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RESEARCH PAPER

The role of heterogeneity controls in shaping the Asmari Formation reservoirs in the Zagros region, Iran: insights for regional characterization

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Abstract
Various depositional and post-depositional factors interact to shape a reservoir, typically causing heterogenies in reservoir properties on different scales. This study investigates depositional and diagenetic factors controlling reservoir properties of the Asmari Formation as the most prolific reservoir rock in Iran. Data from six surface and 12 subsurface sections show that both primary and secondary factors governed reservoir quality. Lithology is the principal primary control, with major differences between siliciclastics and carbonates. Other primary controls include rock texture, facies, and depositional setting. Dolomitization, dissolution, and cementation are the main diagenetic factors that modify the original rock fabric. Dolomitization improved reservoir quality. Early diagenetic dissolution also enhanced porosity. However, the created spaces are separated vuggy and moldic pores with no effect on permeability. Cementation and compaction are major porosity-occluding processes. Anhydrite cementation degraded reservoir quality of oolites, one of the best productive facies of Asmari. Results show that tectonics, paleo-climate, and sea-level changes were allogenic controls on reservoir configuration. Lithology variations, as a principal control on reservoir quality, resulted from tectonic movements alongside sea-level oscillations. The diagenetic path—specifically dolomitization, dissolution, and cementation—was controlled by paleo-climate and sea-level changes. Hypersaline conditions prevailed during and after deposition, with major impacts on the reservoir quality (pervasive dolomitization and dissolution), were the consequence of combined paleo-climate and sea-level effects. Regional syn- and post-depositional tectonics created widespread fractured reservoirs with higher production rates than unfractured counterparts. The results of this study can assist in regional characterization of the Asmari reservoir throughout the Zagros area.

Keywords: Reservoir Quality, Diagenesis, Facies, Sequence Stratigraphy

Introduction

Both sandstone and carbonate reservoirs are naturally heterogeneous (Shepherd, 2009; Tyler et al., 1984). Porosity is the product of depositional and diagenetic processes as well as fracturing (Worden et al., 2018). Understanding and characterization of key heterogeneities is vital for porosity prediction during oil field production and development. Depositional criteria such as lithology, texture, facies geometry and depositional settings are fundamental controls on reservoir potential but can be altered by diagenetic modifications and fracturing (Moore & Wade, 2013). Early diagenetic modifications exert strong influences on porosity development while in burial diagenesis, reservoir quality is degraded due to calcite cementation and

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compaction (Lucia, 2007; Machel, 1999, 2004, 2005).

The Oligo–Miocene Asmari Formation in the Zagros region (Figure 1) represents the most prolific and principal reservoir rock of Iran, hosting nearly 50% of the total crude oil reserve and producing approximately 80–90% of Iran's oil (Bordenave, 2014; Esrafili-Dizaji & Rahimpour-Bonab, 2019). This formation is essentially carbonate, but two different lithostratigraphic units also occur in some localities (James & Wynd, 1965; van Buchem et al., 2010). The "Ahwaz Sandstone Member" forms major reservoir zones due to its high reservoir potential. The carbonates of the formation also comprise good reservoirs due to significant fracture development (Hull & Warman, 1970; McQuillan, 1985). These two aspects have made the Asmari Formation a highly productive reservoir rock and the first exploration target of the country.

Previous investigations have revealed significant lateral facies changes in the Asmari Formation (e.g., Ehrenberg et al., 2007; Moghaddam, 2022; van Buchem et al., 2010).

