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ORIGINAL ARTICLE

A syngenetic classification of anhydrite textures in carbonate reservoirs and its relationship with reservoir quality: a case study from the Permo-Triassic Dalan and Kangan formations

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Abstract

The presence of anhydrite in various forms and textures is a common diagenetic feature in many carbonate reservoirs. In this study, focusing on carbonate reservoirs of the upper Dalan and Kangan formations in the Persian Gulf, a syngenetic classification of anhydrite based on petrographic evidence and core description is proposed. As a result, early diagenetic evaporite textures (layered, nodular, and sparse crystals) related to the depositional environment conditions and and burial textures (pervasive, patchy and fracture-filling) in the form of cements are identified. Among these textures, pervasive and patchy cements have the main effect on the destruction of reservoir quality, mostly in grain-dominated facies. Study of facies categories based on dominant diagenetic features and pore types in mud-dominated carbonates (MF-1 and MF-2) and grain-dominated ones (GF-1 to GF-5), and investigation of the introduced reservoir rock types (RT-1 to RT-3) indicate that the distribution of anhydrite in the reservoir and its impact on reservoir quality is predominantly dependent on diagenetic history of the studied formations, before and after anhydrite mineralization. As, the extensive flow of sulfate-rich brines and thus pervasive occurrence of anhydrite in the pore system of reservoir rocks have occurred during shallow burial and before significant compaction and widespread calcite cementation. On the other hand, the essential effect of dissolution on anhydrite cement during the burial has created reservoir facies with large dissolution vugs and high reservoir quality.

Keywords Carbonate reservoir · Diagenesis · Anhydrite textures · Reservoir quality · Dalan and Kangan · Persian Gulf

Introduction

Evaporites are considered a significant part of sedimentary rocks deposited within sedimentary environments under specific conditions. Warren (2006) defines evaporite as a salt rock, initially precipitated from the saturated surface, or near-surface brines hydrologically driven by solar evaporation. Many studies have indicated the presence of anhydrite as a cement in carbonate reservoirs (e.g., Saller and Henderson 1998; Melim and Scholle 2002; Lucia et al. 2004; El-Tabakh et al. 2004; Jones and Xiao 2005; Machel 2005; Lønøy 2006; Ehrenberg et al. 2006; Morad et al. 2012; Daraei et al. 2014). The destructive effect of anhydrite on reservoir quality of the Permo-Triassic carbonates in the Persian Gulf, the target of this study, has been mentioned in previous works (e.g., Kadkhodaie-Ilkhchi et al. 2008, 2010; Esrafili-Dizaji and Rahimpour-Bonab 2009, 2014; Rahimpour-Bonab et al. 2010; Tavakoli et al. 2011; Aleali et al. 2013; Aliakbardoust and Rahimpour-Bonab 2013; Enayati-Bidgoli et al. 2014). Lucia (2007) introduced the first systematic classification of anhydrite textures in carbonate reservoirs. These textures are (a) poikilotopic anhydrite with large crystals and inclusions of dolomite and uneven distribution, formed by replacement and pore-filling mechanisms, (b) nodular anhydrite with microcrystalline masses of anhydrite, formed by displacement within the sediment, (c) pore-filling anhydrite with pervasive distribution occluding all pore spaces of the rock, (d) bedded anhydrite with laterally continuous beds as laminated or coalesced nodules. Among these textures, pore-filling anhydrite has a significant effect on reducing the reservoir quality. Poikilotopic and nodular anhydrite have little effect on porosity and

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permeability. Bedded anhydrite could act as a reservoir seal or barrier (Lucia 2007). The presence and development of anhydrite in various forms and textures is not accidental and it is under the control of sedimentary and diagenetic factors that have not been accurately addressed so far. Accordingly, the segregation of different types of anhydrite textures in the reservoir in terms of their genesis, which has been done in this study, is significantly important in evaluating its impact and control on reservoir characteristics. Therefore, in this research, we considered all factors controlling the distribution of anhydrite in offshore carbonate reservoirs and its effect on reservoirs properties based on the study results from the Permo-Triassic upper Dalan and Kangan formations of the Persian Gulf, south of Iran.

Geology setting

The upper Dalan and Kangan formations that are equivalent to the upper Khuff Formation in neighboring countries (e.g., Saudi Arabia, Oman, and Qatar), are considered as the main reservoir rocks in the studied fields (A, B and C) (Fig. 1). An extensive marine transgression on the Arabian Plate during late Permian resulted in deposition of Permian–Triassic shallow marine carbonates and evaporites. Creation a passive margin related to the opening of Neotethys Ocean in the northeastern part of the Arabian Plate provides the conditions for widespread carbonate-evaporite intervals of Dalan and Kangan and their Arabian equivalent Khuff Formation in this area (Sharland et al. 2001; Alsharhan and Nairn 2003). These formations are composed of carbonate (limestone and dolomite) with interlayers of evaporite (anhydrite). The presence of anhydrite interlayers in the reservoir interval indicates a warm and arid environmental conditions during the carbonate deposition, as indicated by previous studies (e.g., Al-Jalal 1987; Mehrabi et al. 2016). The reservoir interval of the formations is subdivided into four units, including K1 and K2 (Kangan Formation) and K3 and K4 (upper Dalan) (Table 1). The presence of anhydrite with a variety of forms and textures provided the opportunity to investigate its distribution in the reservoir, by which an understanding of its role in controlling the reservoir quality of these formations in the studied fields is achieved.

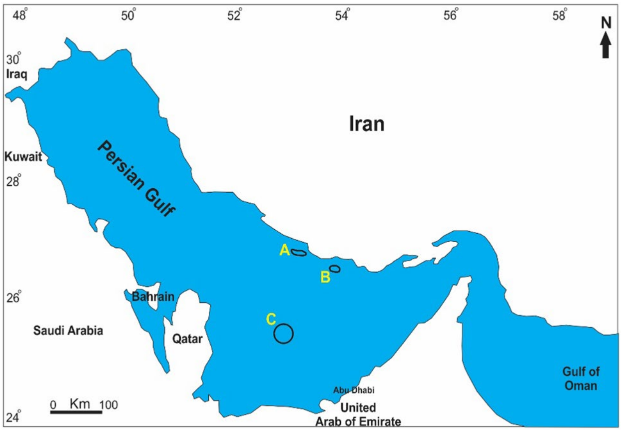


Fig. 1 Location map of the studied fields (**A**, **B**, and **C**) in the Persian Gulf

Data and methods

To investigate the anhydrite textures and their importance on reservoir properties, well data and information, including core and well logs from three wells of the studied fields (A, B, and C), were used. The total thickness of the upper Dalan and Kangan formations are 607 m, 505 m, and 465 m, in A, B and C fields, respectively. Facies analysis was accomplished based on the description of core intervals (248 m in field A, 432 m in field B, and 305.10 m in field C) and 1100, 1054, and 700 thin sections in A, B, and C fields, respectively. Carbonate facies were described according to Dunham's classification (1962). Lucia's scheme (2007) was applied in the description of anhydrite textures under the microscope. Then, the depositional and diagenetic characteristics of the reservoir rocks were correlated with their reservoir properties. For this purpose, core porosity and permeability values (330 data in field A and 220 data in field C) along with neutron (NPHI), density (RHOB) and sonic (DT) logs were used. Consequently, reservoir rock types were separated and the effect of different anhydrite textures on reservoir quality of different carbonate facies was evaluated.

Facies analysis

Facies analysis based on the core description and petrographic observations shows that the carbonate facies of the Dalan and Kangan formations have been deposited in different parts of a carbonate ramp environment. These facies that include mud-dominated facies of tidal flat and

Table 1 Stratigraphic interval of the Permo-Triassic upper Dalan and Kangan formations and their equivalents (upper Khuff) in nearby countries (modified after Insalaco et al. 2006)

Time	Formation		Reservoir Unit
Early Triassic	Aghar Shale	Sudair Shale	_-
	Kangan	Upper Khuff	K1
			K2
Late Permian	Upper Dalan		K3
			K4

Table 2 The main depositional facies, diagenetic features, and pore types of the studied formations

Depositional Facies	Depositional environment	Diagenetic features	Pore types
Ooid-skeletal Grainstone	Shoal	Anhydrite and calcite cementation, dolomitization, dissolution	Intergranular, moldic, dissolution vugs
Skeletal-peloidal ooid Grainstone-Packstone	Shoal	Anhydrite cementation, dolomitization, dissolution	Moldic, dissolution vugs
Pelloidal-skeletal Wackestone-Packstone	Lagoon	Anhydrite cementation, dolomitization, dissolution	Intergranular, moldic, dissolution vugs, microporosity
Boundstone (Stromatolite)	Intertidal	Anhydrite cementation, dolomitization	Microporosity, dissolution vugs
Mudstone	Intertidal	Dolomitization, anhydrite replacement, fracturing	Microporosity
Anhydrite	Supratidal	_	_
Dolostone	_	Anhydrite cementation, dolomitization, dissolution	Intercrystalline, dissolution vugs

grain-dominated facies of lagoon and shoal have endured the effects of diagenetic processes during the early to burial stages of diagenesis. A summary of the depositional facies of the upper Dalan and Kangan formations with their dominant diagenetic features and pore types is given in Table 2. Also, a schematic model illustrating the distribution of facies in different parts of the ramp environment for the studied formations is shown in Fig. 2. Figure 3 demonstrates the facies column of these formations, derived from thin section observations, in three wells of the studied fields. In a peactical view to study the effect of anhydrite mineralization on reservoir quality, carbonate facies based on the dominant diagenetic features and pore types were classified into seven facies categories, as shown in Table 3. Thus, two facies categories (MF-1 and MF-2) in mud-dominated facies and five facies categories (GF-1 to GF-5) in grain-dominated facies were identified.

Anhydrite distribution within the reservoir

Based on petrographic evidence from thin section studies, anhydrite in different forms and textures, as pore-filling cement, replacement, and displacement, has affected various carbonate facies of the reservoir interval during the early to late stages of diagenesis. In this study, in addition to these textures, three other types (spars crystals, seams, and fracture-filling) with minor frequency and less importance from reservoir quality point of view, are described as follows.

