



Full Length Article

Integrated reservoir characterization of the Permo-Triassic gas reservoirs in the Central Persian Gulf

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ABSTRACT

The upper Dalan and Kangan or Permian-Triassic carbonate formations in the central the Persian Gulf are considered as world's giant gas reservoirs. The primary purpose of this research is to model and evaluate the relationship between hydraulic flow units (HFUs), electrofacies and microfacies with systems tracts of Permian-Triassic sequences. By integrating the results of core data, petrographic studies, and petrophysical logs of the studied formations, hydraulic flow units and electrofacies were identified. Based on the results of petrographic studies, twelve microfacies were identified in terms of textural and depositional characteristics. Based on depositional setting, sedimentary facies and INPEFA values obtained from gamma ray log and gamma deviation log (GDL) in the context of sequence stratigraphy, zonation of Dalan and Kangan reservoirs is carried out. The zonation boundaries correspond to the key stratal surfaces (sequence boundary and maximum flooding surface). Seven petrographic rock types (PRT) were identified for the upper Dalan-Kangan reservoirs based on sedimentary texture, diagenetic process and dominant pores. Using porosity and permeability data from the core analysis, five hydraulic flow units were identified based on the flow zone indicator (FZI) method. Using multi-resolution graph-based clustering (MRGC) four electrofacies were detected from petrophysical data (gamma, neutron, density and acoustic logs). Subsequently, the INPEFA, GDL and electrofacies were spatially modeled using the sequential indicator simulation (SIS) and sequential Gaussian simulation (SGS) geostatistical methods. Finally, a clear agreement was revealed between the reservoir zones and the stratigraphic sequence framework. In this regard, the microfacies belonging to the high-energy and grain-dominated settings (packstone, grainstone) of leeward shoal, shoal and seaward shoal belts have the best reservoir units due to the influence of dissolution and dolomitization. The best reservoir units in the Permian-Triassic deposits in the middle of the upper Dalan and lower Kangan are developed in UDS4, upper KS2 and middle KS1 units. On the other hand, mud-dominated facies (mudstone, wackestone) and anhydrite textures are mostly associated with the low-energy lagoonal environments, between tidal flat and Sabkha. Non-reservoir units have been formed in the upper Dalan/Kangan and in the transgressive systems tract of UDS3-a, KS2-a and the lower and upper part of KS1 transgressive-highstand systems tract.

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1. Introduction

Due to the destructive effects of the diagenetic process and the geological complexity at the micro and macro scales, modeling and determining reservoir properties in carbonate reservoirs is very challenging [1]. As a result, the use of integrated reservoir

characterization methods is pivotal in fields development plans [2]. The role of rock typing and its relationship to sedimentary sequences associated with sea-level change is crucial for developing a comprehensive hydrocarbon reservoir model incorporating geological and reservoir features. At the same time, for field development and determination of hydrocarbon reservoir areas and integrated description of the reservoir, study, determination and modeling of petrophysical properties such as rock types and facies expansion are of the important steps [3,4]. In researching carbonate rocks, the first step is to describe the reservoir properties

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(static & dynamic) associated with sedimentary facies, diagenetic processes and fracturing using macroscopic and petrographic (microscopic) studies [5–8]. Petrographic studies were conducted for the analysis of facies, sedimentary environment and depositional sequences. Based on the results of this study, it is easy to identify how the hydrocarbon reservoir rocks are hosted huge amounts of natural gas [9]. Important reservoir parameters such as porosity, pore type, pore size distribution and permeability are related to the initial sedimentary texture and diagenetic processes. Specifically, in the form of sedimentary sequences, we can study the initial sedimentary texture and diagenetic overprints and its relationship with reservoir quality in carbonate reservoirs.

Over the past few years, several geological and reservoir studies have been conducted on the Permian-Triassic Dalan and Kangan formations deposited in the Zagros Basin [10–17]. These studies have further addressed facies, sedimentary environment, diagenetic history and their impact on reservoir quality. To date, many studies have been conducted on facies, sedimentary environment and diagenetic processes of these Formations, so we avoid repeating the topics [12–14,18]. Few studies have been conducted on rock typing, electrofacies analysis and detailed analysis of gamma ray logs for sequence boundaries detection and identification of systems tracts and their relationship with reservoir quality. The main purpose of this study is reservoir zonation and sequence stratigraphy based on gamma ray logs (GDL & INPEFA), rock typing (petrographical & petrophysical) and spatial modeling of electrofacies and system tracts for reservoir quality analysis of the upper Dalan and Kangan gas reservoirs.

2. Geological setting

The South Pars gas field, the north dome in Qatar and the onshore fields including the Kangan, Tabnak, and Nar are considered as the most important non-associated gas fields of the world [18,19]. According to the previous studies on the Persian Gulf basin, the Silurian shales are the source rock of these giant hydrocarbon reserves in Iran and neighboring Arab countries of the Persian Gulf basin [20]. The stratigraphic sequences of the sedimentary basin in this area represent events dating back to the Late Precambrian period (from about 2 billion to half a billion years ago) [21]. The most important sedimentary sequences with hydrocarbon storage potential are four reservoir units of K4 and K3 (upper Dalan Formation) and K2 and K1 (Kangan formation) [11] (Fig. 1). Such a sedimentary sequence is equivalent to the Khuff Formation in the neighboring Arab countries of the Persian Gulf basin [19]. In the study field, the upper Dalan and Kangan formations are identified by carbonate and evaporitic lithology (Fig. 2). The microfacies study reveals mud-dominated (low-energy) to grain-dominated (high-energy) facies. Diverse diagenetic processes have caused the structural complexity of the formation and changed its reservoir quality. Based on previous studies on the sedimentary environment, a homoclinal ramp is recommended for the sedimentary sequence of the studied formations [22].

3. Data & methods

This study aimed to perform petrographic study on 450 m of drilling core and thin sections in the upper Dalan and Kangan Formations in the central Persian Gulf. Petrophysical logs including gamma ray, neutron, density and acoustic logs were studied in 18 wells available from the field. In one of the wells, a total of 1225 samples of porosity and permeability plugs were examined to determine the reservoir quality and rock types of the reservoir. In

the first step, a petrographic analysis (well-A), was performed to determine the sedimentary facies and sequence boundaries of the studied formations. Dunham [24] and Embry and Klovan [25] methods were used to name the facies, and Flügel [26] model was used to interpret the facies. The transgressive-regressive sequence method proposed by Embry and Johansen [27] was used to analyze the sedimentary sequences. The gamma deviation log and INPEFA log were used to detect sequence boundaries. In the gamma deviation log method, the total gamma means is first calculated, then the difference value of each data is calculated from the mean value, and finally, the obtained values are aggregated to calculate the cumulative gamma deviation value [28]. In the INPEFA log method, the gamma peak deviation is determined by normalizing the data in the range of zero to one. Also, the accuracy of sequence boundary detection using both methods was compared with the previous studies. Based on the sediment texture, diagenetic processes and types of dominant pore types, petrographic rock types were defined [29]. Using porosity and permeability plug samples, the hydraulic flow units were determined using the flow zone indicator method [4]. In order to determine the Electrofacies, the Multi Regression Graph Base Clustering was adopted [30]. Finally, electrofacies (EF) are matched to rock types determined using petrographic methods and flow zone indicator (FZI) in the framework of sedimentary sequences. After establishing the relationship between sedimentary tract systems and electrofacies, 3D Modeling of electrofacies and gamma log were investigated to determine the distribution of systems tracts and their relationship with reservoir quality. Sequential indicator simulation (SIS) and sequential Gaussian simulation methods were used to model electrofacies and gamma-based sequence indicators (Fig. 3).

4. Results

4.1. Sedimentary facies and diagenesis

Twelve microfacies with distinct and unique sedimentary characteristics have been identified in the studied formations of the upper Dalan and Kangan. The characteristics of each microfacies are summarized in Fig. 4 and Table 1. Porosity versus permeability diagrams for the identified microfacies (MFs) and their sedimentary environment are plotted in Fig. 5. As is seen in Table 1, the sedimentary facies of the upper Dalan and Kangan formations are attributed to sabkha, intertidal, lagoon, leeward shoal, central shoal and seaward shoal belts representing a homoclinal ramp environment [11,18] (Fig. 6). The diagenetic processes in marine and meteoric realms including micritization, cementation, dolomitization, dissolution, recrystallization and compaction (physical and chemical) have affected the reservoir quality formations under study [10]. Also, anhydrite mineralization in different forms and textures has been played an essential role on controlling the reservoir quality of the upper Dalan and Kangan formations [31,32].

