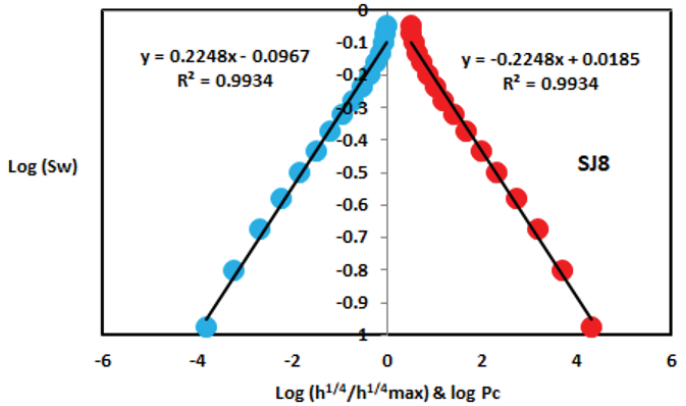


Figure 7: $\log (h^{1/4}/h^{1/4}_{max})$ & $\log (Pc)$ versus $\log Sw$ for sample SJ8.

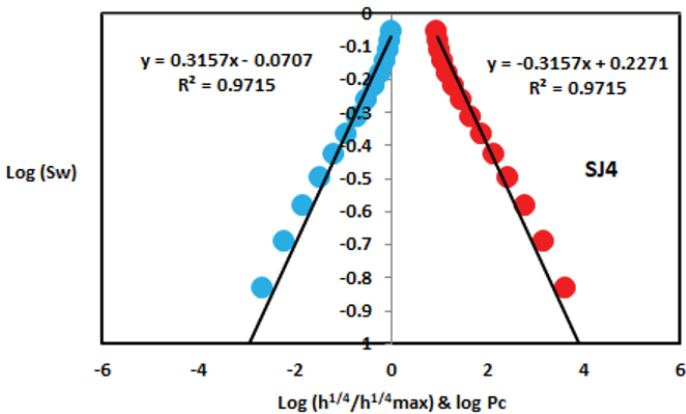


Figure 5: $\log (h^{1/4}/h^{1/4}_{max})$ & $\log (Pc)$ versus $\log Sw$ for sample SJ4.

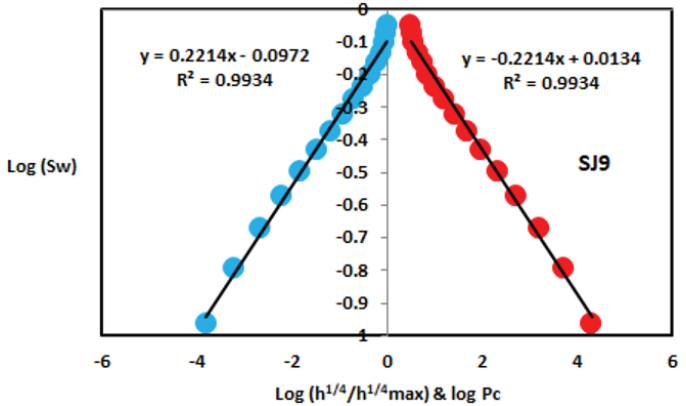


Figure 8: $\log (h^{1/4}/h^{1/4}_{max})$ & $\log (Pc)$ versus $\log Sw$ for sample SJ9.

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 Figure 9, Figure 10 and Figure 11 and Table 1. Moreover, their specific enthalpy 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.

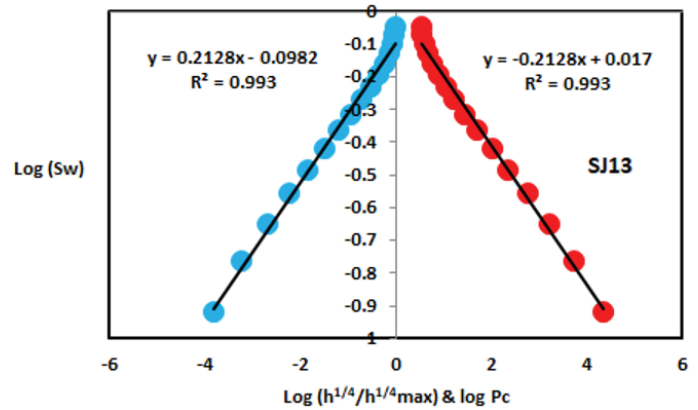


Figure 11: $\text{Log}(h^{1/4}/h^{1/4_{max}})$ & $\text{log}(Pc)$ versus log Sw for sample SJ13.

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 specific enthalpy 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.

