

Research paper

Microfacies, depositional environment and diagenetic evolution controls on the reservoir quality of the Permian Upper Dalan Formation, Kish Gas Field, Zagros Basin



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ABSTRACT

The Upper Permian Upper Dalan Formation contains one of the largest gas reservoirs in the world. The formation consists of carbonates with some evaporite intercalations that developed on a gently sloping homoclinal carbonate ramp facing the Late Permian Paleo-Tethys Ocean. This study focuses on the Kish Gas Field (Zagros offshore basin situated between Iran and Qatar), and is based on a 222-m-thick continuous core. Based on the integration of core- and wireline-log data coupled with petrographic analyses of 580 thin sections, three major depositional environments (facies belts) with 11 carbonate microfacies are identified. These include (1) sabkha to tidal flat (laminated to massive anhydrite, dolomudstone with anhydrite nodules, dolomudstone, and intraclastic dolowackestone), (2) lagoon and leeward shoals (bioclastic wackestone/dolowackestone to packstone, and peloid dolopackstone and peloid–bioclastic dolopackstone), and (3) mobile (windward) sand shoal (oid–peloid dolograstone, ooid dolograstone, ooid–intraclast dolograstone, ooid–bioclast dolograstone–packstone, and coarse bioclast–intraclast dolograstone). Diagenetic evolution of the Upper Dalan Formation is associated with evaporative marine, shallow-water normal-marine, meteoric, and burial diagenetic environments. Common diagenetic effects include dolomite and calcite cementation, mechanical and chemical compaction, dissolution, dolomitization, and evaporative (anhydrite) mineralization.

Reservoir quality is strongly affected by variations in the original rock fabrics and subsequent diagenetic alterations. The most common pore types include interparticle, moldic, and connected vug (fracture and cavernous). The interparticle porosity–permeability relationship for the studied facies suggests that the reservoir quality is not affected by different crystal sizes and most samples plot in the low porosity and low to high permeability field, or display Lucia class 1 or 2 petrophysical relationships. The study shows that the pervasive pore-filling anhydrite mineralization lead to a significant decrease in porosity and permeability; poikilotopic anhydrite cement reduced matrix porosity, but the pore size was less affected.

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1. Introduction

The Persian Gulf Basin is considered as one of the most prolific hydrocarbon basins in the world. It consists of a multi-stage

petroleum system composed of major reservoir units spanning the Paleozoic to Cenozoic (Sadooni and Alsharhan, 2004). In the Late Paleozoic system, the Upper Dalan Formation constitutes one of the most important gas reservoir units due to existence of a thick dolomitized carbonate sequence with appropriate reservoir properties and a few evaporite intervals that act as hydrocarbon (gas) seals (Insalaco et al., 2006) (Fig. 1). The formation contains more than 50% of the current gas reserves discovered in the

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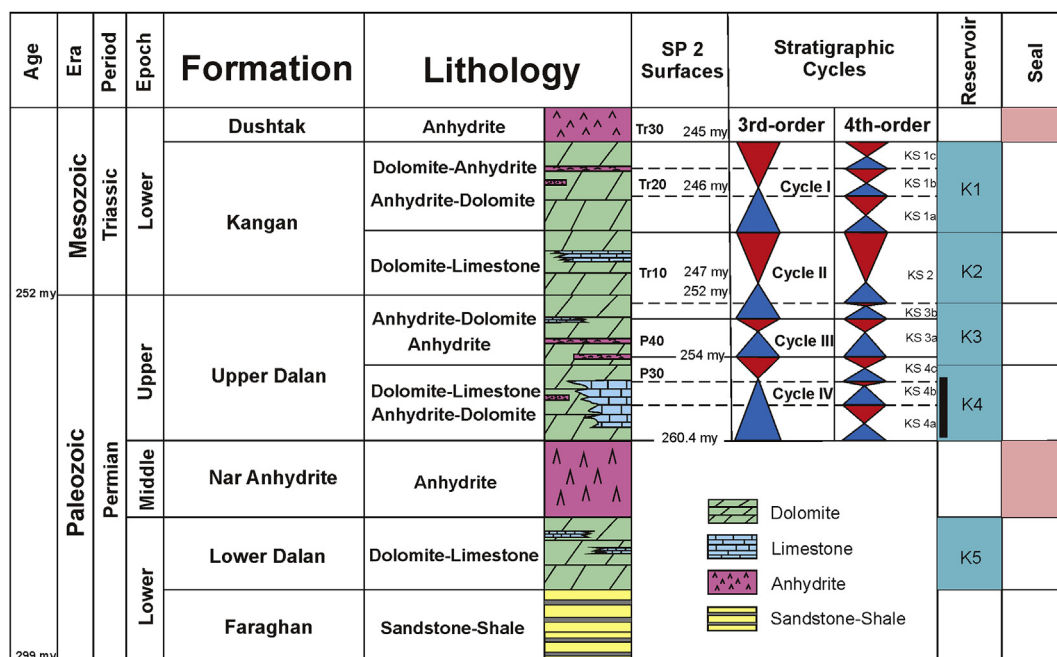


Figure 1. Generalized Upper Permian–Lower Triassic chronostratigraphy, lithostratigraphy, and sequence stratigraphic framework of the Zagros Basin (modified from Sharland et al., 2001; Insalaco et al., 2006). The studied Upper Dalan Formation comprises a major reservoir of the Zagros basin (K4).

Persian Gulf Basin (Sadooni and Alsharhan, 2004), as well as some of the most important upper Paleozoic gas reserves in the world. The Upper Dalan Formation is equivalent to the subsurface Upper Khuff Formation of the Arabian Peninsula (Saudi Arabia, Kuwait and Oman; Ehrenberg et al., 2007), the subsurface Chia Zairi Formation in Iraq (Aqrabi, 1998), the surface Bih and Hagil Formations of the eastern United Arab Emirates (Strohmer et al., 2002; Maurer et al., 2009), and the surface Saiq and Mahil Formations of Oman (Koehler et al., 2010, 2012). However, unlike the well-studied Khuff Formation (El-Bishlawy, 1985; Alsharhan and Kendall, 1986; Al-Jallal, 1987, 1994, 1995; Alsharhan, 1993; Al-Aswad, 1997), the Upper Dalan Formation has received much less attention, both in the subsurface and outcrop-based studies. Szabo and Kheradpir (1978) carried out the first sedimentological and stratigraphical study in the Zagros area in which they established both well- and surface reference sections for the Permian–Triassic of the Zagros Basin, and briefly described the Upper Dalan Formation. Following this pioneer work, Insalaco et al. (2006) published a comprehensive study on the Upper Permian to Lower Triassic reservoirs in Iran, addressing also the stratigraphy and biostratigraphy of the Upper Dalan Formation by using both surface and subsurface data from the South Pars field. Based on the subsurface data from South Pars, North Pars, and Khu-I-Manddata fields, Ehrenberg (2006) and Ehrenberg et al. (2007) focused on the Khuff reservoir porosity destruction and its syn-depositional and diagenetic causes. A review of Permian–Triassic reservoir rock properties, including the Upper Dalan, was recently presented based on re-examination of core, wireline and thin-section data from the Fars Province and the adjacent offshore by Esrafil-Dizaji and Rahimpour-Bonab (2013).

This study focusses on the microfacies, diagenesis, porosity–permeability relationships, and extensive anhydrite cementation of the Upper Dalan Formation in the Kish Gas Field, Zagros region, which is located at the southern end of the Zagros fold-and-thrust belt (Fig. 2). It is the first detailed study in the area

that focuses on the influence of carbonate–evaporite facies and its diagenetic alterations on the reservoir heterogeneity, with the main goal to provide a better understanding of stratigraphy and reservoir complexity of this supergiant gas reservoir in the Middle East.

2. Geological setting

The Phanerozoic Zagros Basin is located between the central Iranian plateau in the NE, the Arabian Shield to the SW and the Taurides of Turkey to the NW (Alsharhan and Nairn, 1997; Bahroudi and Talbot, 2003). The tectonostratigraphy and evolution of the Zagros Basin has attracted the attention of geologists for decades due to its unique and complex geological history characterized by development of a multi-stage supergiant petroleum system (Sadooni and Alsharhan, 2004). Beside the sedimentation processes that resulted in more than 10 km thick sedimentary supersequence (Heydari, 2008), the history of Zagros Basin is marked by long periods of uplift without any sedimentation. The oldest sediments in the Fars Area date from the Precambrian and are composed of evaporitic facies of the Hormuz Formation. These salt deposits are overlain by Cambro-Ordovician mixed carbonate-siliciclastic shallow-marine succession (Bordenave, 2002). During Silurian period (Llandoveryan), the entire basin has been flooded by a rapid sea-level rise that led to the creation of the organic-rich shale within an anoxic basin. This organic-rich shale has been interpreted to be the most prolific source rock for this basin, particularly for the Permo-Triassic reservoirs including the studied Dalan Formation. In the Fars area, the Hercynian uplift in the Devonian and Carboniferous (time-equivalent to the deposition of the Faraghan Formation in adjacent regions) caused a huge sedimentary hiatus. Szabo and Kheradpir (1978) suggested that the Permian (Dalan) and Triassic (Kangan) in the Zagros Mountains are separated by a significant unconformity during the Djulfian Stage; however, Bashari (2005) argues that such a major unconformity does not exist in the

