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GEOPHYSICS

Spatial Porosity Modeling in the Mixed Siliciclastic-Carbonate Kazhdumi Reservoir in an Iranian oilfield located in Abadan Plain

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ABSTRACT

Spatial porosity modeling is vital in static modeling, as variations in both lateral and vertical dimensions significantly influence reservoir quality and volumetric calculations. This study focuses on the spatial modeling of effective porosity in the mixed siliciclastic and carbonate Kazhdumi reservoir within a section of the Abadan Plain. Despite numerous studies on porosity distribution, a suitable model for the studied area has yet to be established. Here, electrofacies analysis is employed to distribute porosity more accurately. Petrophysical logs, including porosity and mineral volumes from eight drilled wells in the Abadan Plain, were analyzed. Electrofacies analysis revealed high porosity in sandy siliciclastic intervals, contrasting with shaly facies that exhibit poor reservoir characteristics. Additionally, two calcareous facies were identified. Data analysis linked porosity to facies codes, ensuring a better match between porosity and relevant facies distributions. The constructed porosity model of the Kazhdumi Formation is a significant outcome of this study. On average, carbonate intervals exhibit 6% porosity, while sandy intervals exhibit 8%. Notably, the northern and western parts of the studied area display increased porosity, reaching up to 9%. Siliciclastic intervals generally exhibit higher reservoir quality compared to carbonate intervals.

Keywords: Kazhdumi reservoir; Effective porosity; Electrofacies; Spatial modeling;

Caracterización del espacio poroso en el reservorio siliclástico y carbonatado de Kazhdumi, en un campo petrolífero en la llanura de Abadan, Irán

RESUMEN

La caracterización del espacio poroso es determinante en el modelado estadístico de un reservorio ya que las variaciones laterales y verticales influyen significativamente en su calidad y en los cálculos volumétricos. Este estudio se enfoca en la caracterización espacial de la porosidad efectiva del reservorio siliclástico y carbonatado de Kazhdumi, en una sección de la llanura de Abadan. A pesar de numerosos estudios en la distribución de la porosidad, aún no se ha establecido un modelo apropiado para el área de estudio. En este estudio se utilizó el análisis de electrofacies para distribuir la porosidad con mayor exactitud. Se analizaron registros petrofísicos, entre ellos la porosidad y el volúmen mineral, de ocho pozos perforados en la llanura de Abadan. Los análisis de electrofacies revelaron una alta porosidad en los intervalos arenosos siliclásticos, en contraste con las facies esquistosas de los reservorios de parámetro pobre. Adicionalmente se identificaron dos facies calcáreas. En el análisis de datos se vinculó la porosidad con los códigos de las facies con el fin de asegurar un mejor acople entre la porosidad y las distribuciones de las facies relevantes. El modelo de porosidad construido para la Formación de Kazhdumi es un logro significativo de este estudio. En promedio, los intervalos carbonatados muestran el 6 % de porosidad, mientras que los intervalos arenosos muestran el 8 por ciento. Se resalta que en las partes hacia el norte y hacia el oeste del área de estudio se registró un incremento en la porosidad de hasta el 9 por ciento. Los intervalos siliclásticos generalmente muestran parámetros mayores de la calidad del reservorio en comparación con los intervalos carbonatados.

Palabras clave: Reservorio de Kazhdumi; porosidad efectiva; electrofacies; caracterización del espacio.

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1. Introduction

Reservoir quality assessment is a vital component of field studies that underpins commercial development. Among different parameters affecting reservoir quality, porosity is a substantial factor. Since porosity is an important parameter in identifying and understanding the behavior of an oil reservoir, its proper spatial distribution is necessary. In fact, porosity is the fundamental rock property which affects the reservoir fluid volume directly (Wong et al., 1995). In addition to reserve estimation, porosity model can be applied for reservoir simulation, pore pressure prediction, etc. (Dvorkin and Nur., 2002).

The spatial distribution of porosity parameter has always been a favorite subject for researchers due to its effect on reservoir management and development. Spatial behavior of the porosity in Shurijeh B gas reservoir in Khangiran gas field has been assessed by Hosseini et al., 2019. They used 32 wells information to model porosity applying kriging and Sequential Gaussian Simulation methods. Artificial neural network method has been used as a strong tool for this purpose (Esmaeilzadeh et al., 2013; Zargari et al., 2013; Arabani and Nabi-Bidhendi, 2002; No., 2011). Also, other geostatistical methods such as ordinary kriging have been used for spatial porosity distribution in the Asmari reservoir of Mansuri oilfield (Nazarpour et al., 2014). Although, previous researches reveal valuable results, they are limited to using geostatistical and artificial intelligence methods for determining spatial distribution of porosity. In this paper, the electrofacies analysis has been applied to be link to the porosity parameter in order to achieve more appropriate spatial distribution. In addition, GRFS algorithm was applied for porosity distribution. Moreover, it must be emphasized that porosity variation of mixed siliciclastic and carbonate of Kazhdumi reservoir has not yet been studied in this area.