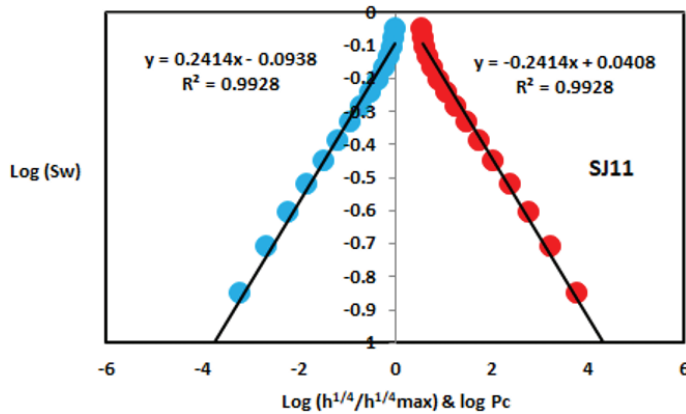


Figure 9: $\text{Log}(h^{1/4}/h^{1/4_{max}})$ & $\text{log}(Pc)$ versus log Sw for sample SJ11.

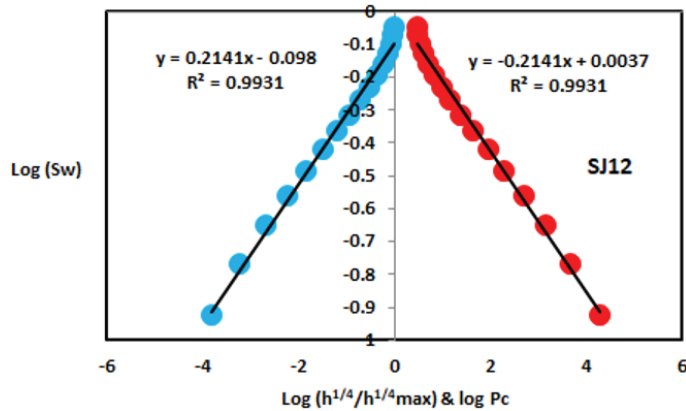


Figure 10: $\text{Log}(h^{1/4}/h^{1/4_{max}})$ & $\text{log}(Pc)$ versus log Sw for sample SJ12.

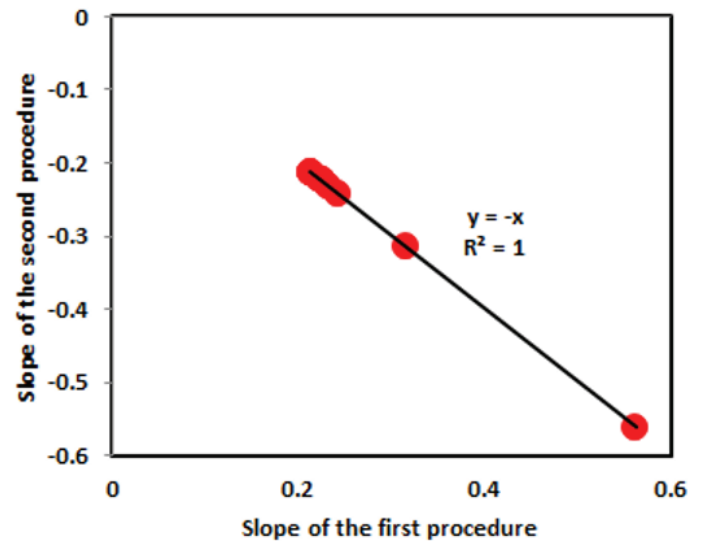


Figure 12: Slope of the first procedure versus slope of the second procedure.

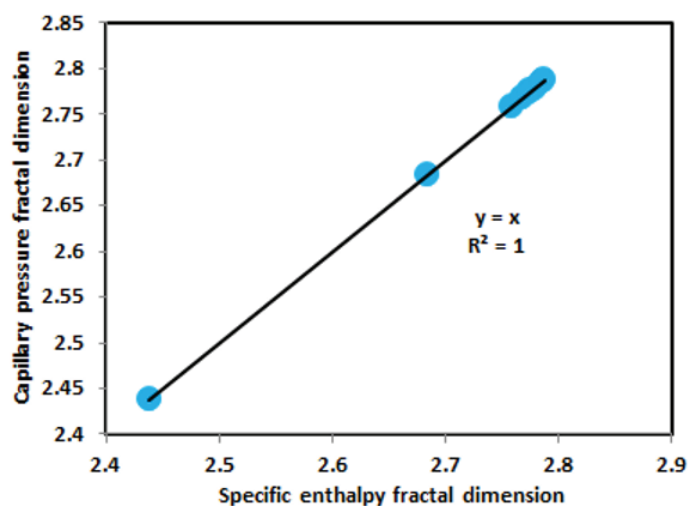


Figure 13: Specific enthalpy fractal dimension versus capillary pressure.

Conclusion

The sandstones of the Shajara Reservoirs of the permo-Carboniferous Shajara Formation were divided here into three units based on specific enthalpy fractal dimension. The Units from base to top are: Lower Shajara Specific Enthalpy Fractal Dimension Unit, Middle Shajara Specific Enthalpy Fractal Dimension Unit, and Upper Shajara Specific Enthalpy 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.

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