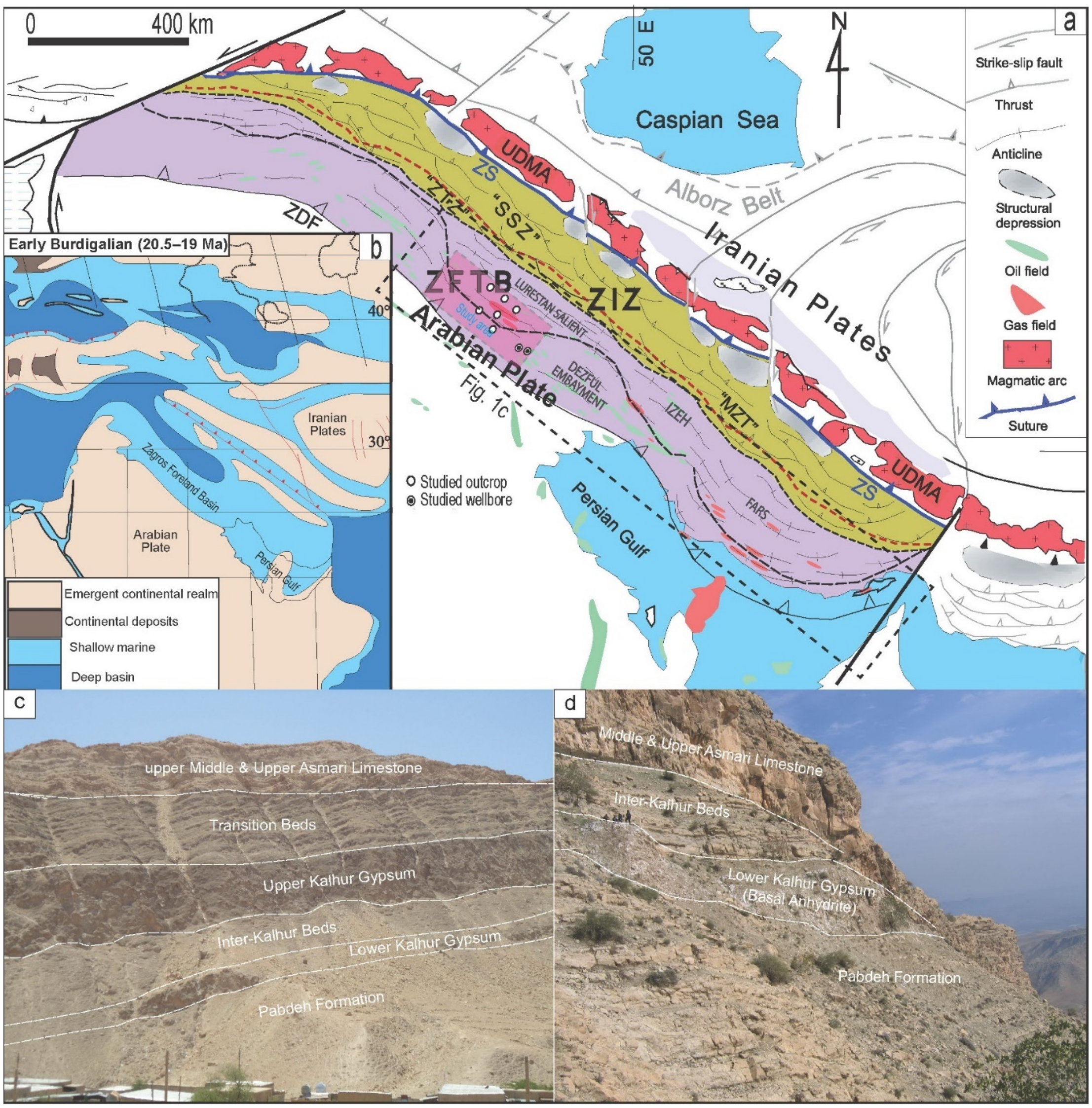

Figure 1. a) subdivisions of the Zagros Orogen. The study area is marked as a pink rectangle (modified from Alavi, 2007). b) a paleogeographic map of the Zagros during the Early Miocene (Dercourt, 2000). c) A photo of the Asmari Formation, featuring its Kalhur Member, taken at the Moormoori section of the Lurestan Zone. d) A filed photo of the Asmari Formation at the Dareh-Shahr section, Lurestan Zone

The formation forms major reservoirs in central Zagros (Dezful Embayment) but no significant reservoir has been discovered in Lurestan province (e.g., Aqrawi et al., 2006; Kavoosi & Sherkati, 2012; Khazaie et al., 2022; Mossadegh et al., 2009; Roozpeykar & Moghaddam, 2016; Vaziri-Moghaddam et al., 2006). Less attention has been drawn to lateral facies changes and their impact on reservoir potential. Understanding factors that controlled porosity generation and evolution is helpful for predicting reservoir zones. This information will provide a basis for future investigations on the Asmari to construct a larger-scale picture of reservoir configuration. This paper aims to (1) investigate facies and diagenetic aspects of the Asmari Formation, (2) construct the sequence stratigraphic framework of the Asmari in the study area, and (3) rationalize the controlling factors on the Asmari reservoir quality within the established frameworks of facies, diagenesis, and sequence stratigraphy. The results of this study will help us to understand how depositional and diagenetic factors have influenced the development of Asmari reservoirs in the Asmari Formation across the Zagros region.

