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RESEARCH PAPER

The Impact of Paleoclimate on Dolomite Reservoir Development in the Zagros and Persian Gulf Regions

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Abstract
Dolomite reservoirs flourished during arid climatic periods in the Middle East, primarily in the Permo-Triassic, Upper Jurassic, and Oligo-Miocene formations. These dolomitized reservoirs are frequently linked to evaporites, exhibit isotopically enriched signatures, and tend to occur predominantly in the more restricted regions of carbonate platforms. These observations strongly support their origin through sabkha and evaporative reflux processes. Consequently, dolomite formation and distribution are primarily influenced by early diagenetic processes and climatic conditions during arid periods. Dolomitization has exerted a significant influence on reservoir properties within the studied carbonate platforms. Porosity distribution and variation are jointly controlled by several factors, including dolomite content, texture, crystal size, anhydrite abundance, dolomite cementation, and the extent of burial compaction. While dolomite textures can vary from fabric-preserving to fabric-destroying, the overall reservoir properties exhibit an ascending pattern from intertidal to shoal facies. This trend is primarily determined by the proximity to the source of dolomitizing brines. The downward percolation of brines, coupled with decreasing dolomitizing potential, leads to an increase in dolomite crystal size within depositional cycles as one moves further away from the anhydrite facies. Proximal areas, characterized by fine-grained intertidal and lagoonal facies, are more susceptible to anhydrite cementation and overdolomitization, resulting in significant porosity reduction. Conversely, in more distal regions, reservoir quality substantially improves, particularly in areas dominated by sucrosic dolomite or grain-rich facies. While this trend may be altered by compaction during burial, it underscores the crucial role of dolomitization in preserving porosity, especially in deeply buried carbonate reservoirs.

Keywords: Dolomite Reservoirs, Dehram Reservoirs, Upper Surmeh Reservoirs, Asmari Reservoirs.

Introduction

Dolomite reservoirs are commonly found in the Middle East, North America, and Southeast Asia (Braithwaite et al., 2004; Qing Sun, 1995). Generally, dolomitization has varying effects on the reservoir properties of the original limestone (Lucia, 2004; Saller and Henderson, 1998). Dolomitization in grain-dominated limestones typically does not significantly alter porosity-permeability relationships. However, it enhances the reservoir quality of mud-dominated facies by increasing crystal size and improving capillary properties (Lucia, 2004). Conversely, porosity is reduced through dolomitization due to dolomite cementation, particularly in cases of overdolomitization (Lucia, 2004; Lucia & Major, 1994; Saller & Henderson, 1998).

While the exact origin of dolomite remains a subject of debate, it is noteworthy that the majority of dolomite reservoirs are often linked to evaporites, occurring in both platform and

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basinal settings (Qing Sun, 1995; Warren, 2000). These reservoirs have been efficiently sealed by sabkha and salina evaporites. Consequently, numerous researchers have interpreted that these early dolomites were formed through the reflux of hypersaline fluids in arid climates (Adams & Rhodes, 1960; Warren, 2000). In such reflux systems, porosity generally increases as one moves away from the source of the hypersaline brines. This is due to a greater volume of dolomite precipitating in the proximal parts (resulting in overdolomitization) of the dolomitizing system compared to the distal parts (Lucia & Major, 1994; Saller & Henderson, 1998). As a result, evaporative tidal-flat dolomites typically exhibit lower porosity compared to the adjacent subtidal dolomites, primarily due to overdolomitization (Qing Sun, 1995; Saller & Henderson, 1998).

The reservoir potential of dolomitized facies can undergo significant modification through post-dolomitization diagenetic processes. Following dolomitization, as sediments undergo progressive burial and compaction, both porosity and permeability are typically reduced (Budd, 2001; Schmoker & Halley, 1982). In general, at shallow depths, dolomites tend to exhibit lower porosity compared to coeval limestones. However, they tend to retain more porosity as they undergo burial and compaction processes (Schmoker & Halley, 1982). Furthermore, because dolostone exhibits lower ductility compared to limestone and sandstone, the reservoir properties of dolomite reservoirs are often improved through the presence of fractures.

Dolomite reservoirs have been extensively developed in the Permo-Triassic Dehram (Khuff Fm.), Upper Jurassic Surmeh (Arab Fm.), and Oligo-Miocene Asmari carbonates of the Middle East (Aqrawi et al., 2006; Cantrell, 2006; Ehrenberg et al., 2007a; Morad et al., 2012; Qing Sun, 1995). These dolomite formations constitute the reservoir rocks for some of the world's largest hydrocarbon reservoirs, including those found in Iran and Arabian countries such as North Dome-South Pars, Ghawar, Marun, Ahwaz, and Gachsaran fields (Alsharhan, 2014). Based on prior research, the process of dolomitization and the reservoir properties of carbonate reservoirs worldwide are significantly influenced by the prevailing paleoclimate conditions (Markello et al., 2008; Mehrabi et al., 2015; Qing Sun & Esteban, 1994). To delve deeper into the influence of the prevailing climate on dolomitization, we commence by reviewing the historical climate fluctuations in the Zagros region from the Permian to the Recent period. These assessments are rooted in the Zagros paleogeographic positions (paleowander path) and paleoclimatic indicators. Subsequently, within this paleoclimatic context, we conduct a thorough reevaluation and comparative analysis of the sedimentological, diagenetic, and reservoir characteristics of the primary dolomite reservoir rocks in the region. This paper consolidates and presents both previously published and newly acquired data.

Geological setting and tectonic framework

The petroleum-rich Zagros domain is structurally situated along the northeastern margin of the current Arabian Plate. It stretches across the Middle East, from the Strait of Hormuz to northeastern Iraq (Fig.1). The geological history and hydrocarbon distribution in the Zagros region can be classified into two primary periods, delineated by tectonic events, paleogeography, paleoclimate, and stratigraphy (Alsharhan, 2014; Alsharhan and Nairn, 1997; Beydoun et al., 1992; Bordenave, 2014; Koop and Stoneley, 1982; Murris, 1980).

In the initial period, spanning from the Infracambrian to the late Carboniferous, the Zagros domain constituted the northern passive margin of the Arabian Plate, which was a part of Gondwana. It bordered the ancient paleo-Tethys Ocean. This phase commenced with the Najd rifting during the Infracambrian period, following the breakup of the supercontinent Rodinia. It was subsequently brought to an end by the Hercynian Orogeny in the late Carboniferous (Al-Husseini, 2000; Ruban et al., 2007). Except for the Cambrian period, this region was positioned at high southern latitudes, within a non-tropical climate belt. Consequently, the pre-Permian stratigraphic record predominantly comprises terrestrial to shallow-marine clastic deposits, with relatively minor occurrences of limestone. As the Zagros region migrated toward lower latitudes, it experienced two glaciation events in the late Ordovician and the late Carboniferous, both of which coincided with regional unconformities in the geological record (Alsharhan, 2014; Konert et al., 2001). The late Ordovician glaciation in the Zagros region is evident in the post-glacial sediments of the Sarchahan Formation, which are characterized by their organic-rich composition. These sediments have served as source rocks for the Permo-Triassic gas reservoirs (Bordenave, 2014).

During the second period, spanning from the Permian to the Neogene, the region constituted the northeastern margin of the Arabian Plate. The tectono-sedimentary history and the presence of hydrocarbons in the Zagros region are primarily associated with the opening and subsequent closure of the Neo-Tethys Ocean in the southern part of the region during this timeframe (Alsharhan & Nairn, 1997). Starting from the Permian period and continuing onwards, the Zagros area was situated within the tropical climatic belts, spanning from 30°S to 30°N latitudes. The stratigraphic sequences during this era are predominantly composed of marine carbonates, accompanied by lesser amounts of shale and evaporites. These sedimentary deposits are indicative of an arid climate during deposition (Alsharhan, 2014; Beydoun, 1998). During this period, the Dehram Group (comprising Dalan and Kangan formations), Khami Group (including Surmeh, Fahliyan, Gadvan, and Dariyan formations), Bangestan Group (encompassing Sarvak and Ilam formations), and Asmari Formation, which constitute the principal reservoir rocks, were formed and developed (Al-Husseini, 2007; Bordenave, 2014).

Paleogeography, paleoclimate and stratigraphy

Subsequent to the Hercynian epirogenic movements, during the early Permian period, a shallow marine transgression occurred, marked by the presence of basal coastal clastics (Faraghan Formation) that covered the Zagros region. As the Neotethys began to open in the mid-Permian, a wide shallow carbonate platform was established across most of the region. During the Permian, the area was positioned at approximately 30°S latitude, and it subsequently migrated northward to near 20°S during the early Triassic (Fig. 2) (Insalaco et al., 2006; Pöppelreiter, 2014). Consequently, the climate gradually became warmer and experienced periodic aridity. These conditions were conducive to the formation of oolitic limestones characterized by widespread dolomitization and the occurrence of anhydrite streaks within the Dalan and Kangan formations (Esrafili-Dizaji and Rahimpour-Bonab, 2013).

By the middle Triassic period (Ladinian), the paleolatitude had shifted to approximately 15°S, which would typically correspond to a region with humid climates. However, during this time, sedimentation was primarily characterized by extensive evaporites (Dashtak Formation), indicating a progressive increase in the aridity (Esrafili-Dizaji and Dalvand, 2018). According to paleoclimate reconstructions (Sellwood and Valdes, 2006; Ziegler et al., 2003), the arid belt extended all the way to the equator during most of the Triassic period, suggesting the likely absence of a humid equatorial belt during this time.

Throughout the Jurassic period, the Zagros region underwent a gradual northward movement, distancing itself from the equatorial region, and eventually reaching a position at approximately 10°S latitude (Alsharhan, 2014; Heydari, 2008; Murris, 1980). An alternation of arid to semi-humid conditions can be inferred from the deposition of thick sequences of dolomitized rocks, anhydrite, and shale. During the early Jurassic period (Hettangian to Toarcian), the climate became increasingly arid, leading to the accumulation of extensive dolomitized successions (Neyriz and lower Surmeh formations) and evaporites (Adaiyah and Alan formations) in the shallow carbonate platforms and their central evaporative depressions (Alsharhan, 2014; Heydari, 2008; Murris, 1980). During the middle Jurassic period (Alenian to Callovian), there was a gradual shift back to a semi-humid climate. This climatic change corresponded with the formation of organic-rich shales (Sargelu Fm.) and the occasional presence of evaporites (middle Surmeh Formation). As the late Jurassic unfolded, there was a progressive increase in climatic warming and arid conditions, leading to the deposition of substantial evaporites in sabkha environments (Hith Formation) as well as in deeper water settings (Gotnia Formation) (Alsharhan, 2014; Heydari, 2008; Murris, 1980).

During the onset of the Cretaceous period, a significant shift in paleoclimate took place. Paleogeographic reconstructions suggest that the studied area was located very close to the equator during the Cretaceous (Berra and Angiolini, 2014; Beydoun, 1998; Heydari, 2008; Murris, 1980). Additionally, this period was primarily characterized by globally elevated temperatures and higher sea levels. Within the equatorial and humid climate regime which accompanied by increased rainfall, the depositional patterns were mainly marked by carbonates associated with shale and the absence of evaporites. By the Neocomian age, a broad carbonate platform (Fahliyan Formation) had been reestablished, contributing to the development of a substantial carbonate sequence (Berra and Angiolini, 2014; Beydoun, 1998; Heydari, 2008; Murris, 1980). During the Hauterivian and Barremian periods, clastic deposits (Gadvan Formation) dominated large portions of the Zagros area, while the carbonate deposits migrated eastward. As a subsequent transgression occurred, the clastic deposits were gradually replaced and overlaid by thick shallow marine carbonates (Dariyan Formation) during the early Aptian (Alsharhan, 2014; Sharland et al., 2001). The carbonates exhibited significant lateral facies variations as they extended toward intrashelf basins, which were formed in the central Zagros and the eastern Persian Gulf regions. Towards the conclusion of the Aptian period, the Zagros region experienced uplift and a relative drop in sea level, leading to a regional exposure. This emergence is evident through the presence of karstic features (Mehrabi et al., 2018).

During the Albian period, a significant influx of clastic sediments led to the deposition of the Kazhdumi shales. This influx was primarily driven by a humid climate and increased rainfall. Subsequently, in the Cenomanian, a rise in sea level occurred, which reduced the input of clastic materials. This rise in sea level resulted in extensive flooding and the deposition of the Sarvak carbonates (van Buchem et al., 2011).

Following the Cenomanian/Turonian period, the region experienced compressional tectonic activity. This orogenic event caused the Sarvak platform to be extensively exposed to subaerial conditions, which in turn led to significant erosion, karstification, and lateritization processes taking place (Rahimpour-Bonab et al., 2013; Razin et al., 2010). A significant shift in the depositional system occurred following the Turonian, although the humid climatic regime persisted. A broad foredeep basin took shape along the Zagros, oriented in a NE-SW direction. Within this basin, deep shales and marls of the Gurpi Formation were deposited (Alavi, 2004).

During the Paleocene period, the area was located at approximately 20°N latitude, which placed it in proximity to the tropical to subtropical climatic belts (Alsharhan, 2014; Heydari, 2008; Murris, 1980). The presence of evaporites (Sachun Formation) in the early Paleocene signifies a significant climate change during that period. Although the region reached approximately 30°N latitude by the Oligocene, the climate was less arid, and evaporites were less common. Consequently, the Eocene and Oligocene are characterized by the presence of Pabdeh shales and alternations of dolomite and limestone in the Jahrum Formation. A major drop in sea level during the latest Eocene led to the exposure of a substantial portion of the region, resulting in the formation of paleosols over the Jahrum platform. The deposition of Pabdeh marine shales persisted into the late Oligocene in the central and northwestern Zagros regions (Alsharhan, 2014; Heydari, 2008; Murris, 1980).

