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ORIGINAL PAPER

Characterization of heterogeneity of the Shajara reservoirs of the Shajara formation of the Permo-Carboniferous Unayzah group

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Abstract Representative sandstone samples were collected from the surface-type section of the Shajara Formation of the Permo-Carboniferous Unayzah Group for reservoir characterization through fractal dimension investigation. Two models based on mercury intrusion technique were employed to represent the pores characteristics of these sandstones. The results show that realistic dimensions and outstanding fractal features of porous structures in Shajara sandstones, when these materials are correlated by thermodynamic model and 3-D fractal model of mercury intrusion. On the basis of sub-Unayzah unconformity, sub-Middle Shajara local unconformity, mudstone of the Middle Shajara and sub-Khuff unconformity, the three porous and permeable sandstone units of Shajara Formation were treated separately and classified here into three fractal dimension units. The units from base to top are: Lower Shajara Fractal Dimension Unit, Middle Shajara Fractal Dimension Unit, and Upper Shajara Fractal Dimension Unit. The thermodynamic model and 3-D fractal model were effectively used to characterize the porous structures of Shajara sandstones in logical and quantitative way.

Keywords Heterogeneity · Shajara formation · Shajara fractal dimension units · Permeability

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Introduction

The Unayzah Formation is hydrocarbon bearing in many oil and gas fields in Saudi Arabia. It is composed of continental siliciclastics of Permo-Carboniferous age. The formation was formally defined by Al-Laboun (1987).

Lithologically, the clastic surface type section of the Shajara Formation of the Permo-Carboniferous Unayzah Group, that is exposed at Ash Shajara, Qusayba area, Al Qassim district, Saudi Arabia, is classified into three members: Lower Shajara Member, Middle Shajara Member, and Upper Shajara Member (Al-Khidir 2007; Fig. 1). Local unconformities were recognized within the Shajara Formation indicating minor stratigraphic break in sedimentation. These local unconformities were interpreted as braided fluvial channels. The clastic sequence starts with a red, porous, permeable sandstone deposited unconformably on the Early Devonian Tawail Formation.

On the other hand, the Middle Shajara Member is separated from the Lower Shajara Member by a local unconformity. Furthermore, a caliche surface (sub-Khuff unconformity) separates the Upper Shajara Member from the overlying Huqayl Member of the Permo–Triassic Khuff Formation. Strongly speaking, the sub-Unayzah unconformity, sub-Middle Shajara unconformity, mudstone of the Middle Shajara Member, and