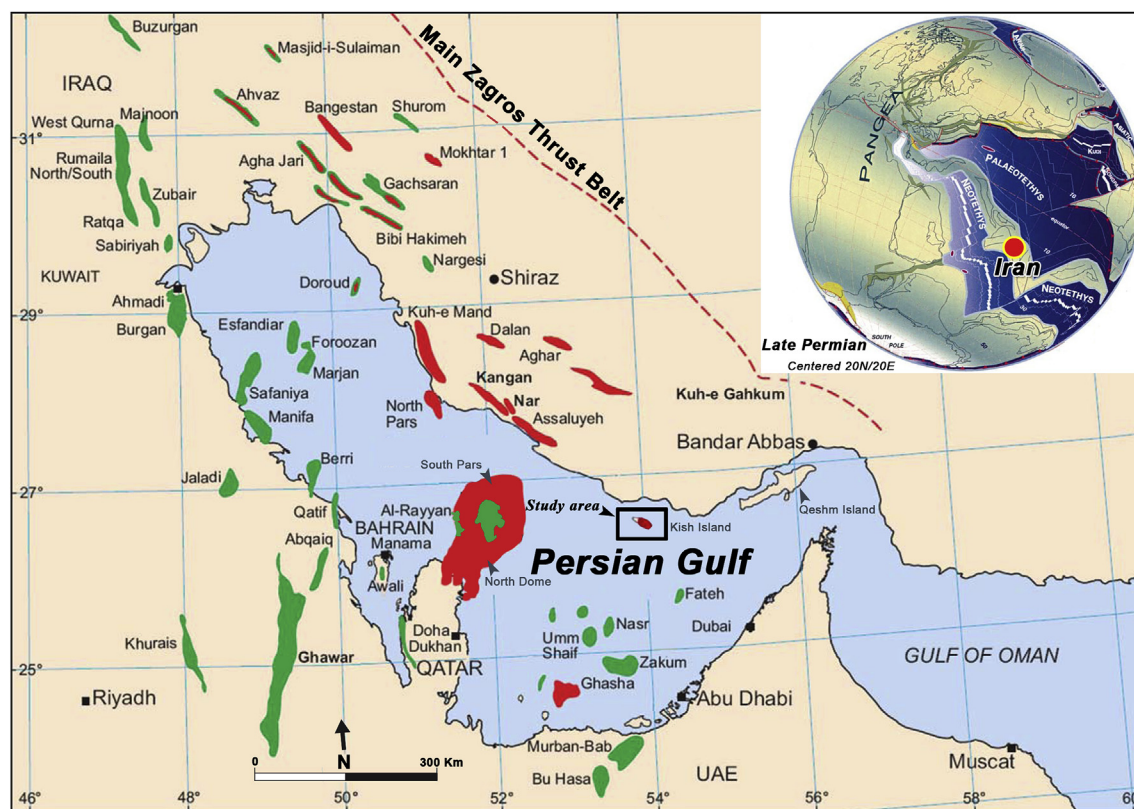


Figure 2. Generalized map of the Persian Gulf. Study area of the Kish Gas Field is indicated with a thick black rectangle. Green (oil) and red (gas) patches indicate major hydrocarbon fields in the Persian Gulf and adjacent areas (modified from Insalaco et al., 2006). Inset map shows Late Permian (250 mya) paleogeography with Iran (encircled in red) located at ~20–30° south of the equator (Scotese et al., 1979). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Zagros Mountains. During the Permian time, the Iran Block rifted northward into the Neo-Tethys basin, and subsequently collided with Eurasia during the Middle–Late Triassic time (Davoudzadeh and Schmidt, 1984; Stampfli et al., 1991; Stampfli, 2000).

During Late Permian, the present-day Iran was located in the southern hemisphere (20–30°S) and characterized by arid and warm climate (Scotese et al., 1979) (Fig. 2). The study area evolved along the eastern passive margin of the Arabian Plate facing Paleo-Tethys; this margin was characterized by a major tectono-eustatic event that was related to the onset of rapid thermal subsidence in the Late Permian (Sharland et al., 2001). The studied Dalan Formation is a part of the Permo-Triassic carbonate series, which was initiated by the Permian transgression and associated deposition of fluvial to shallow-marine clastics of the Faraghan Formation. In most areas the lower boundary of the Faraghan Formation sandstones corresponds to a disconformity, while its contact with the overlying Dalan Formation is gradual (Aghanabati, 2004). The Faraghan (Early Permian), Dalan (Middle to Late Permian), and Kangan (Late Triassic) formations are grouped into the Dehram Group in Iran. The oldest strata (composed of fluvial to shallow marine sediments) of the Faraghan Formation are considered to be of Early Permian age based on palynological evidences (Ghavidel-Syooki, 1997). The Upper Dalan Formation can be subdivided into three stratigraphic units: a lower unit consisting of limestones, a middle unit composed of massive anhydrites (Nar Member), and an upper unit composed of limestones and dolomites; the lower and upper units are major gas reservoirs. The overlying Triassic and Jurassic deposits are dominated by evaporites and carbonates. Based on the above, Iran (Zagros Basin) has more or less similar lithofacies characteristics to the succession in the Arabian Peninsula. The

presence of shallow marine sandstones and carbonates of Cambrian and thick shale units of Ordovician age in the Zagros Basin, indicate more distal location of the Zagros Basin with respect to the Arabian Peninsula (Bordenave, 2002).

The Zagros orogeny created a major structural closure for many petroleum reservoirs (Bordenave and Hegre, 2010). In fact, many anticlines display a northwest–southeast trend that is parallel with the Zagros orogeny direction (Al-Husseini, 2000). Several major tectonic activities during Oligocene until recent have influenced the Zagros system, all of which led to the formation of large-scale anticlinal and fold-and-thrust-belt structures of the present-day Zagros Mountains.

3. Methodology

A continuous, 222-m-thick core through the K4 reservoir of the Upper Dalan Formation was logged in the northern part of the Kish Gas field, Zagros (Figs. 1, 2). The core was analyzed for porosity, mineralogy, sedimentary structures, textures, grain size and type, dolomite crystal size, color, and type of fossils. The wireline log data consisted of gamma ray (GR) and bulk density (RHOB) logs for lithology determination, and neutron porosity (NPHI) log for porosity evaluation. In addition, photoelectric effect (PEFZ) and shear sonic (Shear) logs were measured during the logging processes to help in lithology and porosity identification. Five-hundred eighty core samples were collected at ~30 cm intervals for thin-section sedimentary-petrographic analysis. Carbonate rocks were classified according to Dunham's (1962) classification. After staining with the Alizarin red-S (Dickson, 1965), the thin-sections were analyzed for diagenetic features, including cement types and

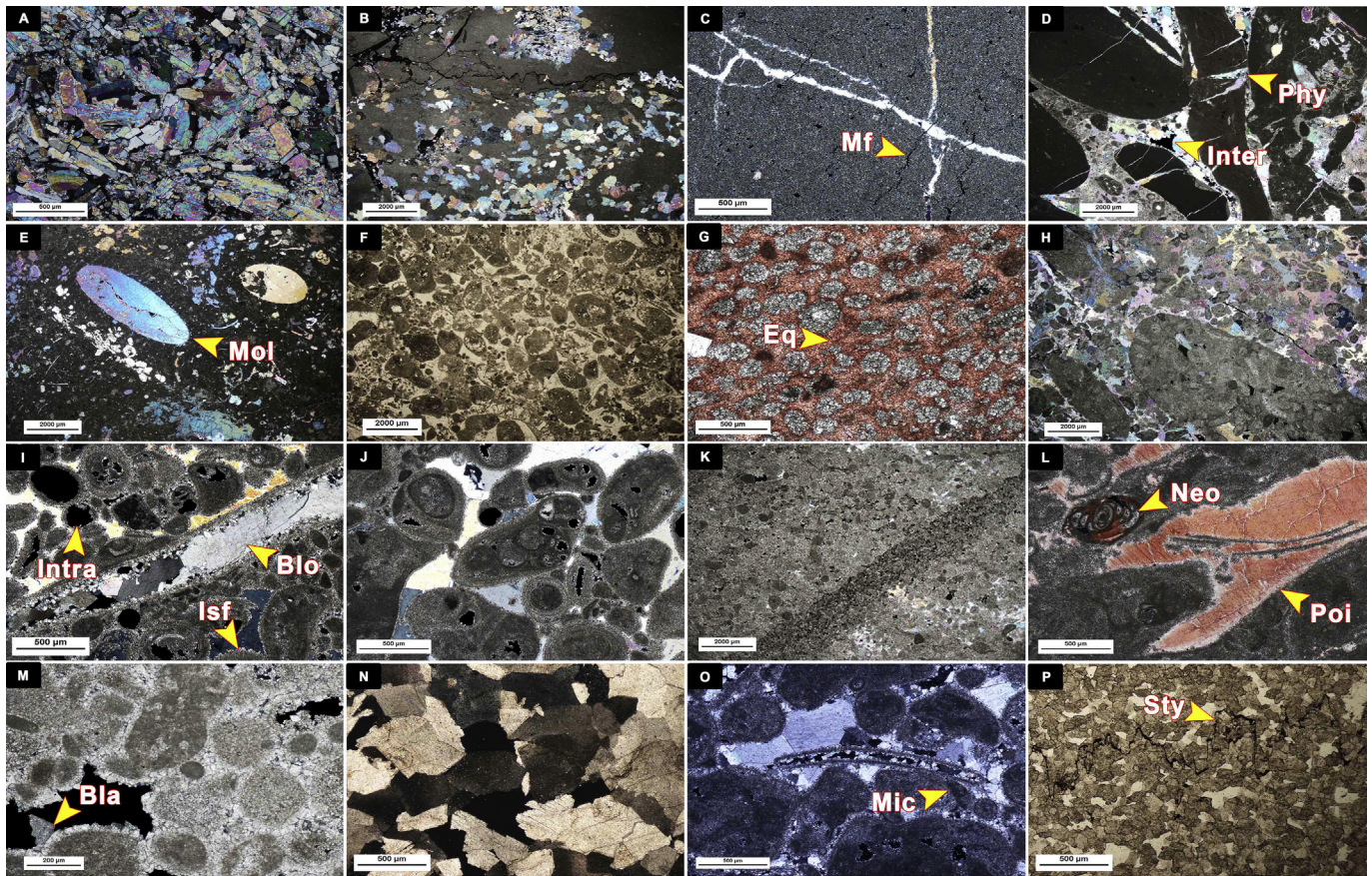


Figure 3. Thin-section photomicrographs of typical facies under cross-polarized (XPL) or plane-polarized (PPL) light. (A) laminated to massive anhydrite (A1), XPL, (B) dolomudstone with nodular and sparse anhydrite (A2), XPL, (C) dolomudstone (A3), XPL, (D) intraclastic dolowackestone to dolopackstone (A4), XPL, (E) peloid dolopackstone to peloid–bioclastic dolopackstone (B2), XPL, (F) bioclastic wackestone to packstone (B1), PPL, (G) ooid dolograinstone (C3), XPL, (H) ooid–intraclast dolograinstone (C2), XPL, (I) ooid–bioclast dolograinstone to packstone (C4), XPL, (J) coarse amalgamated grain–bioclast–intraclast dolograinstone with ooids (C5), XPL, (K) ooid–peloid dolograinstone (C1), XPL, (L) peloid–bioclastic dolowackestone with miliolid foraminifera (B2), XPL, (M) ooid dolograinstone showing fabric retentive and pervasive dolomitization (C3), XPL, (N) saddle dolomite cement, XPL, (O) peloid–bioclastic dolopackstone (B2) with limpid dolomite cement, XPL, and (P) fabric destructive and pervasive dolomitization of packstone facies (XPL). Abbreviations: Mf (micro fracture), Phy (physical compaction), Inter (intergranular porosity), Mol (moldic porosity), Eq (equant calcite cement), Intra (intragranular porosity), Blo (blocky cement), Isf (isopachous cement), Neo (neomorphism), Poi (poikilotopic cement), Bla (bladed cement), Mic (micrite envelope), and Sty (stylolite). For lithofacies codes see Table 1.

dolomitization. Porosity types were quantified based on image analysis of 450 thin sections, with 300 point counts per thin-section.

