Carbonates and Evaporites (2024) 39:85
https://doi.org/10.1007/s13146-024-00998-7

ORIGINAL ARTICLE

Sequence stratigraphy, diagenesis and geological zonation of the lower Triassic carbonate reservoir of the Kangan formation from the central to Northern Persian Gulf

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Accepted: 17 July 2024
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Abstract

The lower Triassic Kangan Formation is one of the most important carbonate reservoir rocks in southern Iran and the Persian Gulf. This formation is part of the Dehram Group and consists of a carbonate-evaporite sequence, including limestone, dolomite and anhydrite. This carbonate sequence has been deposited on a gently-sloping homoclinal carbonate ramp in a warm and dry climate conditions. In this study, by carefully examining geological reservoir zones (GRZs) in three wells in the central (wells A and B) and northern (well C) Persian Gulf, in terms of facies changes, sedimentary environment, diagenesis and sequence stratigraphy, it is possible to determine the reservoir quality by considering the reservoir heterogeneity. Petrographic observations show that the Kangan Formation consists of fifteen microfacies related to four facies belts, including sabkha, lagoon, tidal flat and shoal environments. Facies and environmental changes in the Kangan Formation indicate three third—order and seven fourth-order sequences in the central and northern Persian Gulf. Each sequence includes TST (Transgressive System Tract) and HST (Highstand System Tract) related to sabkha, intertidal, lagoon and shoal environments. The main diagenetic processes in the reservoir are dolomitization, dissolution and cementation. The connection between the depositional facies, sedimentary environment and diagenetic processes (dolomitization, anhydrite and calcite cementation and dissolution), allowed for the identification of seven geological reservoir zones (GRZs) related to the fourth-order sequences. These sequences and GRZs demonstrate vertical and lateral heterogeneity of the reservoir, observed as variation in GR log changes, lithology, facies frequency, diagenetic features and reservoir properties among the studied wells. GRZ-1 to GRZ-3 in the northern Persian Gulf and GRZ-4 to GRZ-7 in the central Persian Gulf show better reservoir quality. Facies analysis of the Kangan Formation indicates higher energy conditions for the central parts than the northern parts.

Keywords Kangan Formation · Geological reservoir zones · Facies · Diagenesis · Sequence stratigraphy · Reservoir quality · Persian gulf

Introduction

The reservoir quality of carbonate rocks depends on several factors, including depositional facies, sedimentary environment, diagenetic processes and sequence stratigraphic position. Therefore, a detailed study needs to be carried out on these factors to investigate reservoir zones (Slatt 2006; Ahr 2008). In general, sequence stratigraphy shows the process of facies and environmental changes affecting reservoir quality (Plint and Nummedal, 2000). The Lower Triassic Kangan Formation, the target of this study, hosts giant gas reserves in the Persian Gulf and is part of the Dehram Group (Alway et al. 2002). The shallow marine carbonates of the Kangan Formation overlies the Dalan Formation. The lower boundary of the Kangan Formation, denoted as (SB1) (Permo-Triassic boundary), signifies the long-term retreat of the carbonate platform from seawater. The upper boundary of the Kangan Formation, characterized by (SB2) (the second type of discontinuity), is covered by the Aghar shale

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Published online: 29 July 2024

of the Triassic Dashtak Formation and indicates a gradual falling of the sea level.

Lithologically, Kangan Formation comprises limestone, dolomite and interlayers of anhydrite, which turn into a limestone sequence towards the north of the Persian Gulf. Shale sequence are visible at the border of reservoir unit K1. Kangan Formation consists of grain-supported and mud-supported facies, indicating of sabkha to shoal environments.

Regarding the reservoir importance of the Dalan and Kangan formations, they have been the focus of various studies in different aspects, especially facies and depositional environment, diagenesis, sequence stratigraphy and reservoir properties (e.g., Alsharhan 2006; Hejr 2007; Kadkhodaie-Ilkhchi et al. 2010; Kakemem et al., 2012; Aleali et al. 2013; Amel et al. 2015; Karimi et al. 2015; Tavakoli et al., 2016; Baharlouei-Yancheshmeh, 2018; Kadkhodaie-Ilkhchi et al. 2018; Shakeri et al. 2021; Shahkaram et al. 2022; Fakhr et al., 2022; Kadkhodaie et al. 2022). Reservoir heterogeneity of these formations resulting from facies and diagenetic features, reflecting in their pore system properties, is a main challenge for their reservoir characterization. This study by considering the results of previous studies, and facies analysis of the Kangan Formation in two fields situated in the central and northern Persian Gulf attempt to make a connection between depositional facies, diagenetic features and reservoir properties to discuss the reservoir heterogeneity in the framework of sequence stratigraphy by which reservoir zones can be characterized in more detail.

Geological background

The lower Triassic Kangan Formation is the most important gas reservoir in the Persian Gulf (Ehrenberg 2006). This formation extends over approximately 2500 km^2 in the Persian Gulf and its surrounding areas. The Kangan Formation was formed after rifting and opening of the Neo-Tethys Ocean (mid Permian) in a passive continental margin during a period of relatively uniform subsidence (Stampfli, 2002). The fields encompassing the Permo-Triassic Dalan and Kangan Formation are situated on the Qatar Arch, located in the inner part of the Arabian platform. These fields are bounded by the folded Zagros belt in the north and northeast (Konyohov & Maleki, 2006). The Qatar arch with an NNE-SSW-trending structural high, divided the Persian Gulf Basin into two eastern and western sections. In the northern Arabian Plate, the Triassic sequence consists of a shallow carbonate – evaporite sequence developed on the northern passive margin of Gondwana (Sharland et al., 2001). During the deposition of the Kangan Formation, the climate was hot and dry similar to the current conditions of the Persian Gulf. The type section of the Kangan Formation is at Kuh-e-Siah, where it is 178 m thick and composed of limestone, superimposed by dolomite with anhydrite intercalations (Szabo and Kheradpir 1978). Figure 1 shows the location of the two fields and three studied wells in the central (wells A and B) and northern (well C) parts of the Persian Gulf.

Kangan Formation consists of limestone, dolomite and anhydrite in the center of the Persian Gulf, transitioning

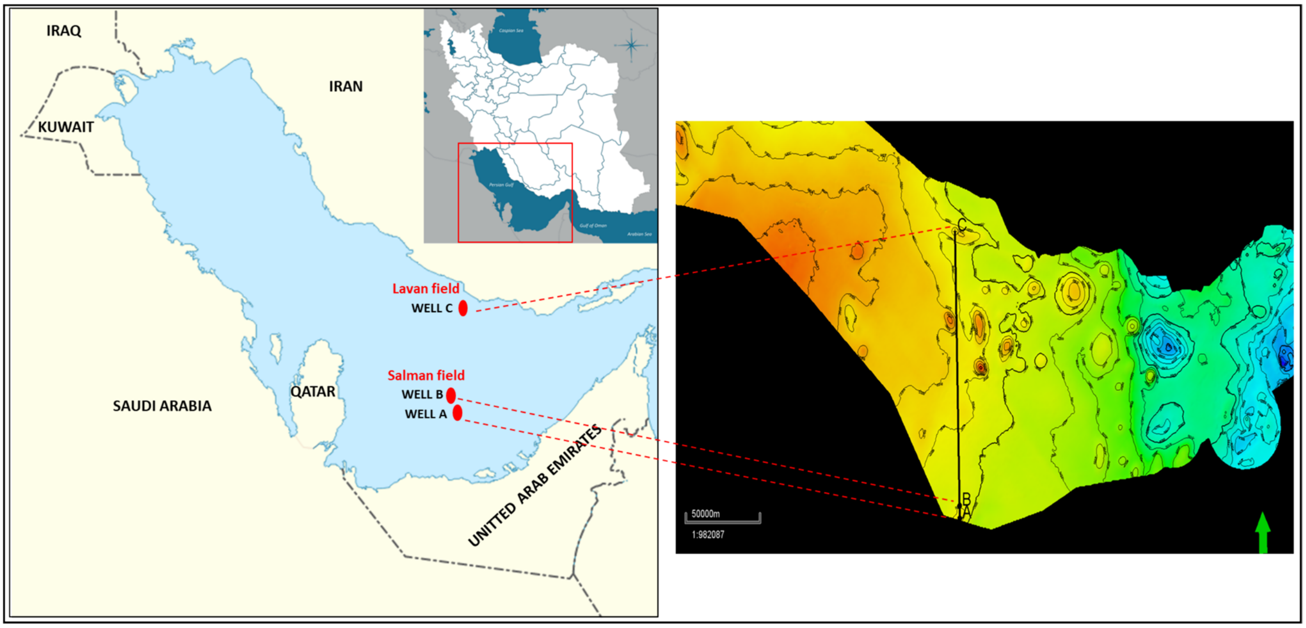


Fig. 1 Location map of the studied fields (Salman- Lavan) and wells (**A**-**B**-**C**) in the Persian Gulf

to a predominantly limestone sequence to the north of the Persian Gulf. The lower boundary of the Kangan Formation with the Dalan Formation (Permo-Triassic boundary), marked by a disconformity (SB1), signifies the long-term regression platform, and it is overlain by Aghar shale at the base of Dashtak Formation with another disconformity (SB2) (Fig. 2). Kangan Formation comprises two reservoir units, K1 (limestone, anhydrite, dolomite and shale) at the top and K2 (limestone, dolomite and anhydrite) at the base. As the sedimentary environment becomes shallower from the center to the north of the Persian Gulf, the shale sequence becomes more prominent towards the K1 border. (Ziegler 2001; Insalaco et al. 2006; Maurer et al. 2009) (Fig. 2).

Data and methods

In this research, various parameters, including depositional facies, sedimentary environment, diagenetic processes as well as reservoir quality (porosity and permeability) were analyzed to identify the reservoir zones of the Kangan Formation in the north and center of the Persian Gulf Basin. A total of 700 thin sections from core samples of three vertical wells with complete data in the Lavan and Salman oil/gas fields were studied. Thickness of the Kangan Formation in all wells is outlined in Table 1. For facies analysis, standard methods of Dunham (1962) and Flügel (2010) were adopted. Depositional sequences and sequence surfaces were identified by following the changes in lithology, facies and GR log responses. Core porosity and permeability data were plotted on petrophysical classes of Lucia (2007) for investigation of reservoir quality of different facies.