As a main reservoir property, porosity can be distributed using geostatistics in 3D static reservoir models (Huysmans and Dassargues., 2013). The reliability of the porosity model is influenced by several factors, including the quality of porosity interpretation, the number of wells, cell size, upscaling methods, geostatistical algorithms, and secondary variables. Incorporating microfacies, electrofacies, or seismic facies can also enhance the understanding of porosity distribution. Furthermore, utilizing an acoustic impedance cube as a secondary variable for co-simulation can provide significant value in the modeling process. To construct a proper model of porosity, an appropriate zonation is required. Obviously, reservoir zonation plays a vital role in field development programs and production management. In this regard, applying sequence stratigraphic concept can provide an efficient reservoir zonation (Magalhães et al., 2020). Due to the efficiency of using sequence stratigraphy in reservoir zonation, widespread researches have been done. For instance, sequence stratigraphic approach has been applied for carbonate, siliciclastic, and carbonate-siliciclastic reservoirs (Jodeyri-Agaii et al., 2018; Mehrabi et al., 2019; Kiani et al., 2022, Asadi et al., 2022; Magalhães et al., 2020; Enayati–Bidgoli and Rahimpour-Bonab., 2022).

Jodeyri-Agaii et al., (2018) conducted a detailed investigation into the depositional and diagenetic characteristics of Mishrif carbonates within a sequence stratigraphy context. Their research demonstrated that substantial portions of the Mishrif Reservoir are shaped by diagenetic processes associated with subaerial exposure, resulting in the development of zones characterized by increased storage capacity and enhanced rates of fluid flow. Mehrabi et al., (2019) examined the reservoir rock typing and zonation of the Cretaceous Dariyan Formation through the concepts of sequence stratigraphy. Their analysis revealed that the reservoirs associated with the lower and upper carbonate units of the Dariyan Formation possess distinct lithofacies and diagenetic modifications. These variations are attributed to deposition within two intrashelf basins situated in the northwestern and southeastern regions of the Persian Gulf, as well as subsequent exposure to meteoric water flow during episodes of subaerial exposure.

In this paper, despite previous publications, sequence stratigraphic zonation and electrofacies analysis have been used to reach better porosity distribution. In other words, the 3D effective porosity model of the Kazhdumi reservoir in the studied field (located in the Abadan Plain) has been modeled using electrofacies of mixed siliciclastic and carbonate facies. To that end, as the primary step, the zonation of the Kazhdumi Formation has been done using sequence stratigraphic concept. Subsequently, interpreted petrophysical logs, which include mineral volumes and effective porosity, were utilized for electrofacies analysis through the application of the MRGC method. In the next step, the electrofacies codes were modeled using SIS algorithm. Eventually, the porosity has been modeled by applying GRFS algorithm and linking to the facies codes. Therefore, average maps were generated based on constructed models which can provide a great insight into the lateral changes of porosity along the studied area which is a beneficial achievement.

Following the introduction, the geological characteristics of the studied area, along with a detailed overview of the Kazhdumi Formation, will be presented. The methodology section will outline the key concepts related to sequence stratigraphy, zonation, and modeling. Finally, in the results section, the constructed porosity model will be evaluated, and maps depicting the porosity distribution in sand and carbonate facies will be generated to illustrate the lateral variations.

2. Geological setting

The Zagros Basin includes both carbonate (such as Ilam, Sarvak, etc) and siliciclastic (Kushk sandstone and Azadegan sandstone) reservoirs. The studied field is located in the Abadan Plain. The Abadan Plain, situated in southwestern Iran, is characterized as a structural subzone. This is limited by Zagros Mountain, Persian Gulf, and Iraq (Motiei, 1993). Abadan Plain is located in the northwest of the Persian Gulf (Figure. 1). The structures of this area follow the N-S trend. Geophysical studies and previously drilled wells are two important sources of information in this area.

Kazhdumi Formation was deposited in the late early Cretaceous (Albian). The Kazhdumi Formation, part of the Cretaceous Bangestan Group, is exposed in the Dezful Embayment and the Fars and Izeh Zones of the Zagros region (Motiei, 1993). This formation is conformably situated above the Dariyan Formation and is underlain by the Sarvak Formation (James and Wynd, 1965). The reference section of the Kazhdumi Formation, characterized by a thickness of 210 meters, is located in Tang-e-Gurguda, approximately 10 km north of Gachsaran City, as originally described by James and Wynd (1965). The formation is widely distributed across southwestern Iran, particularly in the Dezful Embayment, the Abadan Plain, and the northwestern Persian Gulf.

The Kazhdumi Formation was deposited in a mixed environment comprising both carbonate and clastic materials. It includes calcareous and dark bituminous shales that interdigitate with argillaceous limestone and sandstone, especially in its lower section. A significant rise in sea level during the Albian period led to the deposition of dark organic-rich shales and argillaceous limestones of the Kazhdumi Formation in Iran, as well as its equivalents, such as the Nahr Umr Formation, in neighboring regions (Motiei, 1993; Ghazban, 2009). The presence of ammonite fossils and a foraminiferal-oligosteginid assemblage indicates the formation's origination in deep marine conditions characterized by anoxia and a connection to the Neo-Tethys (Ziegler, 2001). The basal sandstone and shale layers of the Kazhdumi Formation are referred to as the "Azadegan Sandstone Member" (Esrafili-Dizaji and Rahimpour-Bonab, 2019; Mehrabi et al., 2019).