4. Results

4.1. Lithofacies

One sulfate and ten carbonate lithofacies are identified and outlined below. The facies are illustrated in Figure 3, and summarized in Table 1.

4.1.1. Laminated to nodular anhydrite

Anhydrite occurs as 5-to-12-cm-thick beds characterized by laminated to nodular structure, and lack any fossils or bioturbation. The anhydrite fabric varies between parallel and sub-parallel crystals and a combination of equant, fibrous-radial crystals with random and irregular direction (Fig. 3A). This facies shows no evidence of macro and micro porosity, and is an excellent impermeable seal that prevents hydrocarbons from upward migration.

4.1.2. Dolomudstone with anhydrite nodules

Barren mudstone to fine-grained dolomudstone locally is characterized by lamination and bioturbation. Gypsum and anhydrite

nodules are common, and are characterized by felted texture (Maiklem et al., 1969) (Fig. 3B) with irregularly intersecting, interwoven sulfate laths suggesting a sabkha-type setting (cf., Steinhoff and Strohmenger, 1999). There is no evidence for an origin by replacement of a precursor fabric. Petrographic study indicates no visible porosity, and consequently low reservoir quality of this facies.

4.1.3. Dolomudstone

Dolomudstone is characterized by scarcity of allochems and sedimentary structures, the latter including anhydrite nodules and fenestral fabric. Major non-skeletal components are very fine peloids and lithoclasts that are found dispersed in a dolomitic matrix with rare bioclasts. The dominant porosity types in dolomudstone facies are intercrystalline and vugular; fracture porosity is subordinate. Pervasive dolomite crystals vary from fine- to medium-grained, and euhedral to subhedral and their growth caused an increase in intercrystalline porosity (Fig. 3C).

4.1.4. Intraclastic dolowackestone to dolopackstone

Dolowackestone to dolopackstone contains predominantly intraclasts, while peloids and algal filaments are subordinate (Fig. 3D). This facies is totally dolomitized and often has fenestral fabric. The cement is anhydrite mostly with poikilotopic fabric with

Table 1
Summary of Upper Dalan Lithofacies.

Lithofacies code	Lithofacies	Thin-section photograph	Sedimentary structures	Depositional texture and grain types	Fossils	Diagenetic alteration	Porosity type	Water energy	Depositional environment	Reservoir quality
A1	Laminated to massive anhydrite	Figure 3A	Nodular fabric and lamination cross-cut precursor fabric.	Anhydrite crystal shape varies from parallel and subparallel crystals to a combination of equant, fibrous-radial crystals with random and irregular orientation.	None	Stylolitization; poikilotopic anhydrite fills intergranular porosity.	—	None to very low	Coastal sabkha and shallow hypersaline lagoon. SMF ^a 25, RMF ^b 25.	None
A2	Dolomudstone with anhydrite nodules	Figure 3B	Gypsum and anhydrite nodules. Dolomudstone is locally laminated and bioturbated.	Felted fabric of intertwined randomly oriented anhydrite crystals.	None	Growth of gypsum from — interstitial water within capillary zone.	—	Very low.	Coastal sabkha. SMF 23, Low RMF 23.	
A3	Dolomudstone	Figure 3C	Anhydrite nodules and fenestral fabric are sparse.	Very fine bioclasts, peloids and lithoclasts. Fine- to medium-grained euhedral to subhedral dolomite crystals.	Unidentified bioclasts.	Growth of gypsum from interstitial water within capillary zone.	Dominant intercrystalline, subordinate fracture porosity.	Low	Intertidal (semi-restricted to restricted evaporative setting). SMF 23, RMF 23.	Good
A4	Intraclastic dolowackestone and dolopackstone	Figure 3D	Common fenestral fabric.	Intraclasts; less commonly peloids and microbial filaments.	Microbial filaments.	Cementation by poikilotopic anhydrite that fills the pore spaces.	—	Low to moderate	Intertidal and shallow subtidal channels on tidal flats RMF 24.	Low
B1	Bioclastic wackestone/ dolowackestone to packstone	Figure 3F	Micrite envelopes and bioturbation.	Peloids and bioclasts.	Green algae and bivalves; gastropods, echinoids, and ostracods are sparse.	Dissolution of carbonate grains.	Moldic porosity is commonly plugged by anhydrite. Cavernous porosity is subordinate.	Moderate	Inner ramp (shallow lagoon and leeward shoals). SMF 18, RMF 17,	Low
B2	Peloidal dolopackstone and peloid–bioclastic dolopackstone	Figure 3E, 3L, 3O	Bioturbation and micrite envelopes.	Fine-grained (<20 µm) dolomite crystals.	Gastropods, green algae, bivalves and benthic foraminifers.	Dissolution of carbonate grains, and replacement by gypsum/anhydrite.	Moldic and intercrystalline porosity.	Moderate	Inner ramp (restricted lagoon). SMF 16, RMF 20.	Low
C1	Ooid–peloid dolograinstone	Figure 3K	Low-angle cross-bedding, normal grading and orientation.	Medium-sized, rounded and well sorted ooids and well-rounded peloids.	Unidentified bioclasts.	Mostly aragonitic composition, pervasive dolomitization.	Moldic, intergranular, vuggy in some cases.	High	Windward shoal (lagoon-facing side), tidal channel. SMF 15, RMF 29.	Good
C2	Ooid–intraclast dolograinstone	Figure 3H	Lack of bioturbation and muddy matrix.	Fairly sorted and well-rounded intraclasts, bioclasts and tangential ooids.	Green algae and gastropods.	Pervasive poikilotopic anhydrite cementation.	Moldic, intergranular porosity plugged by anhydrite.	High	Windward shoal, tidal channel. SMF 15, RMF 29.	Good
C3	Ooid dolograinstone	Figure 3G, 3M	Cross-bedding and graded bedding.	Sorted and rounded coarse- and medium-grained ooids, bioclasts, intraclasts, oncolids and peloids.	Green algae, bivalves, gastropods, benthic foraminifers, and rare echinoids.	Common marine cement rims, dolomitization and anhydrite cementation. Less common is cementation by meteoric blocky cement and pressure solution.	Moldic, Intergranular	High	Windward shoal, tidal channel. SMF 15, RMF 29.	Good
C4	Ooid–bioclast dolograinstone –dolopackstone	Figure 3I	Cross-bedding and graded bedding less developed compared to facies C2 and C3.	Ooids, bioclasts, aggregate grains, peloids and intraclasts.	Green algae, gastropods, benthic foraminifers, bivalves, echinoids, cephalopods.	Fibrous cements around ooid and bioclast grains, dissolution and dolomitization.	Intergranular, moldic and vuggy porosities.	High	Windward shoal, tidal channel. SMF 15, RMF 30.	Good
C5	Coarse bioclast –intraclast dolograinstone	Figure 3J	Intensively micritized, low degree of bioturbation and faunal activity.	Moderately well sorted medium- to coarse-sized bioclasts and intraclasts.	Green algae, bryozoans, bivalves, benthic foraminifers.	Predominantly bladed cement rims around grains. Pervasive anhydrite cementation.	Intergranular porosity plugged by anhydrite.	High	Windward shoal, tidal channel lag. SMF 15, RMF 26.	Low

^a SMF = standard microfacies type based on Wilson (1975) and Flügel (1972, 1982).

^b RMF = ramp microfacies type of Flügel (2010).

large, randomly scattered crystals. This facies indicates low reservoir quality because no visible porosity can be recognized due to the extensive cementation by anhydrite that completely fills the pore space.

4.1.5. Bioclastic wackestone to packstone

This non-dolomitized burrowed facies contains abundant peloids and various bioclasts of predominantly calcareous green algae and bivalves, and less commonly gastropods, echinoids and ostracods. Most of the bioclasts have well-developed micrite coatings as a result of intense microbial activity. Porosity is very low and predominantly moldic; other separate vugs are mostly cemented by anhydrite (Fig. 3E).

4.1.6. Peloid dolopackstone to peloid–bioclastic dolopackstone

This peloid-rich facies is characterized by an abundance of predominantly miliolid foraminifers and calcareous green algae, with subordinate gastropods and bivalves (Fig. 3F). The facies is commonly interbedded with dolomudstone. Similar to intraclastic dolowackestone to dolopackstone, the bioclasts in this facies are commonly coated with thin microbial films (Fig. 3O). The intensity of bioturbation generally increases with increasing benthic diversity. Porosity is low, and predominantly of moldic and intercrystalline origin, with dolomite crystals finer than 20 μm (Fig. 3P). The low reservoir quality is also related to anhydrite cementation following dissolution of skeletal fragments.

4.1.7. Ooid–peloid dolograinstone

This facies is commonly found interbedded with other ooid-rich dolograinstone facies. It mainly consists of ooids and peloids, and lacks any skeletal grains. The ooids range in size from 0.2 to 1.5 mm and are highly micritized (Fig. 3K). The facies is commonly characterized by a low angle cross-bedding sedimentary structure. Lack of anhydrite in the intergranular pore space results in high porosity and good reservoir quality of the facies.

4.1.8. Ooid dolograinstone

This facies is composed of coarse- and medium-grained ooids with tangential cortices enveloping nuclei that predominantly consist of peloids or fine angular intraclasts (Fig. 3G). Other allochems are also abundant and include bioclasts (calcareous green algae, bivalves, gastropods, and rarely echinoids), intraclasts, oncoids, and peloids (in direction of lagoon). Sedimentary structures include cross-bedding and graded bedding. The facies was strongly affected by diagenetic processes, from marine rim cements and anhydrite plugging of intergranular pores, to dolomitization (Fig. 3M), local development of meteoric blocky cement, and pressure solution.

4.1.9. Ooid–intraclast dolograinstone

Ooid–intraclast grainstone is not very abundant in the studied material. It is composed of tangential ooids and fairly-sorted and well-rounded bioclasts and intraclasts (Fig. 3H). Poikilotopic anhydrite cement commonly fills the intergranular pore space, which results in decreased porosity and overall low reservoir quality of the facies.

4.1.10. Ooid–bioclast dolograinstone to dolopackstone

This is the only oolite facies that sporadically contains micrite between the allochems. High-energy sedimentary structures (cross-bedding and graded bedding) are less pronounced compared to the other oolite facies from the study material. Locally, ooid–bioclast dolograinstone to dolopackstone grades into bioclastic–peloid dolopackstone (Fig. 3I). Besides tangential ooids, other abundant non-skeletal allochems are aggregate grains,

peloids, and intraclasts. The most abundant skeletal grains are calcareous green algae, gastropods, benthic foraminifers and bivalves; less abundant are echinoids and gastropods. Intergranular pore space is not plugged by anhydrite, which results in overall good reservoir quality of this facies.