Layered (bedded) anhydrite

This type is observed in milky white color and massive (mosaic) or laminated with contorted laminations on core intervals. It is associated with interlayers of mudstone facies of the tidal flat environment in the reservoir interval (Fig. 4A–C).

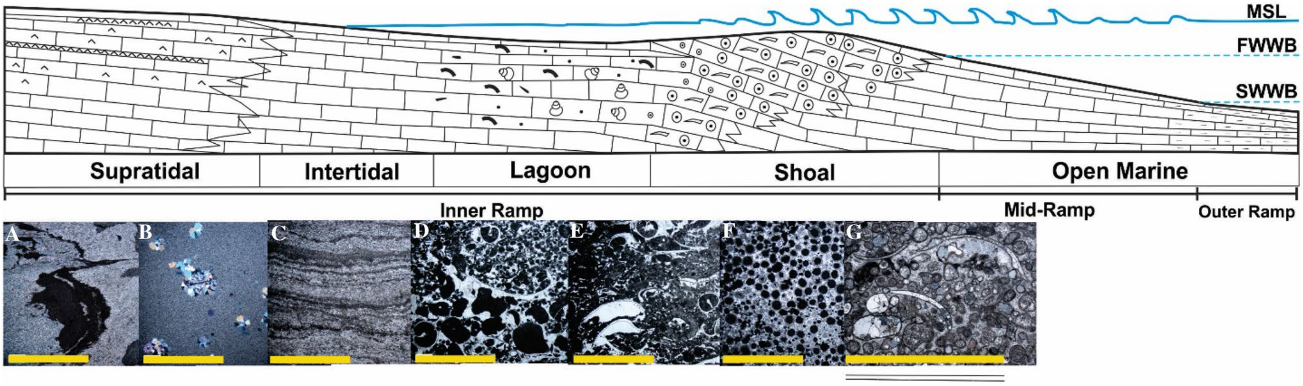
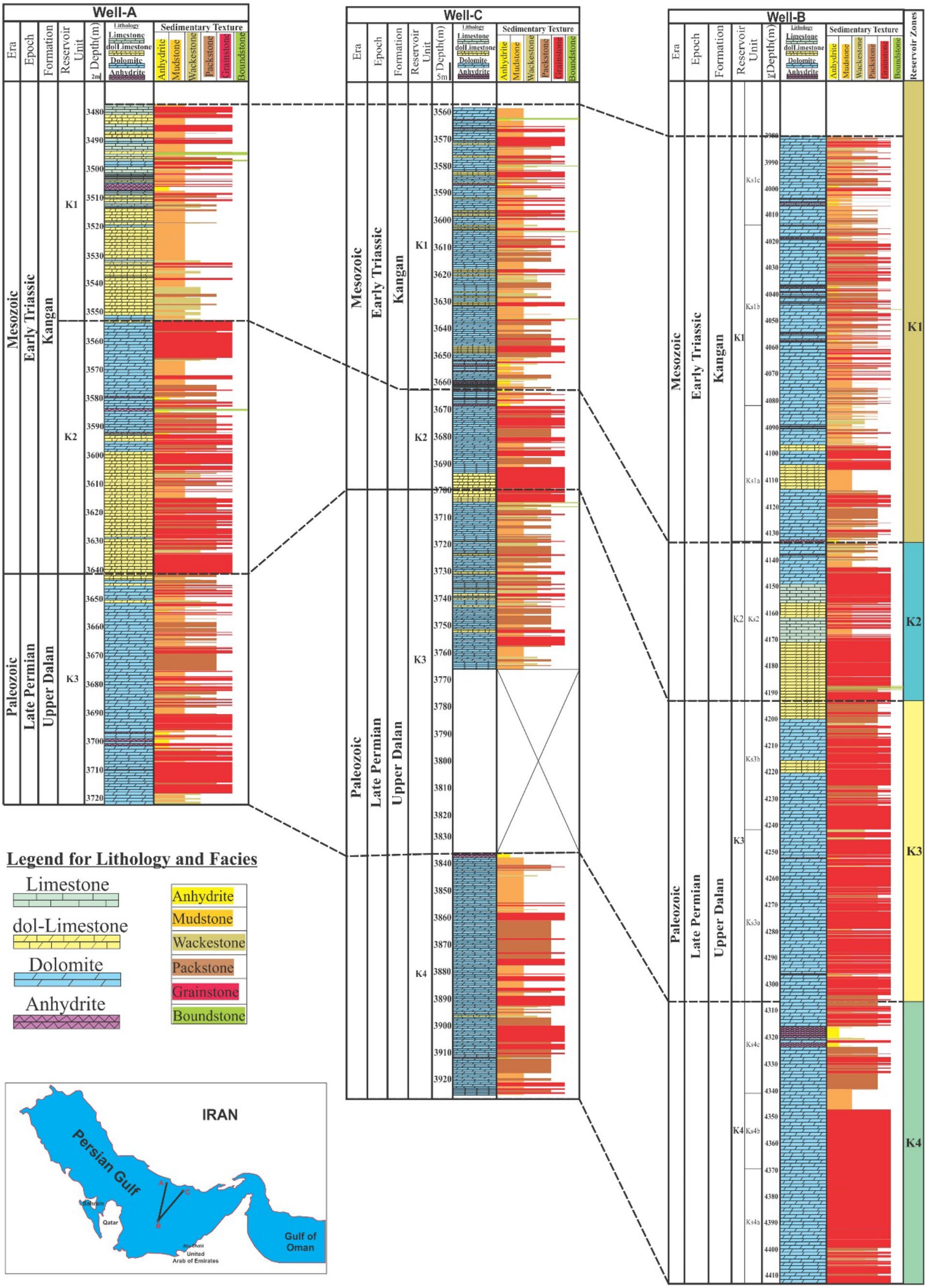


Fig. 2 A schematic model of the depositional environment (carbonate ramp) for different facies of the upper Dalan and Kangan formations in the studied fields. The bar scale on each picture is equal to 5 mm. **A** anhydrite, **B** mudstone, **C** boundstone, **D** and **E** pelloidal-skeletal packstone, **F** ooid grainstone, **G** skeletal-ooid grinstone


Well-A
Well-C
Well-B
Era
Epoch
Formation
Reservoir Unit
Depth(m)
Lithology
Limestone
dol.Limestone
Dolomite
Anhydrite
Sedimentary Texture
Anhydrite
Mudstone
Wackestone
Packstone
Grainstone
Boundstone
Reservoir Zones
Mesozoic
Early Triassic
Kangan
Paleozoic
Late Permian
Upper Dalan
K1
K2
K3
K4
Ks1c
Ks1b
Ks1a
Ks2
Ks3b
Ks3a
Ks4c
Ks4b
Ks4a
2m
5m
Legend for Lithology and Facies
Limestone
dol-Limestone
Dolomite
Anhydrite
Anhydrite
Mudstone
Wackestone
Packstone
Grainstone
Boundstone
IRAN
Persian Gulf
Bahrain
Qatar
Abu Dhabi
United Arab of Emirates
Gulf of Oman
A
B
C

◂**Fig. 3** Facies column of the upper Dalan and Kangan formations in three wells of the studied fields. The reservoir units (K1, K2, K3, and K4) have been correlated between the wells

This texture consists of interwoven crystals of anhydrite with a compacted and impermeable fabric (Fig. 5A).

Nodular anhydrite

This texture is observed in milky white color sparse or a set of coalesced anhydrite nodules on core intervals. The nodule diameter varies from few millimeters to centimeters (less than 10 cm) (Fig. 4D–F). This type consists of fine crystals of anhydrite arranged in a chaotic direction, named felted fabric (Fig. 5C) (Kasprzyk and Orti 1998; Worden et al. 2000). In some cases, due to the growth and coalescence of nodules, a specific structure, named chickenwire (Warren, 2006), is developed (Fig. 4F). Petrographic evidence also shows features of burial anhydrite nodules that are less abundant and important in the reservoir (Fig. 5D). These nodules are formed in facies that are not related to the tidal flat or occure along the stylolites (Machel and Burton 1991).

Sparse crystals of anhydrite

This texture is observed as sparse gray to brown crystals a few millimeters in size, giving a mottled appearance (similar to bird footprins on the mud) to the rock on core intervals (Fig. 4G). The crystals with irregular shape and chaotic orientation are sparsely distributed within the dolomitized mudstone facies of the intertidal environment (Fig. 5E, G). It is also observed in association with algal mats of the intertidal zone as bird's-eye structures (Fig. 5H).

Patchy (poikilotopic) anhydrite cement

This texture with a patchy distribution consists of a set of large crystals, in some cases with inclusions of calcareous matrix or dolomites (Fig. 6A, B). In this study, due to the fact that the main characteristic of this texture is its patchy distribution, it is named patchy cement. This texture in various forms of replacement (Fig. 6A to C) and pore-filling cement (Fig. 6D) has affected different carbonate facies of the reservoir.

Pore-filling pervasive anhydrite cement

This texture as a pervasive cement with uniform distribution occludes all pore spaces, especially in grain-dominated facies such as dolomitized grainstone and packstone facies (Fig. 6E, G, H and I). It is composed of some large crystals that grow from different nuclei (Fig. 6G). In some facies, this cement also shows features of carbonate grain replacement, as remnants of primary carbonate can be seen inside, which has led to the stained and dirty appearance of some components (Fig. 6H).

Fracture-filling anhydrite

This texture consists of large anhydrite crystals, filling the microfractures developed in dolomitized mudstone facies (Fig. 6J). This type is not frequent in the reservoir.

Evaporite seams

This type, in the form of thin seams, is usually derived from anhydrite nodules in dolomitized mudstone facies. It is differentiated from fracture-filling anhydrite by the rugged margins and its association with nodules (Fig. 6K, L).

