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Validation of A Modified Normalized Skillings-Mack Fractal Dimension for Characterizing Pore Structure in Permo-Triassic Khuff Carbonate Reservoirs, Central Saudi Arabia

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Abstract

Carbonate reservoirs are characterized by complex pore systems and significant heterogeneity that strongly influence fluid flow and reservoir quality. In this study, carbonate samples were collected from surface exposures of the Permo–Triassic Khuff Formation in central Saudi Arabia to investigate the relationship between pore-network heterogeneity and reservoir properties using fractal analysis. Porosity and permeability measurements were obtained for all samples and ranged from 2.269 to 11.253% and from 0.264 to 3.445 mD, respectively. Two independent fractal approaches derived from capillary-pressure data were employed to characterize pore structure. The first method utilized the relationship between the logarithm of normalized pore radius, log10(R/Rmax), and log10(water saturation), whereas the second method employed the logarithm of the Modified Normalized Skillings-Mack parameter (MNSM) versus log10(water saturation). In both approaches, the fractal dimension was determined from the positive linear coefficient of a fitted quadratic equation according to Df = 2 + b. Calculated fractal dimensions ranged from 2.3584 to 2.8575 for the MNSM method and from 2.3628 to 2.8647 for the normalized pore-radius method, with mean values of 2.7038 and 2.7101, respectively. Representative samples with low, intermediate, and high pore-network complexity yielded fractal dimensions of approximately 2.36, 2.72, and 2.86. Statistical comparison of the two methods demonstrated excellent agreement, yielding a correlation coefficient of R = 1.0, a coefficient of determination of R² = 1.0, and a root mean square error (RMSE) of 0.0063. Bland–Altman analysis further indicated a negligible mean bias and narrow limits of agreement, confirming the consistency of the two approaches. The results show that increasing fractal dimension is associated with improved pore connectivity and higher permeability, indicating that fractal geometry provides a reliable quantitative measure of pore-network heterogeneity. The near-perfect agreement between the MNSM and normalized pore-radius methods demonstrates that the Modified Normalized Skillings-Mack fractal dimension is a robust alternative parameter for characterizing pore structure and reservoir quality in Khuff carbonate reservoirs. The proposed approach provides an effective framework for evaluating carbonate reservoir heterogeneity and may contribute to improved reservoir characterization and flow-property prediction.

Keywords: Modified Normalized Skillings-Mack Fractal Dimension, Pore Structure, Khuff Formation, Carbonate Reservoir, Permeability, Porosity, Capillary Pressure, Water Saturation, Pore-Network Heterogeneity, Fractal Analysis

1. Introduction

Carbonate reservoirs contain a substantial proportion of the world's hydrocarbon resources and are characterized by highly heterogeneous pore systems that span multiple length scales. The complexity of carbonate pore networks arises from the combined effects of depositional environments, diagenetic processes, dissolution, cementation, and fracturing, resulting in significant variations in porosity, permeability, and fluid-flow behavior.

Consequently, accurate characterization of pore structure heterogeneity remains a critical challenge in reservoir evaluation and production forecasting. Recent studies have demonstrated that pore geometry and connectivity exert a strong control on reservoir quality and fluid transport properties in carbonate rocks [1-5].

Traditional petrophysical parameters such as porosity and permeability provide valuable information regarding reservoir performance; however, they often fail to adequately describe the geometric complexity and multiscale heterogeneity of pore systems. Advances in digital rock physics, micro-computed tomography (micro-CT), nuclear magnetic resonance (NMR), electrical measurements, and image-based characterization have revealed that pore networks exhibit self-similar and scale-invariant properties that can be effectively quantified using fractal geometry [6-9]. Fractal analysis has therefore emerged as a powerful tool for describing pore-throat architecture, pore connectivity, fluid-flow pathways, and reservoir heterogeneity in both sandstone and carbonate formations.