In the Dezful Embayment, the Kazhdumi Formation has been referred to as the source of the accumulated oils in Bangestan Group. It is also the most important source rock for the reservoirs accumulated in Asmari Formation. The Kazhdumi Formation in the studied field has carbonate and siliciclastic intervals which both have hydrocarbon potential (Figure 2). The Azadegan sandstone member (siliciclastic) of the Kazhdumi Formation with a sandstone-shale lithology is known as a reservoir in some Iranian offshore oil fields (Alsharhan, 1994). In the studied field, Azadegan sandstone member is one of the important reservoir intervals, although the carbonate interval of the Kazhdumi Formation also has notable potential. It is a well-known source rock in the Zagros Basin (Bordenave and Burwood, 1990 and 1995; Bordenave and Huc, 1995; Shakib, 1987). In the studied field, thickness of the Kazhdumi Formation is about 230 m, including about 58 m for Azadegan Member.

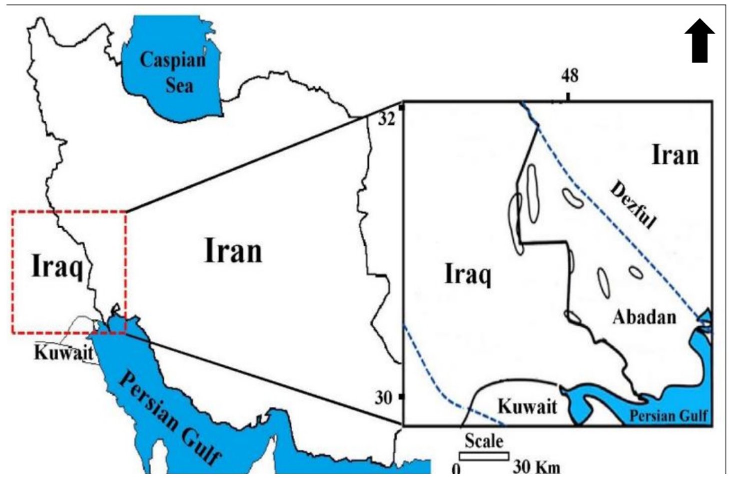


Figure 1. The Abadan Plain location (Shabani et al., 2020)

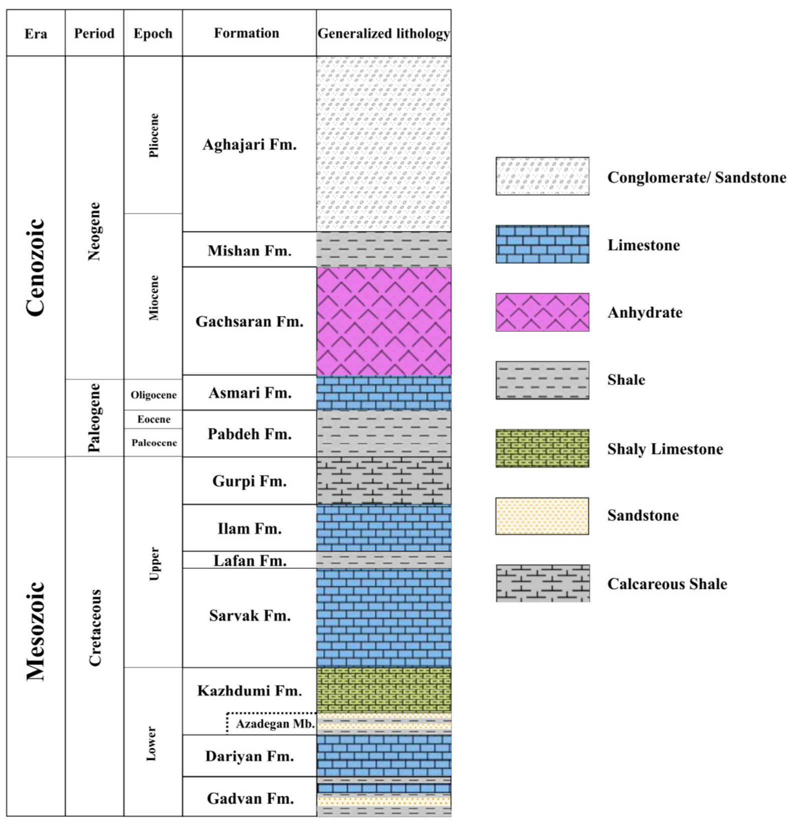


Figure 2. Simplified stratigraphic chart of Abadan Plain. Please note that the dominant lithology in each formation is presented, and this column is drawn in a simple and general form (Sadeghtabaghi et al., 2024).

3. Methodology

In this study, data sets of an Iranian oilfield (eight wells) have been used. Petrophysical data (conventional raw and result logs), well deviation data, well coordinates, depth surfaces, and formation tops are the applied data of this paper. Figure 3 illustrates the fundamental steps undertaken in this paper. A detailed description of these steps is provided in the subsequent sections.

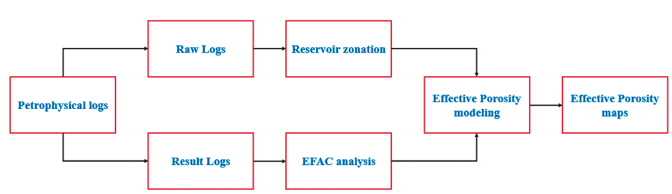


Figure 3. Schematic of this paper's steps.

Reservoir zonation

Estimating rock porosity and its spatial distribution in a heterogeneous reservoir is a significant step in static reservoir modeling. However, separating the reservoir and non-reservoir rocks (zonation) in heterogenous reservoir is very important. In this paper, reservoir zonation has been done based on sequence stratigraphy concept. Reservoir zonation is one of the most important applications of sequence stratigraphy.