Discussion

Paragenetic sequence of anhydrite textures in the reservoir

Study of different anhydrite textures in the reservoir shows that anhydrite mineralization has been occurred during early to burial stages of diagenesis, where sulfate-rich brines developed anhydrite as replacement and pore-filling cement in different carbonate facies of the upper Dalan and Kangan formations. Anhydrite layer is the characteristic of supratidal (sabkha) environment, where the evaporative condition allows for the deposition of evaporites in salina (Lucia 2007). Also, anhydrite nodules and sparse anhydrite crystals show close environmental relationship with the anhydrite layers. During the dolomitization of metastable carbonates of tidal flats by hypersaline brines derived from intense evaporation, sparse anhydrite crystals appear (Carozzi 1989; Flügel 2004), and towards the upper parts of the intertidal environment, the presence of sparse anhydrite crystals is increased due to the increase in pore water salinity, where they are gradually graded upward to anhydrite nodules and layers (Fig. 5G) form as displacement primarily within the dolomudstone facies of the tidal flat environment (upper intertidal to supratidal) during the early stages of diagenesis. Chickenwire structure, nodular fabric, and local laminated and massive fabrics of anhydrite interbedded with tidal flat dolomites are characteristic of costal sabkha and hypersaline lagoons which has been provided by the arid conditions of the

Early Triassic-Late Permian times (Alsharhan and Kendall 2003; Alsharhan 2006). Unlike the early diagenetic nodules formed in the hypersaline conditions of tidal flat, burial anhydrite nodules are not limited to the depositional environment (e.g., Machel 1991) and may develop in any carbonate facies (Fig. 5D). The formation of anhydrite nodules during burial can be derived from pore fluids of high salinity (Kasprzyk 2003).

Anhydrite cements in both patchy and uniform forms have significant effect on reservoir quality. Patchy anhydrite represents a wide range of diagenetic domains from early to burial stages. Burial forms of this texture with coarse crystals cut off the features of chemical compaction such as stylolites and solution seams and are also observed with burial cements such as saddle dolomite (Fig. 6C and D). Coarse and sparry anhydrite crystals is thought to be formed under the burial conditions by elevated temperatures, or recrystallization of fine crystalline anhydrite. Dissolution of anhydrite layers and nodules can be considered as the main source of burial anhydrite cements in the carbonates (El-Tabakh et al. 2004). Also, the presence of coarse crystalline poikiltopic anhydrite cement in carbonates of the Middle Permian to Early Triassic Khuff Formation in United Arab has been attributed to a late deep burial event (Alsharhan 2006). The presence of anhydrite cement with uniform distribution between grains and after the development of circumgranular calcite cement (Fig. 6I) indicates that the carbonate facies have not endured significant compaction or cementation before the infiltration of the sulfate-rich brines responsible for the deposition of this cement in their pore system. Therefore, it is attributed to shallow burial diagenesis, similar to what has been reported by Saller and Henderson (1998) for the Permian carbonate reservoirs of West Texas. Furthermore, the presence of pevasive anhydrite as replacement of allochems and sparry calcite cement in the Late Bathonian–Early Callovian Kuldhar and Keera Dome Carbonates of Western India has been attributed to deep burial environment (Ahmad et al. 2006). Fracture-filling anhydrite with coarse crystals within microfractures is thought to be a burial cement (Tavakoli et al. 2011).

Anhydrite and reservoir quality

Occluding the pore system of reservoir rocks by anhydrite indicates that it could have acted as a destructive diagenetic agent on reservoir quality. Figure 7 demonstrates the anhydrite percent against core porosity and permeability of different carbonate facies (mud-dominate and grain-dominate). According to this figure, there is no definite trend, especially for the mud-dominated facies on the plots. This is attributed to various anhydrite textures in different carbonate facies and also the effect of other diagenetic processes such as compaction, cementation, and dissolution on pore system properties of reservoir rocks. Mud-dominated facies that have been deposited in a tidal flat environment, show different reservoir quality based on their facies categories. Carbonate facies of MF-1 are characterized by low porosity and permeability values (Fig. 8). These facies are partly to completely dolomitized mudstones/wackestones with microcrystalline dolomites and microporosity (Fig. 9A). In some of these facies, anhydrite is observed as sparse crystals, nodules, and patchy replacement forms (Fig. 9B). Also, the presence of microfractures in a few samples shifts the position of the facies on the poroperm plot towards high permeability values (Fig. 8). In contrast, dolomitized mudstone and wackestone facies of MF-2 due to the effect of dissolution (Fig. 9C) are characterized by high values of porosity (Fig. 8). Due to the presence of anhydrite remains in some dissolution vugs (Fig. 9D), a part of the vugs is attributed to the dissolution of sparse anhydrite crystals or cements in these facies. Therefore, it can be concluded that despite the low reservoir quality of mud-dominated facies, the presence of anhydrite as sparse crystals and nodules makes these facies potentially prone to the creation of dissolution vugs, and consequently improving their reservoir quality.

Table 3 Facies categories of the upper Dalan and Kangan formations based on the dominant diagenetic processes and pore types in the studied fields

Carbonate facies	Facies categories
Grain-dominate	
Tight dolograinstone/packstone facies cemented by pervasive anhydrite	GF-1
Tight grainstone facies cemented by clacite	GF-2
Grainstone facies with moldic pore types	GF-3
Facies with patchy anhydrite and dissolution vugs	GF-4
Dolostone facies with intercrystalline porosity	GF-5
Mud-dominate	
Tight dolomudstone/wackestone facies	MF-1
Dolomudstone/wackestone facies with isolated vugs	MF-2

In grain-dominated facies ctegories (GF-1 to GF-5), anhydrite is mainly observed as pervasive and patchy cement. The presence of pervasive anhydrite cement in dolograinstone and dolopackstone facies (GF-1) makes them tight carbonate facies of the reservoir. Therefore,

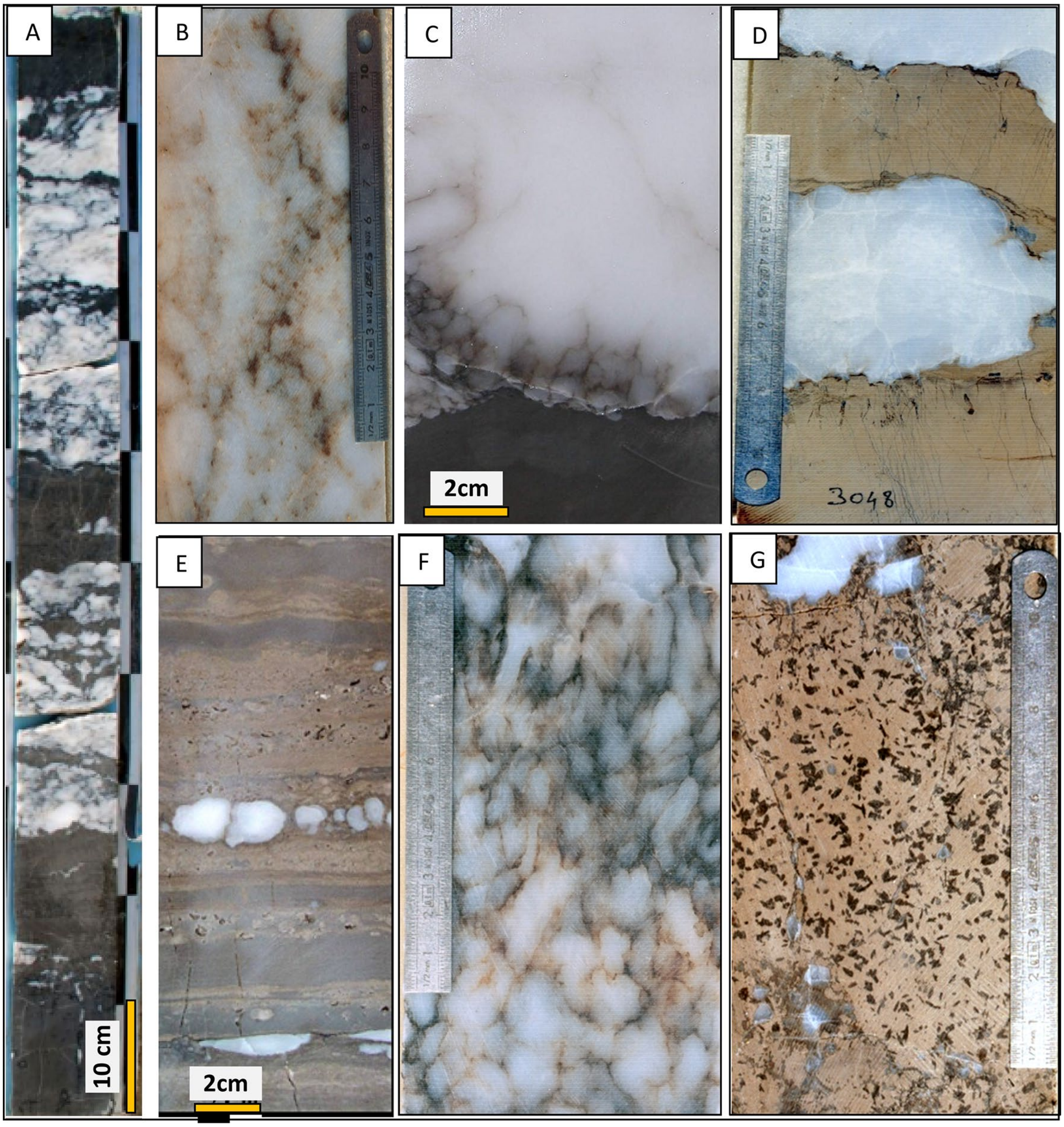
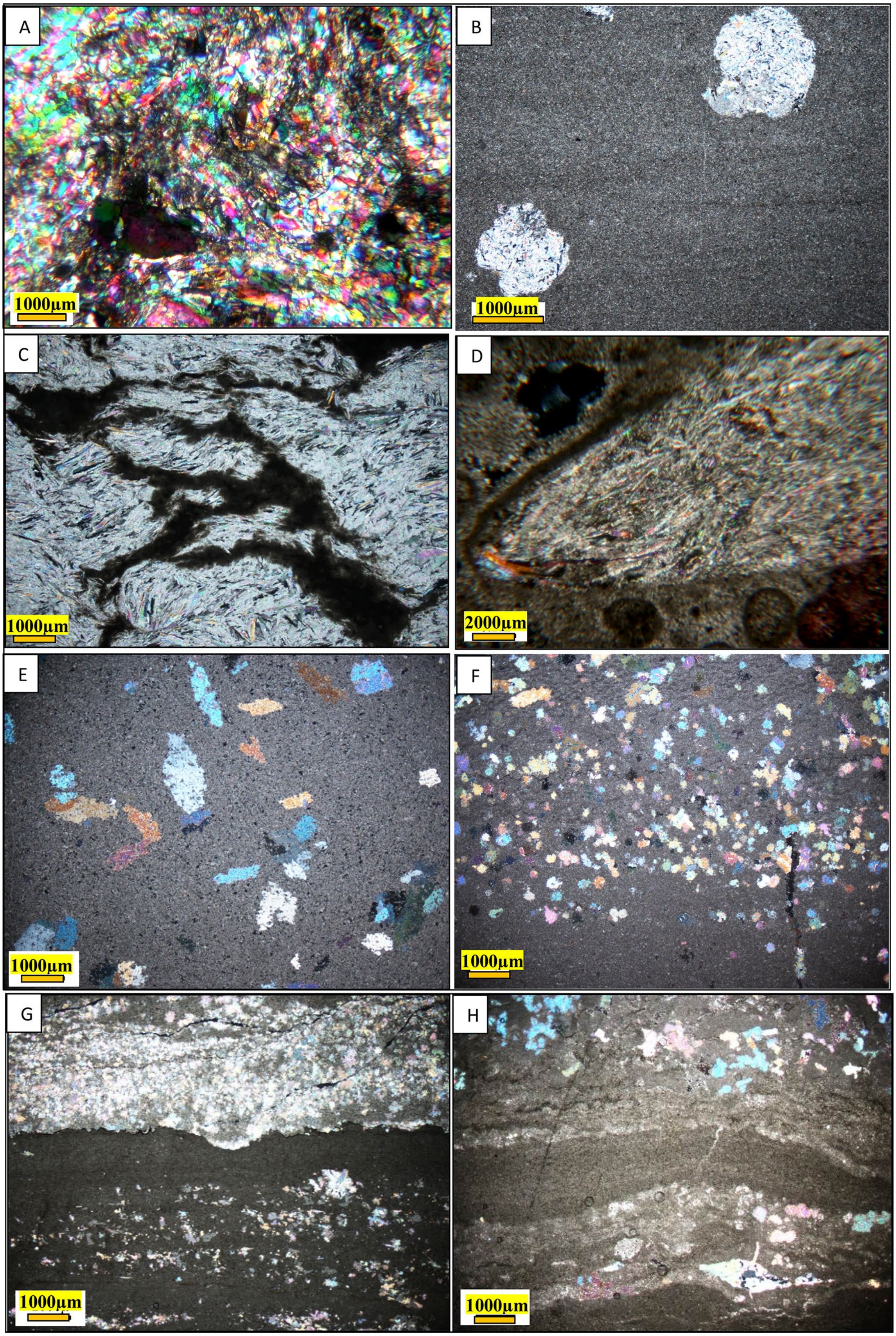