During the period from the early Oligocene to the early Miocene, a broad marine transgression occurred as a result of a global rise in sea level. This transgression covered a significant portion of the Zagros region and facilitated the deposition of the Asmari limestone

(Ehrenberg et al., 2007b; Heydari, 2008; van Buchem et al., 2010). Following eustatic sea-level drops in the Aquitanian, the Kalhur evaporites were deposited within a restricted intraplatform environment under arid climatic conditions. As the region migrated northward to its current position at approximately 35°N latitude, the climate became increasingly arid. This aridification led to the accumulation of thick evaporites in the form of the Gachsaran Formation during periods of sea-level decline throughout the Miocene (Ehrenberg et al., 2007b; Heydari, 2008; van Buchem et al., 2010).

In response to a global rise in sea level during the early to middle Miocene, especially in the eastern Zagros region, the Gachsaran evaporites were covered by marls and carbonates of the Mishan Formation. The initiation of the Zagros folding occurred after the deposition of the Mishan Formation concluded. Subsequent deposition in the Zagros area was primarily characterized by the southwestward dispersal of clastic sediments (Aghajari and Bakhtiary formations) originating from the rising orogenic belt in the northeast (Alavi, 2004; Heydari, 2008).

Materials and methods

This study focuses on the prominent dolomitic reservoirs located within the Zagros region and the Persian Gulf Basin (Fig.1). Our primary objective is to conduct a comprehensive reassessment and comparative analysis of the distribution and attributes of these dolomitic reservoirs while considering the paleoclimatic context. To achieve this aim, we have provided a detailed account of paleogeographic shifts and the stratigraphy specific to the study area in the preceding section.

We selected representative dolomite reservoirs from three distinct hydrocarbon fields (Fig.1): the South Pars Field (Dehram reservoir), the Belal Field (upper Surmeh reservoir), and Marun Field (Asmari reservoir. For each of these reservoirs, our investigation involved the comprehensive integration of data obtained through core logging, thin-section petrography, poroperm measurements, and isotopic geochemistry.

Cores, which were generally accessible from these selected reservoirs, were systematically examined, described, and logged across three wells. This examination was conducted with a specific focus on identifying and characterizing sedimentological features, including facies, lithology, diagenesis, and other relevant characteristics. In total, the cores subjected to examination collectively spanned an approximate length of 932 meters. Additionally, we conducted a thorough analysis of more than 1,116 thin sections obtained from these cores. Notably, these thin sections were partially stained using a solution of alizarin red S, for detecting dolomitized and non-dolomitized parts (Table 1).

Our analysis of core descriptions and petrographic studies of thin sections was further enhanced through the inclusion of geochemical analysis and poroperm data. To determine the content of dolomite minerals, we conducted X-ray diffraction (XRD) analysis on a total of 250 samples (Table 1).

Table 1. Studied fields and used data in this research.

Reservoir	Field	core length (m)	number of thin sections	number of stable isotope data	number of XRD data	number of poroperm data
Asmari Fm.	Marun	352	172	70	24	395
Upper Surmeh Fm.	Belal	130	220	44	44	175
Dehram Fm.	South Pars	450	724	162	182	205

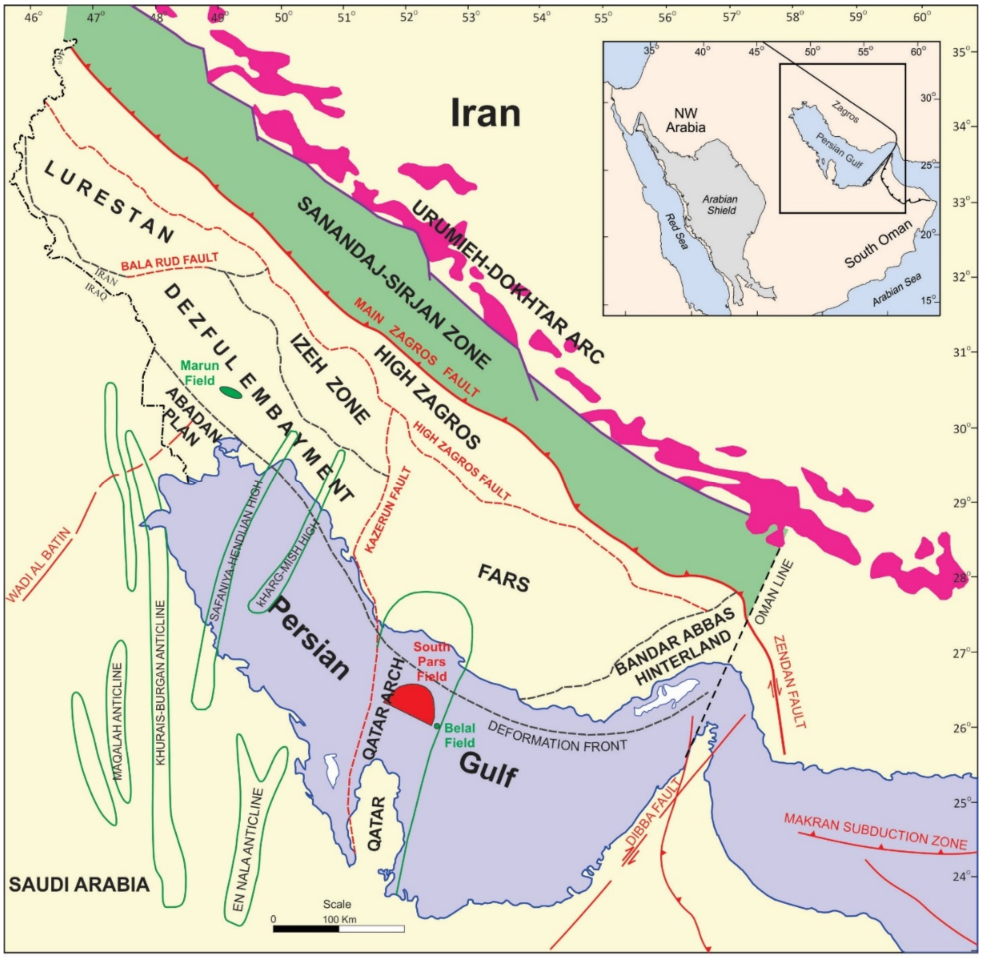

Figure1. Geological setting of the studied dolomite reservoirs in the Middle East

In addition to XRD analysis, we collected 276 bulk rock samples from the cores for comprehensive geochemical analysis. To gain insights into the diagenetic history and environmental conditions, stable isotope ratios, including $\delta^{13}C$ and $\delta^{18}O$, were determined using well-established and standardized methods. All values are reported as ‰ in the d notation, relative to the VPDB standard (Table 1).

To determine porosity and permeability, the core plugs (more than 1000 samples), each measuring 1.5 inches in diameter, underwent a thorough cleaning process involving organic solvents such as toluene and methanol. These tests were conducted under ambient conditions. Porosity values were determined using Boyle's law, a method commonly employed to measure grain volume through helium porosimetry and bulk volume. Permeability measurements were obtained using Darcy's law and a gas permeameter apparatus, maintaining steady-state flow at ambient conditions.

To comprehensively assess geological and petrophysical variations with depth, geological data were collected and integrated with poroperm values and well logs. For each reservoir, a sedimentological log was created to establish a sequence stratigraphic framework, which relied on observations of vertical facies changes, wire-log responses, and geochemical data.

Stratigraphic distribution of dolomite reservoirs

Dolomite reservoirs within the Zagros-Persian Gulf region are predominantly found within three stratigraphic units: in the Permo-Triassic Dehram Group (Esrafili-Dizaji & Rahimpour-

Bonab, 2013), upper Jurassic, upper Surmeh Formation (Daraei et al., 2014; Ehrenberg et al., 2007a) and Oligo-Miocene Asmari Formation (Aqrawi et al., 2006; Ehrenberg et al., 2006) (Table 2).

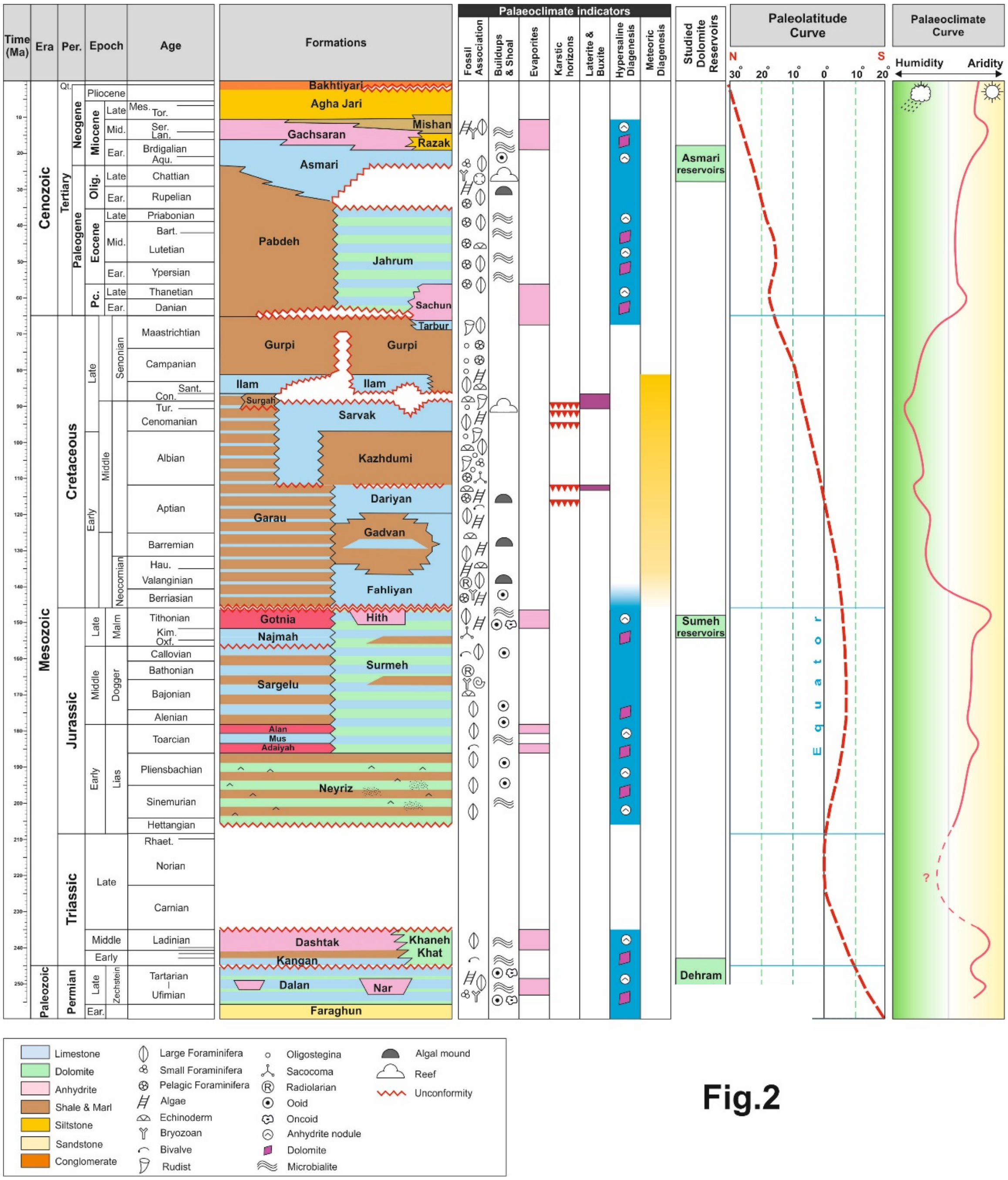

Figure 2. Reconstruction of paleoclimate changes in the Zagros area based on data from stratigraphic record and paleogeographic location. As shown, paleoclimate has changed dramatically, mainly due to the Arabian Plate continental drift leading to the immense facies and lithology variations. Several paleoclimatic indicators, such as general lithology (evaporites), allochems, diagenetic imprints justifying these changes (based on data from Alavi, 2004; Alsharhan, 2014; Daraei et al., 2014; Esrafili-Dizaji & Dalvand, 2018; Esrafili-Dizaji & Rahimpour-Bonab, 2013; James & Wynd, 1965; Mehrabi et al., 2018; Murris, 1980; Rahimpour-Bonab et al., 2013; Razin et al., 2010; Wynd, 1965; Ziegler, 2001)

Table 2. Major dolomite reservoirs of the Zagros region and Persian Gulf Basin

Reservoir rocks	Dehram group (Dalan-Kangan formations)	Upper Surmeh Fm.	Asmari Fm.
Age	Permo-Triassic	Upper Jurassic	Oligo-Miocene
Major facies	ooid grainstone, bioclast, peloid pack/wackestone, microbialite, nodular dolomudstone, anhydite	bioclast, ooid grainstone, bioclast, peloid pack/wackestone, microbialite, nodular dolomudstone, anhydite	red algae –coral facies, ooid grainstone, bioclast , benthic foram pack/wackestone, microbialite, nodular dolomudstone, anhydite
Diagenesis	hypersaline, meteoric and burial	hypersaline, meteoric and burial	hypersaline, meteoric and burial
Pore type	moldic, intercrystalline, interparticle	Interparticle, moldic, intercrystalline, intracrystalline	fracture, moldic, intercrystalline, interparticle, intraparticle
Regional climate	warm and arid	warm and arid	warm, semi-arid and arid
Paleo-latitude	Tropical (30° S latitude)	equatorial	tropical (30° N latitude)
Cap rock	Dashtak Fm. (shale and evaporite)	Hith Fm. (evaporite)	Gachsaran Fm. (evaporite and marl)
Field examples	South Pars, North Pars, Kish, Golshan fields	Salman, Ferdowsi, Golshan, Reshadat fields	Ahwaz, Gachsaran, Marun, Aghajari fields
References	(Ehrenberg et al., 2007a; Esrafili-Dizaji & Rahimpour-Bonab, 2013; Esrafili-Dizaji & Rahimpour-Bonab, 2014)	(Daraei et al., 2014; Ehrenberg et al., 2007a)	(Aqrawi et al., 2006; Ehrenberg et al., 2006)

The Permo-Triassic Dehram carbonates are a highly productive source of non-associated gas and condensate in the eastern Zagros region, including its offshore areas. Remarkably, these carbonates account for over 90% of Iran's gas reserves. Notably, the supergiant gas fields are primarily situated within the Dehram reservoirs, which are equivalent to the Khuff Formation, and are found in key locations such as the South Pars, Kish, North Pars, and Golshan fields in the Persian Gulf. These fields represent significant contributors to Iran's gas production and play a pivotal role in the nation's energy resources (Bordenave, 2014; Esrafili-Dizaji & Rahimpour-Bonab, 2013).