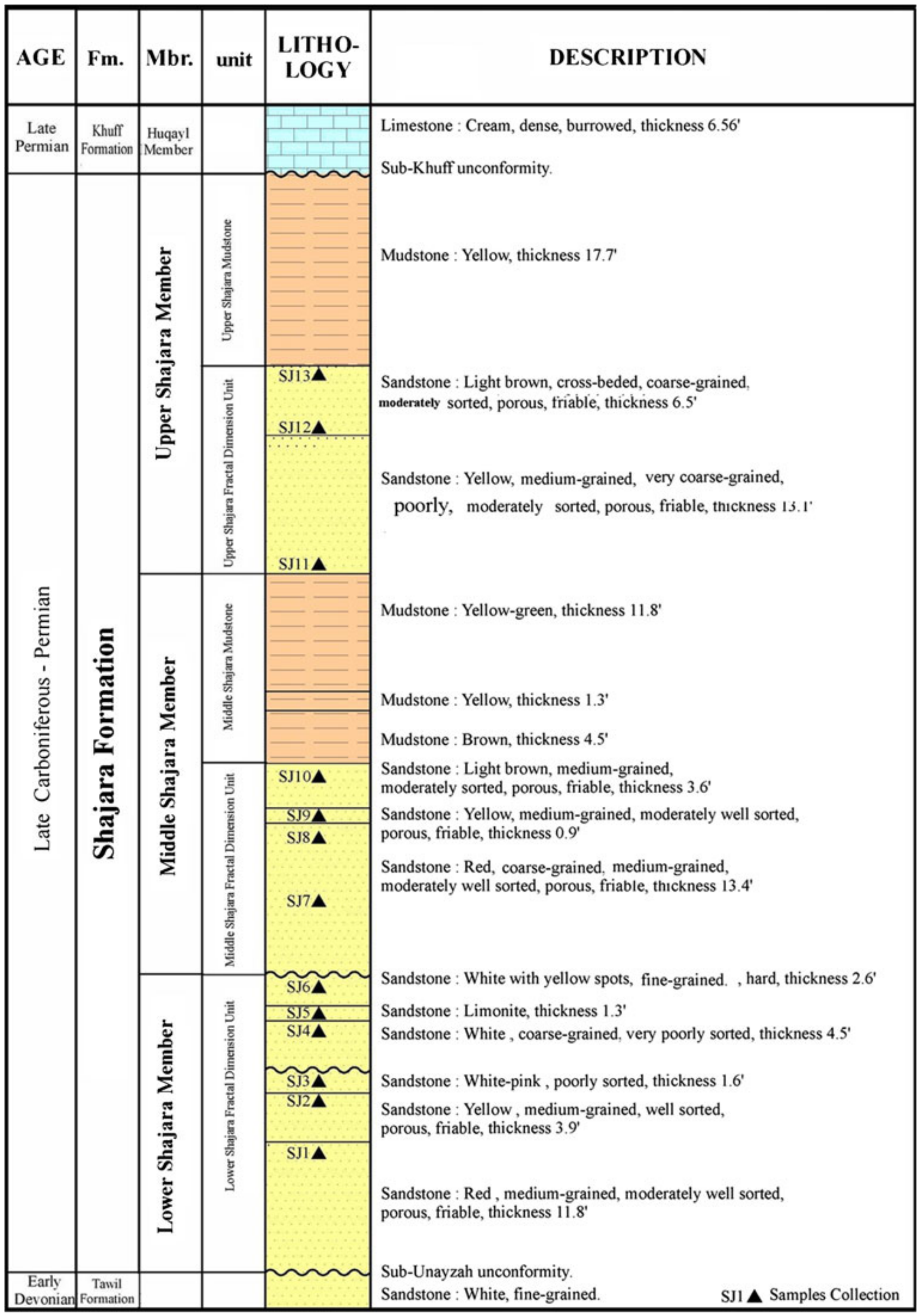

Fig. 1 Surface type section of the Shajara Formation of the Permo-Carboniferous Unayzah Group, showing the three fractal dimension units, N 26° 52 17.4, E 43° 36 18; Al-Khidir et al. (2012)

sub-Khuff unconformity represent the backbone to classify the Shajara Formation into three lithological units.

From the Petrophysical point of view, the sandstones of the Shajara Formation were divided into three porous and permeable zones: Lower Shajara Permeable Zone, Middle Shajara Permeable Zone, and Upper Shajara Permeable Zone (Al-Khidir 2007). Therefore, the three permeable zones represent the backbone to study the fractal dimensions of the porous structures of Shajara sandstones using mercury intrusion technique with certain degree of accuracy.

Methodology and experimental work

Two models were used to characterize the fractal dimensions of the sandstones of the Shajara Formation. These models are: thermodynamic and 3-D fractal model of mercury intrusion technique using autopore III. The term fractal was first introduced by Mandelbrot (1977). It is defined as a material that changes in size but not in geometrical shapes. An important property of a fractal is self-similarity, which refers to a characteristic of a form exhibited when substructure

resembles a superstructure in the same form. The fractal dimension is used to study heterogeneity of a system. The greater the fractal dimension, the greater the heterogeneous system. Many authors have studied the fractal dimension, among them Katz and Thompson (1985), Friesen and Mikula (1987), Hansen and Skjeltrop (1988), Krohn (1988), Lenormand (1990), Angulo and Gonzalez (1992), Toledo et al. (1993), Shen and Li (1994, 1995), Li and Horne (2003), Li (2004), and Kewen (2004). Mercury intrusion method was used on samples representing the investigated area. This was done by injecting mercury under pressure using Micromeritics Autopore 111. The output of this experiment is construction of capillary pressure curve as a function of mercury saturation. The capillary pressure data was then used to calculate the pore radius using Washburn's equation.

$$r = 2 \times \sigma \times \cos\theta / Pc \qquad (1)$$

r Pore radius in meter (m)
σ Mercury interfacial tension in Neuton per meter (0.485 N/m)
θ Mercury contact angle measured in degrees (130°)
P_c Capillary pressure in Neuton per square meter (N/m^2)