Fig. 4 Core photos of some anhydrite textures in the upper Dalan and Kangan formations in the studied fields. **A** Interlayers of anhydrite and mud-dominated carbonates. **B** Anhydrite layer with mosaic fabric and residuals of carbonate muds. **C** Mosaic anhydrite layer with dolomudstone at the base. **D** Anhydrite nodule within a mudstone facies. **E** Anhydrite nodule within the laminated facies of intertidal environment. **F** A set of coalesced anhydrite nodules in the form of a chicken-wire structure. **E** Sparse anhydrite crystals associated with anhydrite nodule (top of the picture) within the carbonate matrix. The length of the ruler on core photos is 10 cm.

these facies, similar to tight grainstone facies (GF-2) (cemented by equant and blocky calcite), are characterized by low reservoir quality (Figs. 10A, 11A, and B). Pore-filling anhydrite cement was also considered to be the predominant cement in the Silurian shallow marine carbonates of the Dirk Hartog Group of the Gascoyne Platform in Western Australia (El-Tabakh et al. 2004). Patchy anhydrite cement has occluded pore spaces in grain-dominated facies of the reservoir to varying degrees. In grainstone facies with moldic pores (GF-3), there is no sign of anhydrite, or it has been developed as patchy cement occupying a part of total porosity (Fig. 11C, D). In some tight calcite-cemented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◂**Fig. 5** Thin section photomicrographs (all in XPL) of anhydrite textures in the upper Dalan and Kangan formations in the studied fields. **A** Anhydrite layer with interwoven crystals and a compacted fabric. **B** Sparse anhydrite nodules within a dolomitized mudstone facies of supratidal environment. **C** Anhydrite nodules consisting of fine crystals with a felted fabric. **D** Burial anhydrite nodule developed in a grain-dominated facies. **E**, **F** Sparse anhydrite crystals with irregular shape in a dolomitized mudstone of intertidal environment. **G** The presence of anhydrite crystals as growth within algal mats of the intertidal zone in the form of bird-eye structure. **H** Sparsely distributed anhydrite crystals in a dolomitized mudstone of the intertidal zone

facies, patchy anhydrite has acted as a final burial cement, mostly replacing grains and calcite cement (Fig. 6B). In addition, partial dissolution of pervasive anhydrite cement, as observed in some dolograinstone facies (GF-4), gives a patchy feature to this cement. Similarly, the presence of ptachy anhydrite cements associated with non-cemeted parts in dolostones of the Jurassic Arab C and D members has been attributed to partial dissolution or incomplete cementation by anhydrite (Morad et al. 2012). The produced large dissolution vugs effectively contribute to high porosity values and especially permeability observed in these facies (Figs. 10C and 11E, F). In dolostone facies (GF-5), anhydrite is marked as a patchy burial cement. The development of intercrystalline and dissolution vugs with good connectivity makes these facies characterized by high reservoir quality (Figs. 10D and 11G, H). Table 4 summarizes the average values of well logs and core porosity and permeability data for different facies categories, and their related reservoir rock types introduced in this study. Generally, the identified facies categories could be classified into three main reservoir rock types (RT-1, RT-2, and RT-3) based on their reservoir properties. RT-1 includes the tight carbonate facies with low reservoir quality related to their cemented fabric (GF-1 and GF-2) and mud-dominated texture (MF-1). RT-2 includes carbonate facies with isolated vugs and moldic pore types. Therefore, this rock type is characterized by high porosity and low permeability values (GF-3 and MF-2). RT-3 includes the carbonate facies with the highest reservoir quality related to large dissolution vugs and intercrystalline pore types (GF-4 and GF-5).

The vertical distribution of the introduced facies categories and reservoir rock types in one of the studied fields is shown in Fig. 12. Also, Fig. 13 demonstrates the thickness of the introduced facies categories in different reservoir zones (K1 to K4) of the upper Dalan and Kangan formations.

Despite the destructive role of anhydrite on reservoir quality, as a pore-filling cement, later diagenetic processes such as dissolution on this cement can improve the reservoir quality. Therefore, the impact of anhydrite on reservoir quality can be considered in two extremes. On one hand, pervasive cementation of pore spaces in grain-dominated facies related to RT-1 (GF-1) has created tight facies with low porosity and permeability values. On the other hand, the effect of dissolution on this cement during burial has resulted in reservoir facies with high reservoir quality related to RT-3 (GF-4). This has been discussed in previous studies (Kadkhodaie-Ilkhchi et al. 2008) as the dual role of pore-filling and pervasive anhydrite as a destructive cement and a constructive agent on reservoir quality. At the same time that this cement occludes the pore spaces of the rock during the shallow burial, it prevents the facies from more compaction, and dissolution of this cement in the next stages leads to the development of dissolution vugs and improvement of reservoir quality. Between these extremes, the effect of anhydrite as a patchy cement on reservoir quality is different, which depends on the percent of pore volume occupied by this cement. Similarly, Mohammed-Sajed and Glover (2022) in their studies on the Lower Jurassic Butmah Formation in northwestern Iraq, mentiioned anhydritization as the main controlling factor in reducing and improving the reservoir quality through cementation and late anhydrite dissolution, respectively.

Although the impact of anhydrite on reservoir quality in mud-dominated facies of tidal flat is not as significant as that observed in grain-dominated facies (Fig. 7), the presence of anhydrite as sparse crystals in these facies increases their chance for improving the reservoir quality through dissolution (Fig. 8 and Fig. 9C, D).

Investigation of facies and reservoir rock types shows that the destructive effect of anhydrite on reservoir zones in the Kangan Formation is more dominant than the upper Dalan. In contrast, the upper Dalan includes a higher percent of facies and rock types with the effect of anhydrite dissolution (Figs. 12 and 13). The reservoir interval of these formations consists of some shallowing upward sequences, starting with grain-dominated facies of shoal/lagoon at the base, terminated by mud-dominated facies and evaporites of tidal flat. These sequences in K3 and K4 zones of the upper Dalan Formation predominantly include tight and cemented carbonate facies with low reservoir quality (RT-1). In K1 and K2 of Kangan Formation, grain-dominated facies at the base of shallowing upward sequences include the most promising facies (RT-2 and RT-3), where the effect of dissolution is predominant.