Based on the findings of the previous studies, the role of the diagenetic process in marine and meteoric environments is greater than burial diagenesis [14]. In general, the two parameters of primary sediment texture and diagenesis determine the reservoir quality. The previous studies also show that the diagenetic processes of dissolution and dolomitization influence the reservoir quality of the Dalan and Kangan formations in shallow meteoric and burial diagenetic environments [14]. Dissolution and leaching out as well as selective dolomitization of the groundmass are the main diagenetic processes enhancing the pore volume [33]. This study considers the dissolution, dolomitization and types of cementations as a critical parameter effective in increasing and

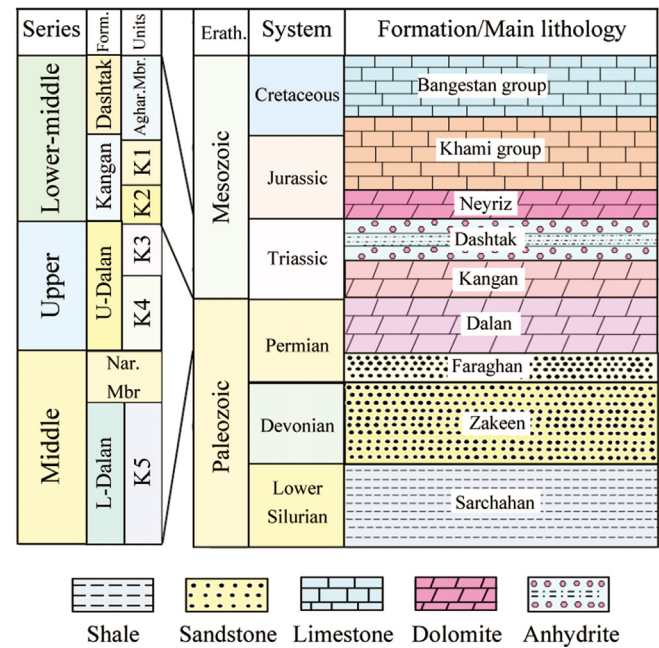


Fig. 1. Stratigraphy of Dalan and Kangan formations in the central Persian Gulf Basin [23].

decreasing the reservoir quality. In general, diagenetic processes affecting the reservoir quality of the Permian-Triassic formations can be divided into reservoir quality enhancing (dissolution and dolomitization) and reservoir quality damaging (compaction and cementation by calcite and anhydrite) agents.

4.2. Petrographic rock types (PRT)

The study of diagenetic processes, dominant pore types and their relationship with sedimentary facies and reservoir quality is necessary in reservoir characterization. In this study, considering the diagenetic processes, types of dominant pore types and the presence of microfractures, 7 petrographic rock types (PRT) were identified in the upper Dalan and Kangan reservoirs. Statistical

parameters and representative photomicrographs of each rock types are shown in Table 2. Following is a brief description of each rock type.

PRT-1: This rock type represents anhydrite facies (MF1). Also, due to its very poor porosity (0.86%) and permeability (0.031 mD), it lacks reservoir quality. In this rock type, compaction features related to burial environments can be found. It is not crystal-shaped on the macroscopic (core) scale but contains micron-size acicular crystals on the microscopic scale. This rock types can be related to sabkha, salinas, coastal evaporitic flats, hypersaline and lagoons environments.

PRT-2: This rock type represents mudstone facies (MF2). Inter-particle porosity (1.34%) and complete pore occlusion by blocky and poikilotopic anhydrite and gypsum has reduced permeability (0.005 mD). It lacks reservoir quality and is closely related to tidal flat environment.

PRT-3: This rock type is associated with microorganisms and includes thrombolite boundstone, stromatolite boundstone, and fossiliferous mudstone (MF3,MF4,MF5). It is often observed in scattered Permian-Triassic sedimentary sequences and is seen frequently in the upper Dalan-Kangan boundary with a thickness of 4 m. The dominant diagenetic overprints are compaction and dissolution. This rock type is characterized by low to medium porosity (mostly fenestral and vuggy porosity), low permeability, and poor reservoir quality. It also has a mass texture reinforced with calcite cement and is often associated with tidal flat and lagoon environments.

PRT-4: This rock type is comprised of wackestone to grainstone containing peloid, bioclast and benthic foraminifera (MF6 and MF7). It also has tepees, open-space structures and fenestral structures. Due to the diagenetic processes of anhydrite cementation and compaction, it has poor to moderate reservoir quality and is often associated with lagoon and leeward shoal sedimentary environments.

PRT-5: This rock type is associated with the grain-dominated facies (mostly grainstones) containing peloid and ooid (MF8). Grain dissolution has developed moldic porosity in this rock type. Therefore, it is characterized by high moldic porosity (24.4%) and low permeability (0.992 mD). PRT-5 is attributed to the beach ridges, shoal and leeward shoals.

PRT-6: This rock type is comprised of grainstone and packstone facies containing bioclastic and benthic foraminifera (MF11). This

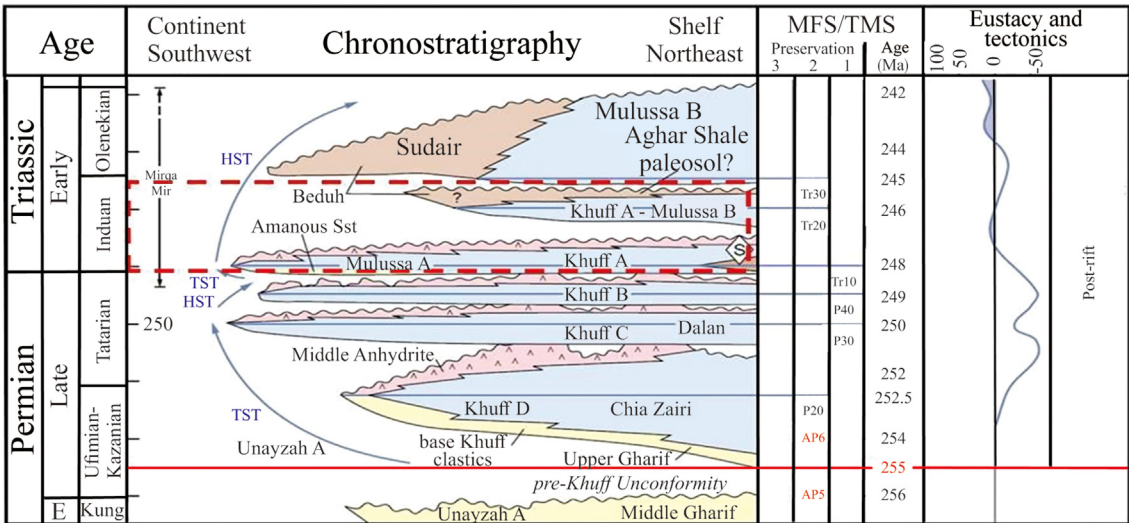


Fig. 2. Permian-Triassic sedimentary sequence of the Persian Gulf basin [19].

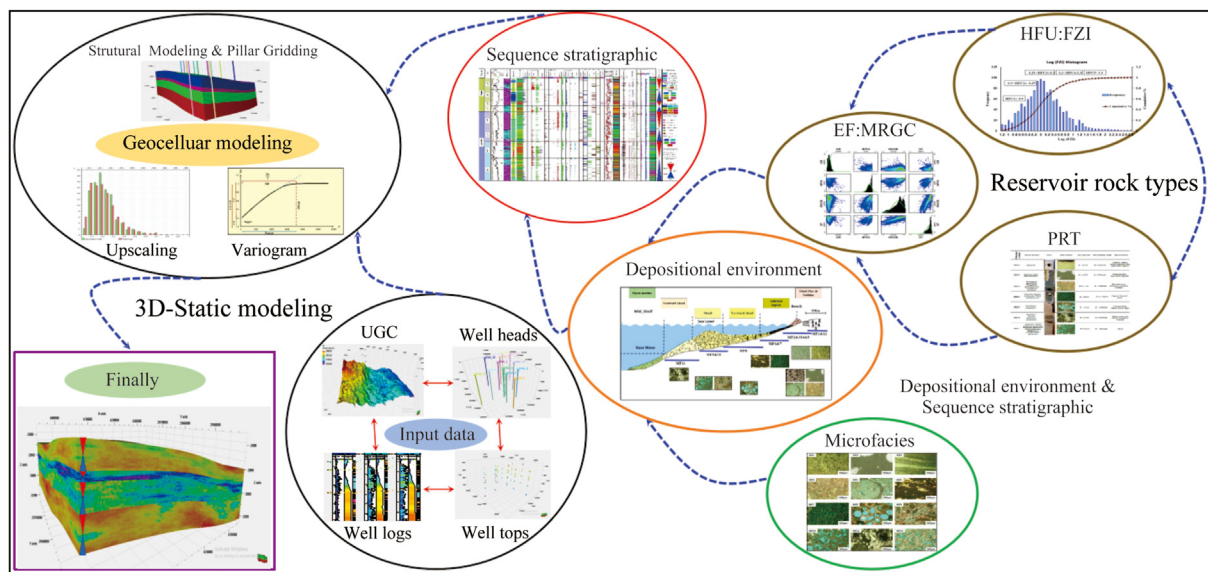


Fig. 3. Workflow for geological studies and reservoir quality modeling of upper Dalan and Kangan formations.