With special reference to the thermodynamic model, logarithm of work done divided by the square of the pore radius was plotted versus the logarithm of pore volume divided by the pore radius, and the value of the slope of the straight line is equivalent to the fractal dimension (D_f). The thermodynamic model equation is given below:

$$\mathrm{Log}(P_c \times v/r\hat{}2) = D_f \times \mathrm{Log}(v\hat{}0.3/r) + c \qquad (2)$$

For the 3-D fractal model, the logarithm of mercury saturation divided by average capillary pressure was plotted versus logarithm of capillary pressure. and the slope was determined from the straight line and its value was added to 4 to give the fractal dimension (D_f).

$$\mathrm{Log}(dS_{Hg}/dP_c) = (D_f - 4) \times \mathrm{Log}P_c \qquad (3)$$

Results and discussion

The results of fractal dimensions of the porous structures in sandstones of the Shajara Formation of the Permo-Carboniferous Unayzah Group were shown in Table 1 Three fractal dimension units were identified depending on thermodynamic model and 3-D fractal model of mercury intrusion technique. These fractal dimension units are: Lower Shajara Fractal Dimension Unit, Middle Shajara Fractal Dimension Unit, and Upper Shajara Fractal Dimension Unit.

Concerning the Lower Shajara Fractal Dimension Unit, it is represented by two sequences, namely lower and upper (Fig. 1). The lower sequence is illustrated by three samples, SJ1, SJ2, and SJ3 as shown in Fig. 1. Sample SJ1 is described as medium-grained, moderately well-sorted, porous, friable, red sandstone as shown in Fig. 1. The result of thermodynamic model of sample SJ1 is demonstrated in Fig. 2 and Table 1. The obtained straight line indicates a porous system, while the value of the fractal dimension (3.1332) assigns for sample heterogeneity. This anisotropy is also confirmed in Fig. 2 which shows the 3-D fractal model acquiring a fractal dimension of 2.8668. Regarding sample SJ2, it is identified as medium-grained, well-sorted, porous, friable, yellow sandstone (Fig. 1). Similarly, this sample is characterized by straight line and a value of fractal dimension equals to 3.1317 as demonstrated in Fig. 3 and Table 1. This heterogeneity is also represented in Fig. 3 and Table 1 revealing a value of fractal dimension equals to 2.8683.

Table 1 Thermodynamic model and 3-D fractal model of the Shajara Reservoirs of Shajara Formation of the Permo-Carboniferous Unayzah Group showing the three fractal dimension units

Formation	Units	No.	Thermodynamic	3-D fractal	Φ %	KmD
Shajara Formation	Upper Shajara Fractal Dimension Unit	SJ-13	3.1279	2.8721	25	973
		SJ-12	3.1317	2.8683	28	1,440
		SJ-11	3.1255	2.8745	36	1,197
	Middle Shajara Fractal Dimension Unit	SJ-9	3.1293	2.8907	31	1,394
		SJ-8	3.1285	2.8715	32	1,344
		SJ-7	3.1284	2.8716	35	1,472
	Lower Shajara Fractal Dimension Unit	SJ-5	3.0929	2.9071	31	55
		SJ-4	3.1046	2.8954	30	176
		SJ-3	3.0937	2.9063	34	56
		SJ-2	3.1317	2.8683	35	1,955
		SJ-1	3.1332	2.8668	29	1,680

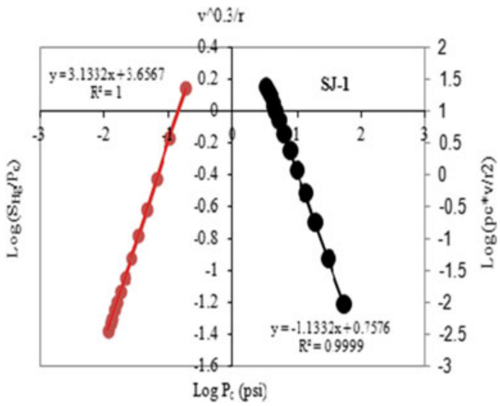

Fig. 2 Thermodynamic and 3-D fractal model fractal for sample SJ-1 from Lower Shajara Fractal Shajar Dimension Unit