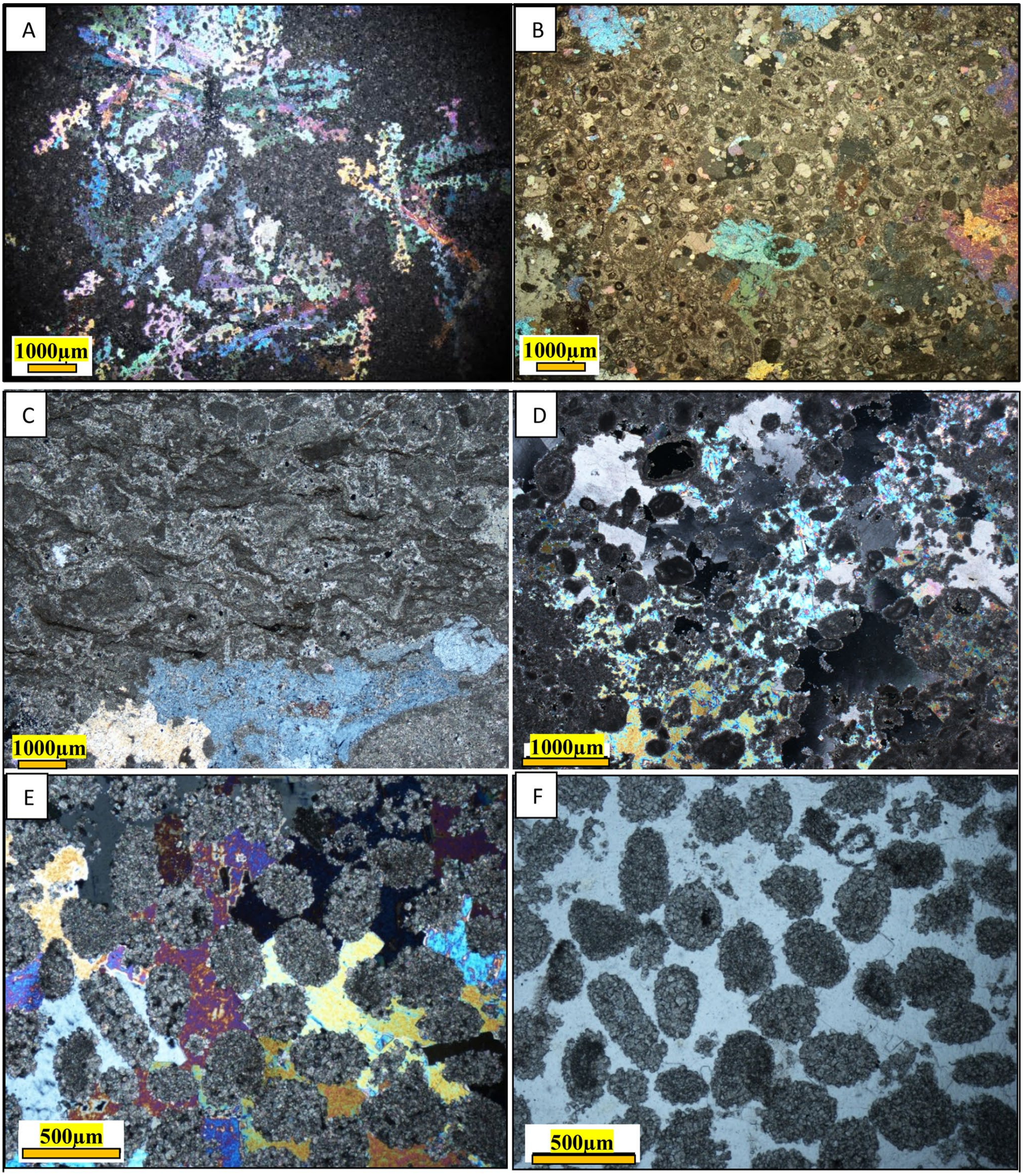


Fig. 6 Photomicrographs (all in XPL except **F** and **H**) of some textures of anhydrite. **A** Patchy (poikilotopic) anhydrite as a replacement form with inclusions of dolomite. **B** Patchy anhydrite cement in a cemented grainstone facies. **C** Development of patchy anhydrite as a burial cement after compaction. **D** Association of burial anhydrite cement with saddle dolomite. **E** Pore-filling anhydrite cement in a dolomitized grainstone. **F** Photomicrograph E in PPL. **G** Pore-filling anhydrite consists of some large crystals. **H** Anhydrite cement as pore-filling and replacement in grainstone facies. **I** Development of pore-filling anhydrite cement at shallow burial depth and after early cricumgranular calcite cement. **J** Fracture-filling anhydrite with coarse crystals developed in a dolomitized mudstone. **K**, **L** Evaporite seams derived from anhydrite nodules

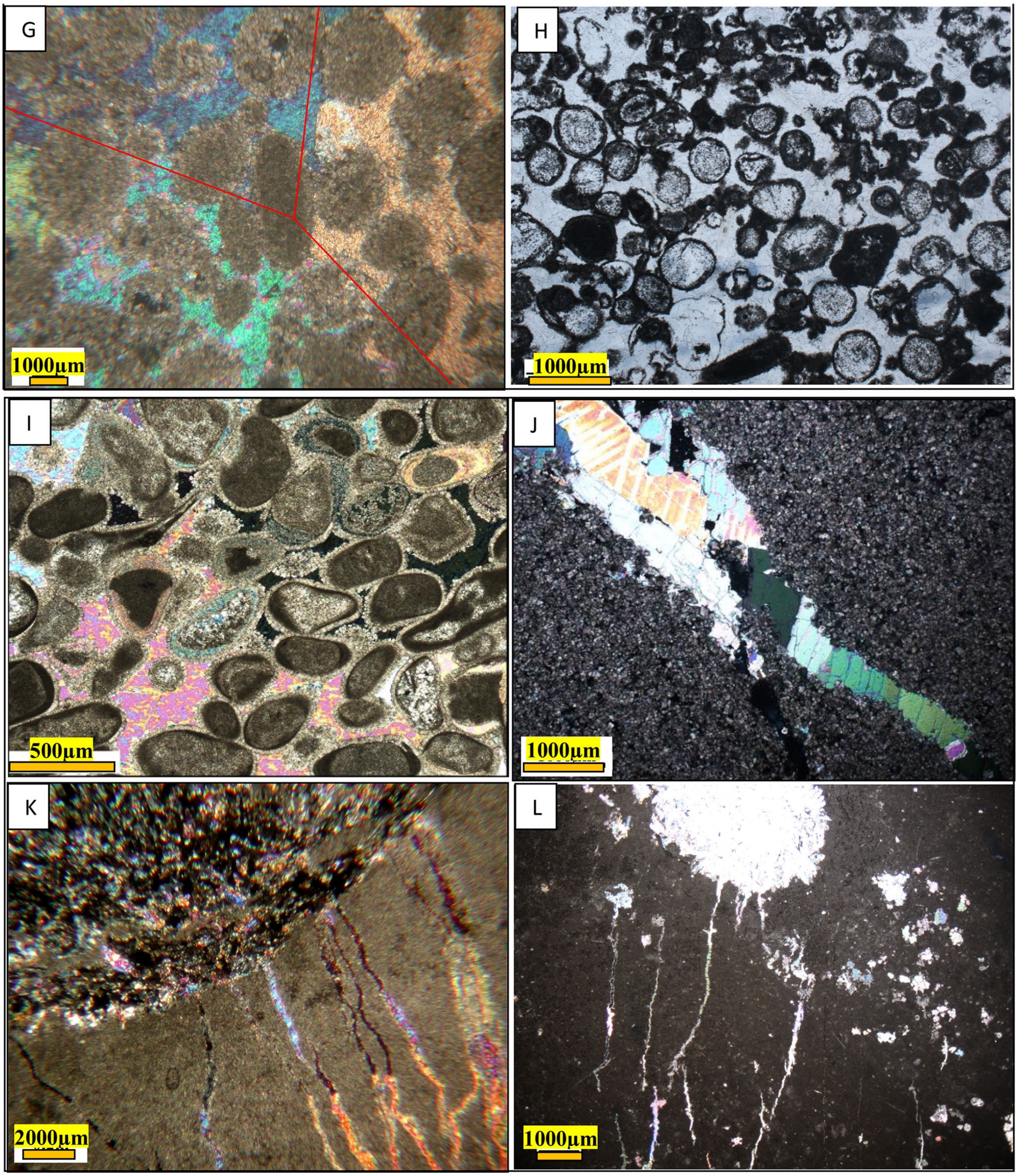


Fig. 6 (continued)

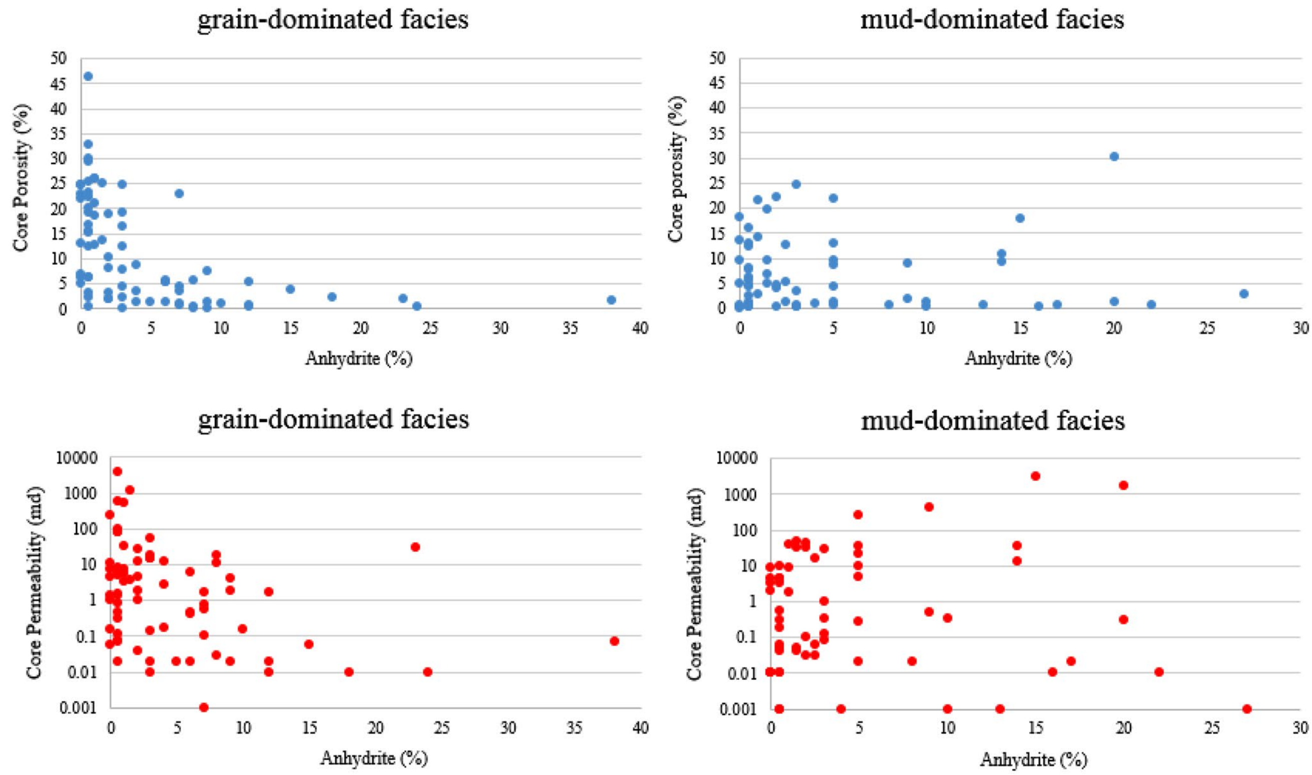


Fig. 7 Cross plots of anhydrite percent against core porosity and permeability data for grain-dominated and mud-dominated facies of the studied reservoirs