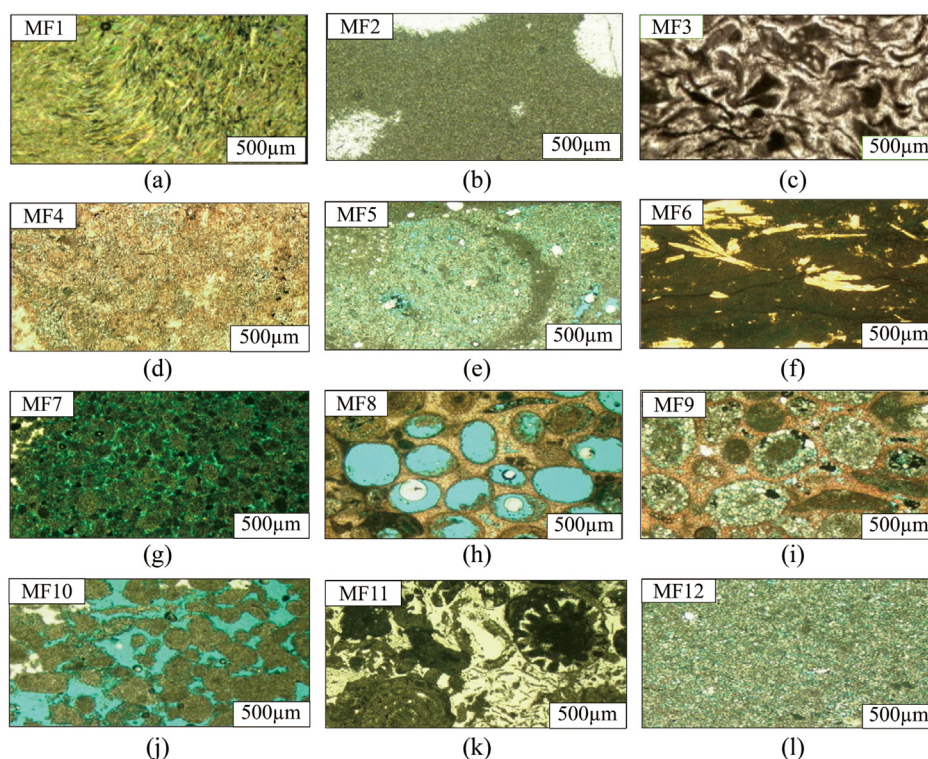


Fig. 4. Microfacies identified in the upper Dalan and Kangan formations in the studied field. (a) MF1: anhydrite, (b) MF2: mudstone often with evaporates, (c) MF3: stromatolite boundstone, (d) MF4: thrombolite boundstone, (e) MF5: bioturbated & fossiliferous mudstone, (f) MF6: intraclast, bioclast wackestone, (g) MF7: peloid ooid grainstone, (h) MF8: ooid Peloid grainstone, (i) MF9: intraclast/peloid packstone/grainstone, (j) MF10: peloid/intraclast grainstone, (k) MF11: bioclastic dolograins, (l) MF12: mudstone or massive dolomudstone.

facies is defined by medium-grained and coarse-grained algal and foraminiferal bioclasts. This rock types have moderate reservoir quality due to high moldic porosity (25.92%) and medium permeability (2.94 mD). Seaward shoal is the representative depositional setting of PRT-6.

PRT-7: This rock type is associated with the grain-dominated facies such as grainstone, packstone and

dolomudstone containing intraclast and peloid (MF9, MF10 and MF12). In this rock type, the diagenetic processes (mainly dissolution and dolomitization) has led to the dominance of vuggy and intercrystalline porosity (18.2%) and very high permeability (508.4 mD). PRT-7 is the best rock type of the upper Dalan and Kangan formations. It is mostly associated with the shoal environments.

Table 1
Microfacies identified in the Upper Dalan and Kangan Formations in the studied field.

Facies code	Facies groups	Facial characteristics	Environment	Standard microfacies [26]
MF1	Anhydrite	Anhydrite, not crystal shaped at macroscopic scale, generally mosaic or distorted mosaic, made up of micron-size acicular crystals (felted to microcrystalline textures) – commonly associated with gypsum laths, and more rarely, salt	Sabkha	RMF25
MF2	Mudstone often with evaporates	Mimetic grain replacement by dolomite Complete pore occlusion by blocky and poecilitic anhydrite and gypsum. Tight dolomite	Intertidal	RMF19
MF3	Stromatolite boundstone	–	Intertidal	–
MF4	Thrombolite boundstone	Boundstone, with a typical non-layered “clotted” texture of micritic masses tightly cemented by calcite.	Intertidal	–
MF5	Bioturbated & fossiliferous mudstone	Very fine- to fine-grained dolostone/limestone mudstone to packstone, with bioclastic content including echinoids, sponge spicules and foraminifera	Deep lagoon/seaward shoal	RMF19
MF6	intraclast, bioclast wackestone	Laminated dolomudstones and bioclastic dolowackestones, associated with thin anhydrite interbeds	Lagoon	RMF18
MF7	Peloid ooid grainstone	Well-sorted, Very-fine to fine-grained dolograinstone with abundant peloids and restricted foraminiferal content. Commonly associated with lithoclasts	Lagoon/leeward shoal	RMF29
MF8	Ooid Peloid grainstone	Well-sorted, medium-grained (more rarely fine-grained) ooidal dolograinstone/grainstone, with admixed peloidal material. Moldic porosity within grainstones	Leeward shoal	RMF29
MF9	Intraclast/peloid packstone/grainstone	Development of calcitic intergranular rim cement Moldic porosity partially filled by rhombic dolomite cements	Central shoal	RMF30
MF10	Peloid/intraclast grainstone	Mimetic grain replacement by dolomite Little or no anhydrite spotting	Central shoal	RMF29
MF11	Bioclastic dolograinstone	Medium to coarse grained bioclastic grainstone/dolograinstone, with dominant algal and foraminiferal content, plus molluscan debris. Commonly associated with peloids and lithoclasts	leeward, seaward shoal	RMF26&27
MF12	Mudstone or massive dolomudstone	Presents occasional matrix or intercrystalline porosity when dolomitised. Dolomitization can alter all original fabrics. Commonly presenting open space structures, Main diagenetic alterations: Extensive recrystallization of original dolomudstone (pore diameter less than 16 µm).	Tidal flat	RMF19

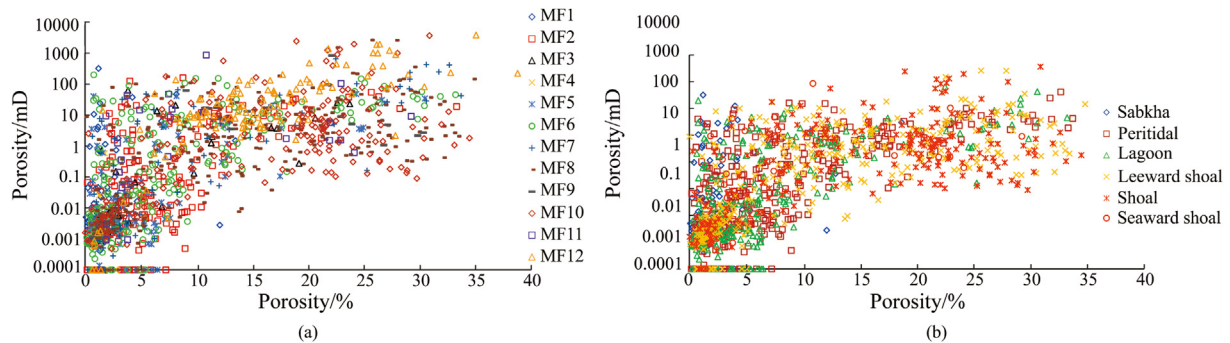


Fig. 5. Porosity versus permeability diagrams for (a) microfacies (MFs) and (b) sedimentary environment of upper Dalan and Kangan formations.