The upper Surmeh reservoir, which is equivalent to the Arab Formation in Arabian countries, constitutes the primary hydrocarbon reservoirs in several oil fields located in the Persian Gulf. Notable among these fields are Salman, Ferdowsi, Golshan, Reshadat, Dorud, Belal, Foroozan, Resalat, and Alvand. These fields play a crucial role in the oil production of the Persian Gulf region, and the upper Surmeh reservoir serves as a key source of hydrocarbons in these areas (Al-Husseini, 2007; Bordenave, 2014; Ghazban, 2007).

The bulk of Iran's oil production has historically originated from the Asmari reservoirs, which continue to be the primary producing interval in the country. These Asmari reservoirs hold nearly half of Iran's proven oil reserves. The supergiant oil reservoirs are notably found in the Gachsaran, Marun, Ahwaz, and Aghajari fields. These fields are significant contributors to Iran's oil production, and they primarily extract oil from the Asmari Formation situated in the Dezful Embayment (Al-Husseini, 2007; Bordenave, 2014) (Table 2).

Facies and depositional environment

Facies analysis reveals that the dolomitized facies within the studied reservoirs can be categorized into six major types, closely associated with anhydrite facies. These facies encompass: a) bioclast, ooid grain/packstone; b) bioclast, peloid pack/wackestone; c) bioclast, foraminifer pack/wackestone; d) microbialite, and e) fenestral nodular dolomite.

These dolomitized facies are typically situated immediately below the anhydrite seal facies at the uppermost part of depositional cycles, following a brining-upward trend. They frequently contain anhydrite cements, both in pore-filling and poikilotopic forms, along with nodules (Fig. 3). Dolomite distribution is primarily concentrated within peritidal and lagoonal settings of carbonate platforms, although complete dolomitization can also be observed in open marine facies (as summarized in Table 3).

The stacking pattern of facies observed in the studied reservoirs closely resembles the oolite-microbialite-anhydrite cycle types, which are commonly associated with arid-climate platforms, (Fig.3). This pattern has been documented in previous studies by some authors (Csoma and Goldstein, 2012; Lipinski et al., 2013; Tomás et al., 2013).

In such arid conditions, characterized by a high rate of evaporation, paleo-salinity levels tend to rise within shallow marine settings. Consequently, active ooid factories thrive in the agitated water zones, typically located above the fair-weather wave base. In response to the environmental stress induced by increasing water salinity, the development of microbialites and anhydrite facies experiences a significant upsurge, while fauna diversity and bioturbation tend to decline. These observations are consistent with the findings reported by many researchers (Csoma and Goldstein, 2012; Mossadegh et al., 2009; Rahimpour-Bonab et al., 2010).

Based on the analysis of facies types and their distinctive features, which encompass components, fossils, and structures, as well as drawing from insights presented in previous studies such as (Esrafili-Dizaji and Rahimpour-Bonab, 2014), it is inferred that the dolomitized intervals within these reservoirs were originally deposited in the shallow regions of the carbonate platform. These facies underwent partial to complete dolomitization, with some instances where texture details were obliterated during the dolomitization process. This phenomenon is particularly notable in the Surmeh Formation. These observations collectively suggest the depositional environment and subsequent diagenetic history of the dolomitized intervals within the studied reservoirs.

Table 3. Major facies types in the dolomite reservoirs of the Zagros and Persian Gulf regions

Facies	Dominant components	Dominant structure	Depositional setting	Reservoirs
bioclast, ooid grain/packstone	coated grains (ooid and oncoids), bioclasts (foraminifera)	cross bedding, massive, reactivation surfaces	shoal	common in the Dehram and Surmeh reservoirs, minor in Asmari reservoir
bioclast, peloid pack/wackestone	bivalve, ostracoda, gastropoda, green algae, fecal pellet (favreina)	bioturbation, lamination, graded lamination	lagoon	common in the Dehram and Surmeh reservoirs
bioclast, foraminifer pack/wackestone	bivalve, ostracoda, gastropoda, miliolid, peneroplis,	bioturbation, lamination, graded lamination	lagoon	common in the Asmari reservoirs
(bioclast), sandy dolomudstone	Quartz sands, various bioclast and foraminifers	bioturbation, lamination, graded lamination	lagoon-intertidal	common in the Asmari reservoirs
calci-microbial boundstone (microbialite)	thrombolite, stromatolite (peloid, ostracoda, foraminifera)	Lamination, fenestral	lagoon-intertidal	common in the Dehram and Surmeh reservoirs, minor in Asmari reservoir
fenestral, nodular dolomudstone	algal clasts, quartz sands, intraclast, peloid	nodular, fenestral	intertidal-supratidal	Dehram, Surmeh and Asmari reservoirs

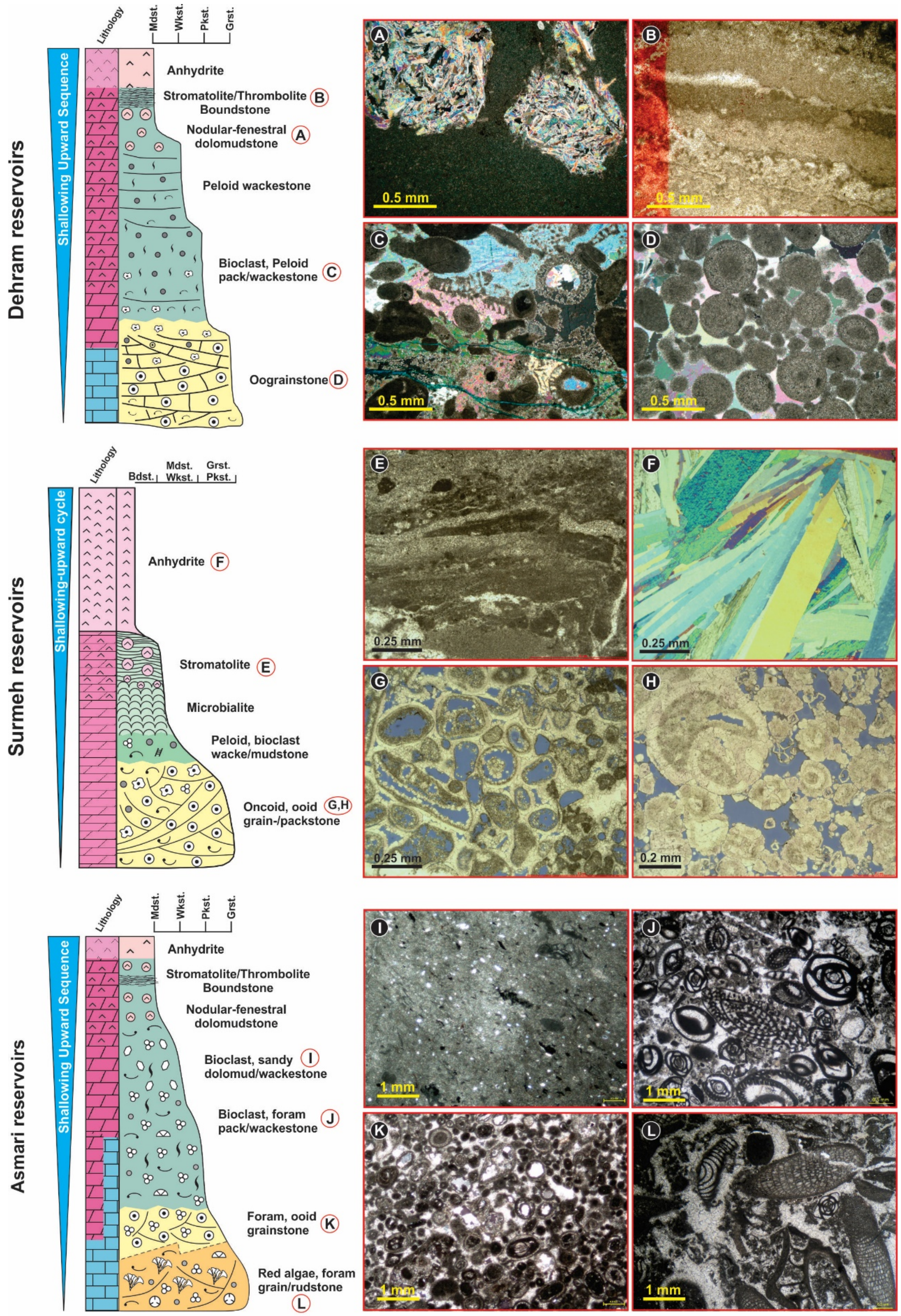

Figure 3. Dolomitic reservoirs of the Zagros area and its offshore, comprise repeated cycles of dolomitized subtidal and peritidal facies with subaqueous anhydrites deposited in restricted parts of the carbonate platforms

The facies association observed in the studied reservoirs reveals a close relationship between the dolomitized facies and evaporites. These can be categorized into two primary types, designated as Type 1 and Type 2, in accordance with Qing Sun's classification (Qing Sun, 1995). Type 1 is peritidal-dominated facies associated with sabkha evaporites, and Type 2 is subtidal facies associated with evaporitic tidal flat/lagoon.

Specifically, these types correspond to peritidal- and subtidal-dominated carbonates. The dominant process responsible for the dolomitization of these carbonates is brine reflux. These brines originated from restricted conditions that prevailed during the arid paleoclimate on the platform tops, particularly during periods of falling sea levels. This brine reflux mechanism played a crucial role in shaping the characteristics and distribution of dolomite within these reservoirs.

Dolomitization

Dolomite petrography

Based on detailed petrographic examinations, the dolomite textures present in the studied reservoir rocks can be classified into two fundamental end-member categories of replacement dolomite: a) microcrystalline, fabric-retentive textures, and b) medium to coarsely crystalline, fabric-destructive textures. There is a gradual transition between the fabric-retentive and fabric-destructive textures, primarily driven by variations in crystal size. Additionally, dolomites with textures that fall between fabric-preserving and fabric-destructive are commonly encountered. The degree of fabric preservation within the fine-crystalline dolomite can vary, ranging from mimetic (faithfully preserving the original rock fabric) to destructive. Partially dolomitized facies generally exhibit fabric-preserving textures. It is worth noting that anhydrite nodules and cements are frequently associated with these dolomites, further illustrating the complexity of diagenetic processes and their impact on the rock textures.

Fabric-retentive dolomite: The fabric-retentive or fabric-preserving dolomite is a prevalent feature within the reservoir rocks and typically manifests as early matrix and selective replacement dolomite. This type of crypto- to microcrystalline dolomite is characterized by a xenotopic fabric, meaning it exhibits a nonplanar structure. It is composed of equant crystals with an average diameter of less than 30 microns (Fig.4 D from the Surmeh Fm., E and F from the Dalan Fm.).

These dolomite varieties generally excel at preserving the original depositional texture and porosity of the rock. They replace not only allochems such as grains and matrix but also near-surface diagenetic products, including micritized grains, bioturbation structures, and isopachous marine calcite/aragonite cements. Early matrix dolomite, often found in association with anhydrite nodules and patches, is typically restricted to intertidal to lagoon facies and replaces fine-grained carbonate muds. In contrast, selective replacement occurs in grain-dominated facies, where dolomite replaces both the matrix and allochems (grains).

Petrographic evidence suggests that the fabric-retentive dolomite precipitated prior to mechanical and early chemical compaction processes (Fig.4 A, B, E and F). It is worth noting that this type of dolomite is frequently intersected by dissolution seams and microstylolites. In terms of volume, it constitutes the majority, accounting for more than 90%, of the dolomite present in the Dehram and Asmari reservoirs.

Fabric-destructive dolomite: This type of dolomite displays a polymodal fabric characterized by variable crystal sizes (Fig.4 B and C). Fabric-destructive or fabric-obliterative dolomites, in most cases, take the form of medium to coarsely crystalline mosaics, referred to as microsucrosic fabric. Within this fabric, crystal sizes typically range from 30 to several hundred micrometers. These dolomites often exhibit a planar texture, featuring crystals that are subhedral to euhedral in shape. Cloudy cores and clear rims are commonly observed in these crystals (Fig.4 B and C).