Factors controlling the distribution of anhydrite in the reservoir

According to petrographic evidence, different carbonate facies have been affected to varying degrees by anhydrite mineralization during the early to burial stages of diagenesis. In other words, anhydrite in various forms (i.e., displacement, replacement, and pore-filling) and textures have imported its effects on reservoir properties of carbonate facies of the reservoir interval. Investigation of different anhydrite textures in the reservoir interval demonstrates that the presence of anhydrite is not random, and its distribution is controlled by the various factors, including carbonate facies (mud-dominate versus grain-dominate), the source and accessibility of sulfate-rich brines, and the effect of compaction and cementation before anhydrite mineralization, and dissolution after it. In grain-supported and grain-dominated carbonate facies, anhydrite is developed as pore-filling cement with uniform and pervasive distribution (Fig. 14A). In contrast, in mud-supported and mud-dominated facies, in which the brine flow is limited, anhydrite is mainly developed as a replacement form with limited distribution and smaller crystal sizes (Fig. 14B). Furthermore, the presence and accessibility of sulfate-rich brines in pore systems of the rock is another critical factor for anhydrite development and mineralization. As in grainstone facies with moldic pore types, anhydrite is not observed (Fig. 11B, C), or it exists as a late burial cement with limited and patchy distribution (Fig. 6B). These facies have not expirenced the effects of brines, or the brines flow was limited due to the effect of compaction and significant calcite cementation. Besides, the brine source, related to the condition of the depositional

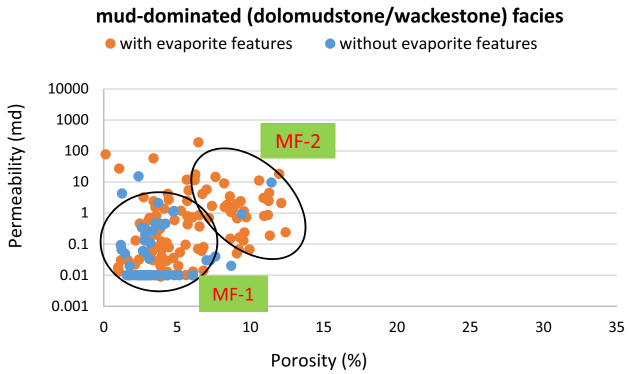


Fig. 8 Core porosity–permeability plot for mud-dominated facies of the upper Dalan and Kangan formations in the studied fields. MF-1: tight facies without the effect of dissolution. MF-2: facies with isolated dissolution vugs

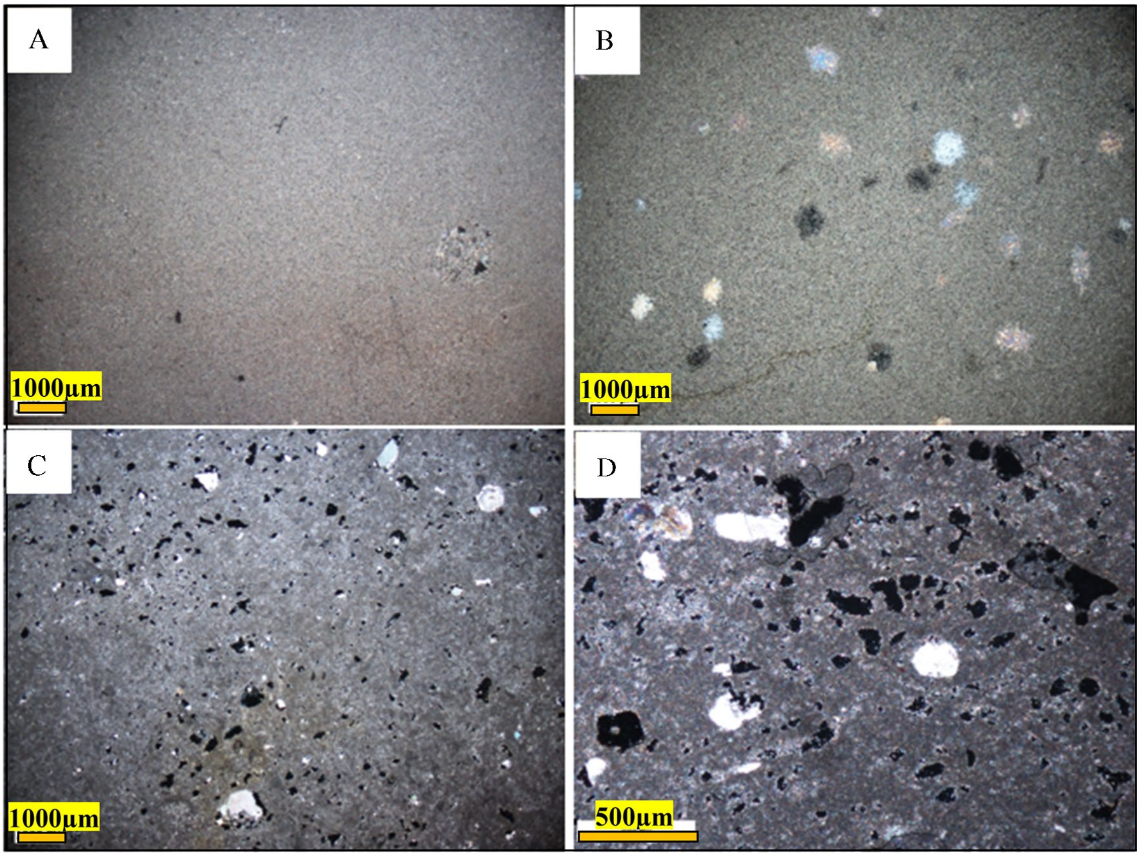


Fig. 9 Thin section photomicrographs (in XPL) of mud-dominated carbonates of the studied reservoirs. **A** Dolomudstone of tidal flat environment. **B** Dolomudstone with sparse anhydrite crystals. **C** Dolomudstone to wackestone with isolated vugs and bioclast molds. **D** Dolomudstone with isolated vugs. In some vugs, traces of evaporite cement indicate some of them are the molds of sparse anhydrite crystals