4.3. Hydraulic flow units (HFUs)

In this study, a link was made between rock types based on hydraulic flow units and the sedimentary facies derived from core description and thin-sections petrographic studies. In reality, due to the impact of diagenetic overprints it is hard to find appropriate equivalent microfacies for each individual reservoir rock type [34]. Reservoir flow units were classified based on the flow zone indicators (FZI) approach using the following equations [35]:

$$RQI = 0.0314 \times \sqrt{\frac{k}{\phi}} \quad (1)$$

$$NPI = \frac{\phi}{1 - \phi} \quad (2)$$

FZI is defined as:

$$FZI = \frac{RQI}{PMR} \quad (3)$$

where RQI is the reservoir quality index; NPI is the normalized porosity; FZI is the flow zone indicator; ϕ is the porosity and K is permeability.

There are several methods to determine the optimal number of hydraulic flow units. In this study, the logarithm of the flow zone indicator and histogram analysis were used to identify and pick the break points (changing point of reservoir properties). Normal probability plotting and histogram analysis were led to the discrimination of 5 hydraulic flow units with individual reservoir characteristics (Fig. 7). The porosity-permeability and RQI-PMR for the identified flow units are plotted in Fig. 8. High regression coefficient and acceptable separation between each flow unit indicate the correct choice of the number of hydraulic flow units. As shown in Table 3, the reservoir quality increases from the HFU1 to the HFU5.

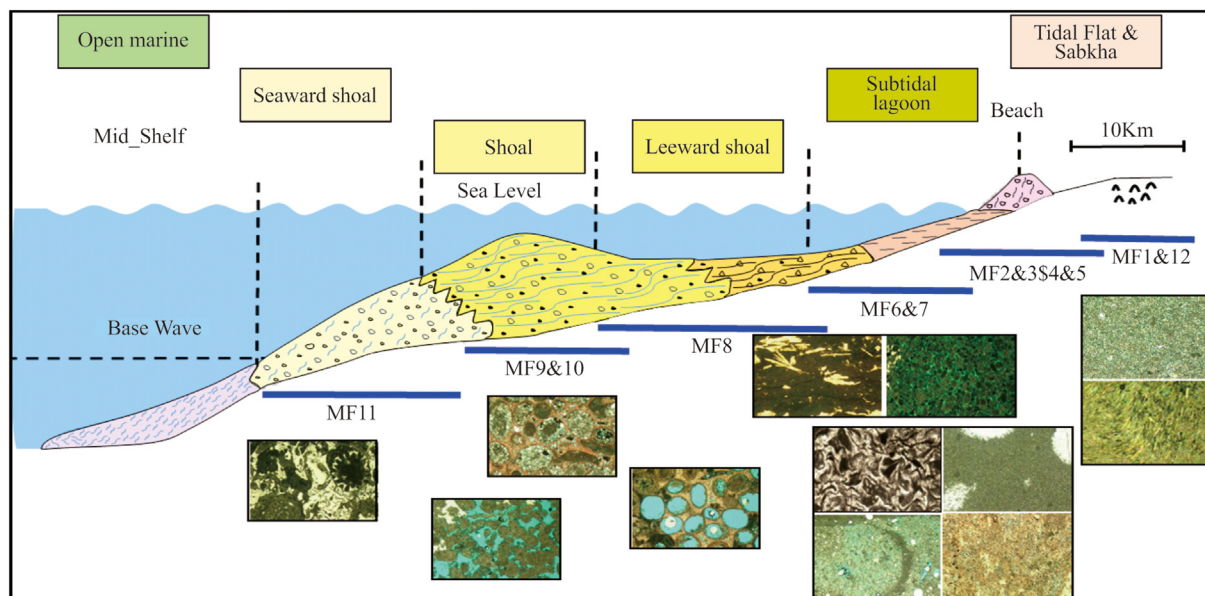


Fig. 6. Conceptual model of the depositional environment for Upper Dalan and Kangan Formations.

4.4. Electrofacies (EF) classification

In order to determine electrofacies and their correlation to hydraulic flow units in the framework of sequence stratigraphy, as well as to determine the distribution of reservoir zones in the upper Dalan and Kangan formations, a suite of logging measurements including gamma, neutron, density and acoustic log in 18 wells were used. The multi-resolution graph-based clustering (MRGC) algorithm was used to classify the input well logging data [30]. Fig. 9 shows the frequency plot of the input logs for creation of the electrofacies model. The clustering of petrophysical logs is a mathematical model classifying input data based on similarities between them. The variables in each class are most similar and completely separable from the other classes. Given the dimensions of studying petrophysical logs relative to the earth's dimensions and geological complexities, the electrofacies identification process is very challenging [36,37]. According to the input logs, four electrofacies were identified as is seen in the box plots of Fig. 10. These plots are used to evaluate reservoir quality in the entire formation sequence. EF4 and EF3 have the highest reservoir quality. They have high neutron and acoustic readings with low gamma log and density responses. EF1 and EF2 have the lowest reservoir quality with low neutron and acoustic readings and higher gamma and density responses. EF2 has high-density readings representing the anhydrite layers of the reservoir and strongly affecting reservoir quality in the K1 and K3 zones.

4.5. Geocellular modeling

In geostatistical modeling, the spatial position of samples is also taken into account while identifying the value of a specific quantity in a sample; hence, the quantity could be investigated with its spatial positioning, simultaneously [38]. Generally, geostatistics as a branch of applied statistics estimates unknown properties by employing a series of data with known coordinates ([39,40]. In this research, the following steps were carried out to generate the reservoir geological model of the upper Dalan and Kangan formations.

4.5.1. Structural modeling and pillar gridding

Three main steps for building the structural modeling include define model, fault modeling and pillar gridding [41]. In this study, advanced structural modeling was made with respect to geophysical data, including horizons associated with the top of the reservoir formation (Fig. 11). After defining the structural model, smaller three-dimensional cells were generated (Fig. 11), where any of these small 3D cells contains an average of input parameters (petrophysical and facies). Depending on the dimension and area of the field and the accuracy in any reservoir zones of the field under study, a proper estimate of the total cells could be achieved by selecting suitable gridding [42]. In this study, the dimensions of the grid cells are 50 × 50 square meters in X and Y directions and 5 m in the Z direction for reservoir zones (K4 and K2), and 10 m for the non-reservoir zones (K1 and K3).

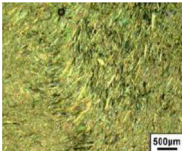
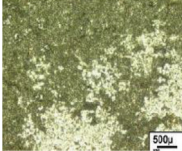
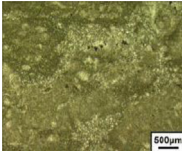
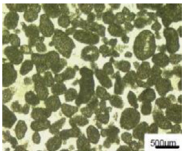
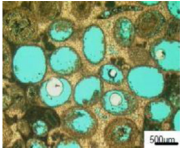
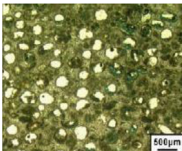
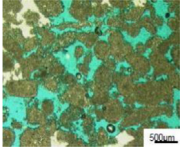
4.5.2. Upscaling

The results of the petrophysical evaluation are in the form of well logs data in the drilled well route. Before modeling, these petrophysical parameters must be defined in all dimensions of the structural cell, which is referred to as data upscaling step. This is done using various averaging methods [43]. Among the most common averaging techniques is the "Arithmetic" method, which is a kind of center assessment (central index) calculated from the sum of the values. Data upscaling for petrophysical parameters and lithofacies for all studied zones are illustrated in Figs. 12 and 13, representing a favorable estimate for the entire structural cells.

4.5.3. Data analysis

The normalization operations should be carried out after data up-scaling so that both the data distribution is normal (mean = 0 and standard deviation = 1) and the effect of the process on the data is eliminated. In geostatistics, the analysis of the spatial position of the samples with the intended quantity is always performed at the same time, where a correlation should be established between different values of a parameter in the sample population and the distance and orientation of the samples relative to each other [42]. Thus, the spatial relationship between the values of a quantity

Table 2
Sedimentological and petrophysical description of petrographic rock types (PRT) in the Upper Dalan and Kangan Formations.