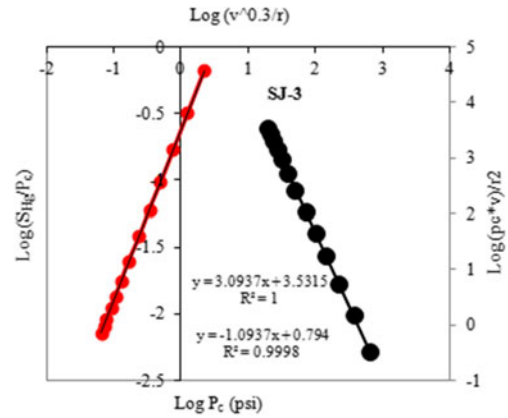

Fig. 4 Thermodynamic and 3-D fractal model for sample SJ-3 from Lower Shajara Fractal Dimension Unit

On the other hand, decrease in grain size occurred as we proceed from sample SJ2 to SJ3 in the same lower sequence of the Lowe Shajara Fractal Dimension Unit. Lithologically, the sample SJ3 consists mainly of white to pink, fine-grained sandstone, hard and fair to good sorting. Such grain size variability can lead to reservoir quality assessment of the Lower Shajara Fractal Dimension Unit, through fractal dimension and permeability investigation (Fig. 4). That is to say, grain size is directly proportional to fractal dimension obtained from thermodynamic model as well as permeability. In other words, high values of fractal dimension and permeability correspond to the medium-grained sandstone facies of this lower sequence (Table 1). In the case of 3-D fractal dimension model, grain size and permeability are inversely proportional to the fractal dimension. That is to say, high value of fractal dimension and low value of permeability consign to the fine-grained sandstone sequence (sample SJ3, as shown in Table 1).

The second sedimentary sequence of the Lower Shajara Fractal Dimension Unit is isolated from the underlying lower sequence by an intra lower Shajara unconformity as delineated in Fig. 1. This sequence is illustrated by three samples, namely SJ4, SJ5, and SJ6 as viewed in Fig. 1. With regard to sample SJ4, it is described as coarse-grained, very poorly sorted, white sandstone as mentioned in Fig. 1. This sample possesses a fractal dimension value of about 3.1046.which is also account for heterogeneous system as demonstrated in Fig. 5 and Table 1. This heterogeneity is also documented by the value of the fractal dimension (2.9954) obtained from the 3-D fractal model as shown in Fig. 5. Again, reduction in grain size takes place as we proceed from sample SJ4 to samples SJ5 and SJ6. Sample SJ5 attained a fractal dimension value of about 3.0929 indicating a heterogeneous system as represented in Fig. 6. Further verification of heterogeneity is shown in Fig. 6, which displays a value of fractal dimension equals to 2.9071. No capillary pressure data available for sample SJ6, but field observation demonstrates the presence of fine-grained, compacted sandstone with yellow spots (Fig. 1).

Based on the obtained results of sample SJ4 and SJ5, grain size is also directly proportional to the fractal dimension obtained from thermodynamic model, in addition to

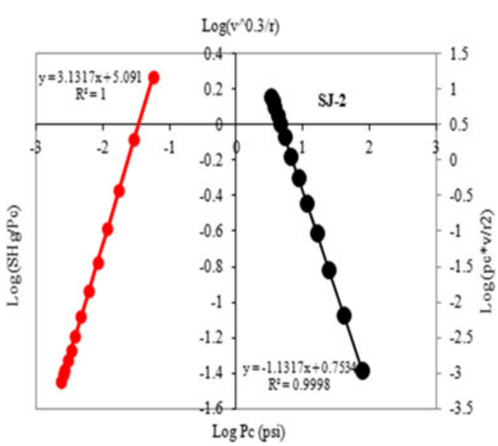

Fig. 3 Thermodynamic and 3-D model for sample SJ-2 from Lower Fractal Dimension Unit