4.1.11. Coarse bioclast–intraclast dolograinstone

Bioclast–intraclast dolograinstone is made up of moderately well-sorted coarse intraclasts and medium- to coarse-grained skeletal allochems (calcareous green algae, bryozoans, echinoids, bivalve fragments and foraminifers). Bladed cement coats the grains, and pervasive anhydrite locally fills the intergranular pore space (Fig. 3J).

4.2. Reservoir properties

Understanding the relationship between the rock fabric and the pore size distribution is fundamental to reservoir characterization. In order to enable discussion of the porosity development and permeability distribution within the Upper Dalan Formation, the porosity and permeability within the studied core are described below. Characteristic pore types and porosity–permeability plots of core analysis data are illustrated in Figures 4–7. The terminology used for pore types and rock-fabric petrophysical classes follows the classification of Lucia (1995) and Lucia et al. (1999).

4.2.1. Porosity vs. permeability

The porosity over the studied reservoir thickness varies from 0.0 to 21.06%, with a sampled population mean of 4.63%. The permeability varies from 0.009 to 4110.96 md, with a sampled population mean of 53.494 md. Common pore types include interparticle (Fig. 3D; intergrain and intercrystal), separate vug (Fig. 4A; moldic), and connected vug (Fig. 4B and C; fracture, cavernous). The most common pore type in dolomites is intercrystalline, while intergranular pore type dominates in limestones. Fabric-selective moldic porosity is common, both in lagoonal wackestone/dolowackestone and packstone/dolopackstone, as well as in the ooid-dominated facies. The presence of well-preserved oomoldic porosity is one of the major characteristics of the Upper Dalan Fm. in the South Pars and Kangan Fields of Iran (e.g., Insalaco et al., 2006), as well as in the equivalent Khuff reservoir (e.g., in Oman and the UAE; Alsharhan and Nairn, 1994).

Dolomite facies (Figs. 5–7) displays predominantly class 1 and class 2 petrophysical relationships, with majority of data plotting left of the class 1, i.e., in the low porosity and low to high permeability range; petrophysical class 3 relationship is extremely rare. Grain-dominated dolomite facies (dolograinstone and grain-dominated dolopackstone) are scattered in four separate areas on the porosity–permeability cross-plot (Fig. 6): left of petrophysical class 1 (low porosity and low permeability, or low porosity and high permeability), class 1, and class 2. Finely crystalline (crystal size <20 μm) grain-dominated dolomite predominantly plots left of the class 1, and shows both high and low permeability in a low porosity range; petrophysical class 1 is common, while class 2 is subordinate. Medium crystalline (20–100 μm) and coarse-grained (>100 μm) grain-dominated dolomite display characteristics of petrophysical class 1 relationships, with many samples also occupying regions left of class 1. Majority of mud-dominated dolomite facies (Fig. 7A, B; dolomudstone, dolowackestone, and mud-dominated dolopackstone) plot left of the class 1, and are characterized predominantly by both low porosity and permeability; only four samples plot right of the 500 μm boundary, two of which exhibit class 3, and two show class 1 relationships.

Due to a limited number of limestones, dolomitized limestones and calcareous dolomites, all of these facies were plotted together

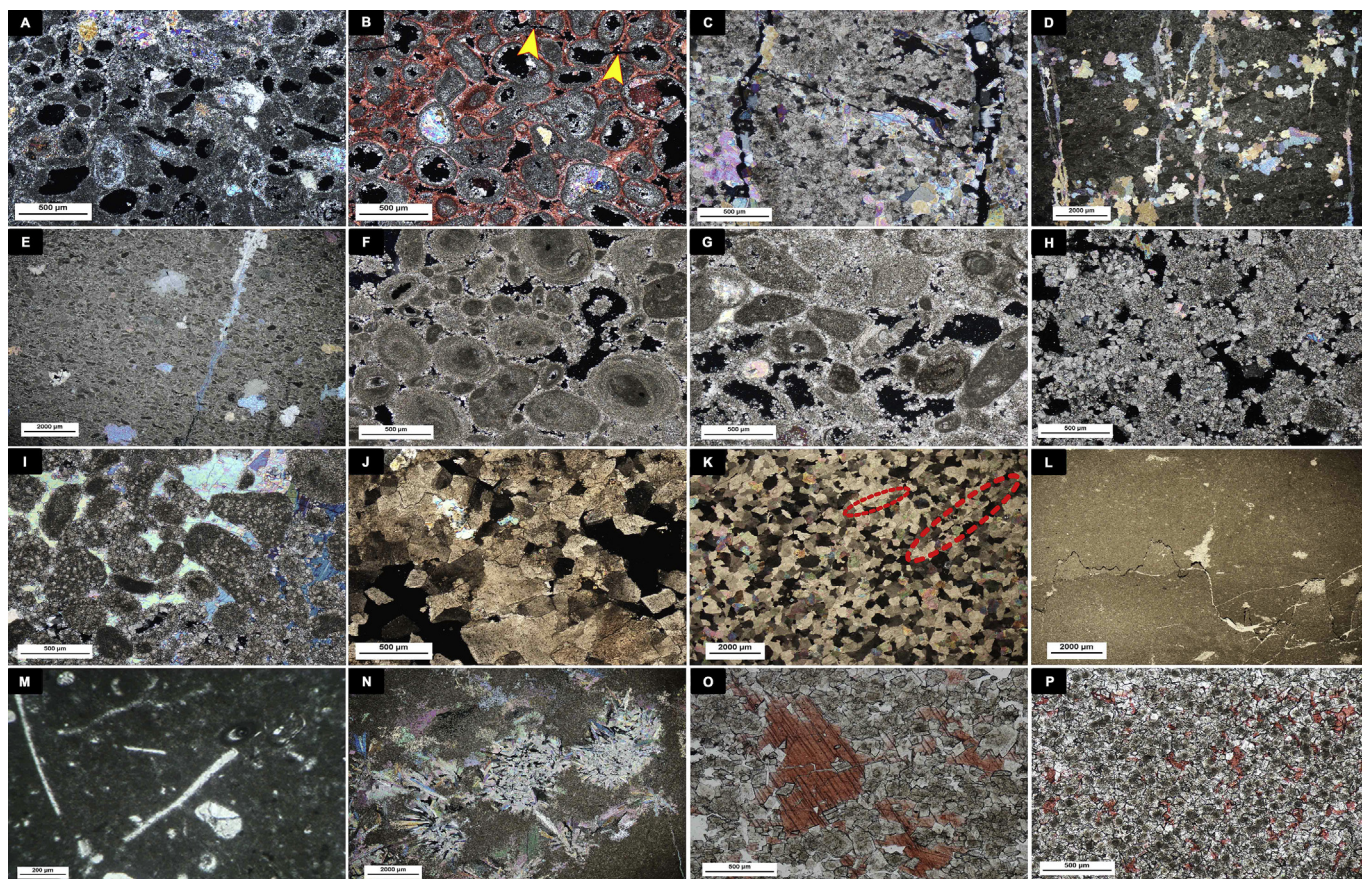


Figure 4. Thin-section photomicrographs showing characteristic porosity types and fabrics in dolomudstones, dolowackestones, dolopackstones and dolograinstones under cross-polarized (XPL) or plane-polarized light (PPL). (A) Moldic pores in a dolograinstone. Note some moldic pores and intergranular space are filled with anhydrite showing bright interference colors (depth 4215.26 m, $\phi = 8.53\%$, $k = 0.656$ md) (XPL). (B) Intraparticle and subordinate interparticle pores in dolograinstone. Blocky anhydrite locally plugs intraparticle pores. Yellow arrows indicate fracture pores (depth 4218.33 m, $\phi = 12.92\%$, $k = 0.711$ md) (XPL). (C) Extensive fracture pores in dolopackstone. Anhydrite cement partially fills some pores and vugs (depth 4350.59 m, $\phi = 5.66\%$, $k = 0.774$ md) (XPL). (D) Low porosity and low permeability dolograinstone, crystal size <20 μ m (depth 4299.11 m, $\phi = 2.64\%$, $k = 0.305$ md) (XPL). (E) Low porosity and high permeability dolograinstone, crystal size <20 μ m (depth 4290.7 m, $\phi = 1.33\%$, $k = 22.931$ md) (XPL). (F) Petrophysical class 1 dolograinstone, crystal size <20 μ m (depth 4408.06 m, $\phi = 6.83\%$, $k = 96.98$ md) (XPL). (G) Petrophysical class 2 dolograinstone, crystal size <20 μ m (depth 43.95 m, $\phi = 13.74\%$, $k = 2.338$ md) (XPL). (H) Petrophysical class 1 dolograinstone, crystal size 20–100 μ m (depth 4389.43 m, $\phi = 12.54\%$, $k = 43.37$ md) (XPL). (I) Low porosity and low permeability dolograinstone, crystal size 20–100 μ m (depth 4391.35 m, $\phi = 1.34\%$, $k = 0.029$ md) (XPL). (J) Petrophysical class 1 dolograinstone, crystal size >100 μ m (depth 4361.08 m, $\phi = 5.69\%$, $k = 301.076$ md) (XPL). (K) Low porosity and high permeability dolograinstone, crystal size >100 μ m (depth 4358.33 m, $\phi = 4.95\%$, $k = 1167.479$ md). Fractures causing increase in permeability are encircled by dashed red lines (XPL). (L) Low porosity and high permeability nodular dolomudstone. Stylolitization and fracturing resulted in high permeability of this “tight” lithofacies (depth 4339.9 m, $\phi = 0.76\%$, $k = 40.554$ md) (PPL). (M) Low porosity and low permeability dolowackestone with separate vugs formed by dissolution of bioclasts and evaporites (depth 4374.56 m, $\phi = 3.06\%$, $k = 0.076$ md) (PPL). (N) Fibrous to bladed anhydrite forms nodules and fills the available pore space, resulting in complete loss of porosity and permeability (depth 4343.78 m, $\phi = 0.0\%$, $k = 0.0$ md) (XPL). (O) Petrophysical class 2 calcareous dolomite. High porosity and permeability resulted from recrystallization, dissolution, and dolomitization (depth 4381.23 m, $\phi = 10.28\%$, $k = 49.469$ md) (PPL). (P) Low porosity and low permeability calcareous dolomite. Intensive dolomitization resulted in porosity and permeability decrease (depth 4206.67 m, $\phi = 1.0\%$, $k = 0.046$ md) (PPL). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Fig. 7C, D). Calcareous dolomites show greatest range of values, with classes 1 and 2 relationships, as well as several samples left of petrophysical class 1 (showing a range of permeability values in a low porosity field). All three samples of dolomitic grainstones show a range (from <0.1 to >10 md) of permeability values within a range of 1–5% porosity. On the contrary, all four limestone samples have low permeability and porosity, with an outlier grainstone sample showing class 2 relationships. Within the above limestones, dolomitized limestones and calcareous dolomites, all but three samples are grainstones. The grainstones plot left of class 1, as well as display class 1 and 2 petrophysical relationships.