PRT	Facies	Core	Thin section	Porosity (%)	Permeability (mD)	Environment
PRT1	Anhydrite			$\phi = 0.86$	$k = 0.031$	Sabkhas, salinas, coastal evaporitic flats, hypersaline lagoons
PRT2	Mudstone often with evaporates			$\phi = 1.34$	$k = 0.005$	Evaporitic flats, hypersaline lagoons
PRT3	Stromatolite boundstone, thrombolite boundstone and bioturbated & fossiliferous mudstone			$\phi = 2.33$	$k = 0.005$	Biosedimentary structures, formed in Peritidal
PRT4	Intraclast, bioclast wackestone, peloid ooid grainstone			$\phi = 3.9$	$k = \text{NPP}$	Lagoon/leeward shoal
PRT5	Ooid peloid grainstone			$\phi = 24.4$	$k = 2.052$	Leeward shoal, shoals, beach ridges
PRT6	Intraclast/bioclast packstone/ grainstone			$\phi = 25.92$	$k = 2.94$	Mainly dunes and shoals (seaward or leeward)
PRT7	Intraclast/peloid packstone/ grainstone packstone/ grainstone, peloid/Intraclast grainstone, mudstone or massive dolomudstone			$\phi = 18.2$	$k = 508.4$	Shoal

in the sample population is defined in the form of the reservoir structure [44–46]. This spatial structure is the experimental variogram described in three vertical, major and minor directions (well route). As expressed above, variogram is among the essential means for spatial communication between data. The performance of the variogram is so that it displays the mean-square difference between the two values (data) as an incremental function between them.

5. Interpretation of the results

Petrographic rock typing (PRT) was realized based on hydraulic flow units classified by the flow zone indicator (FZI) method, electrofacies derived by multi-resolution graph-based clustering (MRGC) and the results of microfacies studies in the stratigraphic framework. Accordingly, a correlation of information obtained from PRT, hydraulic flow units, sedimentary facies, electrofacies,

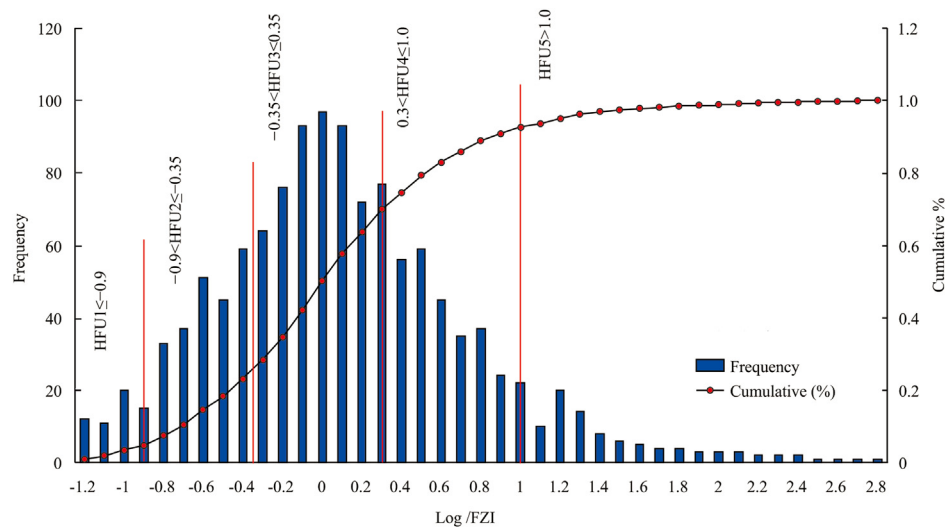


Fig. 7. Normal probability plot of logarithm of flow zone indicator classifying the reservoir rocks of upper Dalan and Kangan formations into five hydraulic flow units based on the breaking points on the cumulative frequency plot.

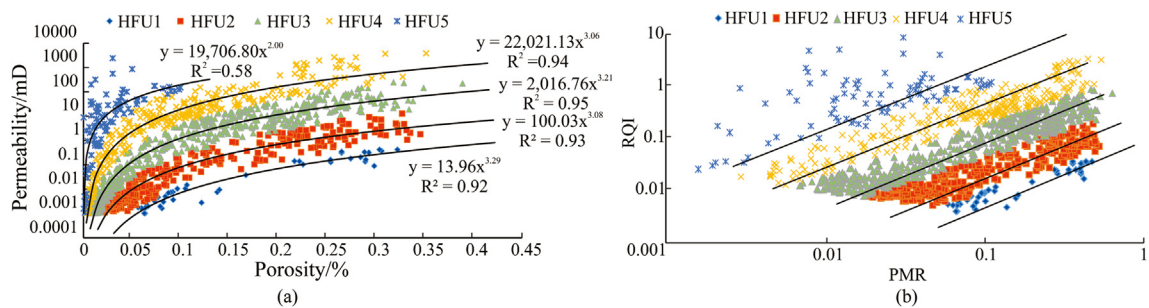


Fig. 8. Cross-plot of porosity and permeability for (a) the identified hydraulic flow units and (b) RQI–PMR cross-plot for upper Dalan and Kangan formations.

Table 3
Statistical parameters of porosity, permeability, reservoir quality index, flow zone indicator for five individual hydraulic flow units in the Upper Dalan and Kangan Formations.

HFU	Permeability	Porosity	Reservoir quality index	Flow zone indicator	Log-flow zone indicator
	K (mean)	PHI (mean)	RQI (mean)	FZI (mean)	Log FZI (Domain)
HFU1	0.09	0.16	0.015	0.075	−1.50 _ −0.90
HFU2	0.80	0.13	0.041	0.264	−0.90 _ −0.35
HFU3	11.00	0.11	0.150	1.020	−0.35 _ 0.30
HFU4	154.10	0.10	0.522	4.236	0.30 _ 1.00
HFU5	76.86	0.03	1.049	426.0	1.00 _ 2.80

petrophysical logs and sedimentological data (Fig. 14), demonstrates an interesting relationship between them. This relationship is explained in system tracts and sedimentary facies of each sequence. Based on changes in sedimentation conditions, sedimentary facies, gamma deviation log (GDL), INPEFA obtained from gamma plot, zonation of the upper Dalan and Kangan was performed. Accordingly, four zones corresponding to four sedimentary sequences (UDS4, UDS3, KS2, and KS1) and eight sub-zones (UDS4-a, UDS4-b, UDS3-a, UDS3-b, KS2-a, KS2-b, KS1-a, KS2-b) were introduced. The boundary of reservoir zones corresponds to the key strata surfaces (sequence boundary and maximum flooding surface). Subsequently, the adaptation of changes in the INPEFA plot obtained from the gamma log and the Gamma deviation log (GDL) plot was extended to other wells in the field. To map the spatial distribution of reservoir quality, electrofacies, gamma-based INPEFA gamma and gamma deviation log (GDL) were modeled

using sequential indicator simulation (SIS) and sequential Gaussian simulation (SGS) algorithms (Fig. 15).

5.1. UDS4 sequence

The transgressive systems tract (TST) of this sequence is equivalent to the sub-zone UDS4-a and its regressive systems tract (RST) corresponds to zone UDS4-b. The transgressive systems tract (TST) of the first sedimentary sequence is characterized by dolomitic limestone and calcareous sequences. The sub-zone KS4-a has various lithology, including dolomite and anhydrite. The lower boundary of this transgressive systems tract corresponds to the first sequence boundary (SB1) and is characterized by dolomitic facies. Its upper boundary is associated with calcareous lithology. Due to rising sea level, the dolomitization process was stopped and calcareous lithology was prevailed. The KS4-a zone corresponds to

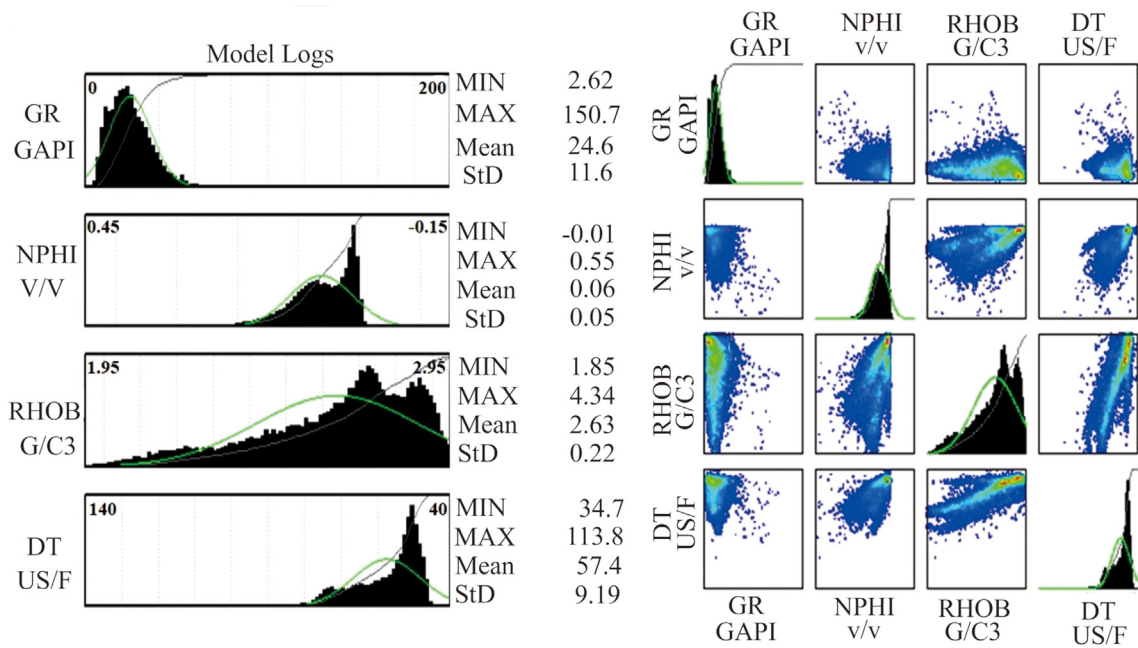


Fig. 9. Frequency of input logs to build the electrofacies model and to compare input logs.