Table 1 Thickness of the Kangan Formation in the studied wells

Field	No. of drilled wells	Well	Thickness (m)
Salman	15	A	187.33
		B	189.18
Lavan	3	C	186.8

Depositional characteristics

Facies analysis and depositional setting

- Kangan Formation consists of a carbonate-evaporite interval with limestone, dolomite, and anhydrite layers in wells A and B in the central and limestone in well C in the north of Persian Gulf. This sequence corresponds to K1 and K2 reservoir units, transitioning into shale units towards the K1 boundary. To analyze the facies and their depositional environment, several parameters, including allochemical components, sedimentary texture and facies order were investigated. As a result, 15 facies (F1

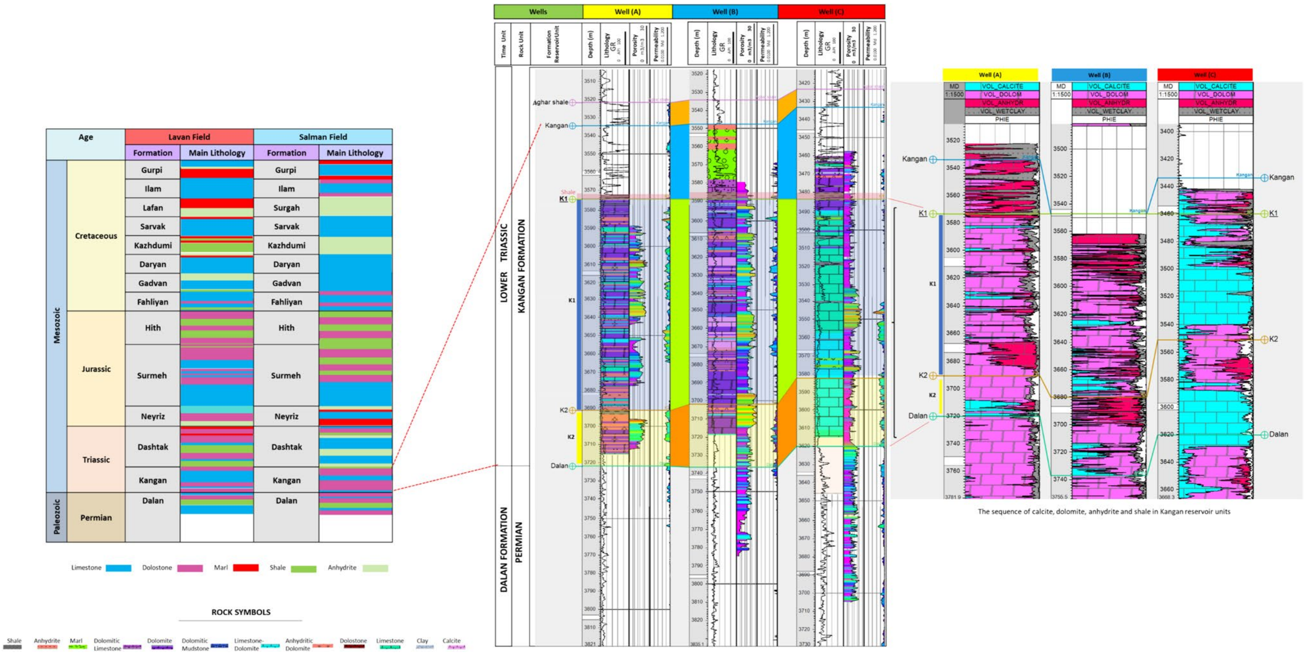


Fig. 2 Stratigraphic sequence of the Kangan Formation in the studied wells (**A**, **B**, and **C**). Lithology shows significant variations from limestone, dolomite and anhydrite in central wells (**A** and **B**) to limestone in well C of the northern Persian Gulf

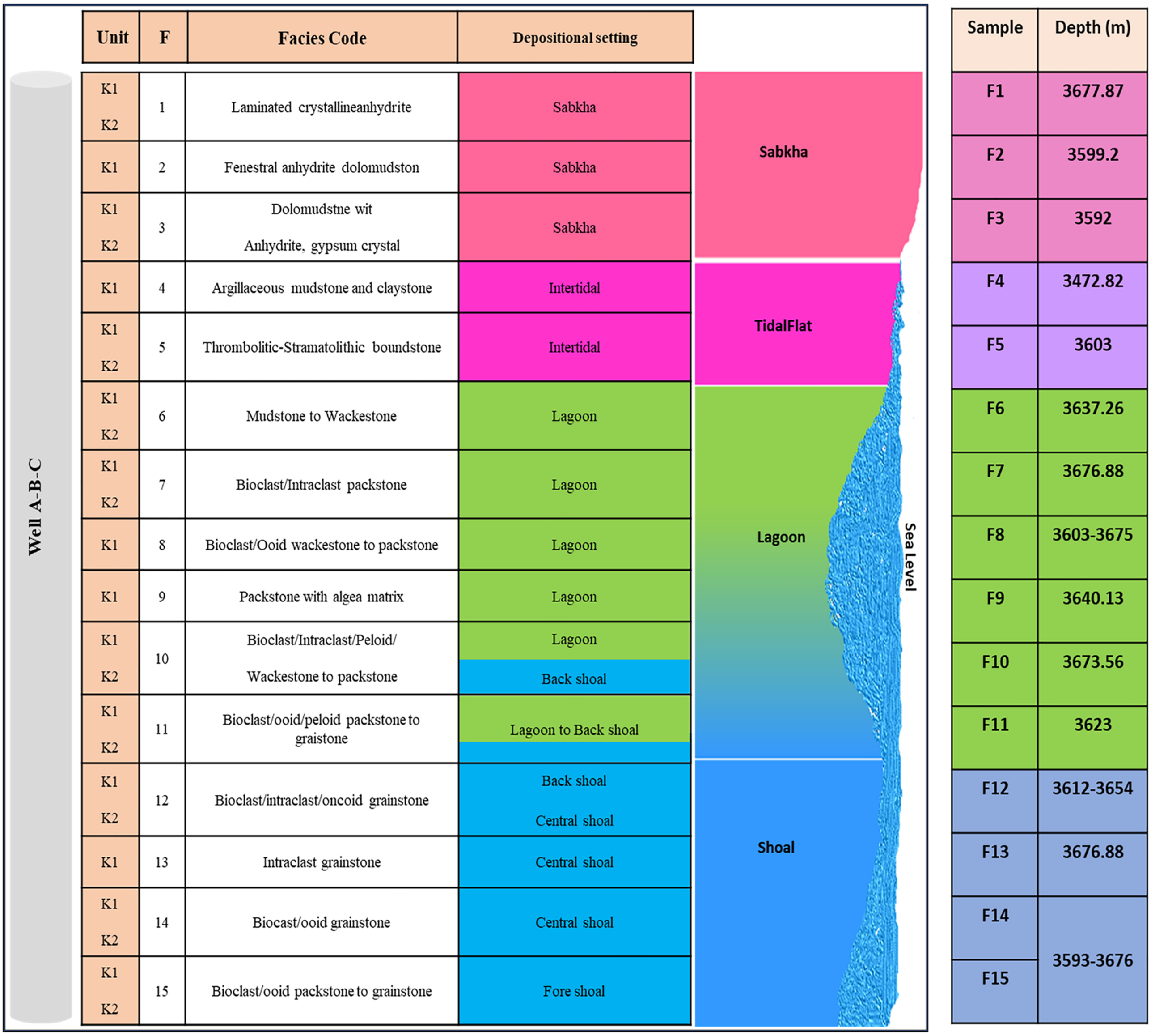
to F15) related to four facies belts of sabkha, intertidal, lagoon and shoal environments were identified (Table 2 and Fig. 3). Sabkha to tidal flat environment are characterized by mud-dominated facies (mudstone to wackestone) facies and anhydrite layers and nodules. Lagoon environment includes mud and grain-dominated facies (wackestone to packstone with benthic foraminifera and algae), and shoal environment consists of grain- dominated facies (ooid grainstone).

These facies belts are described based on their sedimentary characteristics and reservoir quality as follows.

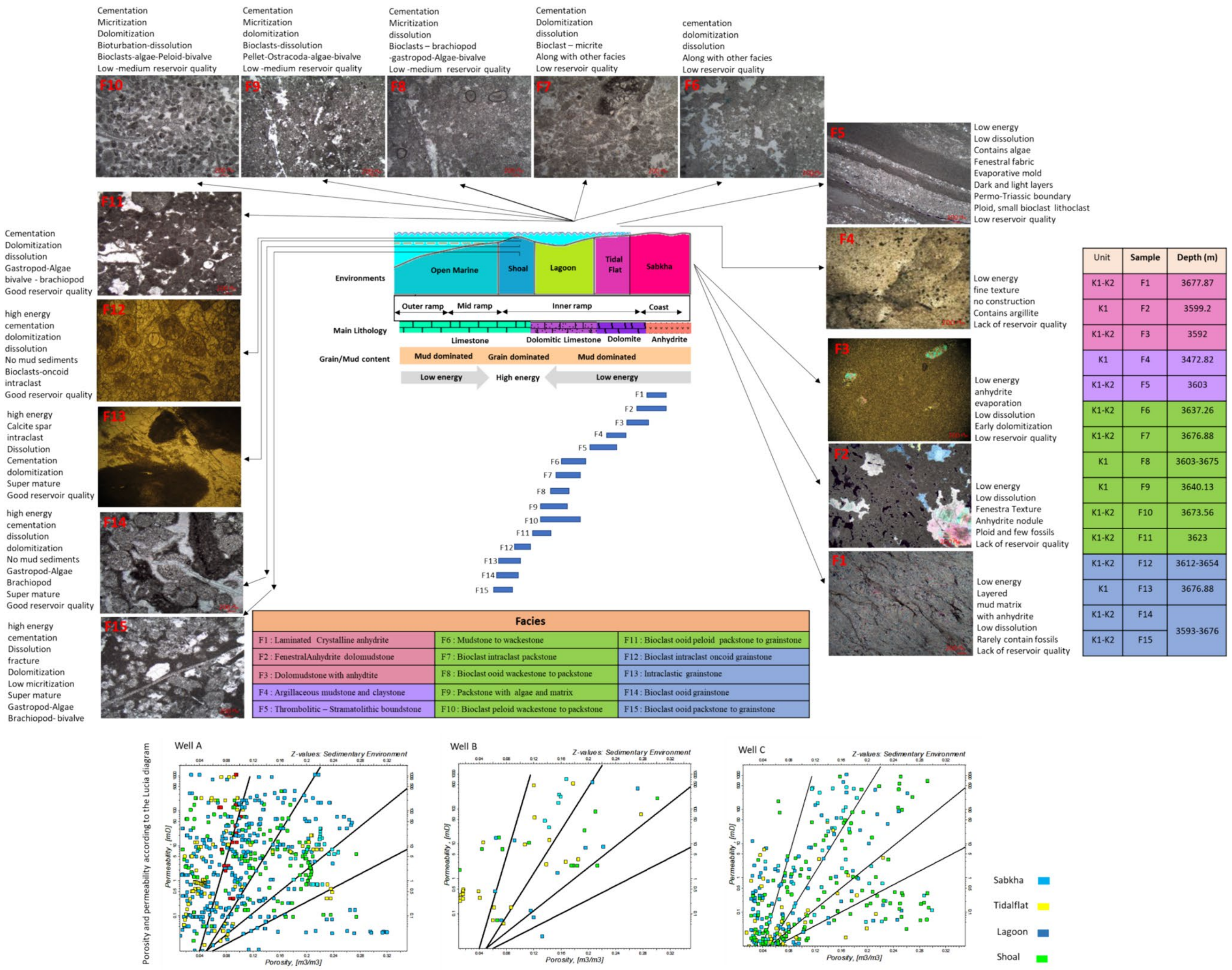
Sabkha facies belt: This group includes anhydrite and mudstone facies with fenestral texture (F1, F2, and F3). These facies represent the hot and dry climate at the time of deposition (Warren, 2006, Tucker, 2001, Lucia 2007). The depositional environment of these facies shows low-energy condition and rarely contains fossils, attributed to the Sabkha environment, lacking good reservoir quality in the studied wells. Facies of this group correspond to FZ-9 Wilson (1975).