Variations in porosity and permeability can also be evaluated using the reservoir quality index (RQI), which is equal to $0.0314 \sqrt{k/\phi}$ (Amaefule et al., 1993). The variations of RQI with depth for the K4 reservoir in the studied well are illustrated in Figure 8. The lower part of the reservoir has high porosity and permeability, and exhibits RQI values ranging from 0 to 0.5. The middle part of the reservoir with two anhydrite intervals is dominated by mud-dominated fabric in its

lower part, has low porosity and high permeability, and RQI values in a range similar to the lower part of the reservoir. The studied upper part of the reservoir unit has high porosity but lower permeability than the lower and middle part of the reservoir, and exhibits very low (<0.2) RQI values.

4.2.2. Anhydrite cementation

Anhydrite is the most common cement in the Upper Dalan Formation, and thus is an important diagnostic proxy for the reservoir quality. Based on the frequency of anhydrite cement studied in thin sections, its abundance does not show a clear relationship with porosity and permeability (Fig. 9A and B). This is especially so for the low anhydrite cement content ($<20\%$), where both porosity and permeability show a wide spread of values. Also, several of the samples with the highest anhydrite cement content ($>60\%$), exhibit high permeability (10–100 md).

The three common types of anhydrite cement found in the Upper Dalan reservoir are poikilotopic, pervasive (pore filling), and

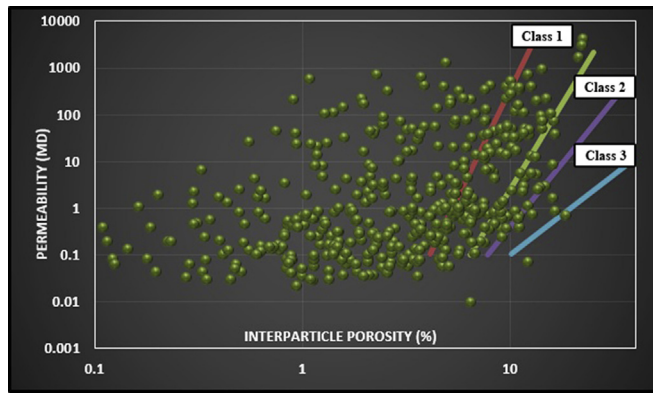


Figure 5. Cross plot of interparticle porosity and permeability for all dolomite lithofacies. The graph shows that most dolomites plot in the low porosity and low to high permeability range, left of the petrophysical class 1. Petrophysical class 1 and class 2 relationships are common, while class 3 relationships are subordinate.

nodular (Table 1). Poikilotopic cement is randomly distributed as patches of large anhydrite crystals in all of the microfacies analyzed. Pore filling anhydrite cement is pervasive in dolograinstones and dolopackstones, as well as in dolomudstones and dolowackstones. As previously described from studies of Permian–Triassic carbonates in this area (Rahimpour-Bonab et al., 2010), samples with poikilotopic cement show better reservoir quality characteristics with respect to samples with pervasive anhydrite cement. Pervasive pore filling cement fills in most of the available pore throats and pore spaces, which results in low porosity and low permeability, especially in dolograinstones and dolopackstones (Fig. 10A). On the contrary, poikilotopic patchy cement reduces matrix porosity, but the pore-size seems to be less affected (Fig. 10A). Limestone and dolomitized limestone rarely contain anhydrite in the form of patchy poikilotopic cement. It makes up a low percentage of the bulk volume and has very little effect on porosity or permeability (Fig. 10C). The third and the least common type of anhydrite cement in the Upper Dalan Formation is nodular, which is composed of microcrystalline masses of

anhydrite observed within all of the dolomite lithofacies. Samples with nodular cement almost exclusively occur left of the petrophysical class 1 and have both low permeability and porosity (Fig. 10A, B); however, due to a limited number of samples with nodular anhydrite, it likely has an overall little effect on either porosity or permeability (Fig. 10A, B).

5. Interpretation and discussion

5.1. Depositional model of the Upper Dalan Formation

Based on the vertical and lateral distribution of facies between the Arabian Plate and the Zagros Suture Zone (Al-Jallal, 1995; Stampfli, 2000; Sharland et al., 2001; Insalaco et al., 2006), the Upper Dalan carbonate platform likely represents a gently sloping homoclinal ramp *sensu* Read (1985), similar to modern day Persian Gulf (Purser, 1973) and Shark Bay (Logan et al., 1974). This studied part of the platform (Kish Gas Field) evolved during Late Permian arid climate at paleolatitudes of 28–29°S (Berra and Angiolini, 2014); the arid, shallow-marine setting is evidenced by an association of sabkha-type and shallow subaqueous anhydrites and tidal-flat dolomites. Based on the microfacies analysis of the Upper Dalan Formation in this study, eleven microfacies types are arranged into three main paleogeomorphological features (depositional settings). From proximal to distal, they are (Fig. 11): (1) sabkha to tidal flat, (2) lagoon and leeward shoals, and (3) mobile (windward) sand shoal. The relative landward or seaward position of facies and major paleogeomorphic features is schematically illustrated in Figure 11. Paleoenvironmental interpretations are discussed below.

5.1.1. Sabkha to tidal flat facies belt

Four different lithofacies have been recognized in this environment. These include, from landward to seaward position: laminated to massive anhydrite (coastal sabkha and shallow hypersaline lagoon), dolomudstone with anhydrite nodules (coastal sabkha), dolomudstone (semi-restricted to restricted evaporative intertidal), and intraclastic dolowackestone (intertidal to shallow subtidal channels on tidal flats). An abundance of evaporite deposits, their fabric and association with peritidal dolomites

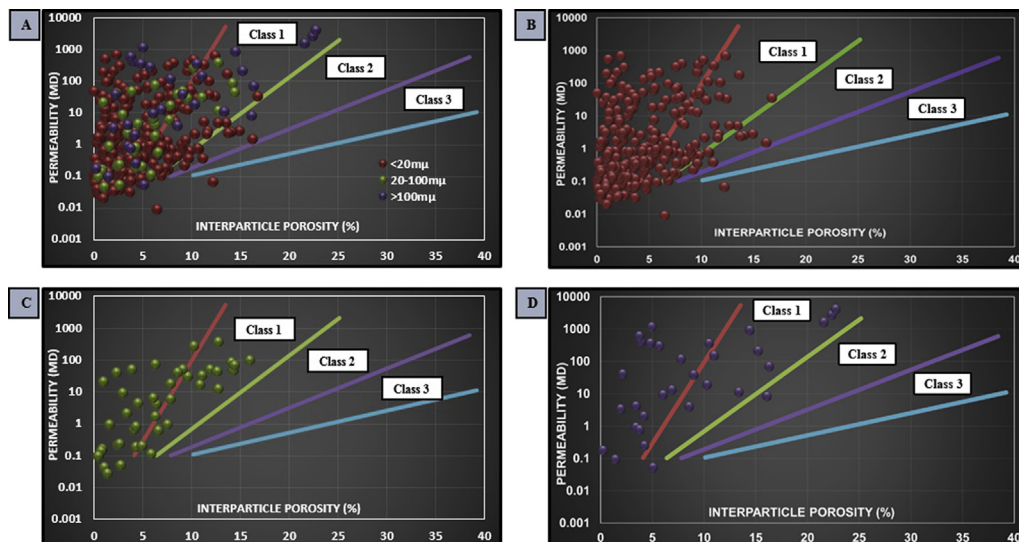


Figure 6. Cross plot of interparticle porosity and permeability for grain-dominated dolomites (dolograinstone and grain-dominated dolopackstone): (A) all grain-dominated dolomites, (B) fine-crystalline (<20 μm) grain-dominated dolomites, (C) medium-crystalline (20–100 μm) grain-dominated dolomites, and (D) coarse-crystalline (>100 μm) grain-dominated dolomites. Reservoir quality is not affected by different crystal sizes and most samples plot in the low porosity and low to high permeability field, or display class 1 petrophysical relationships.

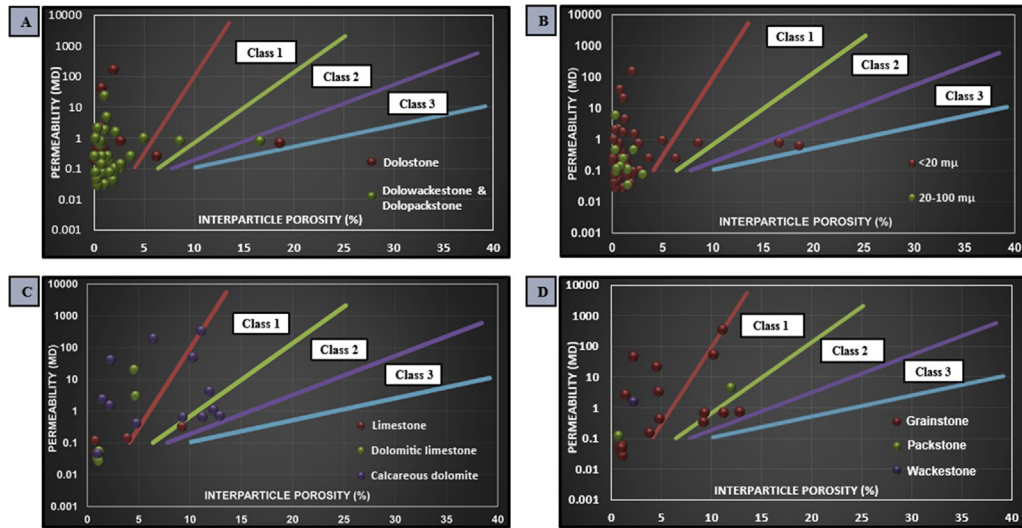


Figure 7. Cross plot of interparticle porosity and permeability for (A) mud-dominated dolomites (dolomudstone, dolowackestone, and mud-dominated dolopackstone), (B) fine- and medium-crystalline mud-dominated dolomites, (C) limestone, dolomitic limestone and calcareous dolomite, and (D) grainstone, packstone and wackestone.

