



Extended Abstract

Application of Shannon Entropy in Quantifying Geological Heterogeneity, Porosity, and Permeability: A Case Study of the Kangan Formation in the Central Persian Gulf

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Abstract

This study aims to apply Shannon entropy to analyze and compare facies and petrophysical heterogeneity in the K1 and K2 units of the Kangan Formation. Facies were first classified into twelve groups based on petrographic studies, and facies entropy was calculated from their relative frequencies. Subsequently, core porosity and permeability were categorized into value classes, and Shannon entropy was computed independently for each parameter. Diagenetic features were also examined to interpret data distribution patterns. The results demonstrate that Shannon entropy can quantitatively express structural differences between the two units. While facies entropy values are similar in both units, their facies distribution patterns differ. Porosity entropy in K2 is 1.58 compared to 1.12 in K1, indicating a wider porosity distribution in K2. Permeability entropy values are 1.95 in K2 and 1.60 in K1, reflecting greater diversity in permeability classes within K2. The higher porosity and permeability entropy in the K2 unit is consistent with its diagenetic characteristics, where intergranular and intragranular dissolution has created or expanded secondary pore spaces, distributing porosity and permeability values across multiple classes. In contrast, more extensive microcrystalline dolomitization, cementation, and particularly anhydrite cementation in K1 have resulted in pore filling or throat tightening, concentrating data in low-permeability and low-porosity classes. Thus, porosity-reducing diagenetic processes in K1 yield lower entropy, while porosity-enhancing or pore-preserving processes in K2 produce higher entropy. This relationship indicates that Shannon entropy can effectively reflect the differentiating effects of various diagenetic styles through a quantitative index. Based on these findings, Shannon entropy provides a simple, reliable, and appropriate approach for assessing heterogeneity in carbonate reservoirs and can serve as a valuable complement to conventional petrophysical and sedimentological methods for analyzing reservoir units and modeling reservoir behavior.

1. Introduction

Carbonate reservoirs commonly exhibit substantial heterogeneity that arises from their complex depositional environments and subsequent diagenetic modifications [1]. This heterogeneity plays a decisive role in controlling fluid flow, reservoir quality, and hydrocarbon recovery. Traditional approaches for assessing reservoir heterogeneity—such as facies

classification, hydraulic flow units, statistical clustering, or pore network evaluations—provide valuable insights but often lack a unified metric that allows direct comparison between geological and petrophysical domains. The Kangan Formation, a Lower to Middle Triassic carbonate–evaporite succession in the central Persian Gulf, is a prime example of a reservoir system shaped by diverse depositional and diagenetic processes [2].

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Its mud-supported to grain-supported facies, together with microbial and evaporitic intervals, have undergone dolomitization, anhydritization, cementation, and dissolution, resulting in highly variable porosity and permeability distributions. As a major gas-producing interval in the region, a precise understanding of its heterogeneity is essential for reservoir modeling and field development strategies.

In this study, Shannon entropy—a measure originally developed in information theory—is applied to quantify heterogeneity within the Kangan Formation. Shannon entropy offers a flexible mathematical framework capable of handling both discrete datasets, such as facies types, and continuous datasets, such as porosity and permeability, once they are classified into frequency-based classes. This feature makes it especially suitable for integrated reservoir studies where geological, petrophysical, and diagenetic data must be evaluated together. The objective of this research is to quantify heterogeneity in the two major reservoir intervals of the Kangan Formation, known as K1 and K2, and to compare their complexity using a single, coherent quantitative index. The results offer insights into the distribution patterns of facies and petrophysical properties and help relate these patterns to the dominant depositional and diagenetic processes operating in the formation.

2. Methodology

The dataset used in this study originates from a fully cored well in the central Persian Gulf. A total of 2,123 thin sections and 1,984 laboratory-derived porosity and permeability measurements form the basis of the analysis. Lithologies observed include limestone, dolomite, anhydrite, dolomitic limestone, and limestone dolomite. Thin sections were examined under a polarized microscope, and approximately one-third were stained with alizarin red to differentiate calcite from dolomite. Porosity was measured after solvent extraction and oven drying, using the helium gas method based on Boyle's law. Permeability measurements were acquired using air flow through core plugs according to Darcy's law.

Facies were classified into twelve groups using the Dunham classification system, with consideration of texture, grain type, cement characteristics, the matrix-to-grain support ratio,

and microbial structures. These facies represent a range of depositional settings, from shallow-marine platform environments to evaporitic and grain-supported conditions. The relative abundance of each facies type in intervals K1 and K2 was calculated to determine facies entropy.

Porosity values were screened for outliers, then grouped into 5% intervals to convert continuous measurements into discrete classes suitable for entropy calculation. Permeability values were log-transformed (\log_{10}) to normalize their skewed distribution and then categorized into equal-width classes. For all datasets, identical class definitions were applied to both units to ensure valid comparisons.

Shannon entropy [3] was computed separately for facies, porosity, and permeability using the standard formula:

$$H = - \sum_{i=1}^n (p_i) \ln p_i \quad (1)$$

where p_i is the relative frequency of the i th class. Higher entropy indicates greater heterogeneity in the distribution of facies or petrophysical values. Graphical representations—including bar charts, radar diagrams, scatter plots, and semilog ϕ - k relationships—were constructed to support interpretation. Geological context, such as the position of the study area on the northeastern margin of the Arabian Plate and its Triassic shallow-platform setting, was incorporated to understand the origins of observed complexity.

3. Results and Conclusions

The results demonstrate clear differences in the heterogeneity levels of the K1 and K2 reservoir units. Facies entropy values reveal that K1 exhibits a slightly more diverse facies distribution, reflecting its greater variety of depositional textures and more pervasive diagenetic alterations. Porosity and permeability entropy results show noticeable contrasts between the units as well: K2 displays narrower porosity classes but broader permeability variability after log-transformation, suggesting that pore-throat modification by diagenesis played a more significant role in this interval. These findings align with petrographic observations indicating that dolomitization and anhydritization—both of which exert strong influence on pore-network

architecture—are more pronounced in specific depths of the formation.

The entropy-based framework demonstrates that Shannon entropy provides an effective, unified index for quantifying reservoir heterogeneity in carbonate systems. Unlike conventional approaches that treat facies, porosity, and permeability separately, entropy allows direct comparison among these parameters using a consistent mathematical basis. This integrated perspective enhances understanding of how depositional and diagenetic processes combine to produce the observed reservoir architecture. The outcomes of the study hold practical implications for static geological modeling, dynamic flow simulation, and reservoir development planning in the Kangan Formation and similar heterogeneous carbonate–evaporite reservoirs. By quantifying complexity in a systematic way, entropy can help reduce uncertainty and improve representation of reservoir heterogeneity in subsurface models.

5. References

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