Intertidal facies belt: This facies belt with interlayers of anhydrite and dolomite includes F4-F5 facies related to argillaceous mudstone in the K1 reservoir unit and thrombolite-stromatolite boundstone in the K1 and K2 reservoir units. The presence of this facies indicates a low energy environment in tidal flat. Mudstone facies lack reservoir quality due to very low porosity, and boundstone facies have poor reservoir quality due to the presence of anhydrite, dolomite, and fibrous and burial calcite cements (Rahimpour–Bonab,

Table 2 Microfacies and depositional setting of the Kangan Formation in the studied wells (A, B and C)



Unit	F	Facies Code	Depositional setting	Sample	Depth (m)
K1 K2	1	Laminated crystallineanhydrite	Sabkha	F1	3677.87
K1	2	Fenestral anhydrite dolomudston	Sabkha	F2	3599.2
K1 K2	3	Dolomudstne wit Anhydrite, gypsum crystal	Sabkha	F3	3592
K1	4	Argillaceous mudstone and claystone	Intertidal	F4	3472.82
K1 K2	5	Thrombolitic-Stramatolithic boundstone	Intertidal	F5	3603
K1 K2	6	Mudstone to Wackestone	Lagoon	F6	3637.26
K1 K2	7	Bioclast/Intraclast packstone	Lagoon	F7	3676.88
K1	8	Bioclast/Ooid wackestone to packstone	Lagoon	F8	3603-3675
K1	9	Packstone with algea matrix	Lagoon	F9	3640.13
K1 K2	10	Bioclast/Intraclast/Peloid/ Wackestone to packstone	Lagoon Back shoal	F10	3673.56
K1 K2	11	Bioclast/ooid/peloid packstone to graistone	Lagoon to Back shoal	F11	3623
K1 K2	12	Bioclast/intraclast/oncoid grainstone	Back shoal Central shoal	F12	3612-3654
K1	13	Intraclast grainstone	Central shoal	F13	3676.88
K1 K2	14	Biocast/ooid grainstone	Central shoal	F14	3593-3676
K1 K2	15	Bioclast/ooid packstone to grainstone	Fore shoal	F15	



Unit	Sample	Depth (m)
K1-K2	F1	3677.87
K1	F2	3599.2
K1-K2	F3	3592
K1	F4	3472.82
K1-K2	F5	3603
K1-K2	F6	3637.26
K1-K2	F7	3676.88
K1	F8	3603-3675
K1	F9	3640.13
K1-K2	F10	3673.56
K1-K2	F11	3623
K1-K2	F12	3612-3654
K1	F13	3676.88
K1-K2	F14	3593-3676
K1-K2	F15	

Facies		
F1 : Laminated Crystalline anhydrite	F6 : Mudstone to wackestone	F11 : Bioclast ooid peloid packstone to grainstone
F2 : FenestralAnhydrite dolomudstone	F7 : Bioclast intraclast packstone	F12 : Bioclast intraclast oncoid grainstone
F3 : Dolomudstone with anhydtite	F8 : Bioclast ooid wackestone to packstone	F13 : Intraclastic grainstone
F4 : Argillaceous mudstone and claystone	F9 : Packstone with algae and matrix	F14 : Bioclast ooid grainstone
F5 : Thrombolitic – Stramatolithic boundstone	F10 : Bioclast peloid wackestone to packstone	F15 : Bioclast ooid packstone to grainstone

Fig. 3 A schematic carbonate ramp model showing facies changes (F1-F15) and sedimentary environment of the Kangan Formation in the studied wells. F1to F3: crossed Polarized light (XPL); F4 to F15: plane polarized light (PPL)Core porosity and permeability data for different sedimentary environments have been shown on three petrophysical classes of Lucia(2004)

2010). Facies of this group correspond to FZ-8 of Wilson (1975).

Lagoonal facies belt: This facies belt includes F6 to F11 facies with bioclast, intraclast, ooid and peloid allochems, attributed to a lagoon environment with low energy and limited water circulation. (Asaad, I.S., Balaky, S.M., Hasan, G.F. and Aswad, M.K., 2021).

The facies show a micritic texture with sparry calcite cement. and medium to high reservoir quality in wells A and B, but their reservoir quality decreases towards the north of the Persian Gulf (well C). Facies of this group correspond to FZ-7 and FZ-8 of Wilson (1975).

Shoal facies belt: This belt includes F12 to F15 facies containing bioclast, intraclast, oncoid, ooid packstone to grainstone. The facies of the shoal environment are mainly grain- supported, and under the effect of primary depositional texture and positive effect of diagenetic processes, they are characterized by high reservoir quality. Facies of this group correspond to FZ-6 of Wilson (1975).

Depositional model

Based on the results from facies analysis and according to the sedimentary evidence (i.e., texture, allochem type and facies order), a homoclinal carbonate ramp platform is attributed to depositional environment of the Kangan Formation in the studied fields (Fig. 3). This model also has been indicated by previous works (e.g., Insalaco et al. 2006; Karimi et al. 2015). The main reasons for introducing this ramp model are (a) the presence of grainstone facies in high-energy environments, and (b) gradual changes from shallow to deep marine environment (Dunham (1962). The presented model shows the low frequency of sabkha and tidal flat facies and the dominance of lagoon and shoal facies in the studied fields (Fig. 4). A decrease in sedimentation depth, grain-dominated facies and reservoir quality is observed from the center (wells A and B) to the north (well C) of the Persian Gulf.

Diagenetic processes

The Triassic sequence in the Zagros basin includes carbonate and evaporite sediments, which underwent various diagenetic processes, during the early to late stages of diagenesis (e.g., Dasgupta et al. 2002; Fontana et al. 2010; Koehrer et al 2010, 2012; Esrafili–Dizaji and Rahimpour–Bonab, 2014). The main diagenetic processes affecting the pore system and reservoir quality of carbonate facies of Kangan Formation are compaction, cementation, dolomitization and dissolution that are briefly described as follows. These processes and their effects on the reservoir quality are illustrated in Figs. 5 and 6.

- Compaction: This process has been affected the carbonate facies just after deposition, which is observed

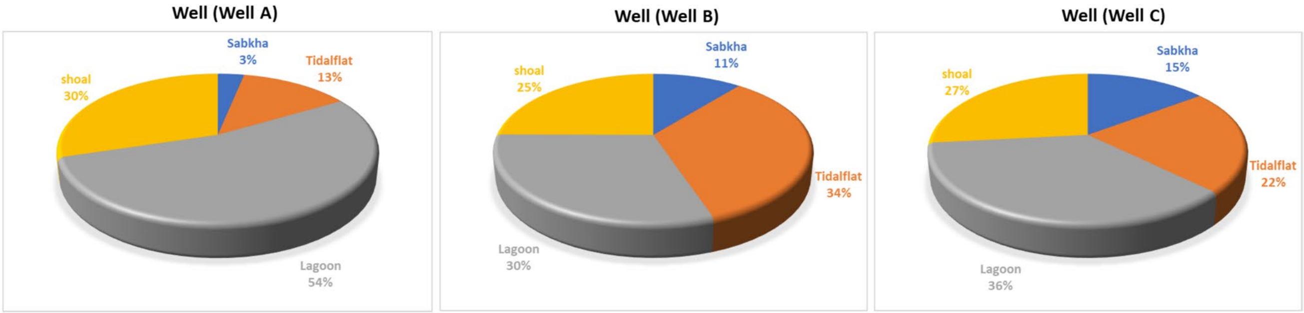
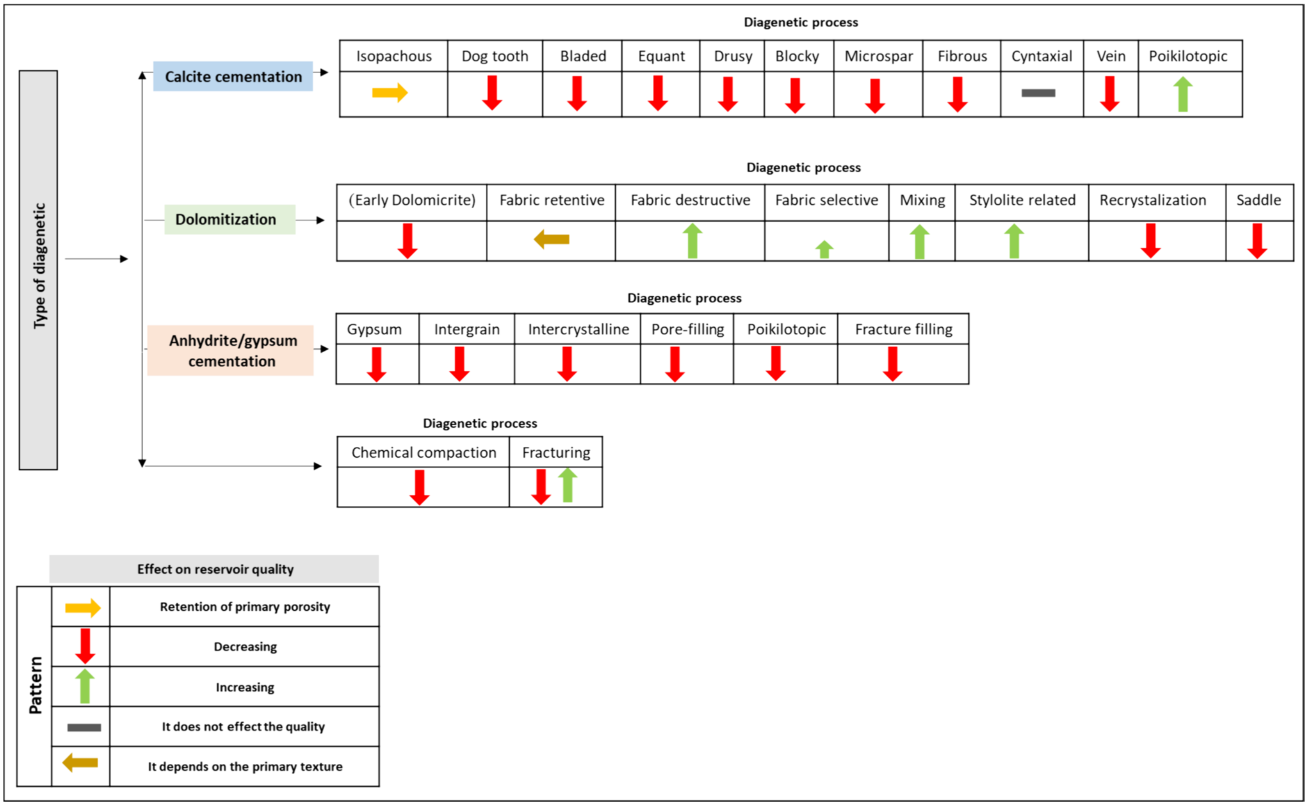