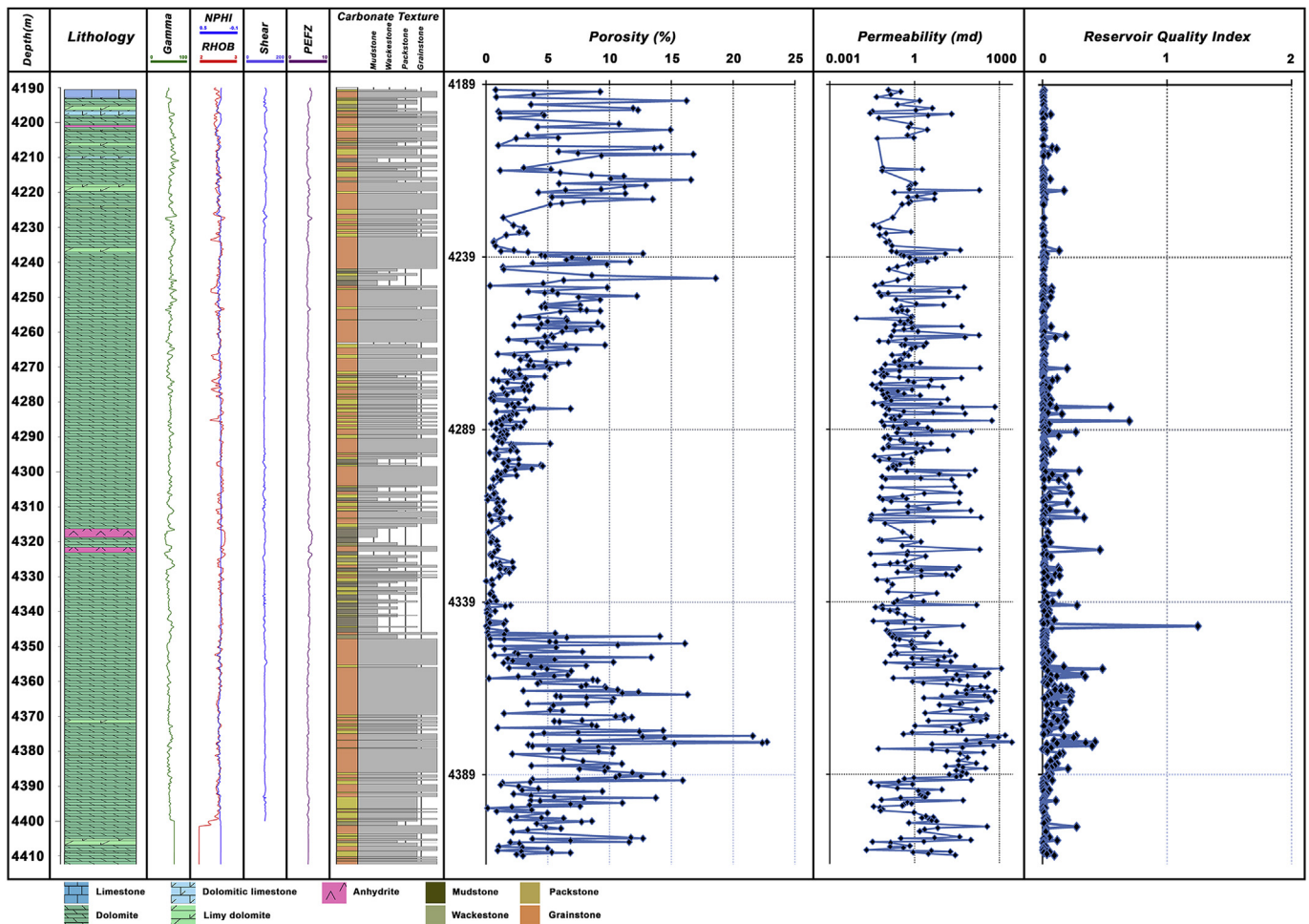


Figure 8. Lithology, well logs (gamma ray (GR), bulk density (RHOB), neutron porosity (NPHI), photoelectric effect (PEFZ) and shear sonic (Shear)), porosity, permeability and reservoir quality index (RQI) of the studied K4 reservoir, Upper Permian Upper Dalan Formation, Kish Gas Field.

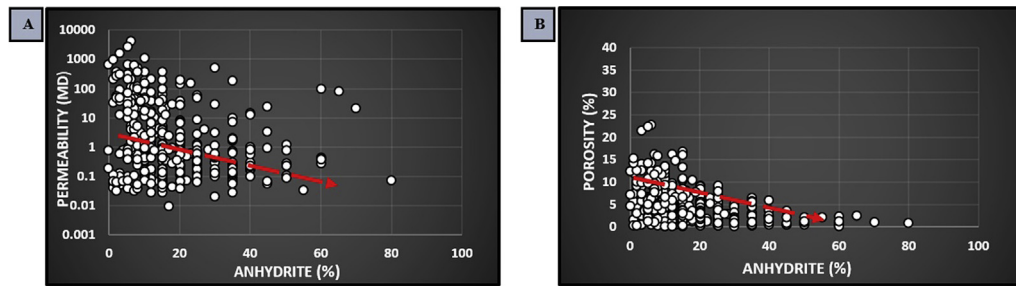


Figure 9. Cross plots of percent of anhydrite cement vs. permeability (A) and porosity (B). Red dashed line indicates the expected trend for porosity and permeability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

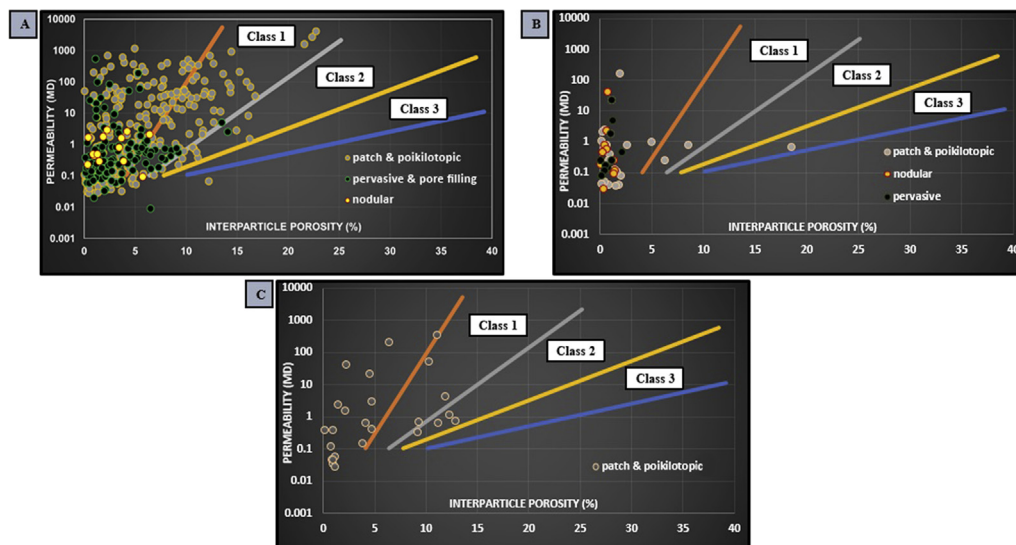


Figure 10. Cross plots of porosity and permeability showing different types of anhydrite cement present in (A) dolograins and dolopackstone, (B) dolomudstone and dolowackestone, and (C) limestone, dolomitic limestone, and calcareous dolomite.

indicates shallow subtidal to supratidal depositional environment under an arid climate, similar to present day Persian Gulf (Kendall and Alsharhan, 2011; and references therein). The anhydrite commonly exhibits nodular structure typical of modern-day sabkhas (e.g., Warren and Kendall, 1985). The massive anhydrite likely formed in a shallow subaqueous salina-type setting where pure gypsum precipitated out of dense hypersaline water; fine structural details were lost during the process of anhydritization (Warren and Kendall, 1985). The association of the bedded to laminated anhydrite units suggests shallowing of the salina and increase in salinity fluctuations (Warren, 1982; Warren and Kendall, 1985). Two types of dolomudstone lithofacies occur: the first type commonly has anhydrite nodules and lacks any fossil remains, and suggests a restricted, low-energy peritidal sabkha setting; the second type of dolomudstone is characterized by an absence (or very sparse occurrence) of anhydrite nodules. Presence of bioclasts, peloids and lithoclasts, as well as sparse fenestrae, and close association with other sabkha-type and peritidal facies, suggests a semirestricted evaporative intertidal setting (cf., Weber et al., 1995). Fenestral fabric is more common in intraclastic dolowackestone and dolopackstone, a lithofacies that also contains microbial filaments. The overall fabric and association with other shallow (and hypersaline) lithofacies suggests that intraclasts likely represent ripped-up clasts of desiccated intertidal deposits that were reworked during transgressive episodes and associated increase in water energy. The irregular fenestrae could have formed in this setting by the burial of pustular mats, similar to the cryptalgal fabric of the Hamelin pool in

Western Australia (Logan et al., 1974). The absence or low benthic assemblage diversity throughout this facies belt strongly suggests a very restrictive coastal setting with elevated salinities. Similar to Maurer et al. (2009) study of the Khuff Formation outcrops from Oman, our material shows no association of grain-supported fabric with tidal-flat facies belt. The major diagenetic processes that affected these deposits are extensive dolomitization and anhydritization. Similar to the subsurface dolomitization of argonitic intertidal sediments in the modern-day sabkhas of the Persian Gulf (Patterson and Kinsman, 1977), it is likely that the anhydritization and dolomitization occurred syndepositionally or during shallow burial. The former of the processes resulted in low porosity and consequently low reservoir quality.