The application of fractal concepts to porous media can be traced to the pioneering work of Toledo et al. (1994), who demonstrated relationships among capillary pressure, relative permeability, electrical conductivity, and fractal pore geometry [10]. Since then, numerous investigators have successfully employed fractal models to characterize pore structures and predict reservoir properties. Fractal dimensions derived from capillary pressure data, NMR measurements, electrical resistivity, and imaging techniques have been shown to correlate strongly with permeability, pore-throat distributions, fluid mobility, and reservoir quality [11-15]. Similar relationships have been reported for tight sandstone reservoirs, where fractal dimensions provide quantitative measures of pore-network complexity and heterogeneity [16-20].

Recent developments have extended fractal analysis to carbonate reservoirs. Cheng et al. (2024) demonstrated that fractal dimensions can effectively describe pore-structure complexity in carbonate formations [21]. Ouyang et al. (2025) applied monofractal and multifractal approaches to investigate pore heterogeneity and sealing capacity in carbonate rocks, while Zhang et al. (2026) showed that variations in pore morphology and fractal dimensions can explain production differences between adjacent carbonate wells [4,5]. Likewise, Wang et al. (2025) used dual-resolution computed tomography to establish quantitative relationships among pore-throat parameters in ultradeep carbonate gas reservoirs [2]. These studies collectively confirm that fractal geometry provides a robust framework for evaluating pore-network architecture and reservoir quality in carbonate systems.

Capillary pressure measurements constitute one of the most effective methods for investigating pore-size distributions and pore connectivity because they directly reflect the interaction between fluid saturation and pore-throat geometry. Several studies have demonstrated that capillary pressure data can be used to estimate relative permeability and derive quantitative descriptions of pore structure [22,23]. Fractal dimensions derived from capillary-pressure relationships therefore provide valuable insight into the heterogeneity and flow characteristics of porous media. However, despite substantial progress in fractal reservoir characterization, there remains a need for further investigation of carbonate reservoirs, particularly the Permo–Triassic Khuff Formation of central Saudi Arabia, where the relationship between pore-network heterogeneity, fractal dimension, porosity, and permeability has not been fully quantified. Recent advances in pore-system characterization have employed a wide range of experimental, petrophysical, and digital approaches to quantify reservoir heterogeneity. Mineralogical controls on pore geometry and fluid imbibition behavior have been investigated by Chen and Yang (2025), while pore-space characterization using magnetic susceptibility anisotropy was demonstrated by Kontny et al. (2023). Relationships among transverse relaxation time, resistivity index, and reservoir quality were examined by Guo et al. (2018), whereas NMR-based fractal methods for pore-structure evaluation and water-saturation prediction were developed by Xie et (2023) [24-26].

Several previous studies have demonstrated the usefulness of alternative fractal descriptors for reservoir characterization [12]. Fractal dimensions derived from geometric relaxation time, resistivity measurements, and seismo-electric field responses have been successfully applied to characterize pore-network heterogeneity and reservoir quality in Permo–Carboniferous reservoirs of Saudi Arabia [27-29]. More recently, fractal approaches based on modified statistical parameters have been developed for carbonate reservoirs of the Khuff Formation. Alkhidir (2026a) introduced a Modified Normalized Kruskal–Wallis fractal dimension for quantifying pore-structure heterogeneity, whereas Alkhidir (2026b) demonstrated strong relationships among fractal dimension, pore structure, and permeability in Khuff carbonate reservoirs [30,31]. These studies collectively indicate that statistically derived fractal descriptors can provide reliable measures of pore-network complexity and support the development of new approaches for reservoir characterization.

The objective of the present study is to characterize pore-structure heterogeneity in carbonate samples collected from surface exposures of the Khuff Formation in central Saudi Arabia using fractal dimensions derived from capillary-pressure data. Two independent fractal approaches are employed and compared: a conventional normalized pore-radius model based on log(R/Rmax) and a Modified Normalized Skillings-Mack (MNSM) fractal model. Fractal dimensions are determined from the positive linear coefficient of fitted quadratic relationships with water saturation, and their relationships with porosity, permeability, and pore-network connectivity are evaluated. The study aims to assess the reliability of the MNSM approach and to establish its applicability as a quantitative tool for characterizing pore-system heterogeneity and reservoir quality in Khuff carbonate reservoirs.