Sequence stratigraphy examines how sediment responds to variations in sea level and the resulting depositional patterns that arise from the interaction between accommodation (the space available for sediments) and sedimentation. This field offers significant insights into the Earth's geological history, revealing responses to both local and global changes, and enhancing predictive capabilities in economic exploration and production. The foundational principles of sequence stratigraphy largely transcend the specific depositional environments found within sedimentary basins, such as siliciclastic versus carbonate settings. Typically, clastic systems are used to illustrate these concepts (Van Wagoner et al., 1988; Catuneanu et al., 2009).

Researchers often describe sequence boundaries and stratigraphic units in relation to shifts in relative sea level, which involve a combination of global eustatic sea level changes and regional subsidence due to tectonic activity, thermal effects, and load-induced subsidence. The alterations caused by these vertical forces either increase or decrease the accommodation space available for sediment accumulation in a basin. Additionally, the rate of sediment supply influences how quickly that space is filled. Sequence boundaries are considered the most critical surfaces and are defined as unconformities or their corresponding conformities, typically resulting from a fall in sea level.

The idea of systems tracts has emerged to connect contemporary depositional systems. These tracts serve as subdivisions within a sequence, classified based on their strata stacking patterns, sequence position, sea level fluctuations, and types of bounding surfaces.

- A low-stand systems tract (LST) occurs when sedimentation rates exceed the rate of sea level rise early in the sea level curve, defined by a subaerial unconformity or its equivalent at the base and a maximum regressive surface at the top.
- A transgressive systems tract (TST) is delineated by a maximum regressive surface at the base and a maximum flooding surface at the top, forming when the rate of sedimentation cannot keep up with rising sea levels.
- A high-stand systems tract (HST) develops during the later phase of rising base levels, when the rate of sea level rise falls below the sedimentation rate, resulting in a high-stand period defined by a maximum flooding surface at the base and a composite surface at the top.
- A regressive systems tract forms in the marine portion of the basin during a fall in base level, coinciding with the development of subaerial unconformities on the landward side of the basin (Van Wagoner et al., 1988; Catuneanu et al., 2009).

INPEFA, an acronym for Integrated Prediction Error Filter Analysis, is a methodological framework that facilitates the transformation of the Gamma Ray (GR) curve into a spectral trend attribute curve, commonly referred to as the INPEFA curve. This analytical technique is particularly adept at processing facies-sensitive well logs. The resultant INPEFA curves elucidate discontinuities present in the log data, which, from a geological perspective, can be interpreted as hiatuses, erosional surfaces, or shifts in lithology and sedimentation rates. Given that these geological phenomena may occur at both field and regional scales, INPEFA curves provide significant utility in well correlation and reservoir zonation (Nainggolan et al., 2019; Soua., 2012).

The INPEFA curve represents a robust alternative method for interpreting wireline log (GR) data, allowing for the extraction of key sequence stratigraphic information and offering a comprehensive framework for understanding sequence stratigraphy. This curve effectively captures the succession of climatic phases during sediment deposition and is principally governed by the processes of relative transgression and regression occurring across the sedimentary basin throughout the sedimentation process. Consequently, the INPEFA curve delineates the ordering of sequences that evolve within a stratigraphic package, thereby contributing to a refined understanding of sedimentary processes and stratigraphic architectures (Nainggolan et al., 2019; Soua., 2012).

As known, sequences can be defined based on stacking patterns and stratigraphic surfaces (Magalhães et al., 2020). Gamma-ray data can be used for reservoir zonation based on sequence stratigraphy concept using some softwares such as Cyclolog which applied in this study (Emery and Myers, 1996). The system tracts, along with their associated boundaries—such as the Maximum Flooding Surface (MFS) and Sequence Boundary (SB)—are identified through variations in the gamma ray log, which exhibit decreasing and incremental patterns. As decreasing trend of the gamma ray log, represents the regressive system tract and increasing trend of the gamma ray log, indicate transgressive system tract (Sarg, 2001). The Cyclolog software has been used in this paper which applies INPEFA trends.

Electrofacies analysis

In this study, Geolog software has been used for electrofacies analysis. The electrofacies determination and clustering were done using Facimage module of this software. The term "electrofacies" was originally defined as a set of log responses that characterizes a bed and permits it to be distinguished from others (Serra and Abbott, 1980). These properties are defined by the physical characteristics of the rocks to which the wireline logs respond. Effective porosity, along with the mineral volumes of calcite, quartz, and shale, were chosen as the input interpreted logs. After normalizing the input data, the logs were trained using the MRGC algorithm. Figure 4 displays the cross plots of the input logs organized into different clusters.