5.1.2. Lagoon and leeward shoals facies belt

Two mud-dominated lithofacies make up the lagoon and leeward shoals facies belt. These include bioclastic wackestone/dolowackestone to packstone, and peloid dolopackstone and peloid–bioclastic dolopackstone. Both of these facies formed in a moderately shallow lagoon with shoals, beneath and around the fair-weather, and above the storm-weather wave base. The lagoon was protected from the open-ocean swell by the well-developed belt of ooid shoals seawards. The presence of abundant skeletal components, many of which are characteristic of normal-marine to slightly increased salinity, and abundant bioturbations, suggests connection with the open ocean mostly through high-energy tidal channels cross-cutting the ooid (winward) shoals. Previous studies

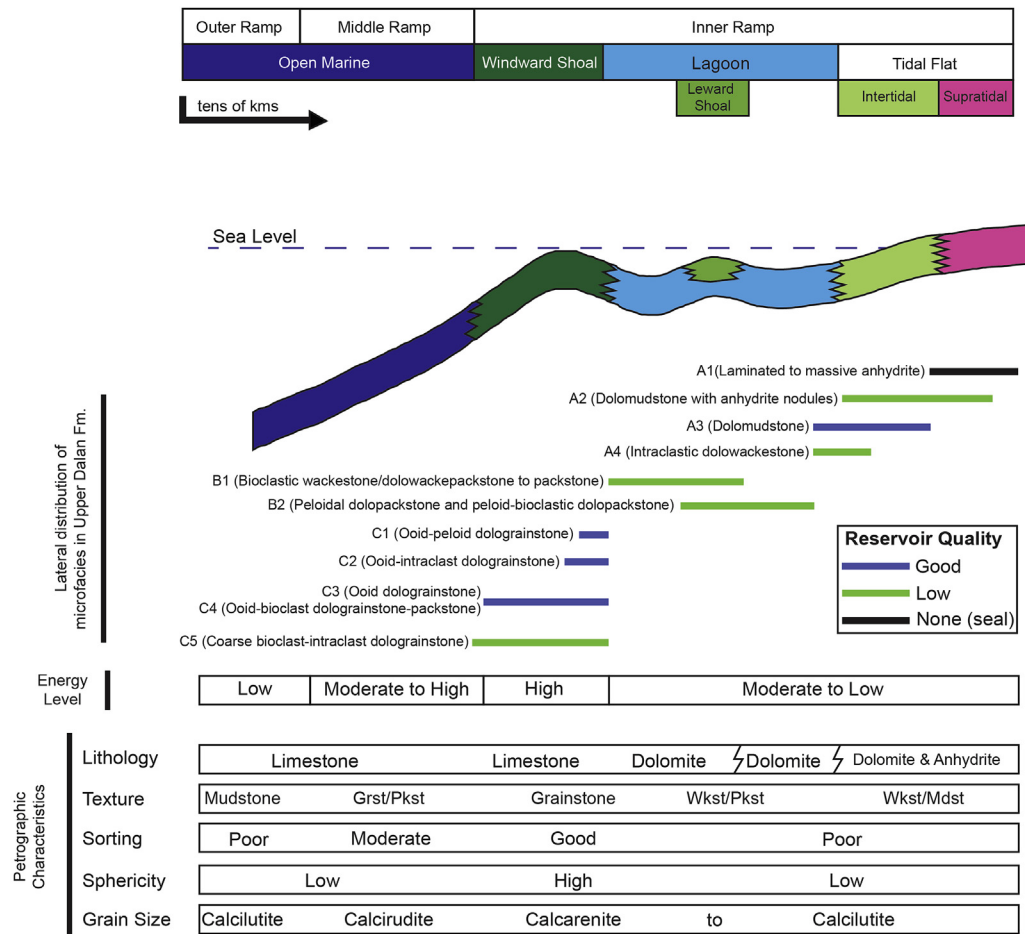


Figure 11. Petrographic characteristics and distribution of microfacies types along the homoclinal carbonate ramp model for the Upper Dalan Formation.

documented the abundance of calcareous green algae throughout the Permian–Triassic carbonate strata in the Zagros area (Insalaco et al., 2006), and attributed the high-diversity of benthic assemblages and presence of coated grains to an open lagoon environment (Insalaco et al., 2006; Adabi et al., 2010). The abundance of calcareous green algae and common development of micrite envelopes around bioclasts suggests a well-oxygenated and well-lit sea floor, likely with moderate water-energy and alternating periods of mostly calm water that enabled microbial colonization of bioclasts, and moderate water-energy that was associated with winnowing currents and wave activity. The bioclastic dolopackstone is the highest-energy facies in this belt, and likely formed leeward shoals within the lagoon (cf., Maurer et al., 2009; Koehrer et al., 2012). The main diagenetic features in this environment are dolomitization and micritization, and subordinate calcite replacement. Predominantly moldic porosity formed by dissolution of originally aragonite particles, but was later plugged by anhydrite. Dolomites likely formed beneath the prograding (or offlapping) evaporitic tidal flats, which was promoted by an arid climate with little mineralogic stabilization or sparry calcite cementation (Read and Horbury, 1993). Reservoir quality in this facies is low except in cases where dolomitization resulted in increased secondary porosity and permeability.

5.1.3. Mobile sand shoals (windward shoals) facies belt

The high-energy mobile sand shoal facies belt is made up of five lithofacies that are mainly composed of ooids and bioclasts with minor presence of peloids and intraclasts. This belt constitutes a

major part of the Upper Dalan carbonate succession; it includes ooid–peloid dolograinstone, ooid dolograinstone, ooid–intraclast dolograinstone, ooid–bioclast dolograinstone–packstone, and coarse bioclast–intraclast dolograinstone. Ooid buildups likely formed on a raised topographic surface above the fairweather wave base (cf., Weber et al., 1995). This barrier was constantly exposed to intense wave and current agitation, as evidenced by the tangential fabric of ooids, sorting and rounding of bioclasts and intraclasts, development of cross-bedding and graded bedding structures, as well as general lack of micrite. From the lagoon-facing to the open platform-facing part of the barrier, the mobile sand exhibits a trend from ooid–peloid dolograinstone, to ooid–bioclast–intraclast dolograinstone, to bioclast–intraclast dolograinstone; in addition, all of these facies occurred within tidal channels. This is similar to the modern Abu Dhabi coast of the United Arab Emirates, where nearshore skeletal sands pass landward into oolitic sands of the barrier islands with tidal channels, which in turn pass landward into a complex of channels and banks covered by pelletal sands (e.g., Evans et al., 1964, 2011; Kinsman, 1964; Kendall, 1966; Skipwith, 1966; Kendall and Skipwith, 1968, 1969; Kendall and Alsharhan, 2011). Major diagenetic alterations in this environment are micritization, cementation, dissolution and physical compaction. Ubiquitous marine cements suggest an active marine cementation and a barrier or shelf margin sedimentary environment (e.g., Elrik and Read, 1991; Weber et al., 1995). Meteoric blocky cements present in ooid dolograinstone lithofacies suggest that topographically highest parts of the barrier were periodically subaerially exposed. Overall, this facies belt provides a good

reservoir quality, where porosity mostly depends on selective dissolution, as well as presence or absence of marine cements and burial anhydrite.

5.2. Diagenesis

Based on sedimentary-petrographic analysis of the Upper Dalan Formation, four major diagenetic settings can be identified: evaporative marine, shallow-water normal-marine, meteoric, and burial diagenetic environments. Some of the diagenetic processes are closely related to depositional texture and mineralogy (e.g., cementation, compaction, selective dissolution), while others (e.g., reflux dolomitization, evaporite mineralization) are more related to groundwater (brine) flow (Lucia et al., 1999). The major Upper Dalan diagenetic processes are discussed below.

5.2.1. Evaporative marine diagenesis

The major diagenetic processes active in the evaporative marine diagenetic setting were dolomitization and evaporative mineralization, both of which are ubiquitous in the sabkha to tidal flat facies belt. Progressive evaporation of marine waters resulted in sabkha pore waters reaching gypsum saturation state and led to precipitation of gypsum from interstitial waters within the shallow sabkha subsurface, where it displaced the uncompacted tidal-flat aragonite mud (cf., Butler, 1969; McKenzie et al., 1981; Warren, 2006). In addition, gypsum likely readily precipitated subaqueously from shallow salinas as salinity in them reached gypsum precipitation field. The evaporative mineralization subsequently resulted in the destruction of primary structures and development of massive and nodular anhydrite. As observed in this study, the diagenetic anhydrite is associated with dolomite, which requires the downward flow of sulfate- and magnesium-charged hypersaline water through the underlying tidal-flat and subtidal sediments, converting the aragonite mud into dolomite and precipitating gypsum (Lucia et al., 1999). Similarly, based on the presence of anhydrite nodules and their association with early dolomite, Rahimpour-Bonab et al. (2009) inferred that the anhydrite formation within the Dalan carbonate of the South Pars field is primary in origin. It is likely that the replacement of both subaqueously precipitated and displacement gypsum by anhydrite subsequently occurred during burial to depths below the gypsum–anhydrite reaction isotherm (Jowett et al., 1993; see also Amadi et al., 2012).

5.2.2. Shallow-water normal-marine diagenesis

The major diagenetic processes that modified porosity under shallow-water, normal-marine conditions were microbial micritization, early (mechanical) compaction and marine phreatic cementation. Based on the results of the sedimentary-petrographic analysis, the shallow-water normal-marine diagenetic environment is characterized by slight grain deformation, fibrous isopachous cements, and micrite envelopes coating both skeletal and non-skeletal grains. Given the ocean carbonate chemistry that during Permian was associated with aragonite seas (Stanley and Hardy, 1999), the shallow-marine cements should have precipitated as fibrous or bladed isopachous crusts of either aragonite or magnesian calcite mineralogy (Moore, 2001). This is confirmed by the circumgranular calcite cement textures that in places contain ghosts of the original aragonite texture, suggesting later burial stabilization to calcite and subsequent meteoric processes. Microbial micritization of carbonate grains was a common process during early diagenesis of the Upper Dalan Formation, and was characterized by precipitation of microcrystalline aragonite or magnesian calcite cements (both later replaced by calcite) around carbonate grains or infilling tiny voids formed by microborers. In some cases, the micrite envelope is still visible while the grain has been totally

dissolved; in other cases, microbial envelopes locally served as a substrate for cement growth.

The most common type of porosity in this diagenetic setting is associated with selective dissolution of aragonite bioclasts, peloids and ooids. The resulting moldic porosity found in the finely crystalline dolomite matrix and its association with sabkha sequences suggests preferential syndepositional (or shortly after deposition) dolomitization of aragonite mud, and subsequent, perhaps shortly after dolomitization, dissolution of aragonite allochems under influence of fresh water (Moore, 2001). Given that separate vugs are connected mostly through the interparticle pore network, the moldic pore space probably contributes very little to the overall permeability (Lucia et al., 1999).

5.2.3. Meteoric diagenesis

The meteoric diagenesis affected the Upper Dalan carbonates during sea-level lows associated with subaerial exposure and development of a meteoric lense (Rahimpour-Bonab et al., 2010). Given the arid climatic setting, however, the groundwater flow likely encountered a zone of refluxing hypersaline water near the shoreline and formed a zone of mixed meteoric and hypersaline water, which in turn favored dolomitization and sulfate mineralization instead of massive dissolution (Lucia et al., 1999). The meteoric diagenetic setting is characterized by ubiquitous cementation processes, including precipitation of calcite blocky cements, drusy mosaic cements, and minor gravitational cements, followed by dissolution of skeletal and non-skeletal grains. The latter resulted in development of fabric- and non-fabric selective moldic pores. Most of the cements were originally formed as low magnesium calcite and progressively occluded primary pore spaces in the grain-dominated carbonate facies. Tavakoli et al. (2011) suggested that the presence of gas-escape structures, fenestral fabrics formed by microbial activity, desiccation cracks, and planar grain contacts may also be used to indicate shallow meteoric diagenetic conditions in the Upper Dalan carbonates. However, many of the meteoric diagenetic features are hard to identify because of the later burial obliteration through dolomitization.