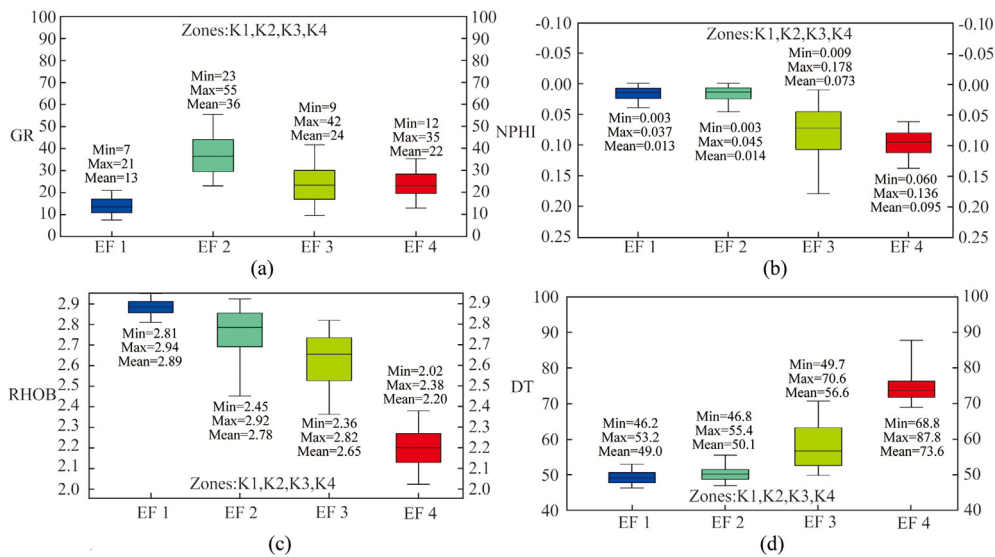


Fig. 10. Box plots of the electrofacies for gamma, neutron, density and acoustic logs in upper Dalan and Kangan formations.

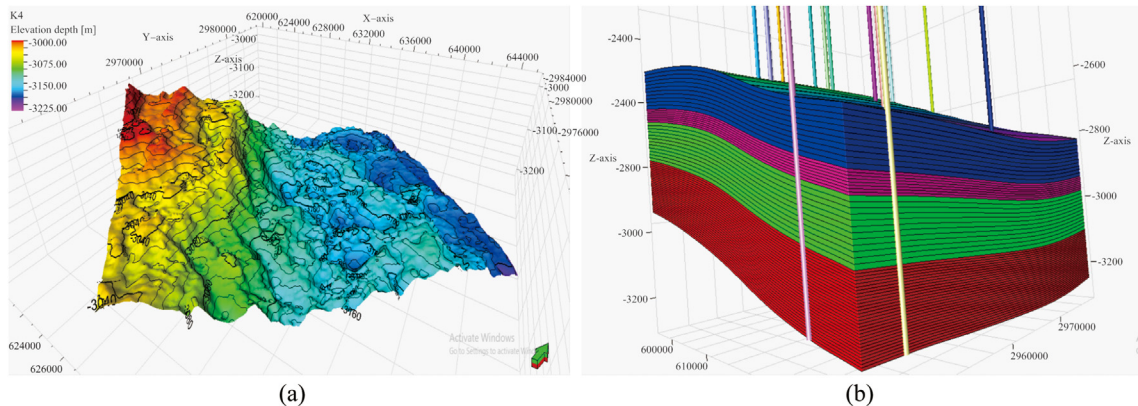


Fig. 11. (a) Underground contour map (UGC) of K4 horizon and (b) 3D grid and layering model in the gas reservoir of upper Dalan and Kangan formations.

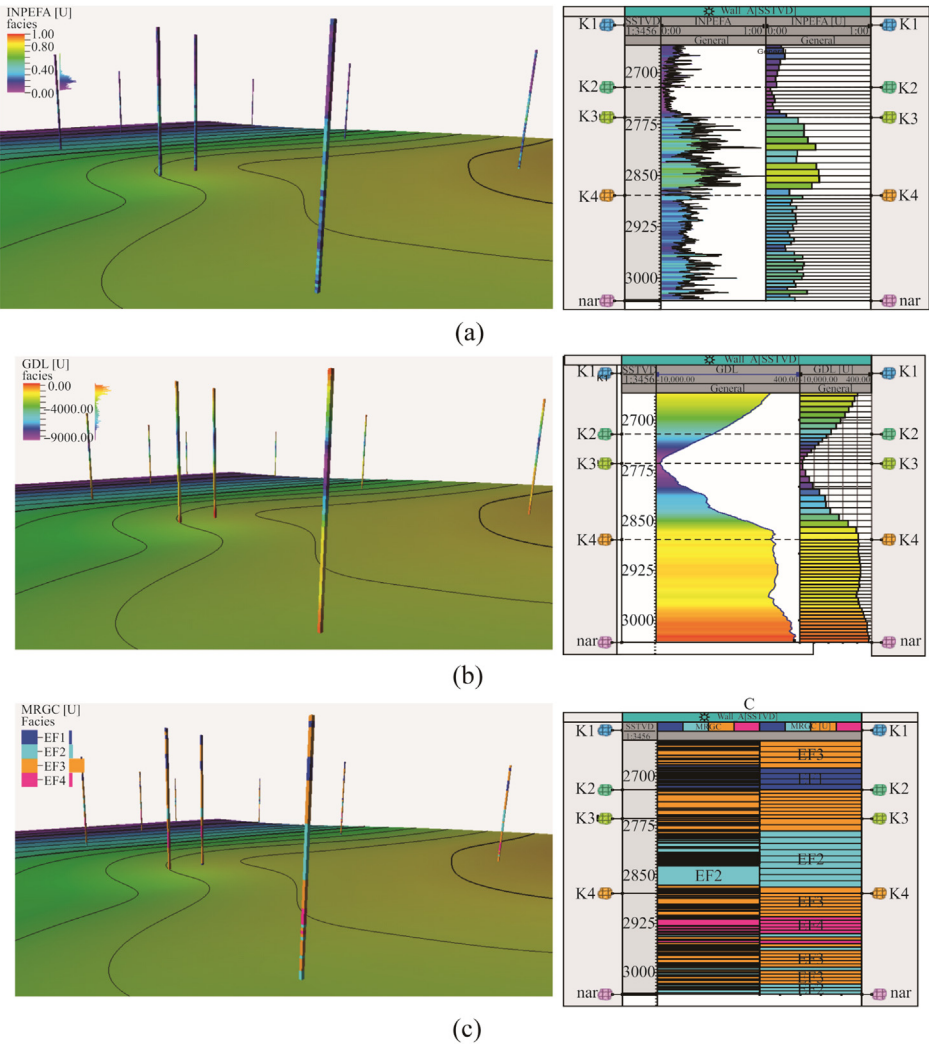


Fig. 12. Upscaling of (a) INPEFA GR, (b) gamma deviation log and (c) electrofacies.