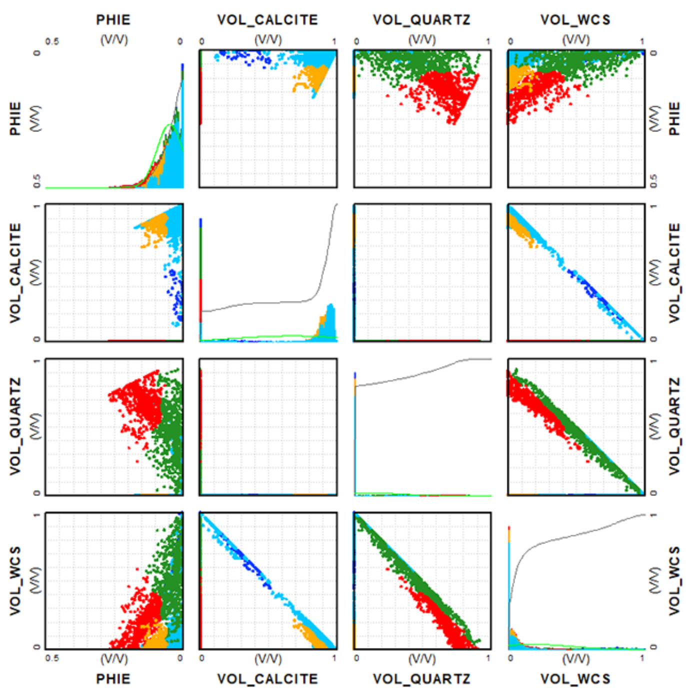


Figure 4. Cross plots between input logs in different clusters (Kazhdumi Formation from the eight studied wells). Note that PHIE refers to effective porosity, while VOL_CALCITE, VOL_QUARTZ, and VOL_WCS represent the volumes of calcite, sand, and shale, respectively. The colors utilized in the figures are designated according to Facies classes. For understanding these colors, please refer to the Table. 4.

Property modeling

The primary purpose of creating a static model is to create a 3D representation of the reservoir in order to assist in the development of the hydrocarbon resources. Static modeling consists of two important steps structural and property modeling followed by volumetric calculation, uncertainty analysis, and sensitivity analysis. Structural modeling contains fault modeling, 3D geocellular modeling, making horizons, making zones, and layering (Mehdipour et al., 2023). Property modeling is the process of assigning data, discrete (facies) or continuous petrophysical properties (such as porosity, and permeability …), to the cells of the 3D fine grid.

Sequential Indicator Simulation (SIS) is a variogram-based technique for categorical simulation that has gained considerable traction in the modeling of categorical variables. This method is particularly advantageous in situations where there are no discernible genetic shapes amenable to object-based modeling. In the context of petrophysical modeling, Sequential Gaussian Simulation (SGS) has been found to exhibit slower computational performance when compared to Gaussian Random Function Simulation (GRFS). This disparity in speed arises from SGS's sequential computation of input variables, which enables it to encompass a broader spectrum of uncertainty. This sequential characteristic is the fundamental distinction between SGS and GRFS; the latter operates with random sampling in a more expedited manner, thereby capturing a narrower range of uncertainty. Consequently, the integration of GRFS with any facies modeling algorithm generally results in a reduced range of uncertainty when juxtaposed with the integration of SGS with the same algorithmic approaches (Alabert, 1987; Aduomahor and Ibezim, 2020; Bai and Tahmasebi, 2022).

The amalgamation of SIS and SGS is noteworthy for yielding the highest range of uncertainty, attributable to the sequential nature inherent in both methodologies. SIS employs upscaled cells to establish the proportions of various facies types being modeled, while the variogram serves to regulate the distribution and connectivity among these facies. This renders SIS particularly effective for modeling facies characterized by ambiguous or undefined shapes, especially in scenarios where input data are sparse. Conversely, SGS is founded on a straightforward and mathematically robust algorithm that, while providing flexibility, does not replicate the input variance with the same level of precision. The synergistic combination of SIS and SGS facilitates the effective capture of extreme values, both maximum and minimum; however, it is generally considered to be slower in execution compared to alternative methods (Alabert, 1987; Aduomahor and Ibezim, 2020; Bai and Tahmasebi, 2022).

In this study, a structural model with 100m × 100m gridding was constructed. After structural modeling, the electrofacies codes and effective porosity were scaled up. Then, data analysis has been done for both of them. Therefore, vertical proportion setting (for EFAC) and data transformation setting (for PHIE) were set, and then variography setting has been done for both properties. Major, minor and vertical ranges with other necessary parameters for variography of porosity and electrofacies such as sill, azimuth, nugget and variogram type have been shown in Table 1 and Table 2.

Table 1. Variography setting for porosity distribution

Major range (m)		Minor range (m)		Vertical range (m)		Sill		Azimuth	Nugget	Type
from	to	from	to	from	to	from	to	0	0.0001	spherical and exponential
3571	10790	2817	7149	0.558	10	0.43	33.22			

Table 2. Variography setting for electrofacies distribution

Major range (m)		Minor range (m)		Vertical range (m)		Sill		Azimuth	Nugget	Type
from	to	from	to	from	to	from	to	0	0.0001	Spherical
5509	17193	3272	6731	1.04	3.253	0.3895	1.2737			

In the next step, 3D modeling of electrofacies and porosity was performed using stochastic simulation algorithms. Gaussian simulation methods, including SGS (Sequential Gaussian Simulation), SIS, and GRFS, are conditional geostatistical techniques that utilize kriging mean and variance to generate a Gaussian distribution of parameters (Evans Annan et al., 2019). In this paper SIS and GRFS algorithms have been applied for modeling electrofacies and porosity, respectively. The parallel kriging is the base of estimation in GRFS which is a conditional simulation method. The algorithm of parallel kriging was introduced in 2008 which is faster than the old algorithm (Daly et al, 2010. Parallel kriging method results in more accurate estimates (Zhuo et al., 2011). In addition to high accuracy, parallel algorithm causes lesser duration of execution (Pesquer et al., 2011). Comparing SGS, the performance of GRFS for porosity modeling is better (Daly et al., 2010).