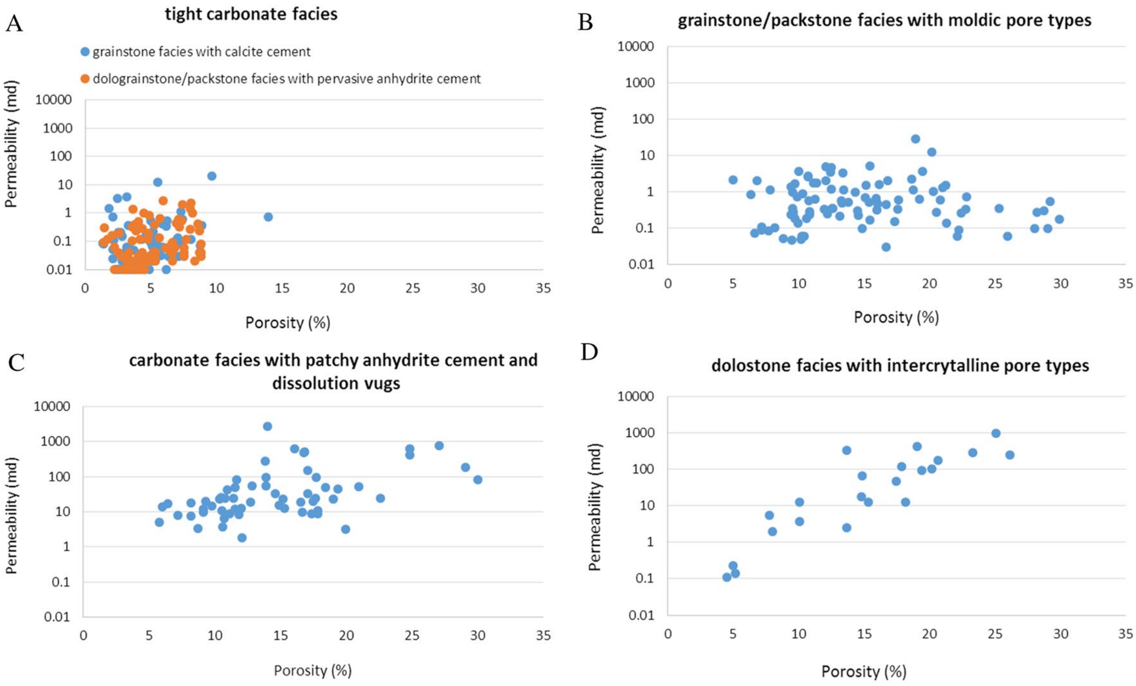
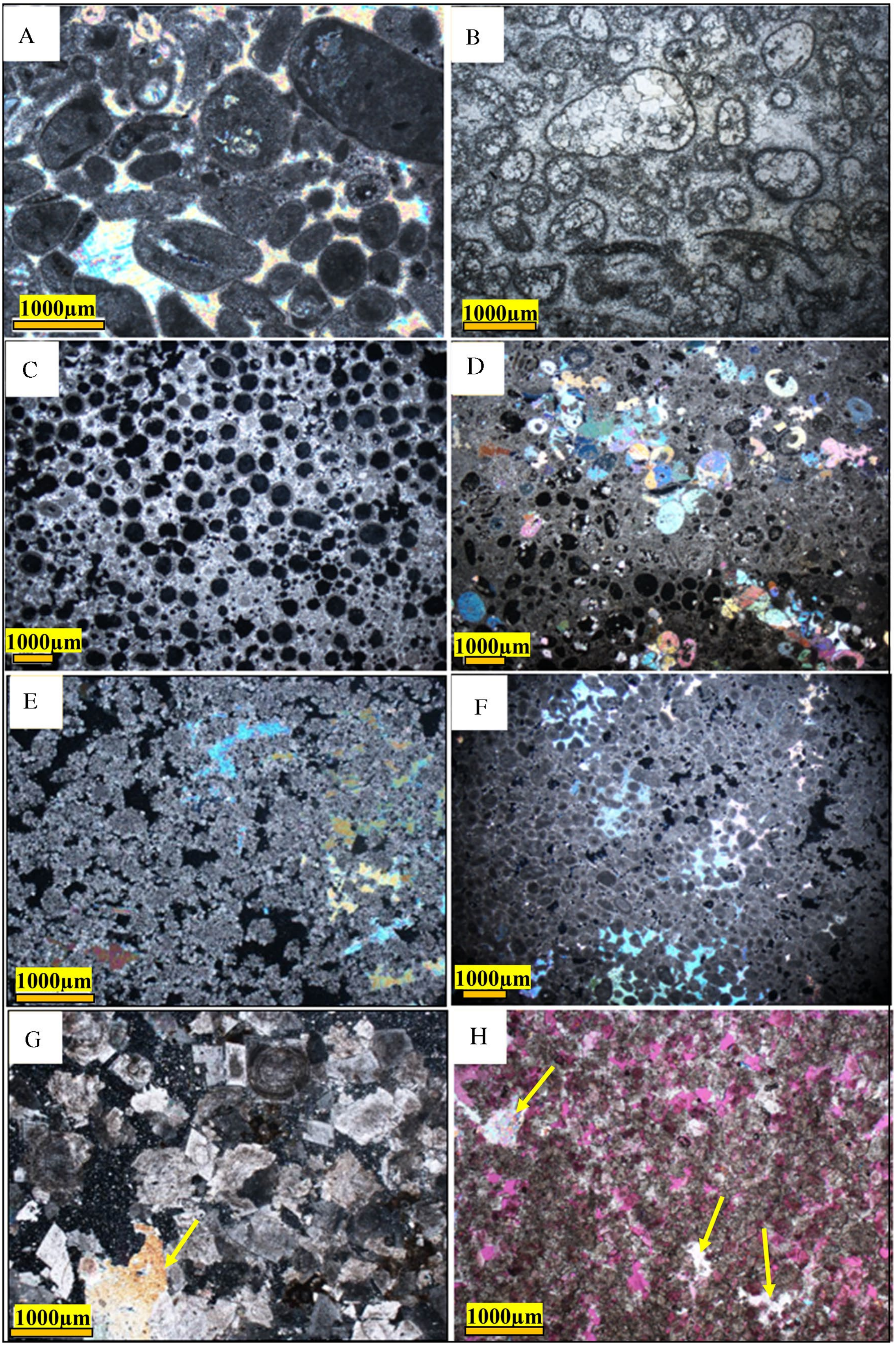


Fig. 10 Core porosity–permeability plot for grain-dominated facies of the upper Dalan and Kangan formations in the studied fields


A
1000µm
B
1000µm
C
1000µm
D
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E
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F
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G
1000µm
H
1000µm

◀**Fig. 11** Thin section photomicrographs of grain-dominated carbonates of the studied reservoirs. All images except B are in XPL. **A** Tight carbonate facies cemented by pervasive anhydrite. **B** Tight carbonate facies cemented by calcite. **C** Carbonate facies with isolated moldic pore types. **D** A part of moldic pores in grainstone facies has been occluded by patchy anhydrite cement. **E** Carbonate facies with large dissolution vugs. The connection between vugs indicates they have derived from the dissolution of pore-filling anhydrite cement. **F** Dissolution of pore-filling anhydrite cement between grains has given a patchy feature to this cement. **G**, **H** Intercrystalline pore types associated with dissolution vugs. In some parts, traces of anhydrite (yellow arrows) are observed as pore-filling cement

environment (early diagenesis), or burial diagenesis, determines the distribution of anhydrite in different forms and textures in the reservoir. Consequently, in a practical view for reservoir studies, the identified anhydrite textures can be genetically classified into two major groups as follows (Fig. 15).

1) Anhydrite textures related to the depositional environment conditions: These textures include layered, nodular, and sparse crystals that are primarily formed as early diagenetic growth of gypsum as replacement and displacement and developed in the hypersaline condition of tidal flat. They are mainly related to the condition dominating the environment and pore water chemistry (e.g., temperature and salt concentration). These textures are associated with the depositional and diagenetic evidence of the depositional environment (e.g., lamination, algal mats, bird-eye structures, and microcrystalline dolomite) (Figs. 4 and 5). These textures are important from the point of view of sequence stratigraphy because their formation is associated with changes in sea level. For example, deposition of evaporites in the Badenian basin of the Carpathian Foredeep in Poland is attributed to regional sea level fall (Oszczypko 1999). Moreover, Schröder et al (2003) in developing a depositional model for the evaporite–carbonate sequences of the terminal Neoproterozoic–Early Cambrian Ara Group evaporites in south Oman, indicated evaporite deposition can occure in all sea level phases including highsatnd (HST), lowstand (LST) and transgressive (TST) system tracts, but the bulk volume of evaporites formed in a lowstand situation.

2) Anhydrite textures related to burial diagenetic fluids: These textures include replacive, and pore-filling anhydrite cements with pervasive and patchy (poikilotopic) distribution as well as facture-filling and evaporite seams (Fig. 6). Burial diagenetic fluids have an essential role in developing these textures in the reservoir. Therefore, their genesis and development are not limited to specific facies and are independent of the depositional environment conditions. These textures are important from a reservoir quality perspective due to their destructive role as a pore-filling cement, as also indicated in other fields related to these formations in Iran and their equivalent in Arabian countries (e.g., Al-Jallal 1987; Ehrenberg et al., 2007; Esrafili-Dizaji and Rahimpour-Bonab 2013).

Conclusion

The carbonate reservoirs of the upper Dalan and Kangan formations in three studied fields of the Persian Gulf have been significantly affected by the effect of diagenesis. The results from petrographic observations and core description show that the main diagenetic processes affecting the pore system properties of these formations are cementation, dissolution, and dolomitization. Anhydrite in various forms and textures is observed in different carbonate facies of the reservoir interval. Textures related to the depositional environment conditions (layered, nodular, and sparse crystals) and textures related to burial diagenetic fluids (pervasive cement, patchy cement, evaporate seams, and fracture-filling) were identified. Among these textures, pervasive and patchy textures have the main effect on reservoir quality, especially in grain-dominated facies. The distribution of anhydrite and its impact on reservoir quality is significantly dependent on the diagenetic history of the studied formations before anhydrite mineralization (i.e., the significant effect of other diagenetic processes such as compaction and calcite cementation) and after it (i.e., dissolution).

Table 4 Average values of well logs and core porosity and permeability data of the carbonate facies categories and their related reservoir rock types in the studied reservoirs

Reservoir rock type	Facies categories	NPHI (v/v)	DT (μs/ft)	RHOB (g/cm3)	Phi (%)	K (mD)
RT-1	GF-1	0.054	50.77	2.79	5.68	0.24
	GF-2	0.049	54.9	2.67	4.26	0.79
	MF-1	0.024	51.57	2.74	3.36	0.68
RT-2	GF-3	0.087	58.12	2.59	17.78	1.54
	MF-2	0.054	52.06	2.75	7.65	3.80
RT-3	GF-4	0.111	56.95	2.65	15.17	160.04
	GF-5	0.085	57.14	2.67	14.03	192.31

Fig. 12 The sedimentological column showing variations in depositional facies and reservoir rock types as well as core poro-perm data in one of the studied fields. Green arrows indicate the shallowing upward sequences within the reservoir interval