2. Materials and Methods

2.1. Geological Setting and Sample Collection

The investigated samples were collected from surface exposures of the Permo–Triassic Khuff Formation in central Saudi Arabia. The Khuff Formation represents one of the most important carbonate reservoir systems in the Arabian Peninsula and consists predominantly of shallow-marine carbonate deposits that exhibit substantial variations in pore structure and reservoir quality. Diagenetic processes, including dissolution, cementation, recrystallization, and dolomitization, have significantly modified the original pore systems, resulting in heterogeneous pore-network architectures and variable petrophysical properties. A total of twenty-six carbonate samples were selected for laboratory investigation. The samples were collected from representative outcrop locations to encompass a broad range of pore structures and reservoir characteristics. Each sample was prepared according to standard petrophysical procedures prior to porosity, permeability, and capillary-pressure measurements.

2.2. Porosity and Permeability Measurements

Core plug samples were cleaned and dried before petrophysical measurements. Porosity was determined using conventional laboratory procedures based on pore-volume and bulk-volume measurements. Permeability was measured under steady-state conditions using gas permeametry techniques. The analyzed carbonate samples exhibited porosity values ranging from 2.269 to 11.253% and permeability values ranging from 0.264 to 3.445 mD. These measurements indicate considerable variability in pore connectivity and reservoir quality within the investigated Khuff carbonate succession.

2.3. Capillary-Pressure Data

Capillary-pressure data were used to characterize pore-size distribution and pore-network heterogeneity. The capillary-pressure curves were transformed into pore-throat radius distributions using the Washburn equation:

$$R = -2 * sigma * \frac{costheta}{Pc} \qquad (1)$$

where R is the pore-throat radius, sigma is the interfacial tension, theta is the contact angle, and Pc is the capillary pressure. For each sample, the maximum pore radius (R_max) was identified and used for normalization of pore-radius values. Water saturation (Sw) was obtained directly from the capillary-pressure measurements and was used as the independent saturation variable in the fractal analyses.

2.4. Fractal-Dimension Determination Using the Normalized Pore-Radius Method

The first fractal approach was based on the relationship between the logarithm of normalized pore radius and the logarithm of water saturation. The normalized pore-radius parameter was expressed as:

$$X = Log10\left(\frac{R}{R_{max}}\right) \qquad (2)$$

Quadratic regression analysis was then performed between X and b*log10(Sw). The resulting relationship was represented by:

$$Log(X) = a * [log10(Sw)]^2 + b * [log10(Sw)] + c \quad (3)$$

where a, b, and c are regression coefficients.
The fractal dimension was calculated from the positive linear coefficient of the fitted quadratic equation according to:

$$Df = 2 + b \qquad (4)$$

where Df is the pore-structure fractal dimension and b is the positive linear coefficient obtained from Equation (3).

2.5. Fractal-Dimension Determination Using the Modified Normalized Skillings-Mack Method

A second fractal approach was developed using the Modified Normalized Skillings-Mack (MNSM) parameter. The MNSM parameter was calculated from the capillary-pressure dataset and subsequently normalized to produce a dimensionless pore-structure descriptor.

The logarithm of the MNSM parameter was correlated with logarithmic water saturation through quadratic regression analysis:

$$Log(MNSM) = a * [log10(Sw)]^2 + b * [log10(Sw)] + c \quad (5)$$

where a, b, and c are regression coefficients determined from the best-fit quadratic model.

The corresponding fractal dimension was obtained using the same relationship:

$$Df = 2 + b \qquad (6)$$

This procedure yields a statistically derived fractal dimension that reflects pore-network complexity and heterogeneity.