4. Results and Analysis

As mentioned, the reservoir zonation of the Kazhdumi Formation has been done using sequence stratigraphic concepts. In fact, the previous reservoir zonation (which was solely derived from the responses recorded from the petrophysical logs) has been updated by applying the sequence stratigraphy concept via Cyclolog software. This software uses INPEFA log for this purpose (Figure 5). Kazhdumi Formation has been divided into two main zones including carbonate and siliciclastic (Azadegan sandstone) zones. In turn, the carbonate zone has been divided into 3 subzones and Azadegan sandstone has been divided into eight subzones. Table 3 indicates reservoir zonation of the Kazhdumi Formation, in which the bolded zones show the high potential hydrocarbon zones. As shown, this reservoir has been divided into eleven zones.

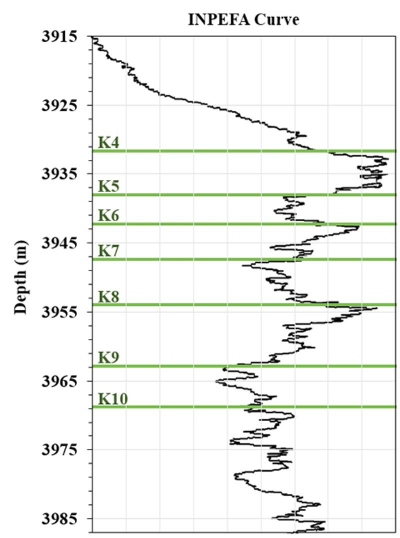


Figure 5. Reservoir zonation based on sequence stratigraphy concept in one of the studied wells (variation of the INPEFA log with depth)

Table 3. Reservoir zonation of the Kazhdumi reservoir (the bolded zones indicate the high potential hydrocarbon zones)

Formation	Lithology	Zones	PHIE (Fraction)
Kazhdumi	carbonate	K1	0.0342
		K2	0.0489
		K3	0.0154
	siliciclastic (Azadegan Sandstone)	K4	0.018
		K5	0.0912
		K6	0.0055
		K7	0.1187
		K8	0.0343
		K9	0.0913
		K10	0.0208
		K11	0.0139

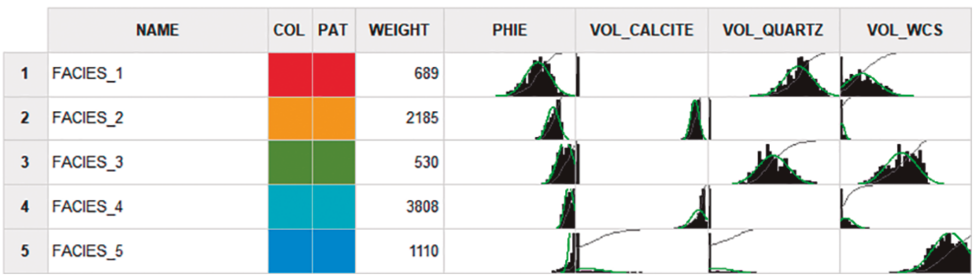
In the next step, the electrofacies analysis has been done. To that end, MRGC method was selected as the most effective approach among all available methods. Finally, 24 facies have been classified. Then these clusters were merged into five final clusters as shown in Table 4. Also, the minimum, maximum, mean, and standard deviation values of effective porosity and mineral volumes of all facies codes have been listed in Table 5.

The reservoir characteristics decreases from facies code 1 to facies code 5. The characteristics of these facies codes are as follows:

- Facies-1: This sandy facies consists of 69% quartz volume (average value), then it is sandstone. The average value of shale volume in this facies is around 17%. Also, due to high porosity (14%) it has the best reservoir characteristics.
- Facies-2: The main lithology of this facies is limestone and the average content of calcite volume is 90%. The average porosity is 9%. Therefore, it can also be considered as a good facies with proper reservoir property.
- Facies-3: This shaly sandstone facies consists 49% quartz and 47% shale volumes. The average value of porosity is about 4%.
- Facies-4: The lithology of this facies is limestone having 93% calcite volume. The average porosity is 3%, then this facies has low reservoir quality.
- Facies-5: This facies which is shale, contains 84% shale volume. The average porosity is 1% which represents a non-reservoir facies.

These electrofacies codes are shown in one of the studied wells (Figure 6).

According to the Fig. 6, zones K1, K2, and K3 are predominantly comprised of carbonate, while the remaining zones of the Kazhdami Formation consist of a heterogeneous mixture of sand and shale. An analysis of the juxtaposition between the mineral volume column and the electrofacies codes reveals that the upper carbonate section is characterized by two distinct electrofacies codes, namely codes 2 and 4. Notably, the dominant electrofacies manifestation in this carbonate region is code 4, which is indicative of dense limestone.