Fig. 4 Distribution of different environments (sabkha, tidal flat, lagoon and shoal) for deposition of carbonate facies of the Kangan Formation in the studied fields



Calcite cementation

Diagenetic process

Isopachous	Dog tooth	Bladed	Equant	Drusy	Blocky	Microspar	Fibrous	Cyntaxial	Vein	Poikilotopic
→	↓	↓	↓	↓	↓	↓	↓	—	↓	↑

Dolomitization

Diagenetic process

(Early Dolomicrite)	Fabric retentive	Fabric destructive	Fabric selective	Mixing	Stylolite related	Recrystalization	Saddle
↓	←	↑	↑	↑	↑	↓	↓

Anhydrite/gypsum cementation

Diagenetic process

Gypsum	Intergrain	Intercrystalline	Pore-filling	Poikilotopic	Fracture filling
↓	↓	↓	↓	↓	↓

Diagenetic process

Chemical compaction	Fracturing
↓	↓↑

Effect on reservoir quality

Pattern		
	→	Retention of primary porosity
	↓	Decreasing
	↑	Increasing
	—	It does not effect the quality
	←	It depends on the primary texture

Fig. 5 Diagenetic processes and their impact on reservoir quality in the Kangan Formation

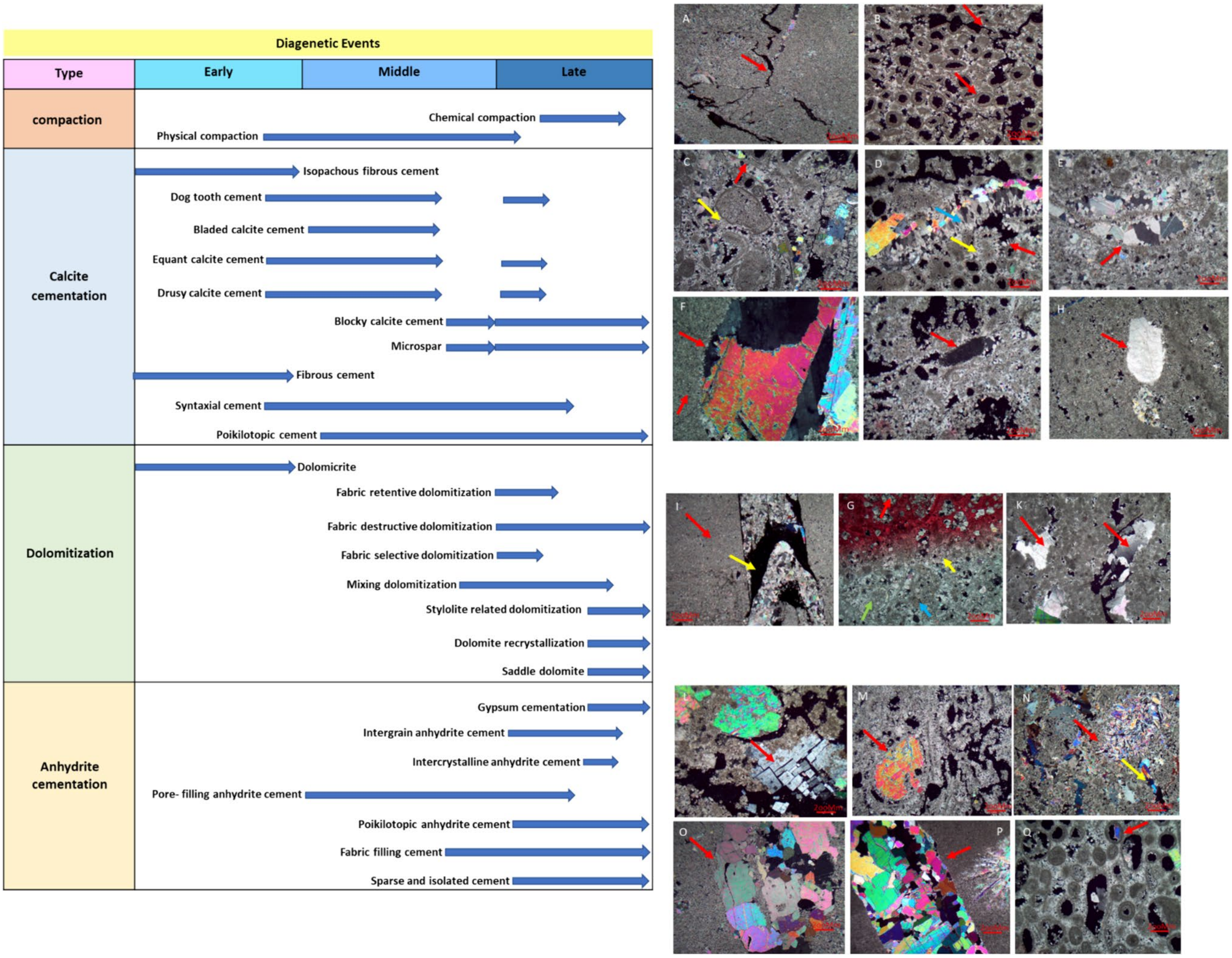


Fig. 6. Paragenetic sequence and photomicrographs of different diagenetic processes indicating marine, meteoric, and burial diagenetic realms in the Kangan Formation. **A**: Chemical compaction (3676.88 m). **B**: Physical compaction (3670.14 m). **C**: Isopachous fibrous cement (red), Dog tooth cementaton (yellow) (3676-3622 m). **D**: Bladed calcite cementation (red), Equant calcite cement (yellow), Fibrous cement (blue) (3660 m). **E**: Drusy calcite cement (3620 m). **F**: Blocky calcite cement (3629.67 m). **J**: Syntaxial cement (3665.96 m). H: Poikilotopic cement (3591-3650 m). **I**: Dolomicrite (red), Stylolite related dolomitization (yellow) (3669.09 m). **G**: Fabric retentive dolomitization(blue), Fabric destructive dolomitization(yellow), Fabric selective dolomitization (red), Dolomite recrystallization (green) (3592.69 m). K: Saddle dolomite (3595.65 m). **L**: Gypsum cement (3616.52 m). **M**: Intergrain anhydrite cement (3620-3690 m). N: Intercrystalline anhydrite cement (red), Pore- filling anhydrite cement (yellow) (3654-3677 m). **O**: Poikilotopic anhydrite cement (3590.8 m). P: Fabric filling cement (3605-3695 m). **Q**: Sparse and isolated cement (3670 m)

as physical compaction during shallow burial and is followed by chemical compaction during deep burial. Stylolites are evidence of chemical compaction in the reservoir.

- Calcite and anhydrite cementation: These cements as destructive diagenetic agents reduced the reservoir quality by filling pore spaces and reducing porosity and permeability. Calcite cements, found in shoal and lagoon facies, include marine, meteoric and burial cements. Marine cements (Bladed, Fibrous, and Equant) reduced reservoir quality by obstructing pore spaces. Meteoric cements (Drusy, Blocky and syntaxial) fill porosity, further reducing reservoir quality. Burial calcite and anhydrite cements in the form of pore-filling and poikilotopic appear in the Kangan reservoir.
- Dolomitization: This process is observed as replacement and cement in the reservoir. Dolomite cements are observed as pore-filling and along stylolites, and their effects on reservoir quality is not important as calcite and anhydrite cements.
- Dissolution: The effect of this process on carbonate facies of the kangan is mainly observed as dissolution vugs and moldic pores. Facies with large dissolution and connected vugs have high porosity and permeability, while

facies with isolated vugs and moldic pores have high porosity and low permeability.

According to the study of facies and identification of cement types, a decrease in reservoir quality from the center to the north of the Persian Gulf is observed.

Paragenetic sequence

The diagenetic processes identified in the Kangan Formation indicate three diagenetic realms, including marine, meteoric and burial (Fig. 6). Dissolution and calcite cements (except blocky cement) mostly occur during meteoric diagenesis (Balaky et al. 2023). Pore-filling anhydrite cements have been affected the reservoir facies during shallow to burial stages of diagenesis. Dolomitization as replacement and pore-filling cement has been acted during the early to late stages of diagenesis. The main deep burial diagenetic processes are recrystallization, chemical compaction (stylolite), cementation (calcite and anhydrite and saddle dolomites). In general, diagenetic processes within the reservoir, especially cementation, show variations in different carbonate facies and also between the studied wells in the central (wells A and B) and north (well C) of the Persian Gulf. This variation reflects the impact of diagenetic alterations on reservoir quality across different depositional settings.

Depositional sequences

The Kangan Formation consists of a series of regressive and prograding sequences. Most gas reservoirs develop within the regressive sequence, particularly in grain-supported facies (Strohmenger et al. 2002). During the sea level fall, the sedimentary sequence shifts towards grain- supported facies, with high porosity and permeability. In this study, three third-order sequences (KS-1 to KS-3) were identified based on facies changes, sedimentary environment, diagenetic features and well log fluctuations (gamma, porosity and permeability). Each third-order sequence includes two to three fourth-order sequences. Both third- and fourth-order sequences include transgressive system tract (TST) and highstand system tract (HST). Local tectonic deformation is a significant factor influencing the development of fourth-order sequences in the basin (Miall 2000). The identified third-order sedimentary sequences are described as follows.