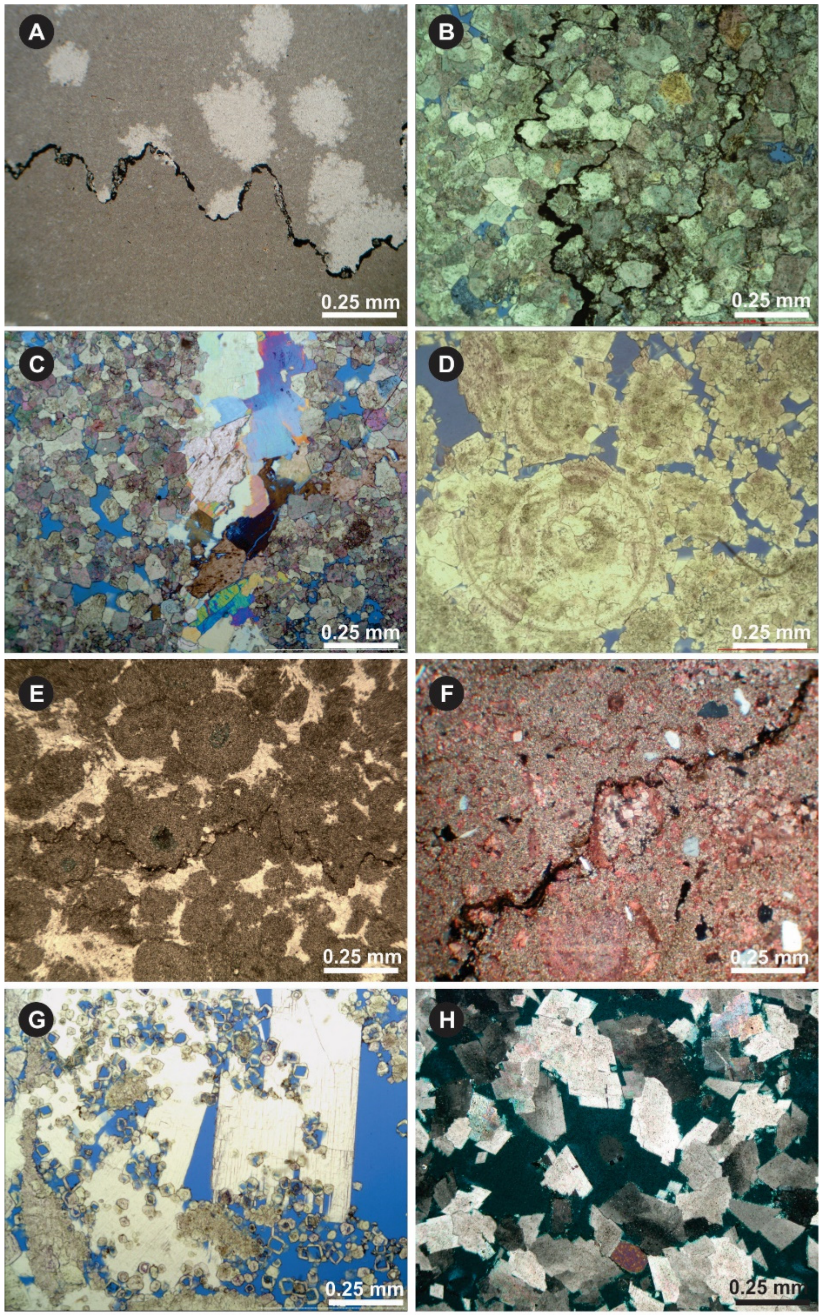

Figure 4. Microphotographs from characteristics and diagenetic relationships of dolomitic reservoir in the studied fields. A) fine-crystalline dolomite containing anhydrite nodules cross cut by stylolites in the Dalan Formation; B) fabric destructive dolomite in the Surmeh Formation, cross cut by stylolite; C) Anhydrite-filled fractures in the destructive crystalline dolomite in the Surmeh Formation; D) fabric destructive dolomitization in the Surmeh Formation, ghost of gastropod are preserved; E&F) Dolomitized grainstone and packstone with anhydrite cement cross cut by stylolites; G) Intracrystalline porosity in rhombic dolomite crystals in the Surmeh Formation; G) Saddle dolomite crystals in the Dalan Formation

The prevailing porosity types associated with this type of dolomite include intercrystalline, intracrystalline, and fractures (Fig.4 C). Dolomitization processes have typically obscured the original precursor fabrics. In cases where relict textures are preserved, they suggest that the dolomite formed by replacing grain-dominated textures such as grainstone and packstone.

It is important to note that, although stylolites and fractures can intersect this dolomite fabric, compaction is generally of minor importance in this type of dolomite. The dolomitization process itself has played a more significant role in shaping the fabric and texture of these reservoir rocks.

It is hypothesized that the size of dolomite crystals in this type varies depending on the grain size of the precursor rock (Rahimpour-Bonab et al., 2010). In this context, micritic particle (lime mud) tend to be replaced by finely crystalline dolomite, while coarse grains and marine cements are typically replaced by coarser dolomite crystals. Consequently, there is a downward increase in dolomite crystal size within the stratigraphic cycles. This means that the smallest crystals replace precursor facies rich in mud under the capping anhydrite facies, while coarser crystals are more prevalent in the lower sections of the cycles, because of coarser grain.

Within the porous zones, medium to coarse, euhedral dolomite crystals with a planar-e fabric are dominated, whereas in the less porous intervals, fine to medium, subhedral to anhedral crystals with a planar-s fabric are common. It is worth noting that this type of dolomite constitutes a relatively minor volume within the Dehram and Asmari reservoirs. In the Surmeh Formation, the core of these crystals has undergone complete dissolution, leaving behind their limpid rims as the preserved remnants (Fig.4 F).

Dolomite cements: Cementing dolomites within these reservoir rocks are observed in the form of overgrowth dolomite rims and coarse saddle dolomite. In zones characterized by extensive dolomitization, the replacive dolomite crystals consist of individual, euhedral rhombs that are enveloped by thin rims of dolomite cement (Fig.14 B). These dolomite crystals typically exhibit a cloudy center and a clear rim. Overgrowing dolomite cement can be found on both dolomite fabrics, but it is more prevalent in the fabric-destructive type.

The amount of dolomite cement is highly variable and can range from 10% to 30% of the dolomite crystals. This cement occurs as euhedral overgrowths that line both primary and secondary pores within the rock.

Saddle dolomite cements (Fig.4 G), on the other hand, are present in very small volumes, constituting less than 1% of the rock composition. They are commonly observed lining fractures and cavities, particularly in the Dehram reservoirs. Petrographic analysis suggests that this type of dolomite cement formed subsequent to phases of fracturing within the rock.

Dolomite geochemistry

The data derived from the measured oxygen and carbon isotopic values of samples taken from the studied reservoirs are presented in Fig. 5. Also, in Figs 6, 7, and 8, changes in the carbon and oxygen isotope data are shown on the sedimentary logs of the studied formations. As depicted in Figure 5, the stable isotope values within the dolomites exhibit considerable variability, spanning a range from +4 to -3.5‰ for $\delta^{18}O$ V-PDB and from +7 to -2‰ for $\delta^{13}C$ V-PDB.

Based on the oxygen isotope composition, the dolomites within the studied reservoirs can be broadly categorized into two groups: dolomites with positive $\delta^{18}O$ values and those with negative $\delta^{18}O$ values. Generally, oxygen isotopic values in the upper Dalan and Asmari dolomites fall within the range of 0 to +4‰ V-PDB. Conversely, the Kangan and Surmeh dolomites typically display negative $\delta^{18}O$ values, ranging from -0.5 to -3.5‰ V-PDB. It is noteworthy that despite these dolomites originating from sabkha and peritidal carbonates, they exhibit a depletion in heavy oxygen isotopes in comparison to co-existing marine dolomites.

The $\delta^{13}C$ values fall within a range similar to the proposed values for dolomites precipitated from Triassic and late Jurassic seawater. Figure 5 illustrates a considerable variability in both oxygen and carbon isotopic data, and these variations can be attributed to their stratigraphic position within the sequence as well as their diagenetic history.

When the oxygen isotopic data is plotted against depth from the top of the sequences, a systematic trend emerges, indicating increasing depletion with depth. In other words, there is an elevated enrichment in $\delta^{18}O$ values from near the maximum flooding surfaces (MFS) to the sequence boundaries in HST, particularly in the Dehram and Surmeh reservoirs. The heaviest oxygen isotopes in the dolomites, particularly early matrix dolomites, are primarily located below these sequence boundaries (SB), which are associated with sabkha facies.

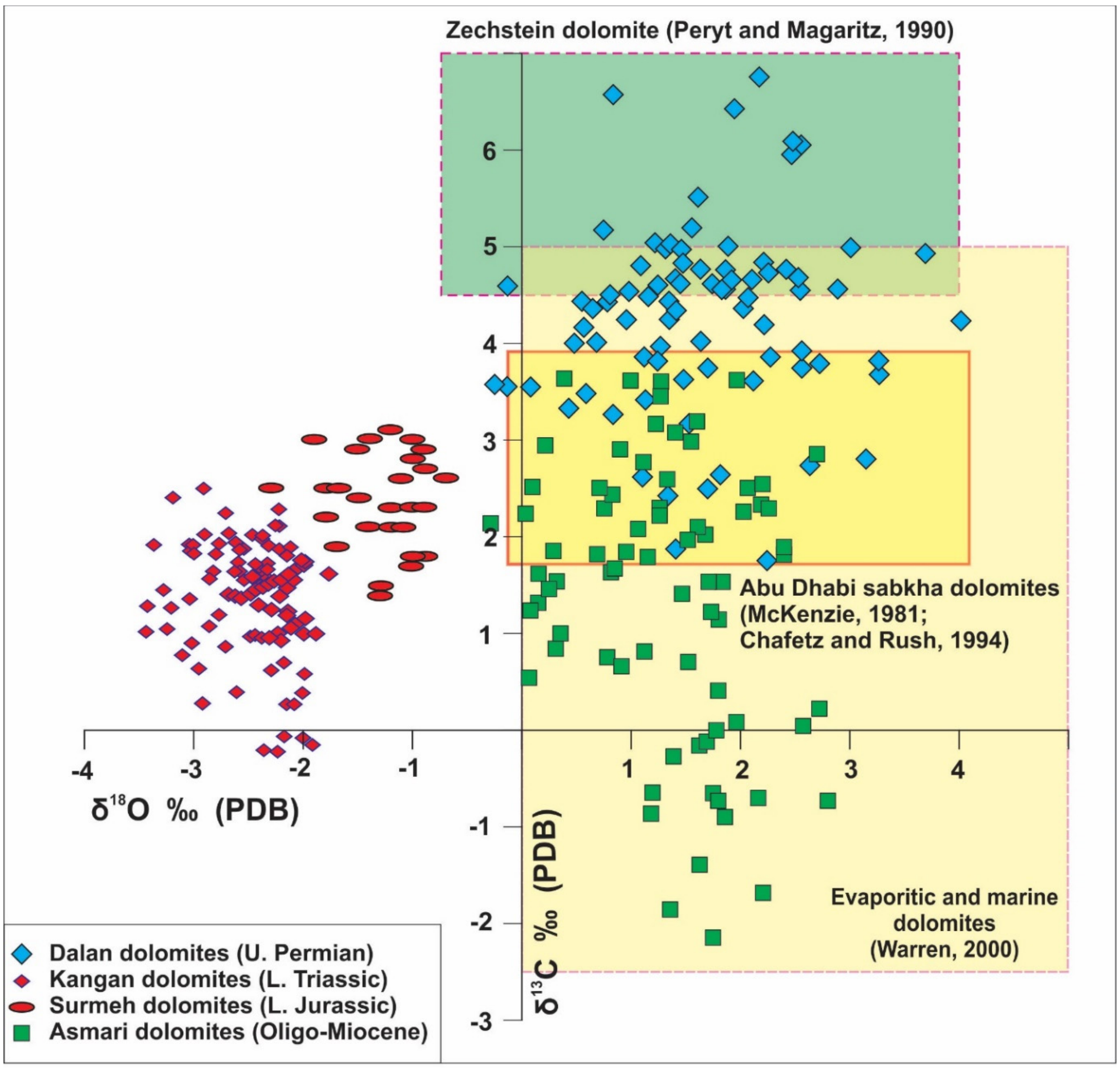

Figure 5. Plot of oxygen vs. carbon isotopic composition of dolomite samples in the Dalan, Kangan, Surmeh and Asmari formations. Sources of Zechstein dolomite data is from Peryt and Magaritz (1990), the field of Abu Dhabi Sabkha dolomite from McKenzie (1981), Chafetz and Rush (1994), the field of evaporitic and marine dolomites from Warren (2000). As seen in this plot, δ18O compositions of Dalan and Asmari dolomites are similar to the fields of evaporitic and marine dolomites (Warren, 2000), but δ18O compositions of Kangan and Surmeh dolomites are slightly depleted relative to expected marine dolomite