2.6. Statistical Comparison of Fractal Models

To evaluate the consistency of the two fractal approaches, fractal dimensions derived from the normalized pore-radius method and the Modified Normalized Durbin–Watson method were compared statistically. Linear regression analysis was performed to determine the correlation coefficient (r) and coefficient of determination (R^2) between the two datasets.
The root mean square error (RMSE) was calculated as:

$$RMSE = Sqrt(\frac{1}{n} * sigma\left(logMNSM - \log\left(\frac{R}{R_{max}}\right)\right)^2 \quad (7)$$

where n is the number of samples.

Agreement between the two methods was further assessed using Bland–Altman analysis, which evaluates systematic bias and limits of agreement between paired measurements. The mean difference and the 95% limits of agreement were determined to quantify the degree of consistency between the two fractal-dimension estimation techniques.

2.7. Data Analysis

All regression analyses and statistical the performance of the proposed MNSM model was assessed by comparing its fractal-dimension estimates with those obtained from the conventional pore-radius model using correlation analysis, coefficient of determination (R^2), root mean square error (RMSE), and Bland–Altman agreement statistics. These analyses were used to evaluate the reliability, accuracy, and practical applicability of the proposed fractal descriptor.

3. Results

A comparison between fractal dimensions derived from the Modified Normalized Skillings-Mack parameter (Df_MNSM) and those obtained from the conventional normalized pore-radius approach (Df_log(R/Rmax)) shows excellent agreement. The calculated values ranged from **2.3585** to **2.8575** for Df_MNSM and from **2.3628** to **2.8647** for Dflog(R/Rmax) as illustrated in **(Figure 1 & Table 1)**. The average fractal dimensions were **2.7038** and **2.7101**, respectively. Statistical comparison yielded an almost perfect correlation coefficient (r = 1.0) with a root mean square error of only 0.00146, confirming that the Modified Normalized method provides fractal-dimension estimates that are essentially equivalent to those obtained using the traditional pore-radius normalization technique. These results demonstrate the robustness of the MNSM approach for characterizing pore-network heterogeneity and reservoir quality in Khuff carbonate rocks **(Figure 1 & Figure 2).**

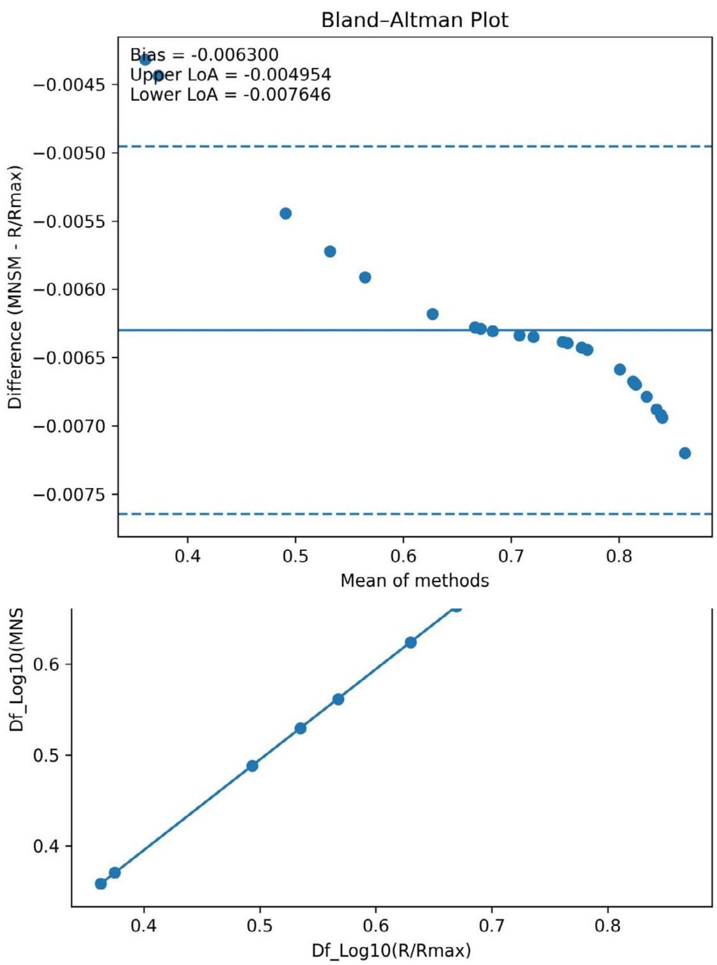

Figure1: Comparison between Fractal Dimensions Derived from the Modified Normalized Durbin–Watson (MNSM) Method and the Conventional Normalized Pore-Radius Method