5.2.4. Burial diagenesis

This diagenetic realm is characterized by aggrading neomorphism, intensive dissolution, compaction, and cementation. These characteristics are readily recognized under petrographic observation, and include poikilotopic cement fabric, dissolution and creation of moldic pores in the presence of marine burial waters, concavo-convex and sutured contacts between grains, stylolite development, undulatory extinction of coarse calcite mosaics, locally coarse dolomite cement and development of saddle dolomite (Fig. 3N), and coarse anhydrite cement. It is likely that most of the cementation, compaction and dissolution processes in the Upper Dalan reservoir took place in the burial diagenetic environment. Later stage of mechanical compaction has resulted in nested fabrics and selectively reduced porosity in ooid dolograins. The chemical compaction resulted in pressure solution and the development of stylolites (Taghavi et al., 2006), the presence of which may be responsible for the anomalous and locally enhanced horizontal permeability (Tavakoli et al., 2011) (Figs. 3P and 4L). Late stage of mechanical and chemical compaction (sutured and concavo-convex grain contacts) affected more intensely the sediment without well-developed early marine cements; the early cements likely would have prevented grains from increasing overburden pressure during burial (e.g., Moore and Druckman, 1981; Shinn and Robin, 1983). Dolomite cements constitute significant part in this study interval, with most of them occurring as fabric destructive dolomite bodies with euhedral to subhedral crystal morphologies. The increase in dolomite crystal size with

depth was caused by greater burial depths and temperatures (Tavakoli et al., 2011) (Figs. 3N and 4J). Similar dolomite character has been reported from the equivalent Khuff reservoirs east of Qatar (Alsharhan, 2006), and offshore Dubai (Videtic, 1994). In addition to coarse dolomite, saddle dolomite occurs sporadically in some of the studied samples, where it is typically associated with coarse anhydrite. The presence of coarse, authigenic poikilotopic anhydrite cement, including the fracture filling anhydrite, suggests late burial fluid flow.

5.3. Porosity development and permeability distribution

The average porosity of the Permian Upper Dalan and Triassic Kangan Formations in the eastern Zagros ranges from >10% in offshore fields to <4% in Interior Fars, reflecting the transition from grain- to mud-dominated facies along the Qatar-Fars Arch (Esrafil-Dizaji and Rahimpour-Bonab, 2013; their Fig. 15). The corresponding Khuff reservoirs of Arabia have an average porosity of <12% (Ehrenberg, 2006). Both Upper Dalan and Khuff reservoirs show normal porosity loss during burial, i.e., their porosity decreases with increasing burial depth (Ehrenberg et al., 2007; Esrafil-Dizaji and Rahimpour-Bonab, 2013). This porosity loss with increasing burial depth (>4 km in the studied well) likely reflects an increase in pressure solution and associated precipitation of thus provided Ca^{2+} and CO_3^{2-} ions as cement, hence reducing both pore-size and porosity (e.g., Schmoker and Halley, 1982; Schmoker, 1984; Ehrenberg, 2006; Ehrenberg et al., 2007). Mechanical compaction presumably occurred within the first kilometer or two (Goldhammer, 1997), and was subordinate to chemical compaction given the early calcite cementation that reduced compaction by the overburden pressure (cf., Ehrenberg et al., 2007).

Although relatively low due to deep burial and associated cementation, porosity is present in all carbonate parts of the studied Upper Dalan Formation. Its variations reflect different original rock fabrics and subsequent diagenetic changes. The Upper Dalan Formation is predominantly composed of both grain- and mud-dominated facies. The studied facies mostly exhibit petrophysical class 1 or 2 relationships (Figs. 5–7), which suggests that the mud-dominated facies that normally are associated with petrophysical class 3, have been altered during diagenesis to medium-crystalline dolomite that exhibits class 2 petrophysics (cf., Harrington and Lucia, 2012). Many samples of medium-sized (20–100 μm) dolomites exhibit class 1 instead of class 2 relationships (Fig. 6C), which likely is due to presence of abundant poikilotopic anhydrite cement; the patchy nature of this cement decreases porosity but has relatively little effect on pore-throat radius, thus it improves permeability with respect to porosity (Lucia et al., 2004; Lucia, 2007; Harrington and Lucia, 2012). On the other hand, pervasive pore-filling anhydrite cementation has resulted in reduced porosity and permeability in many of the studied samples, especially in dolograinstones and grain-dominated dolopackstones. Such permeability loss in some dolograinstones and grain-dominated dolopackstones finer than 20 μm is offset by presence of microfractures, and formation of connected vugs due to dissolution. The presence of connected vugs also increases permeability in medium-grained dolograinstones and grain-dominated dolopackstones, while extensive cementation and dolomitization, in addition to anhydrite cementation reduce it. In dolograinstones and grain-dominated dolopackstones coarser than >100 μm permeability is reduced due to reduction in inter-crystal porosity and associated decrease in pore size; this is partially offset by fracturing as well as by post-stylolitization dissolution that could have partly reversed porosity loss initially induced by stylolitization (Koepnick, 1985; Dawson, 1988). In dolomudstones, dolowackstones, and mud-dominated

dolopackstones, the reservoir quality locally increases due to fracturing and dissolution, the latter resulting in formation of connected vugs. Zero porosity and permeability evident in some of the samples (not shown in Fig. 6A), is likely the result of pervasive pore-filling and nodular anhydrite cementation (Fig. 3B). Many of the limestone, dolomitized limestone and calcareous dolomites exhibit relatively high porosity in the low porosity ranges, which is associated with recrystallization, dissolution, and dolomitization, the latter resulting in increase in crystal size and thus improved capillary properties due to the corresponding increase in pore size (Lucia et al., 1999). Further dolomitization of limestone intervals was obstructed by the inflow of normal-marine waters into the Upper Dalan lagoon during the transgression and early highstand. Several dolograinstone samples normally associated with petrophysical class 1, exhibit class 2 petrophysics (Fig. 6D) due to presence of separate-vug pore space that increases total porosity, but has very little effect on permeability. As noted above, anhydrite cementation has led to occlusion of pore space and decrease in permeability. In reflux settings similar to the Late Permian large epeiric platform that stretched from present day Iran to Saudi Arabia, anhydrite cements that are spatially and temporarily associated with replacement dolomitization can result in a porosity reduction of up to 25% (Jones and Xiao, 2005). On the contrary, anhydrite cementation had a positive role in improving reservoir quality by preventing further compaction of carbonate particles during shallow burial; it also resulted in development of fractures and associated increase in the reservoir quality. Finally, assuming that the highly variable permeability data in the low porosity ranges evident in many samples is not due to data-quality issues (e.g., incomplete cleaning of core-plug samples; Harrington and Lucia, 2012), it likely is related to presence of fractures and connected vugs that could increase permeability in the low porosity field (Lucia, 1983).

Variations in the RQI indicate that the lower and middle part of the studied reservoir have similar fluid flow characteristics that are better compared to the upper part of the reservoir (Fig. 9). Despite quite different lithologies (with lower part predominantly of grain-dominated and middle part of mud-dominated lithologies with two anhydrite intervals), porosity (high in lower, and low in the middle part), permeability and the RQI values are within the similar range. On the other hand, lower and middle part of the reservoir have the same, grain-supported lithologies and porosity values, but permeability and the RQI index values are lower, which indicates that they represent different flow units. The above suggests that fabric-selective and fabric-retentive dolomitization in the lower part of the studied interval enhanced reservoir quality by generating more fabric-selective, moldic and interparticle pores. The abundance of anhydrite in the middle part of the reservoir decreases porosity, but has no effect on permeability and the RQI values due to presence of fabric non-selective microfractures and connected vugs. The dolomitization in the upper part of the reservoir was less fabric-selective compared to the lower part, which in association with dissolution resulted in abundant separate-vugs and lower RQI values.

6. Conclusions

The Upper Dalan Formation, Kish Gas Field, offshore Zagros basin, formed during the Late Permian on a gently sloping homoclinal ramp facing the western Paleo-Tethys. The studied ~222 m thick K4 reservoir sequence of the formation yields the following conclusions on microfacies, depositional environment and diagenetic evolution:

- Microfacies analysis indicates three main depositional settings, including sabkha to tidal flat, lagoon with leeward shoals, and mobile (windward) sand shoal facies belt. This suggests more complex setting for the Upper Dalan Fm. than previously described.
- Sabkha to tidal flat deposits include four different lithofacies: laminated to massive anhydrite (coastal sabkha and shallow hypersaline lagoon), dolomudstone with anhydrite nodules (coastal sabkha), dolomudstone (semi-restricted to restricted evaporative intertidal), and intraclastic dolowackestone (intertidal).
- Lagoon and leeward shoals facies belt is composed of bioclastic wackestone/dolowackestone to packstone and peloid dolopackstone and peloid–bioclastic dolopackstone, suggesting a moderately shallow lagoon with shoals around and below the fair-weather wave base.
- Mobile (windward) sand shoal facies belt is composed of five ooid-rich lithofacies indicating a very high-energy shoal; these include ooid–peloid dolograstone, ooid dolograstone, ooid–intraclast dolograstone, ooid–bioclast dolograstone–packstone, and coarse bioclast–intraclast dolograstone.
- Common pore types include interparticle (intragrain and intercrystal), separate vug (moldic), and connected vug. Sampled population mean of the reservoir porosity is 4.63% (max. 21.06%); permeability is 53.494 mD (max 4110.96 mD). Variations in porosity and permeability within the Upper Dalan Formation reflect different original rock fabrics and subsequent diagenetic changes, with ooid-rich facies exhibiting highest reservoir quality.
- The major diagenetic processes that impacted K4 reservoir quality indicate the presence of evaporative marine setting with early (reflux) dolomitization and associated evaporative mineralization; normal-marine setting with microbial micritization, early (mechanical) compaction, and marine phreatic cementation; meteoric setting with cementation and dissolution; and burial diagenetic setting with aggrading neomorphism, intensive dissolution, compaction, and cementation.
- Fabric-selective and fabric-retentive dolomitization in the lower part of the K4 reservoir enhanced quality by generating more fabric-selective, moldic and interparticle pores. Dolomitization was less fabric-selective in the upper part, which in association with dissolution resulted in abundant separate-vugs and lower RQI values.
- K4 lithofacies exhibit predominantly petrophysical class 1 and 2 relationships, as well as a range of permeability values in a low porosity field. The results indicate that anhydrite cementation, extensive calcite cementation and dolomitization contributed to reduced porosity and permeability; selective, fabric-preserving dolomitization, micro-fracturing and formation of connected vugs resulted in higher permeability for a given porosity.

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