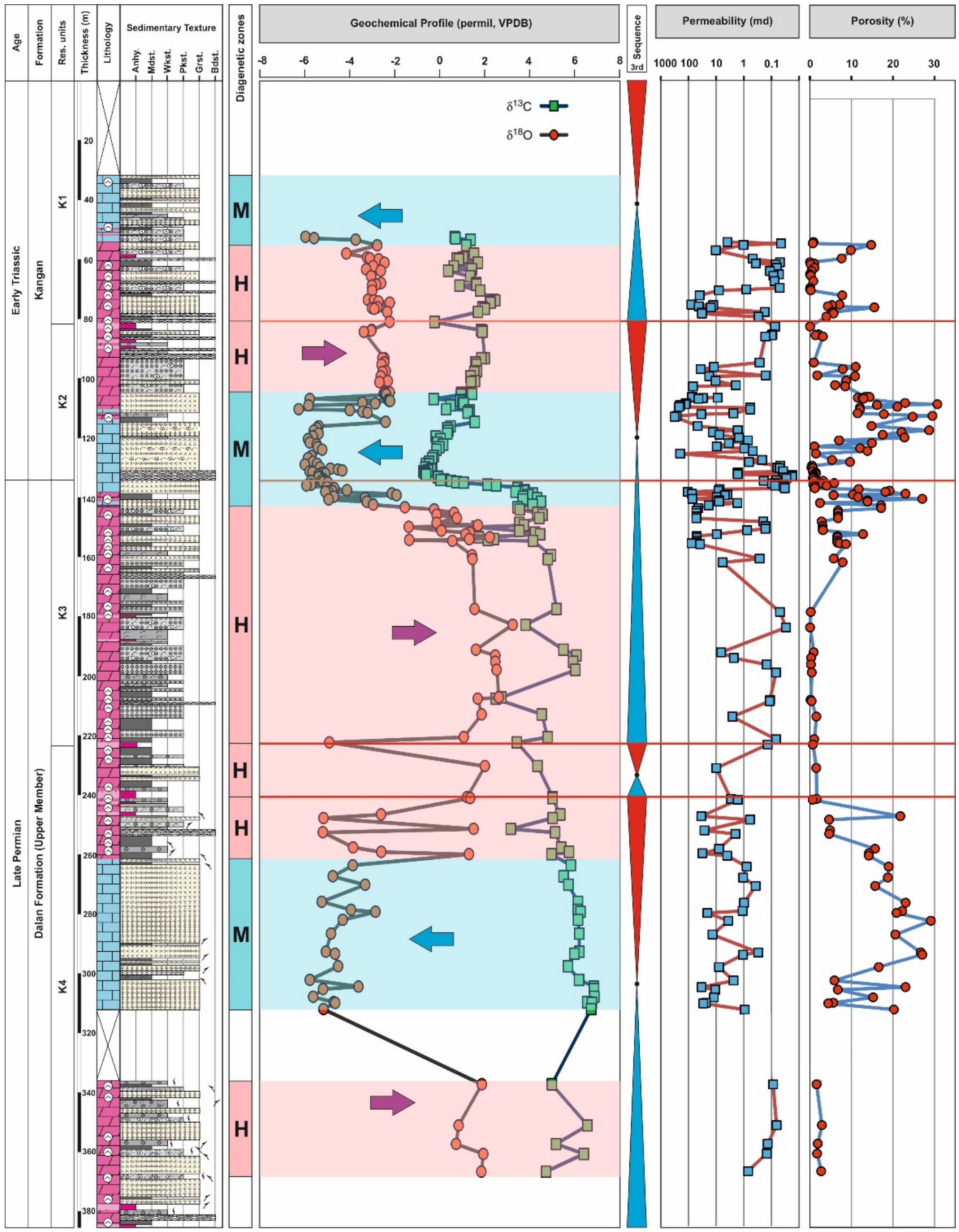

Figure 6. Chemostratigraphic profile (oxygen and carbon isotopes) of the upper Dalan and Kangan carbonates in the South Pars Gas Field. The profile is supplemented by sedimentological log, poroperm values, and depositional sequences. A certain relationship is visible between oxygen and carbon isotopic values and dominant by early diagenetic regime. Two main diagenetic zones are hypersaline (H; violet arrow) and meteoric (M; blue arrow). Generally, dolomitized facies (type H) show higher δ18O values and relatively lower porosity, in comparison to non-dolomitized facies (type M). There are invariant trends between these isotopic data in the sequence boundaries

Dolomitization models

Dolomitization processes associated with evaporite precipitation tend to dominate within hypersaline marine environments, particularly sabkha and reflux dolomitization. The presence of dolomitic intervals within shallowing-upward cycles, often capped by chickenwire nodular anhydrite, indicates a typical sabkha-related system. In these systems, magnesium-rich brines, originating from seawater sources, play a key role in replacing carbonate mud with early micritic dolomite. Additionally, primary evaporites precipitate from these brines (McKenzie, 1981). Furthermore, dolomitization can occur in restricted platform settings due to repeated flooding and the reflux of marine waters with slightly increased salinity. Anhydrite is a common by-product of reflux dolomitization in these settings. These processes collectively contribute to the development of dolomitic reservoirs within such evaporative marine environments.

The geochemical data strongly support this interpretation, as stable isotope values from the early matrix dolomite are either similar to or only slightly depleted relative to coeval seawater dolomite values. In general, the $\delta^{18}O$ composition of all dolomites aligns closely with evaporitic and marine dolomites.

Specifically, the majority of the Dalan and Asmari dolomites exhibit positive oxygen isotope compositions, ranging from 0 to +4‰ V-PDB.

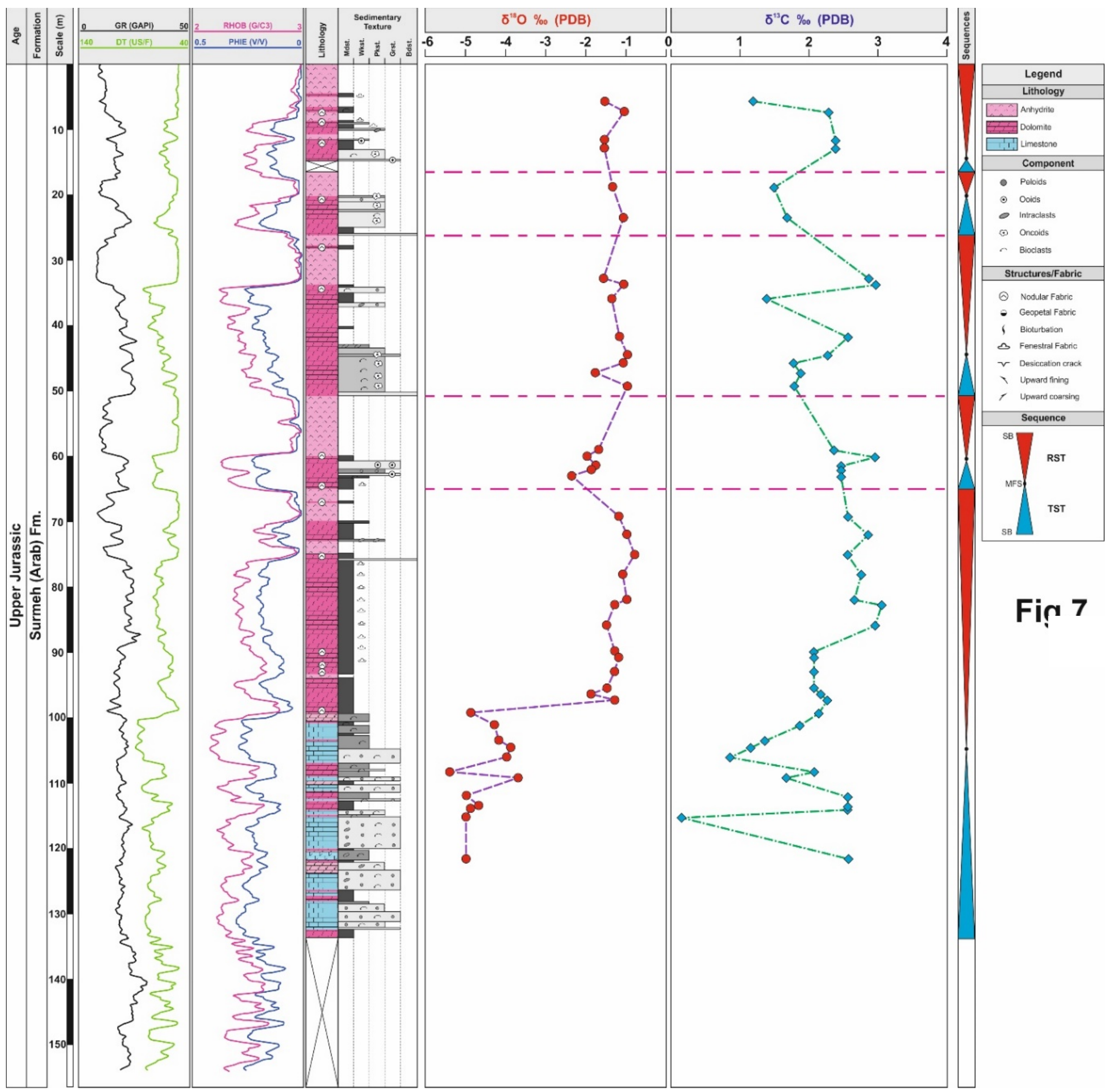

Figure 7. A sedimentological log of the upper Surmeh carbonates in the Belal Field, associated with chemostratigraphic profile (oxygen and carbon isotopes). This log is also supplemented by well logs, poroperm data, and depositional sequences. The reservoir rock consists of highly dolomitized depositional sequences comprised of basal grain-dominated facies (TST), followed by muddy facies and capped by thick anhydrite facies (HST)

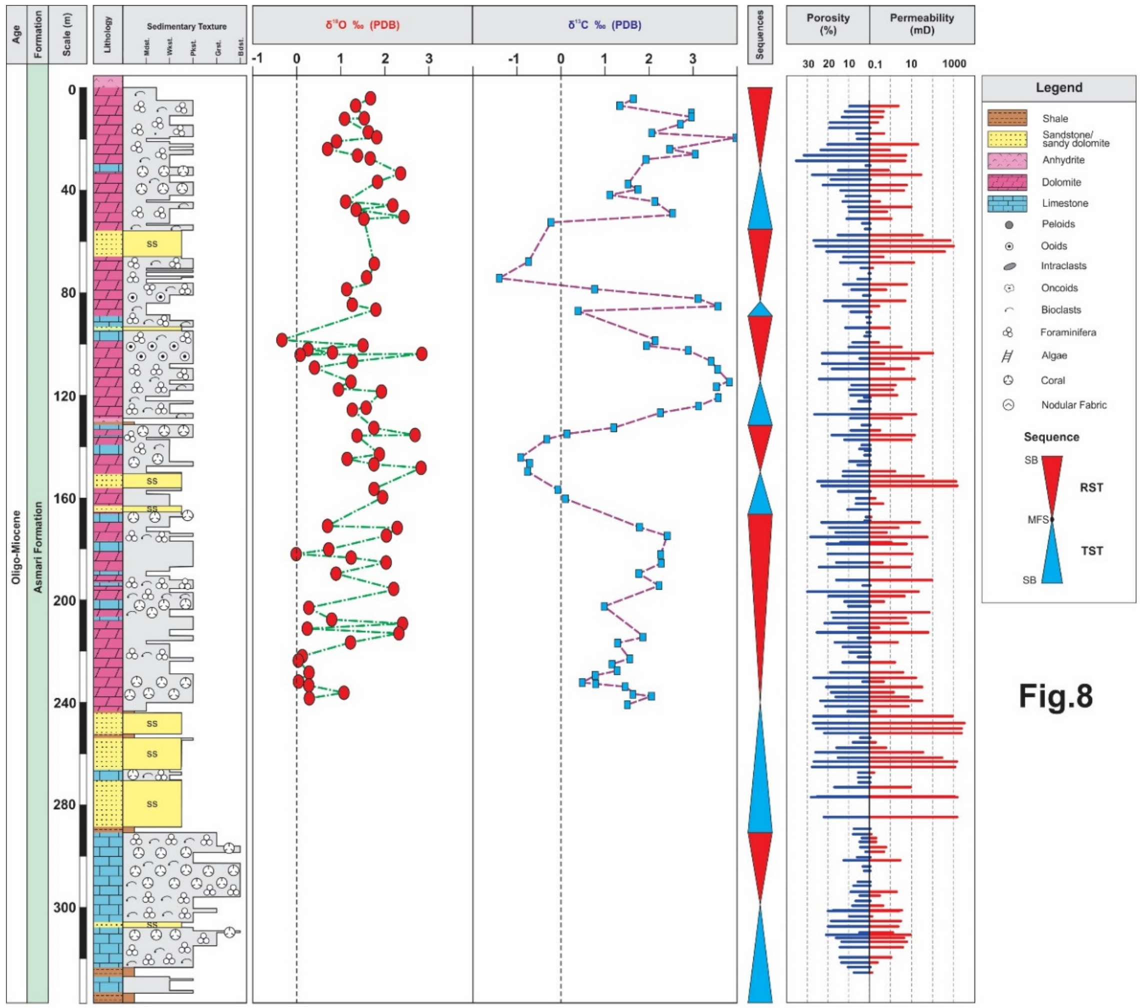

Figure 8. Chemostratigraphic profile (oxygen and carbon isotopes) of the Asmari carbonates in the Marun oil Field. The profile is supplemented with sedimentological log, poroperm values, and depositional sequences. The Asmari Formation in this field is composed of six third order sequences that consist internally of numerous depositional cycles. Most of the porous dolomite occurs within the regressive portion of these depositional sequences. Oxygen isotopic compositions of these dolomites are remarkably constant (between 0 to +2 per mil) suggesting little alteration

These values closely resemble those observed in modern dolomites found in the Persian Gulf's sabkha, as documented by (McKenzie, 1981), as well as evaporitic/marine dolomites, as discussed by (Warren, 2000). This concurrence in isotopic values further supports the interpretation of these dolomites being associated with evaporative marine environments.

The late diagenetic Dalan dolomites exhibit relatively heavy carbon and oxygen isotopes, and their isotopic signatures are comparable to those of the Permian Zechestein dolomites, as noted by (Peryt and Magaritz, 1990). In contrast, the oxygen isotopes of most Kangan and Surmeh dolomites are relatively depleted. This depletion is in line with dolomite recrystallization or re-equilibration that likely occurred during deeper burial and with increasing temperature.

For these dolomites, which show some evidence of minor recrystallization, such as a slight increase in crystal size, their oxygen isotopic values are approximately 2‰ lower than the postulated Holocene values. This suggests that these dolomites underwent post-diagenetic changes and alterations associated with increased burial depth and higher temperatures.

The positive $\delta^{18}O$ excursions observed in the dolomite, occurring from the maximum flooding surfaces (MFS) to positions near the sequence boundaries, strongly suggest that dolomitization processes were primarily driven by hypersaline brines. On the other hand, the $\delta^{13}C$ values indicate that the diagenetic fluids were influenced by the buffering capacity of the carbonate rocks.

During periods of falling sea levels and extensive water evaporation, the remaining brine typically undergoes enrichment in ^{18}O, as explained by (Warren, 2000). Consequently, enriched oxygen isotopic values are commonly interpreted as indicative of dolomitization resulting from higher salinity waters, as proposed by (Land, 1980). These isotopic signatures provide valuable insights into the geological and environmental conditions under which the dolomites in these reservoirs formed.