	NAME	COL	PAT	WEIGHT	PHIE	VOL_CALCITE	VOL_QUARTZ	VOL_WCS
1	FACIES_1			689				
2	FACIES_2			2185				
3	FACIES_3			530				
4	FACIES_4			3808				
5	FACIES_5			1110				

Table 4. Final electrofacies classes (for more information on these histograms, please refer to Table 5)

Table 5. Minimum, maximum, mean, and standard deviation of effective porosity and mineral volumes of all facies codes

		Facies_1	Facies_2	Facies_3	Facies_4	Facies_5
Effective Porosity (Fraction)	Min	0	0.05	0	0	0
	Max	0.27	0.17	0.16	0.1	0.09
	Mean	0.14	0.09	0.04	0.03	0.01
	Std	0.05	0.02	0.03	0.02	0.01
Calcite Volume (Fraction)	Min	0	0.69	0	0.57	0
	Max	0	0.95	0	0.99	0.57
	Mean	0	0.9	0	0.93	0.09
	Std	0	0.03	0	0.06	0.13
Sand Volume (Fraction)	Min	0.33	0	0.22	0	0
	Max	1	0	0.82	0	0.36
	Mean	0.69	0	0.49	0	0.07
	Std	0.11	0	0.11	0	0.11
Shale Volume (Fraction)	Min	0	0	0.16	0	0.38
	Max	0.52	0.17	0.68	0.4	1
	Mean	0.17	0.01	0.47	0.04	0.84
	Std	0.12	0.02	0.12	0.06	0.13

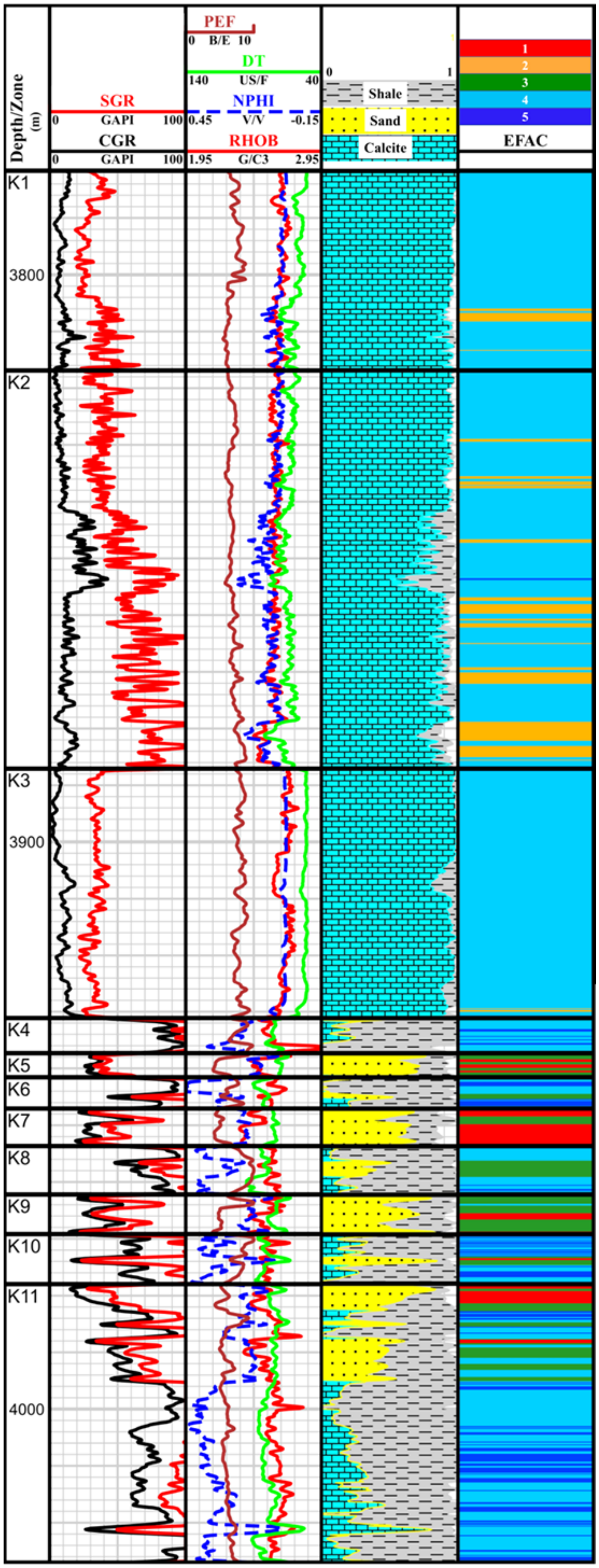


Figure 6. Layout showing the lithology and electrofacies codes

Descending from zone K4, there is a discernible sequence comprising shale, limestone, and sand. The optimal reservoir characteristics, represented by the electrofacies code for sands with high porosity (electrofacies code 1), are prominently identified in zones K5, K7, K9, and K11. Furthermore, from a reservoir property perspective, the sandy intervals within the Kazhdumi Formation exhibit superior conditions relative to their carbonate counterparts. This suggests a greater potential for hydrocarbon accumulation in the sand-rich zones as compared to the carbonate-rich zones.

After electrofacies analysis and constructing the structural model and scaling up the electrofacies and porosity logs, both logs have been distributed via applying geostatistics algorithms. The constructed electrofacies model was checked to provide a great match between initial and modeled data (Figure. 7A). It should be noted that data analysis of porosity was linked to facies codes. 3D model of the effective porosity (PHIE) has been generated using scaled-up effective porosity log into the 3D grid. As mentioned earlier, PHIE has been linked to the facies. Porosity propagation has been done using the GRFS algorithm for propagating the properties during reservoir modeling (Figure. 7B). The constructed PHIE model was checked to provide a great match between the initial and simulated data. In order to a better assessment of the Kazhdumi reservoir, average porosity maps of both siliciclastic and carbonate intervals of this reservoir are shown in Figure 8. As illustrated, there is a general trend that shows porosity increases from southeast to northwest parts of the studied area. It can be concluded that the Kazhdumi reservoir shows the best reservoir characteristics in the northern and western parts of the studied area.