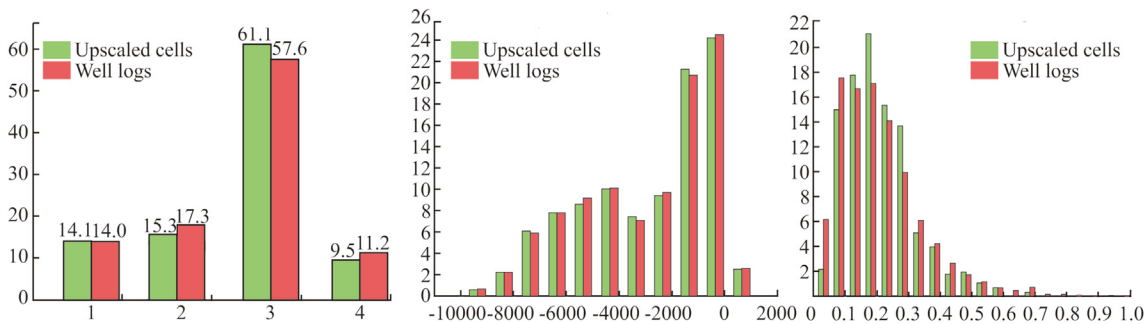


Fig. 13. Upscaling histogram corresponding to the study formations. (a) INPEFA GR; (b) gamma deviation log; (c) electrofacies.

various facies like lagoon and peritidal. Shoal belt includes packstone and grainstone facies together with skeletal fragments. The anhydrites are in the form of nodules and scattered cement, not affecting reservoir quality. The thickness of transgressive systems tract varies from 80 to 90 m. The transgressive systems tract (TST) at the lower boundary is associated with a decrease in the gamma deviation log (GDL) and INPEFA log and a sharp increase in the density (>2.9) due to the presence of a Nar member evaporites. The upper boundary of this semi-sequence corresponds to the

maximum flooding surface (MFS1) and is accompanied by an increase in the readings of the gamma ray log. The transgressive systems tract (TST) is equivalent to the following rock types, hydraulic flow units and electrofacies.

- Rock types: PRT-4, PRT-5, PRT-7
- Hydraulic flow units: HFU-2, HFU-4
- Electrofacies: EF-2, EF-3

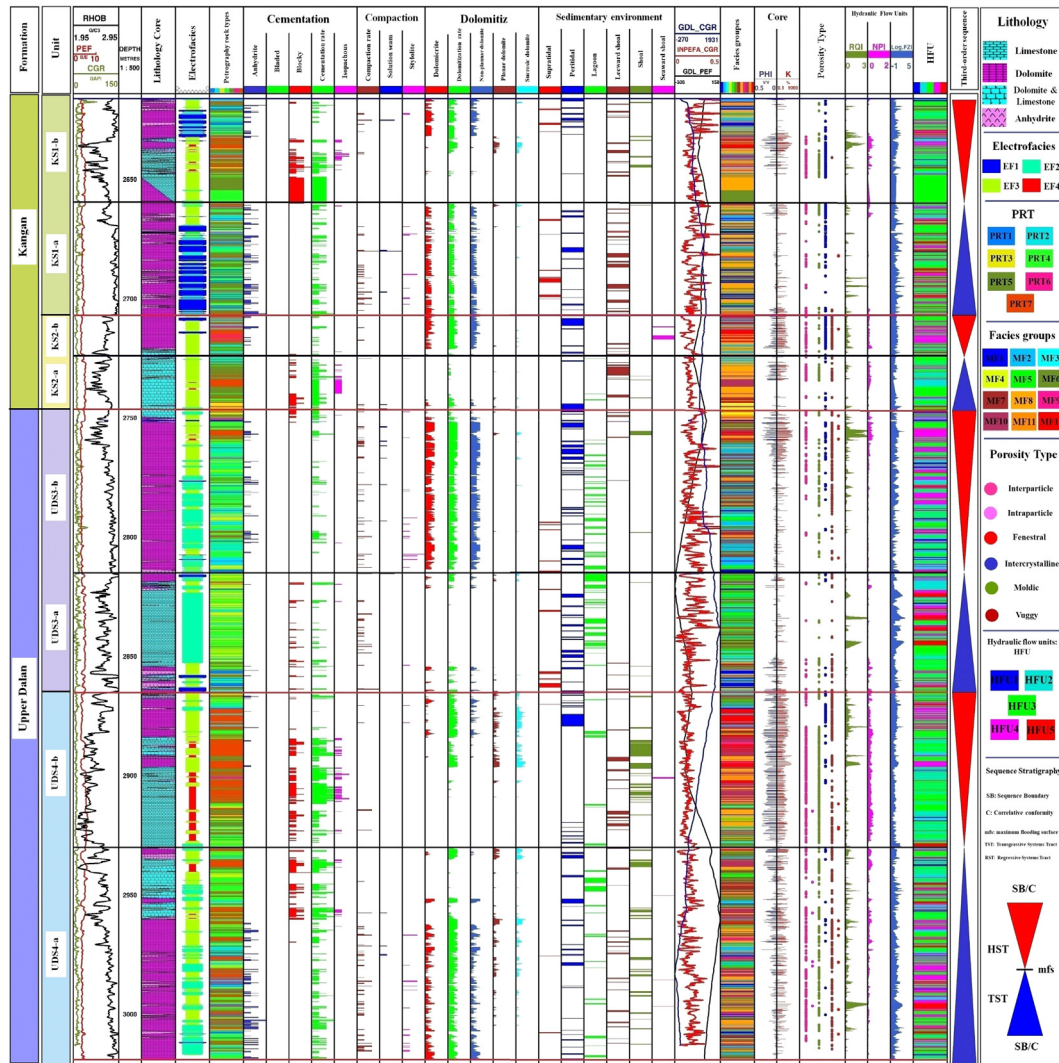


Fig. 14. Integrated sedimentary column and reservoir quality of upper Dalan and Kangan formations showing microfacies, diagenesis, hydraulic flow units and electrofacies in the framework of sequence stratigraphy (well-A).

The regressive systems tract (RST) of the first sequence is associated with the limestone and dolomite lithology sequences. The lower boundary of this systems tract corresponds to the maximum flooding surface (MFS1) and limestone lithology. Its upper boundary is associated with sequence boundary (SB2), which is associated with anhydrite layer and dolomitic sequences. In the lower interval, the dissolution-based diagenetic process has spread and led to the creation of many moldic pores, while in the upper interval, the dolomitization has developed. Gradually, anhydrite was formed where sea level falls and sedimentary environment is shallow. The gamma ray log reading at the lower and upper boundaries of the sequence increases and decreases, respectively. The RST of the first sequence is mainly associated with the shoal, leeward shoal and tidal facies. This system tract has a good reservoir quality due to the development of high-energy facies and diagenetic processes (dolomitization & dissolution). Its thickness ranges from 56 to 70 m. RST is equivalent to the following rock types, hydraulic flow units and electrofacies.

Rock types: PRT-7, PRT-5

Hydraulic flow units: HFU-3, HFU-4

Electrofacies: EF-3, EF-4

5.2. UDS3 sequence

The transgressive systems tract (TST) of sequence UDS3 is equivalent to the sub-zone UDS3-a and its regressive systems tract (RST) is equivalent to zone UDS3-b. This sedimentary sequence has a lower reservoir quality than UDS4 unit due to low-energy and mud-dominated facies. The transgressive systems tract (TST) of the second sequence has two sections. The lower interval consists of calcareous lithology with anhydrite intermediate layers, and the interval section is composed of dolomite with intermediate layers of anhydrite. The lower boundary of TST corresponds to sequence boundary (SB2), which is accompanied by a decrease in the gamma ray log. At the same time, its upper boundary corresponds to the maximum flooding surface (MFS2), which is accompanied by an increase in the gamma ray log. The TST of the second sequence is mainly associated with the low-energy lagoon and tidal flat facies including mudstone to wackestone containing benthic foraminifera and peloid. Wackestones contain skeletal fragments and anhydritic cement and nodules. The average thickness of this systems tract is 50 m. Due to the development of low-energy facies and anhydritic cement, this systems tract does not have a good reservoir quality.

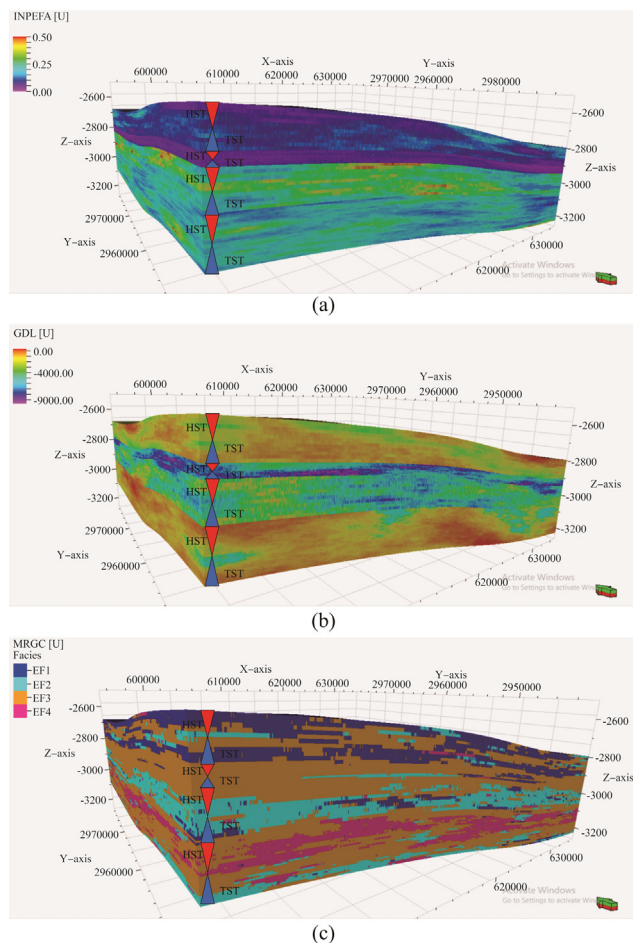


Fig. 15. Spatial modeling of (a) gamma INPEFA, (b) gamma deviation log and (c) electrofacies and its relationship with sedimentary sequences of upper Dalan and Kangan formations.