All available petrographic and geochemical data consistently support the conclusion that dolomitization processes within the studied reservoirs were facilitated by evaporated seawater, following both the sabkha and seepage-reflux models. These processes were primarily driven by increasing aridity during early diagenesis.

Specifically, dolomitization and anhydrite cementation of peritidal facies are proposed to have occurred within an evaporative sabkha setting. In contrast, dolomitization of subtidal packstones and grainstones was driven by the seepage reflux of lagoon brines that formed during significant declines in relative sea level. The rising sea level likely acted as the driving force for reflux dolomitization of the underlying carbonates.

These models provide a comprehensive understanding of the complex diagenetic processes that have shaped the reservoir rocks in the studied area, shedding light on the geological and environmental conditions that prevailed during their formation.

Dolomitization impacts on reservoir quality

Dolomite content

The relationship between dolomite percentage and porosity has been previously documented by researchers such as Murray (1960) and Powers (1962) and Lucia (2004). In this study, the same relationship was explored based on XRD analysis and core porosity data within the dolomitic reservoirs under investigation (Figs. 8 and 9). The plots of dolomite content versus porosity in the Dehram, Surmeh, and Asmari reservoirs (as shown in Fig. 9) exhibit results that are relatively consistent with the findings reported by Murray (1960). This indicates a correlation between dolomite content and porosity, further contributing to our understanding of the reservoir properties within these formations.

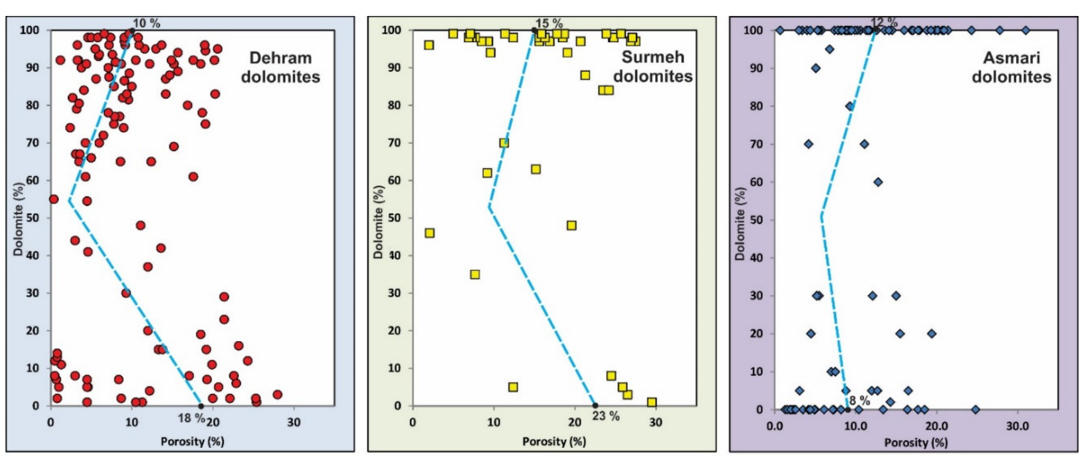

Figure 9. Relationship of dolomite content and porosity in the Dehram, Surmeh and Asmari carbonate reservoirs. Porosity initially decreases with increasing dolomite content to 50%, and then is improved by increasing dolomite percent

According to Murray (1960), the plots in Figure 9 appear to demonstrate that as the replacement of limestone by dolomite progresses, porosity initially tends to decrease as the proportion of dolomite increases, up to around 50% dolomite content. After reaching this point, porosity begins to increase, likely due to the growth of dolomite rhombs and the formation of a supporting crystalline framework. It's important to note that the rate of decrease and subsequent increase in porosity can vary. In essence, rocks dominated by both calcite (or aragonite) and dolomite minerals tend to exhibit high porosity, while intermediate rocks that fall between these two end-members, such as limy dolomite and dolomitic limestone, generally display relatively lower porosity levels. However, it's worth noting that rocks falling into these intermediate categories are not as common as those dominated by pure calcite or dolomite.

As previously observed in carbonate formations in North America, as discussed by (Warren, 2000), carbonate rocks typically tend to be composed primarily of either calcite or dolomite, with intermediate rocks being relatively uncommon. In line with this understanding, the plots indicate that limestones from the Dehram and Surmeh formations generally exhibit higher porosity compared to their dolomite counterparts. Conversely, in the Asmari Formation, the porosity in dolomites tends to be higher than in the limestones. For instance, in the Marun Field, the dolomite within the Asmari Formation has an average porosity of 12%, while the limestone exhibits an average porosity of 10% limestones (see also Ehrenberg et al., 2006 and Ehrenberg et al., 2007a). These trends underscore the influence of mineral composition on porosity within these formations.

The plots depicting dolomites as a percentage of bulk volume (BV) versus porosity reveal several trends within the studied dolomite reservoirs. Porosity initially tends to decrease as the percentage of BV occupied by dolomite increases, ranging from 0 to 70% BV dolomite (as shown in Figure 10). At approximately 70% to 80% BV dolomite, there is an observed increase in porosity as the dolomite percentage continues to rise. However, for carbonates with more than 80% BV dolomite, porosity shows decreasing trends as the dolomite volume increases.
These trends illustrate the complex relationship between dolomite content and porosity, with the initial decrease likely attributed to the replacement of more porous minerals by dolomite. The subsequent increase in porosity could be due to the development of a supporting crystalline framework, as mentioned earlier. Beyond a certain threshold, the dominance of dolomite in the rock composition results in reduced porosity.

The relationship between dolomite content and porosity observed in this study aligns with findings previously documented by Powers (1962) and Lucia (2004). According to Lucia's interpretation in 2004, the decrease in porosity observed from 0 to 80% BV dolomite is likely due to an increase in mud-dominated fabrics and the corresponding rise in compaction. However, when dolomite content surpasses 80% BV, the porosity begins to increase. This phenomenon can be explained by the presence of dolomite-dominated rocks, where the dolomite forms a supporting framework that resists further compaction. This shift in porosity trends provides valuable insights into the diagenetic processes and structural changes within these carbonate reservoir rocks.

Dolomite texture

Fabric-retentive type

As discussed in the earlier sections, dolomitic reservoir rocks can exhibit both fabric-retentive (grainy fabric) and fabric-destructive (crystalline fabric) textures. In the case of the Dehram reservoir, extensive dolomitization has been observed, impacting the porosity of various facies (as illustrated in Figure 11).

Dolomitization in this reservoir is primarily fabric-selective, meaning that certain textures within the rock are preferentially dolomitized while others are preserved. The rate of dolomitization can vary across different facies, ranging from as high as 90% in intertidal facies to around 50% in open marine facies. These variations in dolomitization rates contribute to the heterogeneity of porosity within the reservoir.

The average porosity within non-dolomitized facies exhibits a distinct pattern, starting at 3.8% in the intertidal facies and reaching a peak of 17.6% in the ooid grainstones, before declining in the open marine facies (refer to Fig. 10). In dolomitized facies, this trend is somewhat preserved, albeit with some variability. Notably, porosity remains relatively high in the mud-dominated facies, encompassing both intertidal and lagoon environments.

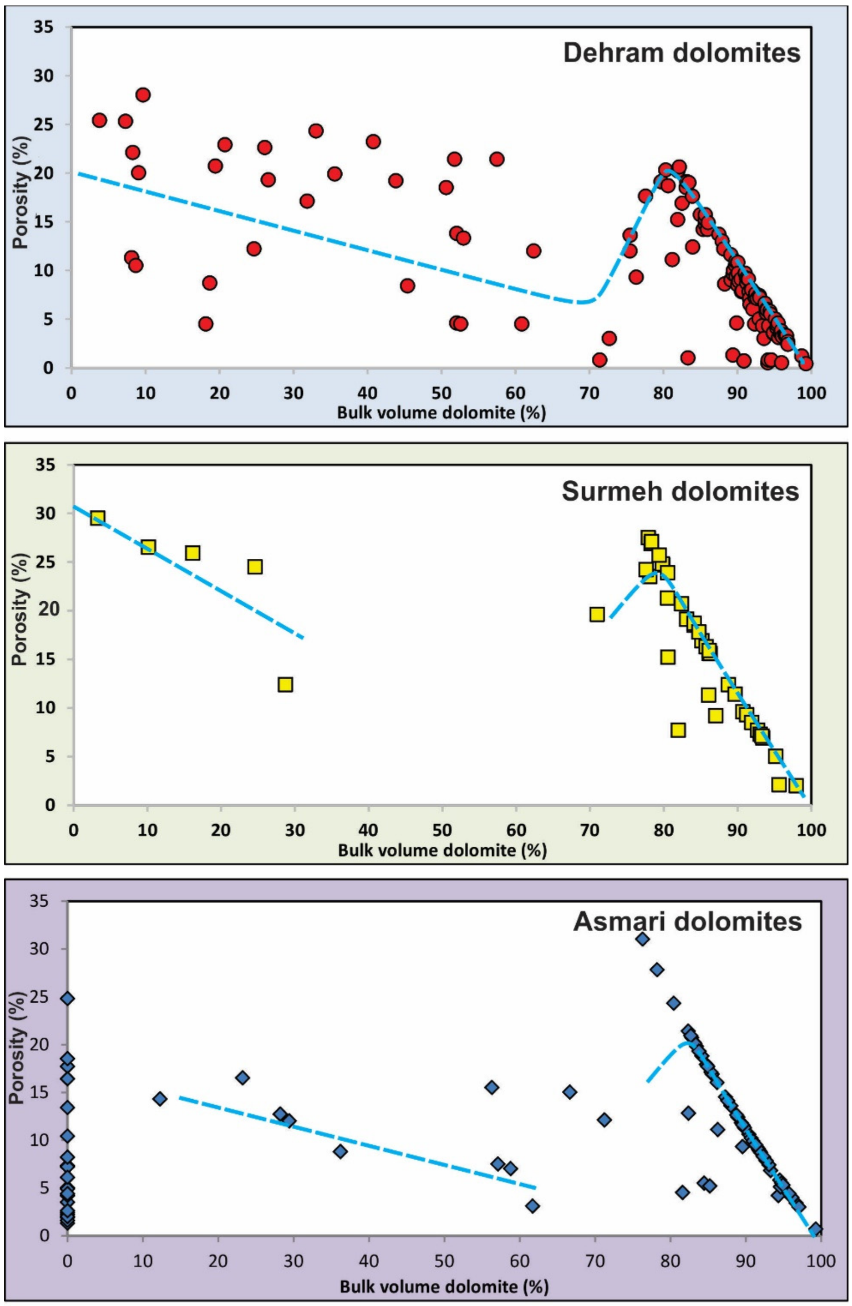

Figure 10. Plots of porosity vs. bulk-volume dolomite (dolomite as a percent of mineral volume plus porosity) for various dolomitic reservoirs, showing that average porosity decreases with increasing dolomite until little or no calcite remains

A substantial porosity range is evident within the ooid grainstone facies, which constitute the primary reservoir rock units. Specifically, dolograinstones exhibit an average porosity of 8%, whereas limy ooid grainstones, characterized by dominant moldic porosity, boast an average porosity exceeding 17%.

A comprehensive examination of the effects of dolomitization on these facies is provided in Figure 12. An analysis of poroperm data encompassing over 3000 samples indicates that dolomitization has a significant influence on the reservoir quality of grainstone facies.

Despite an overall decrease in porosity from non-dolomitized to dolomitized types, there is a notable improvement in permeability within the dolomitized grainstones (as depicted in Figure 12). This suggests that while dolomitization may lead to a reduction in porosity, it enhances the ability of these rock types to transmit fluids, which is a crucial factor for reservoir quality and productivity.

Fabric-destructive type

The Surmeh reservoir is characterized by highly dolomitized depositional cycles, which is consisted of basal grain-dominated facies in the subtidal zone, followed by mud-dominated facies, and ultimately capped by thick anhydrite facies. Dolomitization in this reservoir is predominantly fabric-destructive, and there is a general trend of increasing dolomite crystal size (DCS) moving downward from the anhydrite facies within each cycle (Figure 13).