KS-1 Sequence: The first depositional sequence (KS-1) includes the K1 and K2 reservoir units of the Kangan Formation, and is associated with sabkha to shoal facies belts. This sequence has a thickness of 42 m, 59.7 m and 60 m in wells A, B and C, respectively (Fig. 7), and consists of dolomite and anhydrite in wells A-B (central Persian Gulf) and changes to a limestone sequence in well C (northern Persian Gulf).. It is bounded by two sequence boundary: SB1 at the base (between the Kangan and Dalan formations) and SB2 at the top. This sequence is subdivided into two fourth-order sedimentary sequences. Transgressive system tract (TST1) of this sequence includes mudstone to packstone/grainstone facies related to lagoon and shoal environments in K2 reservoir unit. In this system tract, the amount of calcite, dolomite and anhydrite cements increases towards the maximum flooding surface (MFS). Petrographic observations show increased porosity and permeability in grain-supported facies near the MFS boundary. GR log fluctuations in this sequence indicate two stages of sea level rise in fourth-order sequences, with an increasing trend in GR log response from the center to the north of the Persian Gulf at MFS. At the K1/K2 boundary (HST1), a gradual decrease in GR log is observed, transitioning from a dolomite-anhydrite sequence with limestone interlayers in wells A and B to a limestone sequence in well C. The identified carbonate facies of HST, including mudstone, wackestone and grainstone facies with boundstone interlayers, are related to tidal flat to shoal settings. Despite the presence of calcite, dolomite and anhydrite cements, the highest porosity and permeability towards the north of the Persian Gulf in this system tract are associated with grain-supported facies at the beginning and end of HST interval.

KS-2 Sequence: The second depositional sequence (KS-2) includes K1 reservoir unit and is related to wackestone, boundstone and grainstone facies of intertidal and shoal environments. This sequence has a thickness of 30 m, 49.92 m and 39 m in wells A, B and C, respectively (Fig. 7), it is bounded by two sequence boundaries (SB2). KS-2 comprises two fourth-order sedimentary sequences. GR log of this sequence shows a decrease in intensity and fluctuations from the central to northern Persian Gulf. The TST2 boundary indicates two stages of sea level rise towards the MFS. An increase in GR log fluctuations towards the MFS boundary is associated with the dominance of wackestone to packstone facies of intertidal to shoal environments. The highest porosity and permeability are found in grain-supported facies of lagoon to shoal environments towards the MFS boundary in TST2. In HST2, a decrease in GR log response is seen in grain-supported facies related to lagoon and shoal environment towards the north of the Persian Gulf. Additionally, the amount of calcite, dolomite and anhydrite cements decreases towards the north of the Persian Gulf,. The highest porosity and permeability at the beginning of the HST2 are associated with limestone-dolomitic sequences with grain- supported facies in the center of the Persian Gulf. A decreasing trend in porosity and permeability is observed towards the north of the Persian Gulf due to the presence of boundstone facies at the end of HST2.

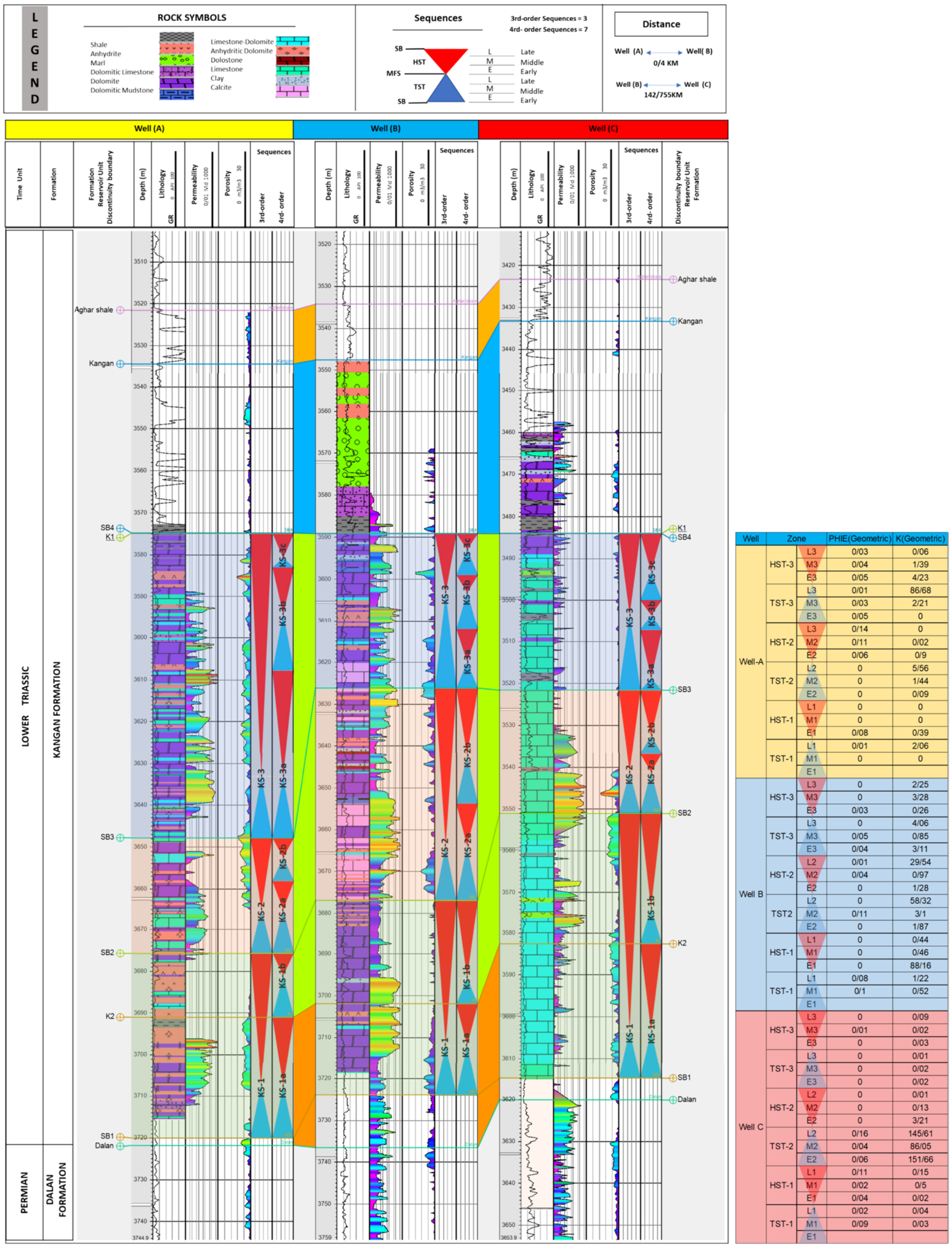


Fig. 7 Graphical representation of the third- and fourth-order sedimentary sequences of the Kangan Formation along with their porosity and permeability in the studied wells (**A**), (**B**) and (**C**)

Well	Zone		PHIE(Geometric)	K(Geometric)
Well-A	HST-3	L3	0/03	0/06
		M3	0/04	1/39
		E3	0/05	4/23
	TST-3	L3	0/01	86/68
		M3	0/03	2/21
		E3	0/05	0
	HST-2	L3	0/14	0
		M2	0/11	0/02
		E2	0/06	0/9
	TST-2	L2	0	5/56
		M2	0	1/44
		E2	0	0/09
	HST-1	L1	0	0
		M1	0	0
		E1	0/08	0/39
	TST-1	L1	0/01	2/06
		M1	0	0
		E1		
Well B	HST-3	L3	0	2/25
		M3	0	3/28
		E3	0/03	0/26
	TST-3	L3	0	4/06
		M3	0/05	0/85
		E3	0/04	3/11
	HST-2	L2	0/01	29/54
		M2	0/04	0/97
		E2	0	1/28
	TST2	L2	0	58/32
		M2	0/11	3/1
		E2	0	1/87
	HST-1	L1	0	0/44
		M1	0	0/46
		E1	0	88/16
	TST-1	L1	0/08	1/22
		M1	0/1	0/52
		E1		
Well C	HST-3	L3	0	0/09
		M3	0/01	0/02
		E3	0	0/03
	TST-3	L3	0	0/01
		M3	0	0/02
		E3	0	0/02
	HST-2	L2	0	0/01
		M2	0	0/13
		E2	0	3/21
	TST-2	L2	0/16	145/61
		M2	0/04	86/05
		E2	0/06	151/66
	HST-1	L1	0/11	0/15
		M1	0/02	0/5
		E1	0/04	0/02
	TST-1	L1	0/02	0/04
		M1	0/09	0/03
		E1		

KS-3 Sequence: The third depositional sequence (KS-3) has a thickness of 74 m, 37.84 m and 35 m in wells A, B and C, respectively (Fig. 7). KS-3 includes three fourth-order sedimentary sequences. It is characterized by dolomite and anhydrite in the center of the Persian Gulf, and it changes to limestone in the north (well C). In the studied wells, the Kangan Formation changes to a shale sequence towards the northern Persian Gulf. This sequence is bounded by two sequence boundaries (SB2) in K1 reservoir unit. The last sedimentary sequence includes three stages of sea level rise towards the K1 reservoir unit leading to a decrease in porosity and permeability. TST3 in the third- order and fourth order sequences includes a dolomitic sequence in the center and a limestone sequence in the north of the Persian Gulf. The facies of this interval include mudstone to grainstone facies related to lagoon and shoal environments in the center and north of the Persian Gulf. The MFS is highlighted by fore-shoal facies and an increase in GR log reading. HST3 boundary in K1 reservoir unit corresponds to a decrease in GR log and the presence of grain-supported and boundstone facies related to tidal flat and shoal setting. The lithology of this system tract consists of limestone and dolomite with layers of marl and anhydrite changing into shale towards the K1 boundary. The best porosity and permeability in this sequence is related to grain- supported facies of shoal and lagoon environments in the center of Persian Gulf. Generally, from the center to the north of Persian Gulf, there is a decrease in in porosity and permeability.

Geological reservoir zones (GRZs)

A detailed reservoir zonation of the Kangan Formation was established bycorrelating facies and environmental characteristics, diagenetic features and pore types to the fourth- order sedimentary sequences (KS-1a, KS-1b, KS-2a, KS-2b, KS-3a, KS-3b and KS-3c) identified in the studied wells. This zonation divided the Kangan Formation into seven geological reservoir zones, (GRZ1 to GRZ7) from the base to the top of the reservoir, respectively (Figs. 8, 9, 10). Each zone exhibits unique lithological, facies and diagenetic characteristics controlling reservoir properties within each fourth-order sedimentary sequence. The trend of reservoir quality in each zone across the studied wells is summarized in Table 3. Below are the descriptions of the identified geological reservoir zones (Fig. 11).