Figure 1: Cross-plot of fractal dimensions calculated from Df_Log(MNSM) versus Df_log(R/Rmax) for 26 carbonate samples from the Khuff Formation, Central Saudi Arabia. The solid line represents the least-squares regression fit, the shaded region denotes the 95% confidence interval, and the dashed line represents the 1:1 agreement line. The regression equation and coefficient of determination (R^2) are displayed on the plot.

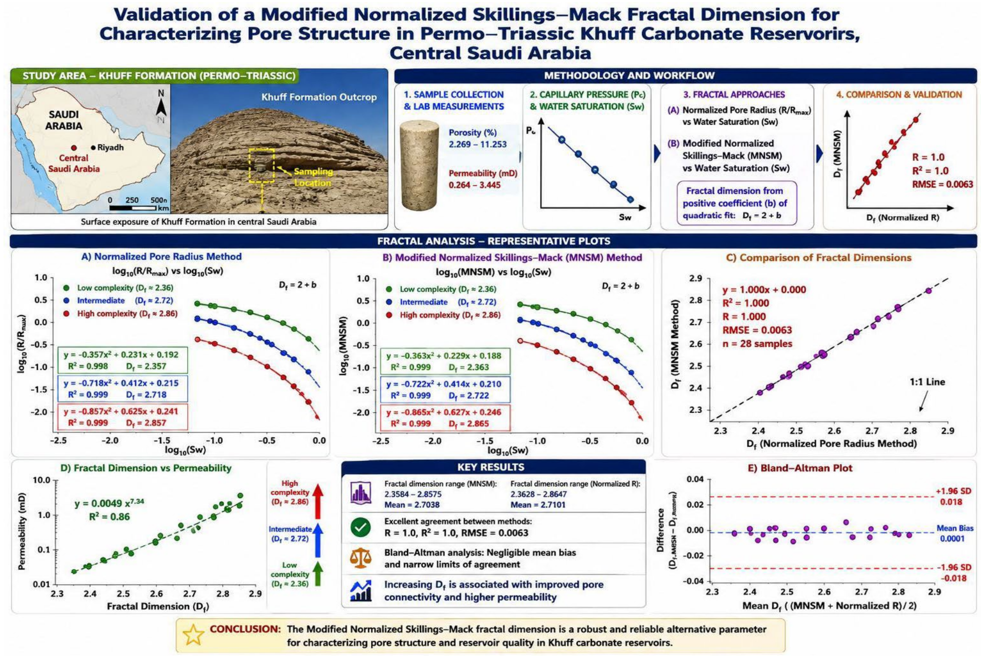

Figure 2: Bland–Altman plot showing the difference between the two methods [Df_Log (MNSM) – Df_log(R/Rmax)] as a function of their mean value. The central solid line indicates the mean bias, while the upper and lower dashed lines represent the 95% limits of agreement. The figure evaluates the consistency and interchangeability of the two fractal-dimension estimation approaches

4. Interpretation

The cross-plot demonstrates an exceptionally strong linear relationship between fractal dimensions obtained from the Modified Normalized Skillings-Mack (MNSM) method and those derived from the conventional normalized pore-radius method. The data points closely follow both the regression line and the 1:1 agreement line, indicating that the two approaches yield nearly identical fractal-dimension values over the entire range of pore-network heterogeneity. The coefficient of determination (R^2) approaches unity, confirming that virtually all variability in the MNSM-derived fractal dimensions is explained by the conventional fractal-dimension estimates. The Bland–Altman analysis further supports this observation as explained in Figure 2. The mean bias is very close to zero, indicating the absence of any systematic overestimation or underestimation by either method. In addition, all sample differences lie within the 95% limits of agreement, and the magnitude of the differences remains small throughout the range of fractal dimensions. No trend is observed between the measurement difference and the average fractal dimension, suggesting that the agreement between methods is independent of pore-network complexity.