Only 10 m from the base of TST has a better reservoir quality compared to the other intervals. TST is equivalent to the following rock types, hydraulic flow units and electrofacies.

Rock types: PRT-4, PRT-3
Hydraulic flow units: HFU-1, HFU-2
Electrofacies: EF-1, EF-2

The regressive systems tract (RST) of the second sequence is affected by dolomitization and formation of anhydrite interlayers. The lower boundary of the regressive phase corresponds to the maximum flooding surface (MFS2), which is accompanied by an increase in the gamma ray log reading. Its upper boundary corresponds to sequence boundary SB3, which is accompanied by a decrease in the gamma ray log reading. The FRST is mainly associated with the low-energy lagoon, tidal flat and sabkha facies, such as mudstone and FRST interval is about 60–65 m. At the end of the regressive systems tract, thrombotic boundstone is observed indicating mass extinction at the Permian-Triassic boundary and formed after mass extinction in tidal facies. The thrombolites and stromatolites correspond to the Permian-Triassic boundary and the main extinction event. Reservoir quality increases in the upper 15 m interval due to the impact of dissolution and dolomitization. This system tract is equivalent to the following rock types, hydraulic flow units and electrofacies.

Rock types: PRT-4, PRT-3, PRT-2
Hydraulic flow units: HFU-2, HFU-5
Electrofacies: EF-3

5.3. KS2 sequence

The transgressive systems tract (TST) of this sequence is equivalent to the sub-zone KS2-a, while the regressive systems tract is equivalent to zone KS2-b. This is the first sedimentary sequence of the Kangan Formation deposited on the Permian-Triassic boundary. This sequence can be divided into non-reservoir (transgressive systems tract) and reservoir (regressive systems tract).

The transgressive systems tract (TST) of the third sequence is characterized by calcareous dolomite. Its lower limit corresponds to sequence boundary SB3 and a decreasing trend in gamma ray response. At the same time, its upper limit corresponds to the maximum flooding surface (MFS3) and is determined by increasing the response of gamma ray log. The reservoir quality of this transgressive systems tract is strongly influenced by the dominant mud facies of the low-energy lagoon, peritidal, and leeward shoal facies (reduced porosity by compaction). The dominant facies consists of packstones with peloid and oncolite and thrombolite boundstone. With average thickness of 27 m, its reservoir quality is poor. This system tract is equivalent to the following rock types, hydraulic flow units and electrofacies.

Rock types: PRT-5, PRT-3, PRT-3
Hydraulic flow units: HFU-2, HFU-3
Electrofacies: EF-2, EF-3

The regressive systems tract of the third sequence is characterized by dolomite. Its lower boundary corresponds to the maximum flooding surface (MFS3), and its upper boundary corresponds to the sequence boundary (SB4), which are associated with increasing and decreasing in response of the gamma ray log, respectively. The thickness of this regressive systems tract is 15–20 m. This systems tract is often associated with the leeward shoal and shoal belt facies, including packstone to ooid/ploid/oncolite and bioclastic grainstones. Such high-energy environmental facies have increased the reservoir quality. The dominance of PRT-7 and PRT-5, hydraulic flow units HFU3 and HFU4 and Electrofacies EF3 with high reservoir quality results from the effects of depositional high energy facies and diagenetic processes such as dissolution and dolomitization. After the UDS4 sequence, it received the second rank in terms of reservoir quality in the Permian-Triassic succession.

5.4. KS1 sequence

The average thickness of this sedimentary sequence is 90–110 m in the studied wells. The transgressive systems tract (TST) of KS1 is equivalent to the sub-zone KS1-a, while its regressive systems tract (RST) is equivalent to zone KS1-b. Shoal high-energy environmental facies including packstone and grainstone with an average thickness of 30–40 m in the middle layer have increased the reservoir quality. The transgressive systems tract (TST) at the base corresponds to sequence boundary (SB4) and at the upper boundary corresponds to the maximum flooding surface (MFS4) detected by a slight increase or decrease in the gamma ray peak value. The transgressive systems tract has a variety of facies associated with the leeward shoal, tidal flat, and sabkha, which alternately dominate facies ranging from ooid packstone to skeletal

fragments and anhydrite. The regressive systems tract (RST) also has a variety of shoal, leeward shoal, tidal flat and sabkha facies. These facies range from packstone, ooid grainstone, mudstone, and anhydrite facies. Reservoir units associated with high-energy facies have been dominated by the following rock types, hydraulic flow units and electrofacies.

Rock types: PRT-4, PRT-5

Hydraulic flow units: HFU-3, HFU-4, HFU-5

Electrofacies: EF-3, EF-4

Non-reservoir units are associated with PRT-1, PRT-2, HFU-1 and HFU-2 and EF-1.

6. Conclusions

This study aimed to determine sedimentary facies, rock types, hydraulic flow units and electrofacies of the Permian-Triassic succession of the upper Dalan and Kangan Formations in a sequence stratigraphic framework. The following conclusions were drawn:

- (1) Based on the results of petrographic studies, 12 microfacies were identified along with textural and depositional features. Microfacies of the upper Dalan and Kangan formations indicate sabkha, peritidal, lagoon, leeward shoal, central shoal and seaward shoal belts of a homoclinal ramp.
- (2) Diagenetic processes have severely affected the reservoir quality of the Permian-Triassic succession and can be divided into categories of reservoir quality enhancing (dissolution and dolomitization) and reservoir quality damaging (cementation and compaction).
- (3) Zonation of Dalan and Kangan successions by using gamma INPEFA log is in a good agreement with previous zonation based on petrophysical logs. This shows the effectiveness of sequence stratigraphy as a robust method for reservoir zonation.
- (4) Based on texture, diagenetic processes and dominant pore types, seven petrographic rock types (PRT) were identified for the studied reservoirs. Rock types containing anhydrite, mudstone and generally all facies affected by cementation and compaction have formed the poor reservoir quality units. Rock types with high-energy and grain-dominated facies (grainstone and packstone) and generally all facies affected by dissolution and dolomitization have formed the best reservoir units.
- (5) Five hydraulic flow units were identified according to the porosity and permeability data obtained from the core analysis and based on the breaking points in the logarithmic plot of flow zone indicator.
- (6) A total of four electrofacies (EF) are identified based on gamma, neutrons, density and acoustic logs by using multi-resolution graph-based clustering (MRGC). Well log values were categorized based on reservoir quality using frequency plot, statistical analysis and box plot.
- (7) Finally, by combining the results of sedimentary facies, rock types, hydraulic flow units and electrofacies in the framework of sequence stratigraphy, the systems tracts were investigated in terms of diagenetic processes and reservoir quality. It was found that the grain-dominated facies (packstone and grainstone) associated with high-energy environments of shoal, seaward shoal and leeward shoal are more affected by diagenetic process (dissolution and dolomitization) increasing the reservoir quality and form the best reservoir units in UDS4, upper UDS3, upper KS2 and middle KS1. In contrast, the mud-dominated facies associated with the peritidal, lagoon, and sabkha low-energy environments,

together with the grain-dominated facies affected by cementation and micritization reduced the reservoir quality and formed the non-reservoir units of the Permian-Triassic successions. They also formed the non-reservoir units of the transgressive systems tract of KS2-b, UDS3-b, and the beginning part of the regressive-transgressive systems tract of the KS1 sequence.

- (8) Finally, the relationship between sedimentary facies, hydraulic flow units and Electrofacies with systems tracts and gamma ray log was evaluated as a criterion for zoning sequences. To achieve this goal, electrofacies were evaluated using sequential Gaussian simulation and sequential indicator simulation. Finally, a geological model of system tracts and electrofacies was constructed to investigate the reservoir quality of the Permian-Triassic succession in the studied field.

Author statement

Milad Moradi: Methodology, Software, Writing- Original draft preparation. **Ali Kadkhodaie:** Conceptualization, Methodology, Reviewing. **Hossain Rahimpour-Bonab:** Conceptualization, Reviewing. **Rahim Kadkhodaie:** Conceptualization, Reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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