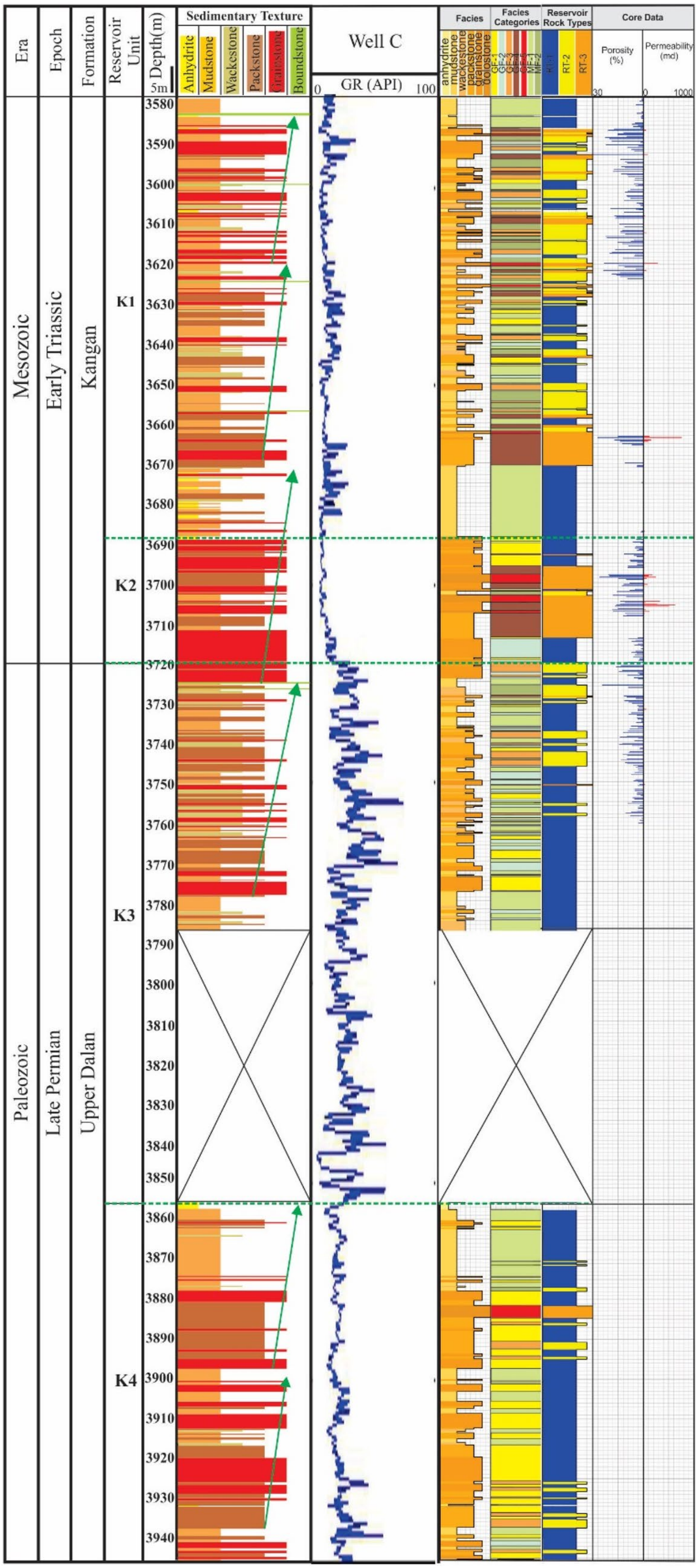
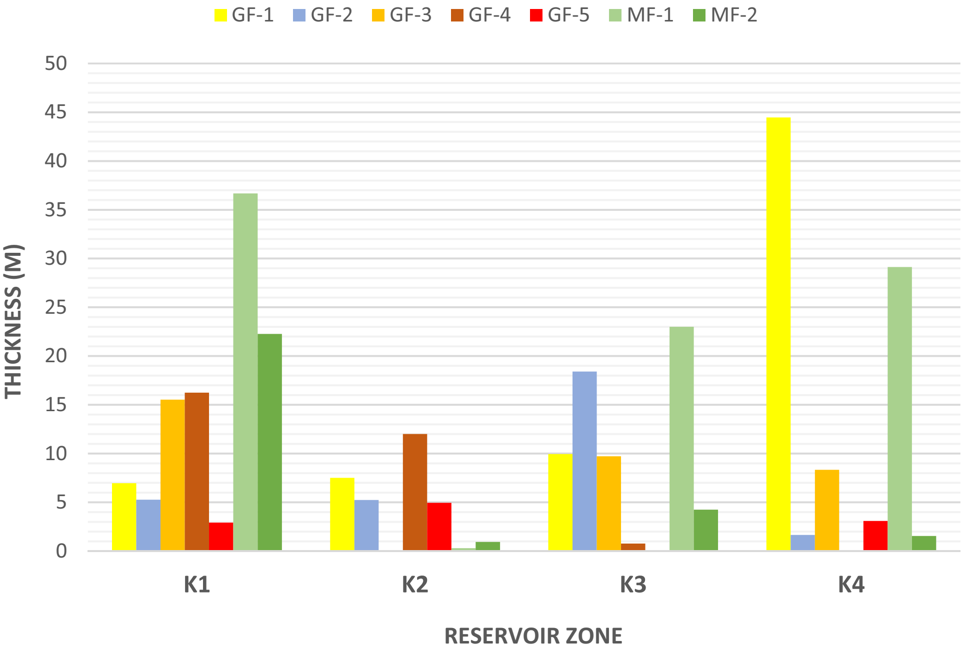


Fig. 13 The thickness of the identified facies categories in different zones (K1, K2, K3, and K4) of the studied formations



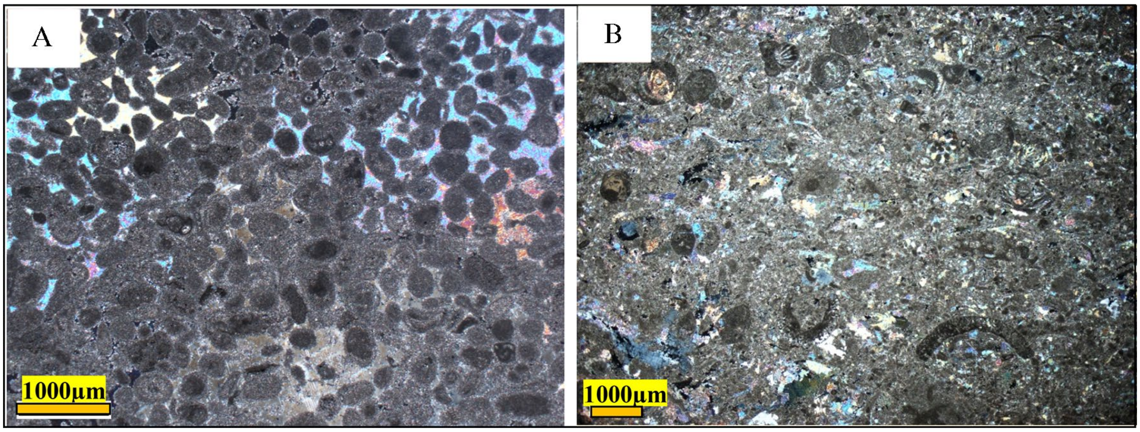


Fig. 14 Photomicrographs (in XPL) showing the effects of depositional texture on the distribution of anhydrite in the reservoir. **A** Pervasive and pore-filling anhydrite cement with large crystals and uniform distribution in a grain-supported carbonate facies of shoal. **B** The presence of anhydrite (colored parts of the picture) with limited distribution and small crystal sizes in mud-supported carbonate facies of lagoon

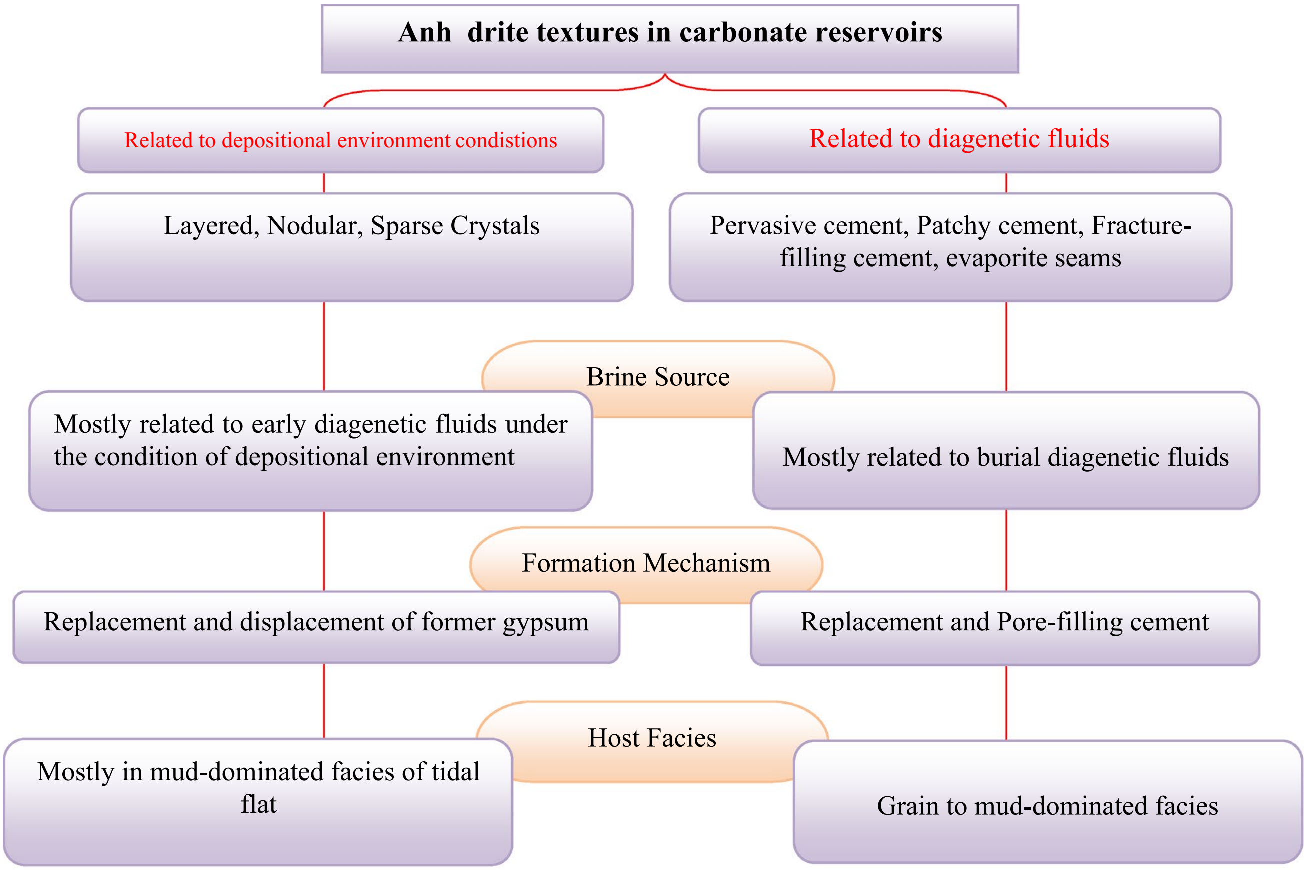


Fig. 15 Genetic classification of anhydrite textures in carbonate reservoirs

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