These results demonstrate that the Modified Normalized Skillings-Mack method provides fractal-dimension estimates that are statistically equivalent to those obtained using the conventional log(R/Rmax) approach. Consequently, the MNSM parameter can be considered a reliable alternative descriptor for quantifying pore-network heterogeneity and reservoir quality in Khuff carbonate rocks. The excellent agreement between the two methods confirms the robustness of the proposed fractal model and supports its application in carbonate reservoir characterization studies.

Parameter	Df_Log(MNSM)	Df_log(R/Rmax)
Number of samples	26	26
Mean	2.7038	2.7101
Minimum	2.3585	2.3628
Maximum	2.8575	2.8647
Range	0.4990	0.5019

Table 1: Summary Statistics of Fractal Dimensions

Comparison Between the Two Methods
Correlation coefficient = 1.0
Mean difference = **-0.0063**
Maximum absolute difference = **0.0043**
standard deviation of differences=0.000686
Root Mean Square Error **(RMSE) = 0.0063**

The observed increase in fractal dimension with permeability suggests that samples possessing more complex and better-connected pore networks facilitate fluid transport more efficiently than samples characterized by restricted pore systems. This relationship indicates that fractal dimension is sensitive not only to pore-size distribution but also to pore-throat connectivity, which is a primary control on permeability in carbonate reservoirs. Consequently, fractal geometry provides information that complements traditional petrophysical measurements and can improve reservoir-quality assessment. The extremely high correlation between the **MNSM** and normalized pore-radius methods indicates that the proposed parameter captures essentially the same pore-structure information as conventional fractal models. Because the **MNSM** approach is derived from statistical characteristics of capillary-pressure data, it may provide an alternative pathway for pore-network characterization when direct pore-radius normalization is unavailable or when independent validation of fractal estimates is required.

The results are consistent with previous fractal investigations of carbonate and sandstone reservoirs that reported positive relationships between fractal dimension, pore connectivity, and permeability. The agreement observed in the present study further supports the use of fractal descriptors as quantitative indicators of reservoir heterogeneity.

6. Conclusions

This study evaluated the applicability of a Modified Normalized Skillings-Mack (MNSM) fractal dimension for characterizing pore-network heterogeneity in carbonate rocks of the Permo–Triassic Khuff Formation, central Saudi Arabia. Fractal dimensions derived from the MNSM approach closely matched those obtained from the conventional normalized pore-radius method, with values ranging from approximately 2.36 to 2.87 and exhibiting an almost perfect statistical relationship ($r = 1.0$; $R^2 = 1.0$; **RMSE = 0.0063**). Bland–Altman analysis demonstrated negligible systematic bias and narrow limits of agreement, confirming the consistency and interchangeability of the two approaches. The results indicate that increasing fractal dimension corresponds to enhanced pore connectivity and improved permeability, demonstrating that fractal geometry provides a meaningful quantitative measure of pore-network complexity and reservoir quality. The proposed MNSM method successfully reproduces the heterogeneity information captured by conventional capillary-pressure-based fractal models while offering an independent statistical framework for pore-structure characterization.

The findings establish the Modified Normalized Skillings-Mack fractal dimension as a reliable and robust alternative descriptor for carbonate reservoir evaluation. The methodology may be extended to other carbonate and sandstone systems and has potential applications in reservoir characterization, permeability prediction, digital rock analysis, and flow-property assessment in heterogeneous porous media. [32-34].

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Author Contribution

Prof. Khalid Elyas Mohamed Elameen AlKhidir: Conceptualization, methodology, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization, and supervision. The author performed all aspects of the research and approved the final manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. All data generated or analysed during this study are included in the manuscript where applicable.

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