- **GRZ–1**: This zone consists of dolomite and anhydrite in wells A and B, and limestone in well C. It includes sabkha to shoal facies in wells A and B, and lagoon and shoal facies in well C. Reservoir quality in the central Persian Gulf (well A and B), due to the dominance of grain-supported facies of shoal and lagoon environments, is higher than that is observed in the northern part (well C).Location: Central Persian Gulf (Wells A and B); Northern Persian Gulf (Well C)
- Lithology:; Limestone sequence (Well C)
- Environment:
- The best quality is observed in the middle to late TST1 and HST1 of the first fourth-order sequence (KS-1a) at the base of Kangan Formation.
- **GRZ–2**: This zone, lithologically is similar to GRZ-1. It includes lagoon to shoal facies as well as boundstone. There is an increase in reservoir quality from the central to northern Persian Gulf. The highest quality is in the middle TST2 and HST2 of the second fourth-order sequence (KS-1b).
- **GRZ–3**: This zone consists of limestone, dolomite, and anhydrite in wells A and B, and limestone in well C. It includes mudstone to grainstone and boundstone facies of sabkha to shoal environments. Reservoir quality of this zone in well C due to the dominance of grain-supported facie is higher than wells A and B, in which mud-supported facies dominate and cementation has destroyed the reservoir quality. These facies are observed in the middle to late TST3 and early HST3 of the third fourth-order sequence (KS-2a).
- **GRZ–4**: This zone consists of limestone, dolomite, and anhydrite sequence in the center of Persian Gulf, and it changes to limestone towards the north. It includes packstone to grainstone facies with interlayers of boundstone of tidal flat to shoal environments. Reservoir qualityof this zone is highest in grain-supported facies in parts of TST4 and middle HST4 of the fourth fourth-order sequence (KS-2b).-
- **GRZ–5**: This zone consists of limestone, dolomite, and anhydrite in wells A and B, and limestone and dolomite in well C. It includes mudstone to grainstone facies of tidal flat to shoal environment. Reservoir quality of this sequence decreases towards the north, due to the dominance of mudstone facies, and it is the highest in grain-supported facies in HST5 and middle TST5 of the fifth fourth-order sequence (KS-3a).
- **GRZ–6**: This zone consists of limestone, dolomite, and anhydrite in wells A and B, and limestone, dolomite, and shale in well C. It includes boundstone and mud-dominated facies of tidal flat and lagoon environments. Reservoir quality of this sequence is the highest in grain-supported facies of shoal environments, mainly in the middle parts of HST6 of the sixth fourth-order sequence in well B. A decreases in reservoir quality is observed towards the north due to the dominance of mud-dominated facies in lagoon environments.
- Facies:
- **GRZ–7**: This zone consists of dolomite and shale in wells A and B, and limestone and shale in well C. It includes mudstone to grainstone and boundstone facies of sabkha to shoal environments. Reservoir quality of this sequence islow due to the dominance of mud-dominated facies and the effect of pore-filling cement.

The reservoir zonation of the Kangan Formation reveals variations in lithology, facies, and reservoir quality from the central to the northern Persian Gulf. Grain-supported facies generally offer better porosity and permeability, while mud-supported facies and facies with extensive cementation show low reservoir quality. Understanding these zonations aids in optimizing reservoir management and hydrocarbon extraction strategies.

Discussion and interpretation

Investigation of the carbonate-evaporite sequence of the Triassic Kangan Formation in the studied gas fields, spanning from the central to the north of the Persian Gulf, reveals significant vertical and lateral reservoir heterogeneity. This heterogeneity is manifested in variations of lithology, facies frequency and diagenetic processes. The analysis of Kangan Formation facies across the studied wells, indicates a variety of mudstone to grainstone facies of tidal flat to shoal environments from the center to the north of the Persian Gulf. As the sedimentary basin

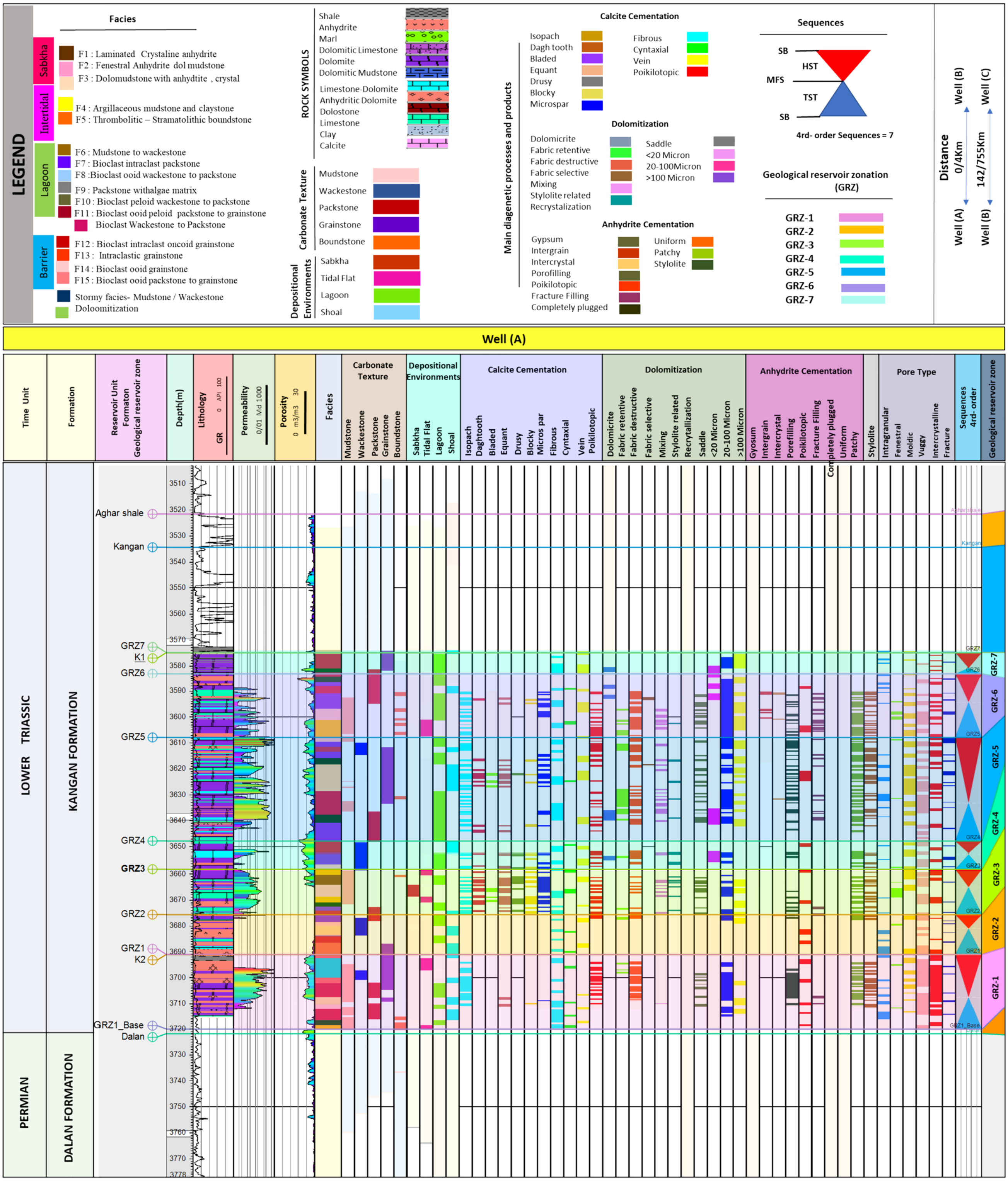


Fig. 8 Geological reservoir zonation from the base (GRZ1) to the top (GRZ7)of the Kangan Formation in well (**A**)

shallows, the diversity of grain-supporting sediments decreases. Diagenetic processes, including compaction, cementation by calcite, anhydrite and dolomites, and dissolution have affected the reservoir quality of facies in K1 and K2 reservoir units. The impact of cements on reservoir quality is most pronounced in the grain-supported

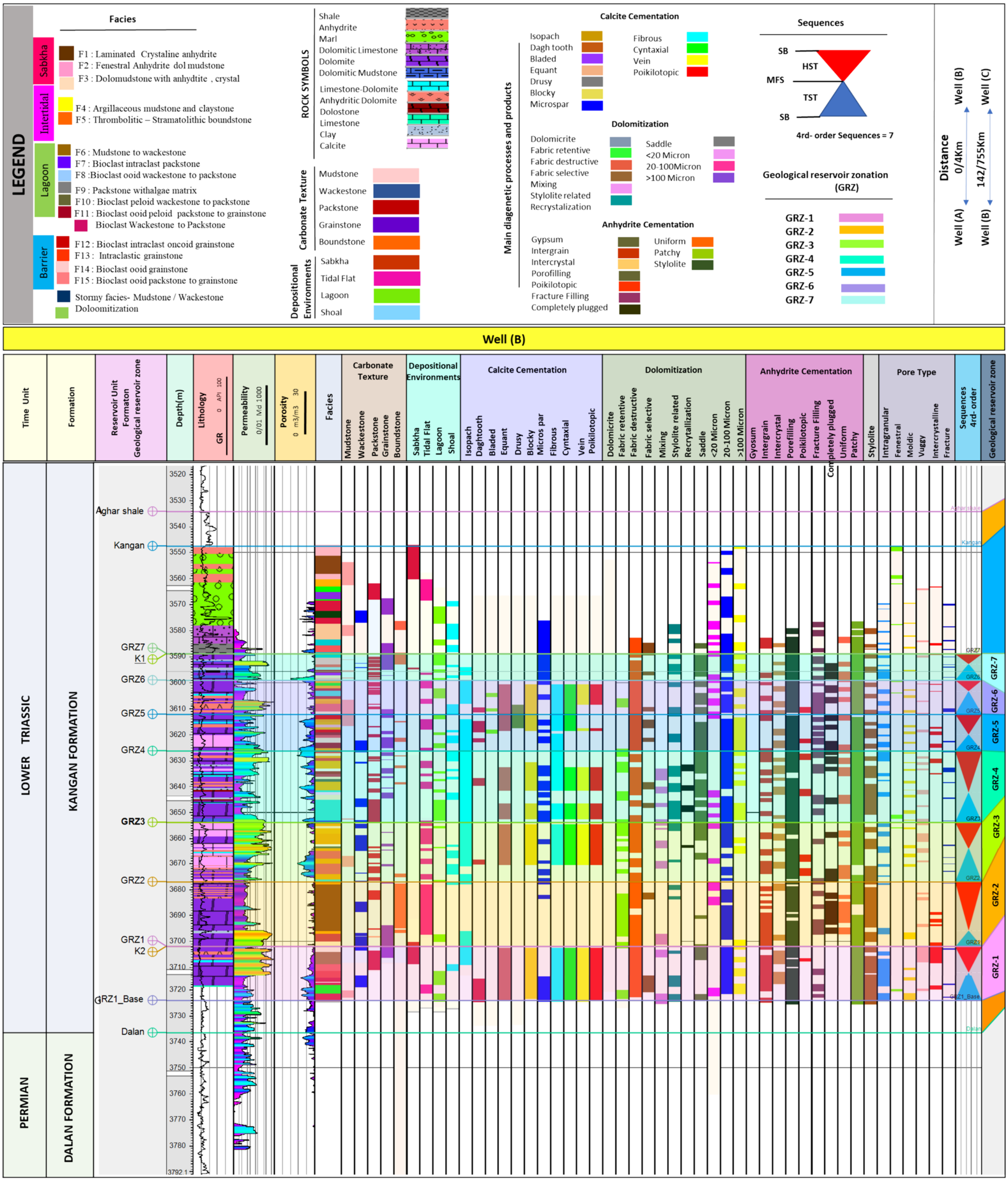


Fig. 9 Geological reservoir zonation from the base (GRZ1) to the top (GRZ7)of the Kangan Formation in well (**B**)