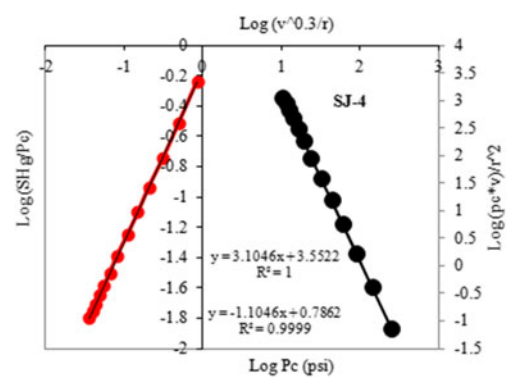

Fig. 5 Thermodynamic and 3-D model for sample SJ-4 from Lower Shajara Fractal Dimension Unit

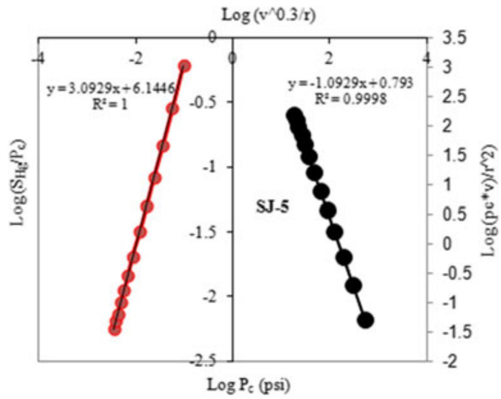

Fig. 6 Thermodynamic and 3-D fractal model for sample SJ-5 from Lower Shajara Fractal Dimension Unit

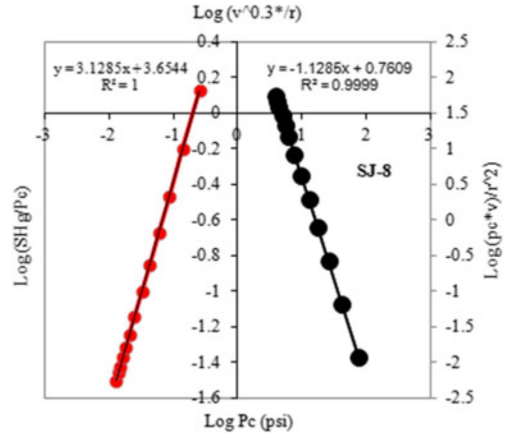

Fig. 8 Thermodynamic and 3-D fractal model for sample SJ-8 from Middle Shajara Fractal Dimension Unit

permeability value. Furthermore high value of fractal dimension and permeability consign to sample SJ4 (coarse-grained sequence) of this sequence as shown in sequence.

With regard to the fractal dimensions of sandstones from Middle Shajara unit, their results were graphically represented in Figs.7, 8, and 9 and Table 1. This unit is separated from the Lower Shajara Fractal Dimension Unit by sub-middle Shajara local unconformity as shown in Fig. 1. This unit is illustrated by four samples, namely SJ7, SJ8, SJ9, and SJ10 as mentioned in Fig. 1. The Sample SJ7 consists mainly of red sandstone is coarse-grained, moderately to very well sorted, porous, and friable. This sample is also characterized by straight line as shown in Fig. 7 which accounts for a porous system. The result obtained from thermodynamic model indicates the presence of a heterogeneous system (D_f=3.1284). Further pronouncement of heterogeneity is viewed by the 3-D fractal model (Fig. 7). Based on this model, sample SJ7 acquired a value of fractal dimension equals to 2.8716.

Similarly, reduction in grain size happened as we proceed from sample SJ7 to SJ8 as illustrated in Fig. 1. Sample SJ8 is described as medium-grained, moderately well-sorted, porous, friable, red sandstone (Fig. 1). This sample attained a value of fractal dimension of about 3.1285 which also delineates the presence of a heterogeneous system (Fig. 8 Table 1). The result displayed in Fig. 8 from 3-D fractal model also announced for a heterogeneous system (D_f= 2.8715). On the subject of sample SJ9, it is identified as medium-grained, moderately well-sorted, porous, friable, yellow sandstone (Fig. 1). As indicated in Fig. 9 and Table 1, this sample has a value of fractal dimension equals to 3.1293, declaring the existence of a heterogeneous system. Further verification of heterogeneity is shown in Fig. 9 and Table 1.which reveals a value of fractal dimension corresponds to 2.8707. On the topic of sample SJ10, it is recognized as medium-grained, moderately sorted, porous, friable, light brown sandstone (Fig. 1). This sample obtained no capillary pressure data to determine its fractal dimension.