As illustrated in Fig. 8A, the porosity values within the studied area exhibit a significant gradient, increasing from 2% in the southern regions to 12% in the northern regions. It is noteworthy that the areas characterized by favorable porosity in the northern part are discontinuous and fragmented. This discontinuity indicates that caution is warranted in planning the drilling of future wells, as the isolated pockets of porosity may affect hydrocarbon recovery efficiency.

Moreover, an examination of the carbonate intervals within the Kazhdumi Formation, as depicted in Fig. 8B, reveals a predominance of dense limestone. The sections exhibiting high porosity are primarily confined to the western part of the study area. This spatial restriction of high-porosity zones further underscores the necessity for strategic planning in drilling operations, taking into account the variability in reservoir quality across different regions of the formation. Also, the statistics values of thickness and effective porosity of the Kazhdumi reservoir have been presented in Table 6. As shown, the siliciclastic intervals have high porosity than carbonate intervals.

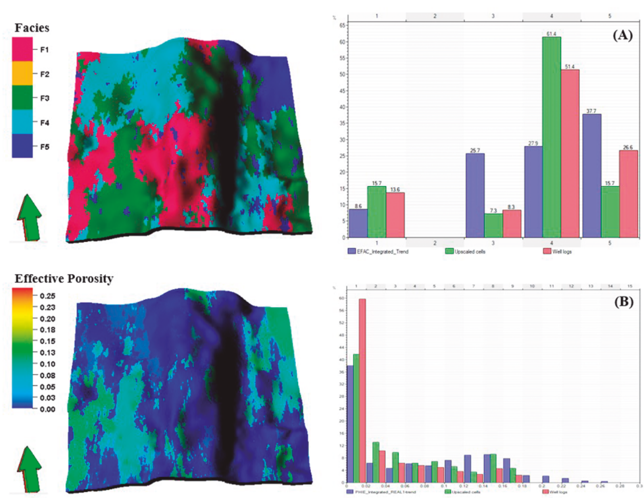


Figure 7. Electrofacies (A) and effective porosity (B) models of the Kazhdumi Formation in a 3D view and their relevant histograms

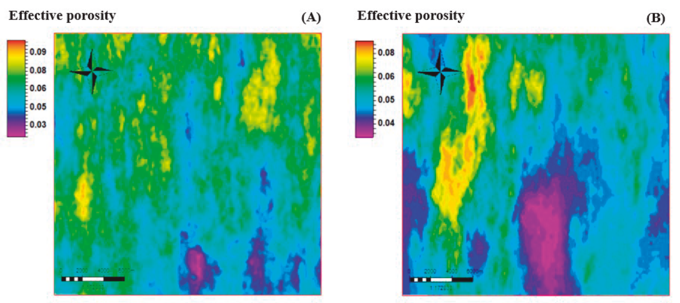


Figure 8. Average porosity distribution for A: siliciclastic intervals and B: carbonate intervals

Table 6. Statistics values of thickness and effective porosity of the Kazhdumi reservoir

Parameters	Lithology	Min	Mean	Max
Thickness (m)	Carbonate	132	172	192
	Sandstone	45	58	93
Effective porosity (%)	Carbonate	0.02	0.06	0.09
	Sand	0.03	0.08	0.12

5. Conclusion

The analysis of electrofacies within the Kazhdumi Formation reveals the presence of five distinct facies codes. Among these, two facies exhibit high porosity: facies 1 (siliciclastic) and facies 2 (carbonate). The remaining facies, consisting of shale and carbonate, are classified as non-reservoir facies. Notably, electrofacies code 1, which indicates sands with high porosity, is associated with the Azadegan Member. The upper carbonate sections of Kazhdumi Formation primarily comprise dense limestone interspersed with layers of porous limestone. Despite the Azadegan Member being characterized by the highest electrofacies code (code 1), it also contains sequences of shale, limestone, and sand that can occasionally diminish reservoir quality.

To model the electrofacies codes, a comprehensive data analysis was conducted for all facies. Subsequently, the electrofacies were modeled utilizing the SIS algorithm, followed by the modeling of effective porosity through a linkage to facies codes using the GRFS algorithm. Given the superior accuracy and speed of the GRFS algorithm, it was favored over the SGS algorithm for this study. The final results indicate that the reservoir characteristics of the Kazhdumi Formation improve from the southeast to the northwest of the study area. Although the reservoir conditions of the Azadegan Member are enhancing in the northern regions, it is important to highlight that the high porosity zones are discontinuous and warrant further investigation in future drilling operations. Additionally, the Azadegan sandstone demonstrates higher porosity compared to the carbonate intervals. Therefore, it is recommended that detailed regional studies be conducted to better understand the sedimentary environment of the Kazhdumi Formation and the origins of its sands.

6. Nomenclature

INPEFA	INtegrated Prediction Error Filter Analysis
EFAC	Electrofacies
GRFS	Gaussian random function simulation
MFS	Maximum flooding surface
MRGC	Multi-resolution graph-based clustering
PHIE	Effective porosity
SB	Sequence boundary
SGS	Sequential Gaussian Simulation
SIS	Sequential indicator simulation

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