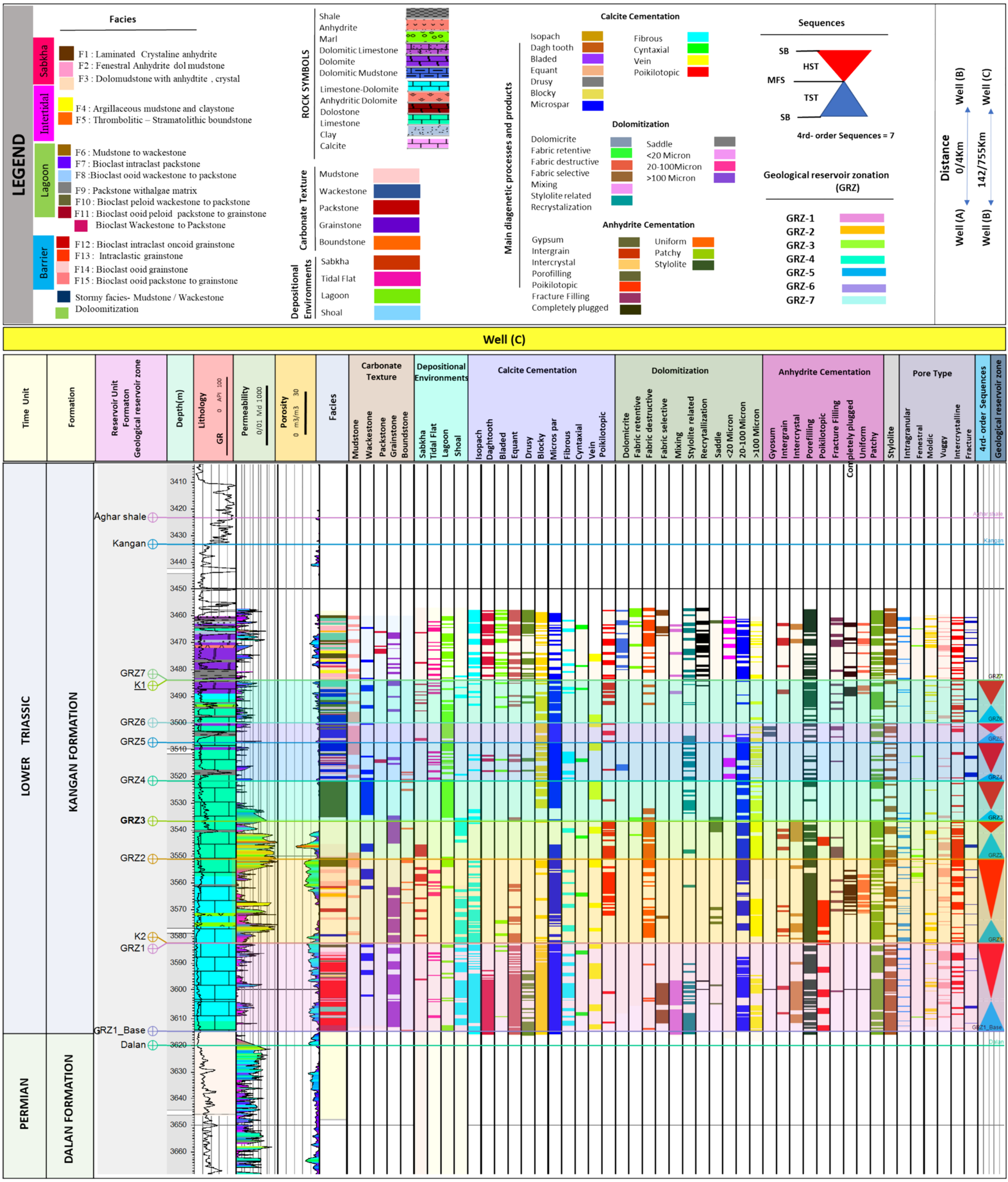
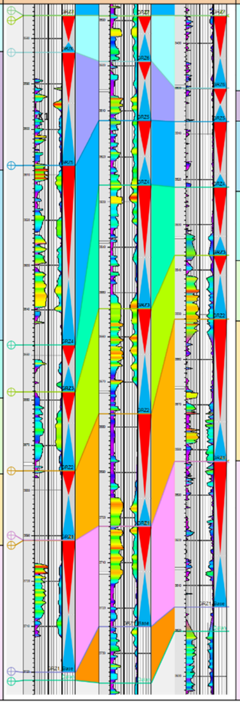


Fig. 10 Geological reservoir zonation from the base (GRZ1) to the top (GRZ7)of the Kangan Formation in well (**C**)

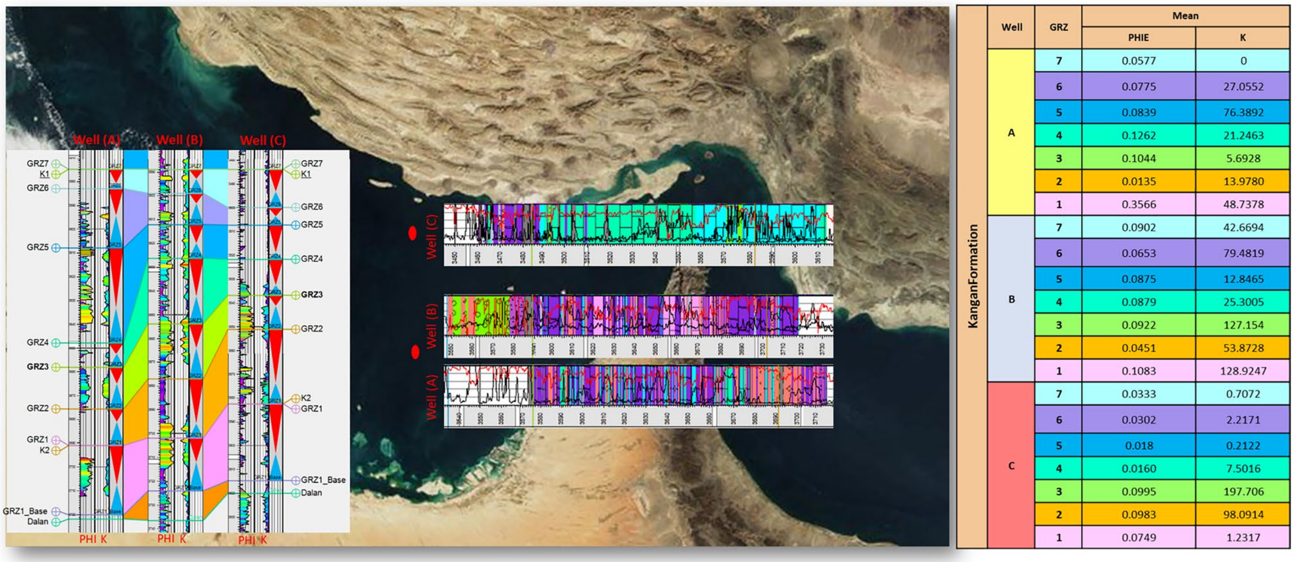
facies, which diminish towards the north of the Persian Gulf.

Reservoir units of the Kangan Formation (K1 and K2) consist of three third-order and seven fourth-order sequences, corresponding to seven geological reservoir zones (GRZs). This subdivision is based on GR log changes, sedimentary facies and diagenetic processes identified within the Kangan Formation sequence. The identified GRZs show

Table 3 The identified geological reservoir zones (GRZs), facies, diagenetic features and reservoir quality of the Kangan Formation in the studied wells A,B and C.