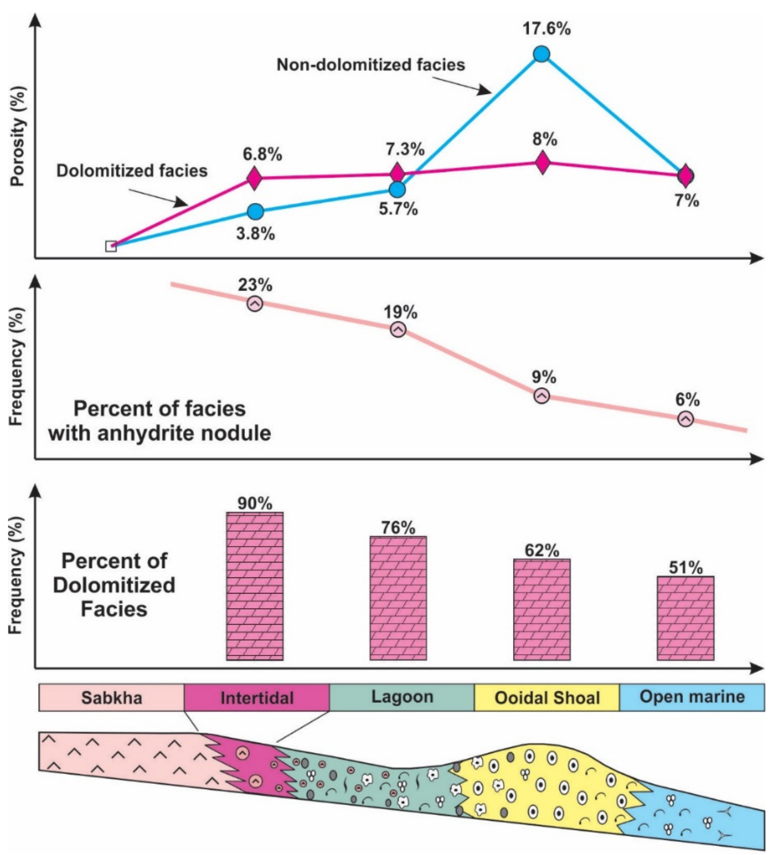

Figure 11. Dolomitization and porosity evolution in the Dehram platform. Integration of petrographic and core porosity data shows that the rate of dolomitization decreases from land-ward (intertidal) to marine-ward (open marine) facies. Average porosity in this platform is a function of depositional energy rather than dolomitization. After the dolomitization, relatively higher average porosity is seen in mud-dominated facies (intertidal and lagoonal facies) than non-dolomitized types, whereas porosity decreases in grain-dominated (ooidal shoal) facies than limy ones

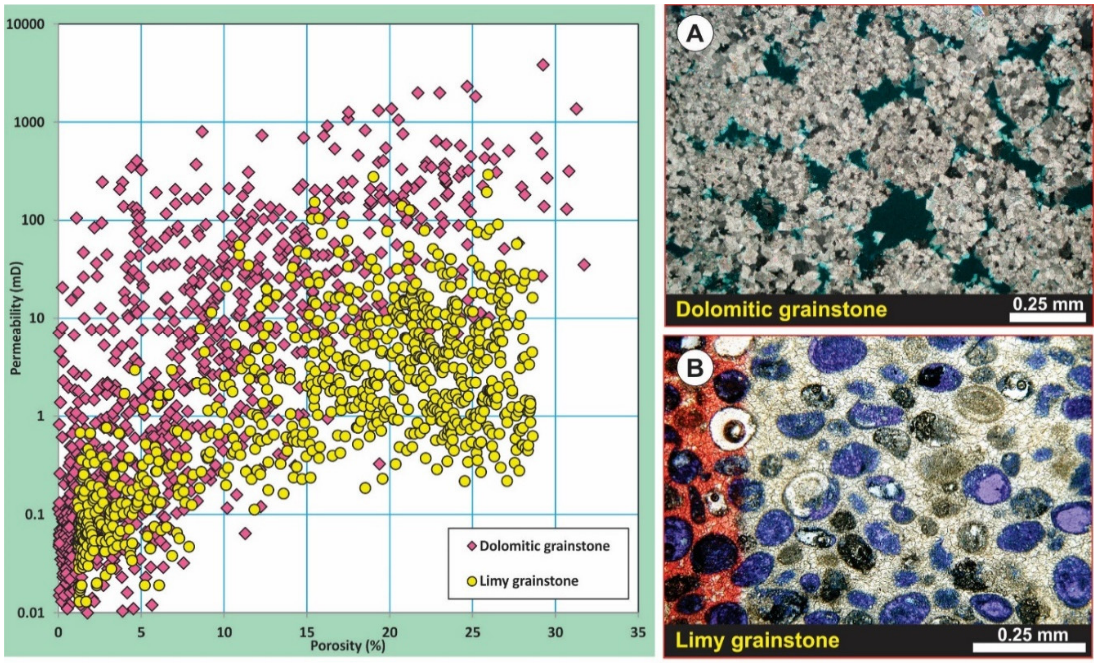

Figure 12. Plot of porosity versus permeability in the non-dolomitized and dolomitized grainstones with two typical microphotographs, as a main reservoir facies in the Dehram reservoirs, South Pars Gas Field

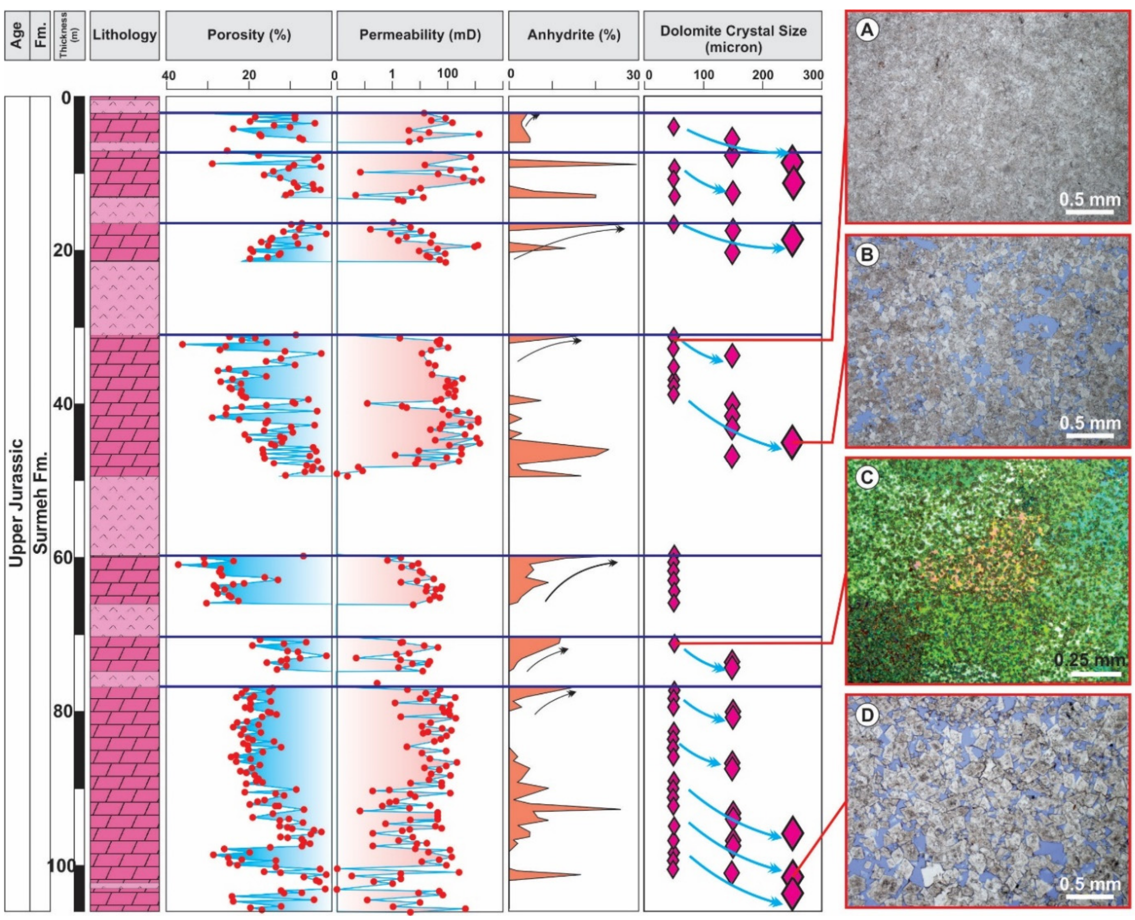

Figure 13. Dolomitization and profile of poroperm data in the Surmeh reservoir (Belal Field). Dolomite crystal size (DCS) generally increases away from the anhydrite facies in each cycle

Porous dolomite is predominantly found immediately beneath the anhydrite facies, where dolomite crystal size is generally less than 100 microns. An investigation into the impact of dolomite crystal size on reservoir quality reveals that the samples can be petrographically categorized into three main types based on DCS: DCS < 100 microns, 100 < DCS < 200 microns, DCS > 200 microns (Fig 12).

The relationship between porosity and permeability within the different groups of dolomite crystal sizes (DCS) is illustrated in Figure 14. In this plot, it becomes apparent that while porosity remains relatively consistent or experiences slight decreases, permeability generally exhibits improvements with increasing crystal sizes. As a result, reservoir properties tend to enhance as one moves downdip from the anhydrite facies at the cycle-top, in accordance with Figure 13. Although dolomite crystal size appears to be a significant controlling factor for reservoir properties, it's important to note that these rocks are subject to intensive anhydrite cementation and compaction, which can also have notable impacts on their characteristics.

Effect of Anhydrite mineralization

The dolomite reservoirs in the studied fields exhibit various types of anhydrite, both depositional and diagenetic, which include: a) Bedded anhydrite; b) Replacive anhydrite nodules; c) Pore-occluding anhydrite cements; d) Poikilotopic anhydrite crystals (c.f. Lucia, 2004).

The thick and impermeable anhydrite facies found in the dolomite reservoirs, capping each shoaling-upward cycle, serve as an effective seal preventing the late influx of freshwater or sulfate-bearing fluids into the underlying subtidal carbonate.

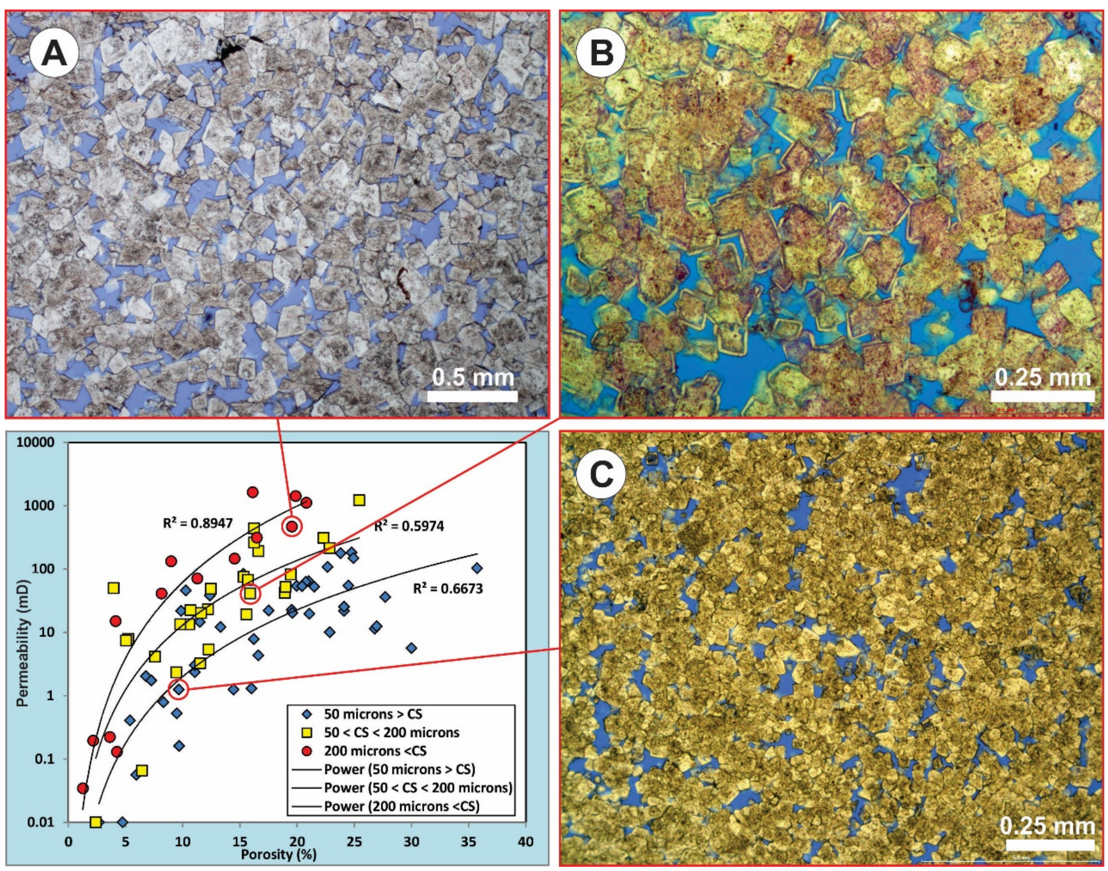

Figure 14. Cross plot of porosity and permeability for dolomites with various crystal sizes in the Surmeh Formation, Belal Field. This plot shows that dolomite with coarse crystalline size have relatively better reservoir properties

This sealing function is similar to what has been observed in other studies (c.f. Saller and Henderson, 1998). The occurrence and distribution of diagenetic anhydrite nodules and cements are primarily controlled by the reflux of hypersaline brines (Warren, 2000; Lucia, 2004). The percentage of facies containing anhydrite nodules decreases from intertidal to open marine facies, as shown in Figure 11. This variation highlights the influence of depositional environment and diagenetic processes on the distribution of anhydrite within the reservoir rocks (Fig. 11).

Core analysis indicates that these anhydrite nodules and cements tend to increase in abundance towards the upper part of the depositional cycles, just below the anhydrite facies. These various types of anhydrite cements, whether partially or completely, can occlude both initial and secondary porosity within the reservoir rocks. Consequently, anhydrite precipitation plays a significant role in influencing the distribution of porosity within the dolomite reservoirs, impacting their overall reservoir quality and fluid flow characteristics.

In many instances, both the original depositional porosity and diagenetic porosity have been completely occluded by the presence of anhydrite cements. This indicates the substantial impact of anhydrite on reducing reservoir porosity, which can have implications for fluid storage and flow in these rocks.

Depth of burial

As also addressed by previous works (see Ehrenberg et al., 2006 and Ehrenberg et al., 2007a), this study highlights the significant impact of differential compaction between coeval limestones and dolomites on porosity reduction during burial diagenesis. The Dehram and Asmari carbonate reservoirs investigated in this study are buried to depths of 2950 m and 3450 m, respectively. The Dehram limestone has an average porosity of 13.5%, whereas associated dolomites exhibit an average porosity of 7.5%. A histogram plot of porosity for both limestone and dolomite in the Dehram reservoir shows that while samples with porosity less than 2% are dominant, limestones generally have higher porosity than dolomites (Fig. 15).

In contrast, within the Asmari carbonates, the average porosity in limestone and dolomite is 8% and 12%, respectively. The histogram plot of porosity in the Asmari reservoir confirms that the Asmari dolomites tend to preserve higher porosity relative to the limestones (Fig. 15). These findings underscore the influence of lithology on the preservation of porosity during burial diagenesis in carbonate reservoirs.