In and overall, concerning the fractal dimensions obtained from thermodynamic model and the 3-D fractal model for the Middle Shajara Fractal Dimension Unit, the scenario is reversed. In the case of thermodynamic model,

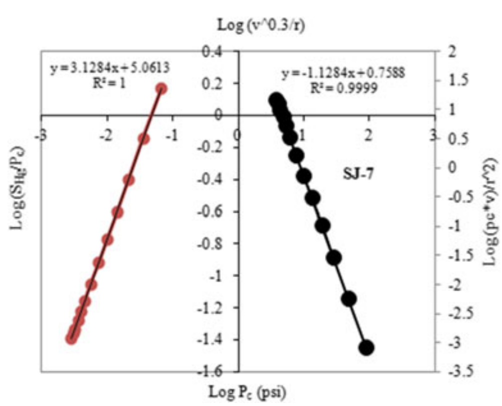

Fig. 7 Thermodynamic and 3-D model for sample SJ-7 from Middle Shajara Fractal Dimension Unit

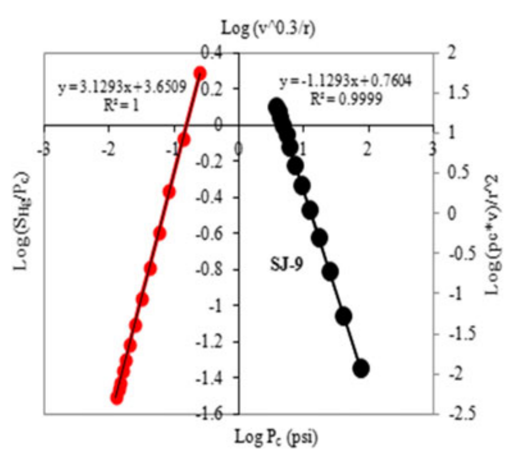

Fig. 9 Thermodynamic and 3-D model for sample SJ-9 from Middle Shajara Fractal Dimension Unit

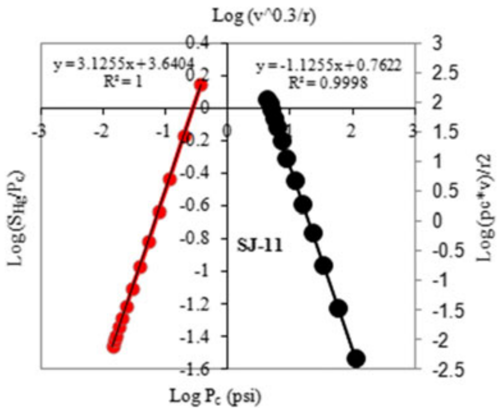

Fig. 10 Thermodynamic and 3-D fractal model for sample SJ-11 from Upper Shajara Fractal Dimension Unit

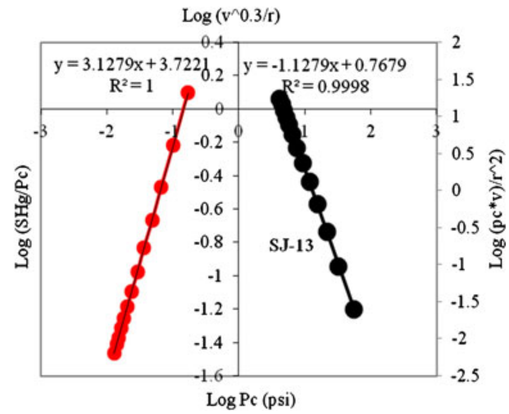

Fig. 12 Thermodynamic and 3-D fractal model for sample SJ-13 from Upper Shajara Fractal Dimension Unit

the obtained fractal dimension enlarges upward with reduced grain size and permeability as shown in Table 1. On the topic of the 3-D fractal model, the determined fractal dimension decreases upward with reduction in grain size and permeability as illustrated in Table 1.