Formation	Geological Reservoir Zone (GRZs)	4rd-order sequence			Main lithology	Main facies group	Sequence stratigraphic position	Main diagenetic features	Depth (m)			Mean porosity (Fraction)			Mean			Mean permeability (md)			Mean			Reservoir quality		
		Well (A)	Well(B)	Well(C)					Well (A)	Well (B)	Well (C)	Well (A)	Well (B)	Well (C)	Well (A)	Well (B)	Well (C)	Well (A)	Well (B)	Well (C)	Well (A)	Well (B)	Well (C)	Well A	Well B	Well C
Kangan	K1 GRZ-7				Dolostone to Limestone, With Shale	Sabkha to shoal	HST	Low cement in Well (A), Low calcite cment in Well (B), Various of cement IN Well (C), fibrous, microspar, blocky, fabric destractiv , dolomite crystal (S-M-L), compaction, dissolution, in boundary K1(Shale)	8.2	10.32	15.87	0.0278	0.0288	0.0366	0.0577	0.0902	0.0333	0	22.8942	1.0137	0	42.6694	0.7072	K1 ↓	↓	↓
							TST	Low calcite cement, Low dolomite and anhydrite cement in Wells (A-C), fibrous, microspar, blocky, fabric destractiv, dolomite crystal (S-M-L), chemical and Physical compaction, dissolution				0.1176	0.1107	0.0256				0	52.5570	0.4007						
	GRZ-6				Dol-Lime-Sh	Tidal to sh	HST-TST	Various of cement in Wells (A-B), dolomite crystal (S-M-L), dissolution	24.35	12.96	7.68	0.0701T	0.0493T	0.032T	0.0775	0.0653	0.0302	20.7089	133.818	6.005	27.0552	79.4819	2.2171	↓	↑	↓
	GRZ-5				Dolostone to Limestone Anhydrite, layer	Tidal flat to shoal	HST	Various of cement,isopach,dog tooth, equent,drusy,blocky,fibrous, cyntaxial,fabric destractiv,dolomite crystal S-M-L,compaction, dissolution	40.21	14.29	14.28	0.0855	0.0764	0.0162	0.0839	0.0875	0.018	76.3941	15.3463	0.2142	76.3892	12.8465	0.2122	↑	↓	↓
							TST	Various of cement in Wells (A-B), low fabric destractiv to Well (C), microspar, fibrous, dolomite crystal (S-M-L), compaction, dissolution				0.0802	0.0999	0.0216				76.3770	9.7216	0.2073						
	GRZ-4				Dolostone Limestone Anhydrite, layer	Lagoon to shoal	HST	Various of cement in Wells (A-B), microspar, blocky, fabric destractiv fibrous, cyntaxial, vein, poikilotopic, dolomite crystal (M-L), dissolution	10.59	27.52	15.09	0.1416	0.0969	0.0160	0.1262	0.0879	0.0160	70.3854	36.03812	0.3705	21.2463	25.3005	7.5016	↓	↓	↓
							TST	Low calcite in WellC,Various calcite cement types,low anhydrite in WellA-C,dolomite crystal S-M-L,compaction,dissolution,fabric destractiv				0.1109	0.0734	0				0.1867	11.8785	17.4852						
	GRZ-3				Anhydrite Dolostone Limestone	Sabkha to shoal	HST	Low calcite in Well (C), low anhydrite in Well (A), , fabric destractiv, chemical and Physical compaction, dissolution, dolomite crystal (S-M-L)	17.2	23.55	14.55	0.1044	0.1282	0.0208	0.1044	0.0922	0.0995	3.7443	142.5327	8.1528	5.6928	127.154	197.706	↓	↑	↑
							TST	Various calcite in Well A-B and low calcite in Well C, dolomite- anhydrite cement, fabric destractiv, dolomite crystal M-L, compaction, dissolution				0	0.0454	0.1138				7.1542	112.8006	311.4379						
	GRZ-2				Anhydrite Dolostone To Limestone	Tidal flat to shoal	HST	Low calcite cement in Wells (A-B), and Various calcite cement typ in Well (C), microspar, isopach, fabric destractiv- retentive- selective, stylolite related, saddle, dolomite crystal (S-M-L), low anhydrite cement in (Well A) and Various anhydrite cement typ in Well (B-C), chemical and Physical compaction, dissolution	15.61	24.6	30.95	0	0.0429	0.1077	0.0135	0.0451	0.0983	13/9780	3.8005	65.1428	13.9780	53.8728	98.0914	↓	↓	↑
							TST	Low calcite cement in Wells (A-B) and Various calcite cement typ in Well (C), microspar, isopach, fabric destractiv- retentive, mixing, No dolomite and anhydrite cement in Well (A), dolomite crystal (M-L), anhydrite cementation, Various calcite cement types to Wells (B-C), anhydrite cementation, fabric destractiv , dolomite crystal (M-L), patchy and stylolite, chemical and Physical compaction, dissolution				0.0135	0.0577	0.0847				0	184.0609	166.7345						
	K2 GRZ-1				Anhydrite Dolostone To Limestone	Sabkha to shoal	HST	Various calcite cement types to Wells (B-C), isopach, dogtooth, equent, blocky, microspar, fibrous, anhydrite cementation, fabric destractiv, dolomite crystal (M-L), patchy and stylolite, chemical and Physical compaction, dissolution	28.57	21.96	32.81	0.4923	0.0387	0.0777	0.3566	0.1083	0.0749	72.4163	216.9075	1.23175	48.7378	128.9247	1.2317	K2 ↑	↑	↓
							TST	Various calcite cement types, isopach, dogtooth, equent, drusy, blocky, microspar, fibrous, cyntaxial, vein, poikilotopic, and fabric selective, mixing,stylolite related (in Well B-C). fabric destractiv (Well B), fabric selective, mixing, Stylolite related,dolomite crystal (M-L), anhydrite cementation, patchy and stylolite, chemical compaction, dissolution				0.0853	0.1451	0.0707				1.3810	40.9418	0.7024						

HST- PHI (0.0839 (Well A) - 0.0858 (Well B) - 0.0293(Well C)), HST-K (39.7478(Well A) – 1.8590 (Well B) – 0.3232 (Well C)),



KanganFormation	Well	GRZ	Mean	
			PHIE	K
	A	7	0.0577	0
		6	0.0775	27.0552
		5	0.0839	76.3892
		4	0.1262	21.2463
		3	0.1044	5.6928
		2	0.0135	13.9780
		1	0.3566	48.7378
	B	7	0.0902	42.6694
		6	0.0653	79.4819
		5	0.0875	12.8465
		4	0.0879	25.3005
		3	0.0922	127.154
		2	0.0451	53.8728
		1	0.1083	128.9247
	C	7	0.0333	0.7072
		6	0.0302	2.2171
		5	0.018	0.2122
		4	0.0160	7.5016
		3	0.0995	197.706
		2	0.0983	98.0914
		1	0.0749	1.2317

Fig. 11 The gradual decrease in porosity of the Kangan Formation from the center (wells **A** and **B**) to the north of the Persian Gulf (well **C**)

good correlation across the studied wells from the central to north of the Persian Gulf.

The lithology of the Kangan Formation in wells A and B (central Persian Gulf) includes limestone, dolomite and anhydrite that changes to a predominantly limestone sequence in well C (northern Persian Gulf). Lithology and facies changes, interpreted as deepening and shallowing upward sequences, reflect sea level fluctuations at the time of deposition (Balaky et al. 2016). Two main stratigraphic surfaces differentiating system tracts (TST and HST) are maximum flooding surface (MFS) and sequence boundary (SB). These surfaces exhibit a close relationship with facies changes. The lower boundary of the Kangan Formation (SB1) indicates a long-term regression on the Arabian platform and in the study area.

Transgressive system tract (TST) is characterized by deepening upward interval from tidal flat to lagoon and shoal facies belt. Conversely, the highsatnd system tract (HST) is marked by shallowing upward sequences where shoal and lagoon facies belts transition into tidal flat facies (intertidal and supratidal).

Grain-dominated facies in shoal and lagoon environments exhibit high reservoir quality, primarily within TST and early to late HST system tracts. They are dominants in GRZ-1, GRZ-2 and GRZ-3 in well C, and GRZ-4, GRZ-5, GRZ-6 and GRZ-7 in wells A and B. Diagenetic processes significantly influence the pore system and reservoir properties of the Kangan Formation, varying across the studied fields and geological reservoir zones. In the lower zones of the Kangan Formation (GRZ-1 to GRZ-3), reservoir quality increases from the central parts (wells A and B) towards the northern parts (well C) of the Persian Gulf. Conversely, in the upper zones (GRZ-4 to GRZ-7), reservoir quality decreases towards the north of the basin (Fig. 10).

The presence of grain-dominated facies of shoal belt as the main reservoir zones underscores the significant role of depositional facies in development of the Kangan Formation reservoir units. The effect of diagenetic processes on pore system and reservoir properties varies across the studied fields and geological reservoir zones, depending on facies type and their position on the carbonate platform. The dominance of grain-supported facies in wells A and B, and mud-supported facies in well C indicates that the central parts of the Persian Gulf experienced higher energy conditions than the northern parts.

Conclusions

The detailed analysis of the Kangan Formation highlights the complex interplay of depositional environments, diagenetic processes, and sea-level changes in shaping reservoir quality. This understanding is crucial for optimizing reservoir management and hydrocarbon extraction strategies in the studied gas fields of the Persian Gulf. The main results of this study are summarized below.

- Facies analysis of the Kangan Formation in the studied wells resulted in the identification of 15 microfacies deposited within four facies belts (sabkha, intertidal, lagoon and shoal) of a homoclinal carbonate ramp platform.

- Grain-dominated facies associated with shoal and lagoon environments exhibit higher reservoir quality compared to mud-dominated facies found in tidal flat (intertidal to sabkha) environment.
- Frequency of grain-dominated facies decreases from wells A-B (Centeral persian Gulf, deep basin), towards well C (Northern persian Gulf, Shallow basin), indicating a transition from high-energy environment in the center to low-energy environment in the north of the Persian Gulf.
- Several diagenetic processes were identified in the studied formations, including dissolution, calcite cementation, dolomitization, anhydrite cementation and chemical compaction. These processes occurred in marine, meteoric and burial diagenetic realms.

  Based on facies analysis and GR pattern, three third order sequences and seven fourth order sequences were recognized within the Kangan interval from the three studied wells.
- Kangan Formation is divided into seven geological reservoir zones (GRZ), based on changes in sedimentary facies, diagenetic processes and reservoir quality. These zones correspond to fourth order sedimentary sequences, each representing similar lithological, facies, environmental and diagenetic characteristics.
- GRZs exhibit variations in reservoir quality from the center to the north of the Persian Gulf. GRZ-1 to GRZ-3 in the northern Persian Gulf and GRZ-4 to GRZ-7 in the central Persian Gulf demonstrate better reservoir quality.
- Variations in lithology, facies, and depositional environment from the center to the north of the Persian Gulf, highlighting a shallowing trend towards the Lavan field. This shallowing is associated with increased calcite and anhydrite cementation and a decrease in reservoir quality within the Kangan Formation sequence.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13146-024-00998-7.

Acknowledgements The authors, acknowledge Iranian Offshore Oil Company (IOOC) for providing data and facilities to publish the results of this research. Mr Ahmad Yahyaei is acknowledged for his sincere participation and contribution towards interpretation of the results. Mr. Ali Assadi and Mr. Ali Imandoust are appreciated for their collaboration and comments on this paper.

Author contributions Marjan Mohammadi: Methodology, Software, Writing- Original draft preparation. Ali Kadkhodaie: Methodology, Reviewing Hossain Rahimpour-Bonab: Methodology, Reviewing Rahim Kadkhodaie: Methodology, Reviewing Mohsen Aleali: Conceptualization, Reviewing.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflicts of interests 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.

Ethical approval (1) This material is the authors' own original work, which has not been previously published elsewhere. (2) The paper is not currently being considered for publication elsewhere. (3) The paper reflects the authors' own research and analysis in a truthful and complete manner. (4) The publication of this manuscript does not engage in or participate in any form of malicious harm to another person or animal.

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