The observations made in this study align with the general trends reported by Schmoker and Halley (1982). As the carbonate platform undergoes progressive burial and compaction, it is typical for porosity to be reduced. In shallowly buried carbonates (less than 2 km), dolomites tend to have lower porosity compared to coeval limestones. However, as burial depth increases beyond 2 km and compaction becomes more pronounced, dolomites lost their porosity more effectively than limestones. This resistance to overburden pressure makes dolomites relatively more porous than associated limestone in deeply buried carbonates. These findings emphasize the importance of considering burial depth and lithology when assessing porosity evolution in carbonate reservoirs.

Discussion

Many research studies and publications have consistently demonstrated the profound influence of paleoclimate on the genesis and attributes of dolomite reservoirs (Lucia, 2004; Lucia & Major, 1994; Qing Sun, 1995). Reservoir quality in dolomite reservoirs is influenced by several key factors. These include dolomite content, texture, crystal size and shape, as well as the presence of anhydrite cementation, dissolution and compaction during burial.

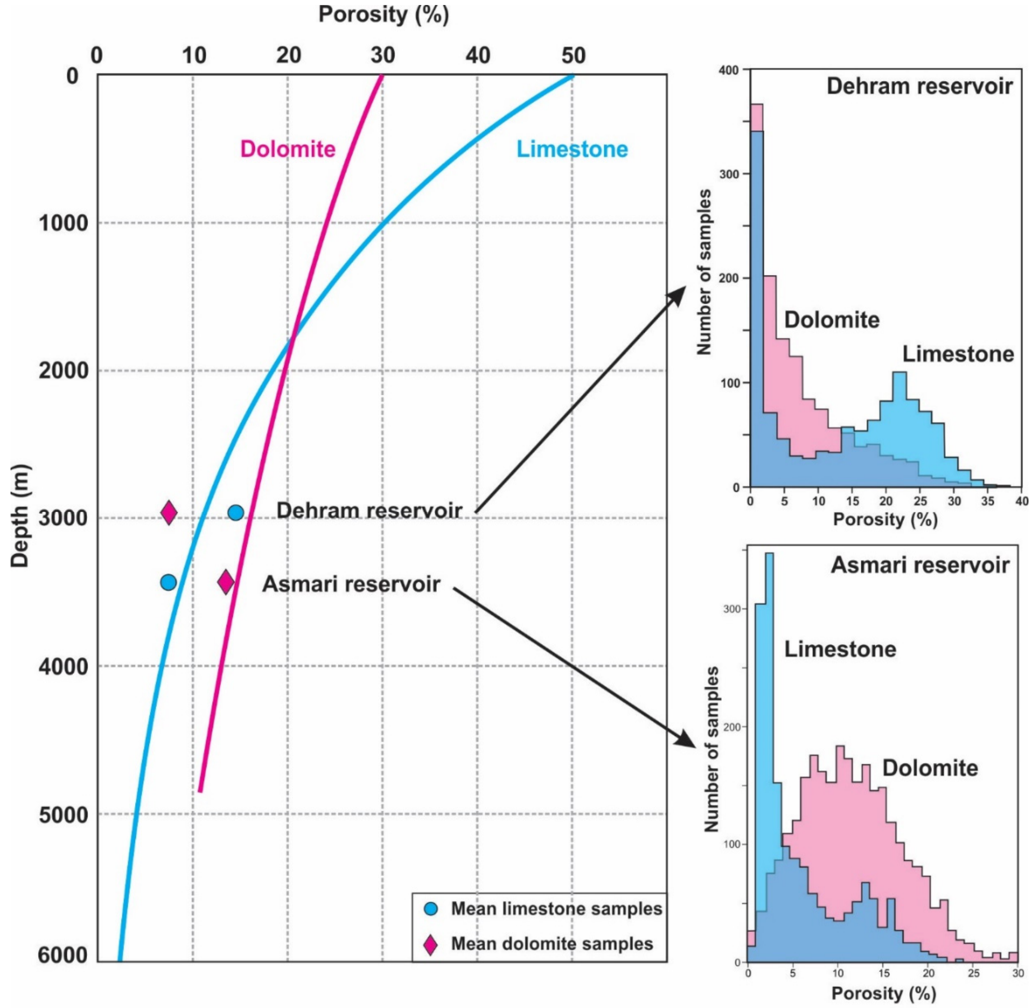

Figure 15. Comparison of the average porosity of limestones and dolomites in the Dehram and Asmari formations with porosity-depth curve of the South Florida limestone (Schmoker & Halley, 1982)

These factors collectively play a significant role in determining the reservoir properties (Lucia & Major, 1994; Murray, 1960; Powers, 1962; Qing Sun, 1995; Rahimpour-Bonab et al., 2010; Saller & Henderson, 1998; Schmoker & Halley, 1982; Warren, 2000; Woody et al., 1996). Dolomitization has a substantial impact on carbonate reservoir characteristics as it alters rock texture, including crystal size and shape. These changes in texture have a direct influence on capillary properties and ultimately impact reservoir performance (Qing Sun, 1995). Extensive anhydrite and dolomite cementation, often referred to as overdolomitization, can significantly occlude both initial and created porosity during the dolomitization process (Lucia, 2004; Lucia & Major, 1994; Machel, 2004). Additionally, the physical strength and chemical stability conferred by dolomitization make the porosity associated with dolomite less susceptible to being lost with increasing depth (Schmoker & Halley, 1982).

Paleogeographic reconstructions spanning from the Permian to the present indicate a substantial climate shift in the Zagros region, transitioning from more humid to arid conditions. Our research, aligning with previous studies (Alsharhan, 2014; Beydoun, 1998), underscores that the development and stratigraphic distribution of these dolomite reservoirs in the studied area have been notably influenced by paleogeographic movements and paleoclimate changes throughout the Permian to Recent periods. Sedimentological and geochemical evidence consistently points to dolomite formation and the dolomitization process being strongly influenced by the arid climate that prevailed during the Permo-Triassic, Late Jurassic, and Miocene epochs.

The dolomite reservoir rocks in question were primarily deposited in shallow marine settings characterized by hypersaline conditions. This observation is consistent with findings from previous research conducted by Aqrawi et al. (2006), Daraei et al. (2014), Ehrenberg et al. (2006, 2007a), Qing Sun (1995), Rahimpour-Bonab et al. (2010), and Taberner (2011). Consequently, these dolomites exhibit a close association with anhydrite precipitation in various forms, including beds, nodules, and cements. Furthermore, they are typically overlain by impermeable evaporitic formations such as the Dashtak, Hith, and Gachsaran formations.

Our investigation indicates that dolomitization in the studied formations has had different effects on porosity compared to permeability. In these dolomite reservoirs, porosity was primarily inherited but often reduced during dolomitization due to overdolomitization (resulting in an increased proportion of dolomite content) and associated anhydrite cementation (see Figs. 8, 9, 10, and 14). However, it appears that permeability was generally improved and enhanced due to changes in rock texture and the increase in dolomite crystal size (see Figs. 11, 12, and 13). Undoubtedly, after dolomitization, poroperm values underwent changes due to compaction, albeit to varying degrees (Figs. 8 and 14). These results align with previous studies by Lucia (2004), Ehrenberg et al. (2006), and others.

In the context of the sequence stratigraphic framework, our observations and results in these dolomite reservoirs can be explained by a model developed by Lucia and Major (1994) and Saller and Henderson (1998). According to this model, due to overdolomitization, porosity in the dolomitized platforms tends to increase from proximal parts to distal parts within the refluxing system (Fig. 16).

Our study on reservoir quality in the major dolomite reservoirs indicates that reservoir quality of dolomite is a function of distance from the main anhydrite cap rocks (see Figs. 10 and 12). As a general trend, reservoir characteristics of dolomite in depositional cycles increase downward and laterally with increasing distance from the anhydrite facies due to increasing grain/mud ratio and dolomite crystal size, along with concurrent decreasing dolomite and anhydrite cementation (Fig. 15).

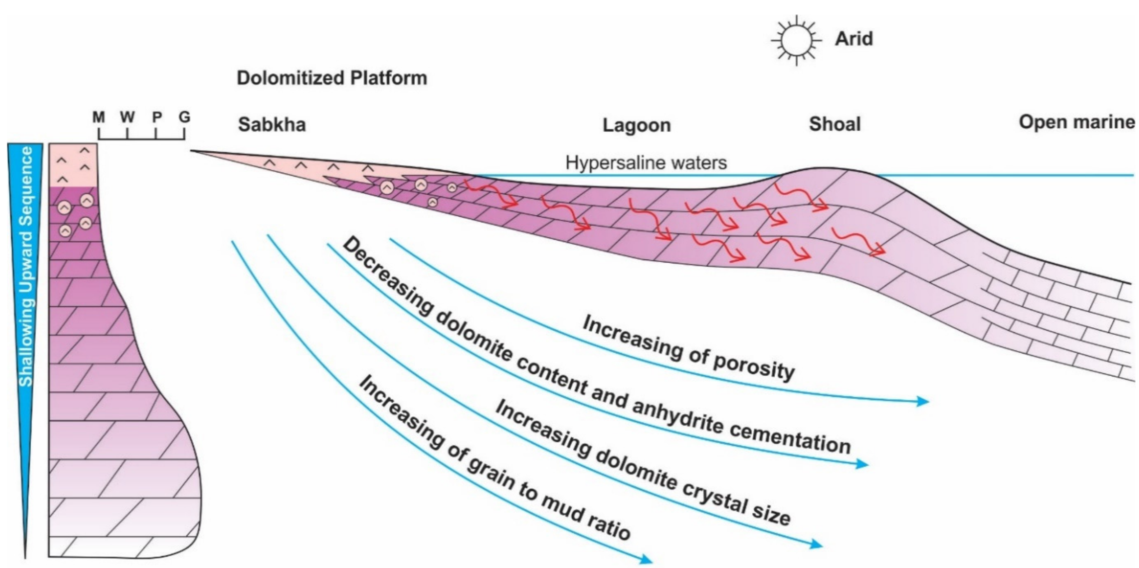

Figure 16. Conceptual model of evaporitic dolomitization (sabkha and reflux dolomitization system) and its effect on reservoir properties. Reservoir quality of dolomite is a function of distance from the main anhydrite cap rocks or source of percolating brine

Due to evaporation under arid climatic conditions, water salinity increases in shallow and restricted parts of the platform. The density difference between the evaporated seawater and underlying pore water results in the reflux of hypersaline brine (Warren, 2000). The downward flux of this dense brine would extensively dolomitize underlying carbonate sediments. The brine is oversaturated with respect to dolomite close to the brine source, typically in lagoonal settings, and progressively becomes less saturated as it moves downdip from the source. The variation in dolomite saturation state in the brine controls the rates of nucleation and growth (Lucia & Major, 1994; Moore et al., 1988; Saller & Henderson, 1998). As a consequence, in proximal parts, the rates of nucleation and growth are higher than in distal parts. Thus, dolomite crystal size increases from the proximal to distal parts. Additionally, overdolomitization and anhydrite precipitation are relatively predominant in the proximal zones. Consequently, these textural and diagenetic modifications strongly affect the reservoir properties of the dolomite that is situated near the surface.

After dolomitization and further burial, the relationship between dolomite and porosity may be disrupted by post-dolomitization diagenesis (Lucia, 2007; Schmoker & Halley, 1982). Due to their different physical and mechanical properties, dolomite and limestone experience differential compaction and porosity loss rates. While limestone is more affected by compaction, dolomite is susceptible to early fracturing. Consequently, fractures tend to occur preferentially in dolomite reservoirs.

Conclusions

By integrating comprehensive core analysis with petrographic and geochemical investigations, several significant conclusions can be drawn concerning the sedimentology and dolomitization processes in the Dehram, Surmeh, and Asmari carbonate reservoirs in the Middle East. Some of these findings may also be applicable to other carbonate reservoirs.

Our research highlights that the development and distribution of major dolomite reservoirs in the Zagros region were significantly influenced by a shift from a more humid to an arid climate. This transition occurred during distinct periods, namely the Permo-Triassic (Dehram reservoirs), Late Jurassic (upper Surmeh reservoirs), and Miocene (Asmari reservoirs).

The presence of dolomitic successions overlying evaporites on a regional scale suggests that the Zagros-Persian Gulf region experienced arid conditions during the Permo-Triassic, Late Jurassic, and Miocene periods. This correlation between climate and dolomite distribution in the Middle East is significant.

Dolomitic reservoir facies are primarily linked to anhydrite, microbialite, and ooid grainstone facies. They are commonly found within shallowing-upward cycles, indicative of brining-upward trends, which are stacked in repetitive sequences.

Petrographic and stable isotope data provide evidence that a significant portion of the dolomite in the studied carbonate formations formed early in the diagenetic process and originated from evaporated seawater. This widespread dolomite generation is consistent with models of sabkha and seepage-reflux dolomitization.

Dolomitization in the studied formations has had varying effects on porosity and permeability. Porosity was primarily inherited and often diminished during dolomitization, primarily due to overdolomitization and the accompanying anhydrite cementation. In contrast, permeability was enhanced and improved through alterations in rock texture and the enlargement of dolomite crystal size. Overall, following dolomitization, poroperm values experienced changes influenced to varying degrees by compaction.

Reservoir properties of dolomite exhibit a clear relationship with distance from the anhydrite facies within depositional cycles. The quality of the reservoir tends to improve downdip from the sabkha and lagoonal settings that served as the sources of dolomitizing brines, which were derived from evaporated seawater. In these cycles, the grain/mud ratio and dolomite crystal size increase while anhydrite and dolomite cementation decrease toward the base of the cycles. Consequently, porosity generally increases in a basin-ward direction where open marine limestones are encountered.

In deeply buried carbonate reservoirs, dolomites are strongly influenced by compaction, leading to the disruption and disappearance of their early relationships and trends during post-dolomitization processes. In such diagenetic settings, dolomite is more prone to early fracturing, which can significantly impact reservoir characteristics.

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