With reference to the Upper Shajara fractal Dimension Unit, it is represented by three samples, namely SJ11, SJ12, and SJ13. Their results of fractal dimensions are shown in Figs. 10, 11, and 12. The Sample SJ11 consists mainly of medium grained-sandstone, fairly well to poorly sorted, porous, friable, and yellow in color (Fig. 1). On the basis of thermodynamic model, this sample acquiring a value of fractal dimension equals to 3.1255 and straight line (Fig. 10) delineates the occurrence of a heterogeneous porous system. This heterogeneity is confirmed in Fig. 10 and Table 1. That is to say, fractal dimension equals to 2.8745. Concerning sample SJ12 it is identified as very coarse-grained, moderately sorted, porous, friable, yellow sandstone (Fig. 1). The fractal dimension obtained for this sample from thermodynamic model was found to be 3.1317 assigning for heterogeneous system (Fig. 11 and Table 1). Moreover, this heterogeneity is verified in Fig. 11 which shows a value of fractal dimension identical to 2.8683. Sample SJ13 is described as coarse-grained, moderately sorted, porous, friable, light brown, cross bedded sandstone as demonstrated (Fig. 1). This sample posses fractal dimension value equivalent to 3.1279 pronouncing also for heterogeneous system as indicated in Fig. 12. This heterogeneity is also affirmed in Fig. 12 which attains a value of fractal dimension equals to 2.8721.

In and overall, such grain size variability can guide to reservoir quality evaluation of the Upper Shajara Fractal Dimension Unit, in the course of fractal dimension and permeability examination. That is to say, grain size is directly proportional to fractal dimension determined from thermodynamic model as well as permeability. On other wards, high values of fractal dimension and permeability correspond to the very coarse-grained sandstone sequence (SJ12) as indicated in Fig. 11 and Table 1. Regarding the3-D fractal dimension model, the value of fractal dimension increases upward with decrease grain size and permeability as shown in Table 1

An excellent correlation factor (1) was determined from Fig. 13 to show the mathematical capability of the two models and their permanence in calculating the fractal dimensions of the porous structures of Shajara sandstones with certain degree of precision. Figure 13 shows that fine-

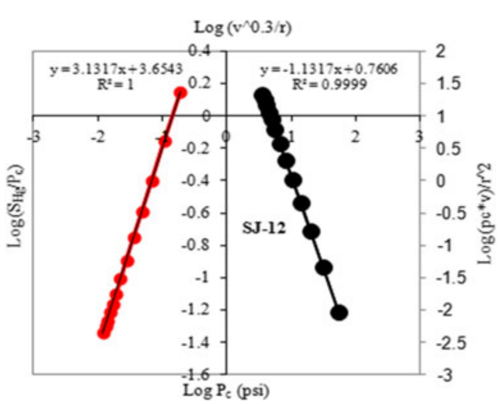

Fig. 11 Thermodynamic and 3-D model for sample SJ-12 from Upper Shajara Fractal Dimension Unit

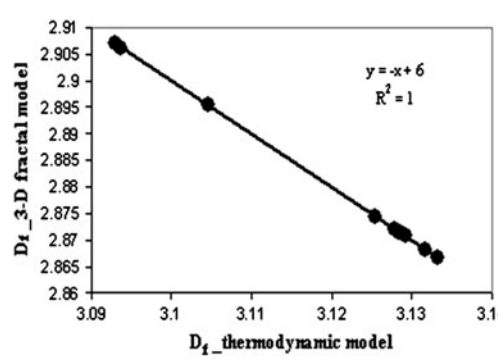

Fig. 13 Thermodynamic model versus 3-D fractal model

grained facies of the Lower Shajara Fractal Dimension Unit attained the lowest values of fractal dimensions obtained from thermodynamic model. On the other hand, medium- and coarse-grained facies of the Shajara Formation are characterized by low values of fractal dimensions obtained from 3-D fractal model, compared to the fine-grained sequence (Fig. 13).

Conclusion

- The thermodynamic model and 3-D fractal model of mercury intrusion show their effectiveness, mathematical capabilities, and continuity in evaluating the fractal dimension of the sandstones of the Shajara Formation of the Permo-Carboniferous Unayzah Group.
- Three fractal dimension units were identified on the basis of unconformities and mudstone of the Middle Shajara unit.
- Excellent correlation factor (1) was obtained which assign for the competency of the two models.
- The results of the fractal dimensions indicate the heterogeneity of the Shajara Reservoirs which account for a wide range of pore sizes.

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