Geologic framework

The Zagros Mountains are the product of the closure of the Neo-Tethys and subsequent collision of the Arabian Plate to Eurasia (Figure 1a). Prior to current morphology of the orogen, there was a peripheral foreland basin between the Arabian Plate and Eurasia (Figure 1b) created due to the initiation of compressional continent–continent collision (Alavi, 2004; Beydoun et al., 1992; Sepehr & Cosgrove, 2004; Sharland et al., 2001; Sherkati & Letouzey, 2004). Several NW–SE trending structural zones were made around the collision interface (Figure 1a) (Alavi, 2007; Berberian & King, 1981). These are known as Urumieh-Dokhtar Magmatic Arc (UDMA), Zagros Imbricated Zone (ZIZ), and Zagros Fault-Thrust Belt (ZFTB). The ZFTB hosts one of the largest petroleum provinces of the world with 8% of the world's hydrocarbon reserve (Bordenave & Hegre, 2010). It is subdivided into several zones based on the position of basement faults (Figure 1). These faults have played different kinematic roles during the development of the orogeny, giving different tectonostratigraphic behaviors to the constituent zones. Most importantly, some intrashelf sub-basins were created within the region due to their activities during geodynamic evolution. For example, during the deposition of the Oligo–Miocene Asmari Formation (McQuillan, 1991; Sepehr & Cosgrove, 2004; Sherkati & Letouzey, 2004).

The Oligocene–Miocene Asmari Formation denotes the last marine depositional system of the Zagros foreland basin. It represents the latest carbonate depositional phase of a megasequence referred to as the "megasequence XI" by Alavi (2004) and "TMS AP11" by Sharland et al., (2001). The Red Sea rifting and its sea-floor spreading were synchronous with this megasequence, influencing the Zagros Foreland Basin. One consequence was the input of siliciclastic sands into the SW margin of the Zagros Foreland Basin during the deposition of the Asmari Formation, known as the Ahwaz Sandstone (Ziegler, 2001). The Asmari was deposited under semi-arid to arid climatic conditions (Ehrenberg et al., 2007; Heydari, 2008). In most places of the Zagros area, the Asmari is underlain by the Pabdeh Formation and overlain by the Gachsaran Formation. The Ahwaz Sandstone Member is extended in central Zagros (Dezful Embayment) and the Kalhur Evaporitic Member occurs in the N part of this region.

Materials and methods

This study was conducted on two zones of the ZFTB: the Dezful Embayment and the Lurestan Salient. It was based on field and laboratory investigations. Six outcrop sections in Lurestan and 12 wells from one hydrocarbon field (CK Field) in Dezful were investigated (latter from the NIOC) (Figure 1). Fieldwork included measuring and logging aspects such as lithology, bedding nature, bed thickness, fossil content, facies trends, stratal surfaces, geometry and sedimentary structures. Standard thin sections, derived from systematic sampling, were prepared from the six outcrop sections and two wells of the studied field (CK#8 & CK#12). A total of 1077 thin sections were petrographically examined under polarized microscope. Additionally, 198 samples were impregnated with blue-dyed resin to inspect pore space characteristics of the Asmari reservoir. A number of 908 porosity-permeability and 899 rock density measurements were available for the two cored wells. Additional data include geophysical well logs from the 12 wells of the CK Field, along with SEM images, XRF, and XRD data (see supplementary data). Archived data and unpublished reports from the NIOC were utilized for comparing results with other parts of the Zagros.

Field and laboratory examinations were integrated to identify facies, facies association, sequence stratigraphic architecture, and diagenetic aspects of the Asmari Formation. Facies were classified and named based on Dunham (1962) and Embry and Klovan (1971) schemes. Depositional environments of facies were determined via comparison with well-known facies models (Buxton & Pedley, 1989; Flügel, 2004; Pomar, 2001; Wilson, 1975). The applied sequence stratigraphic nomenclature follows the definitions proposed by Hunt and Tucker (1992).

Results and Discussion

Facies and depositional environment

Facies description

Based on facies analysis data from field and laboratory investigations, three distinct lithologies (carbonates, siliciclastics, and evaporites) are recognized within the Asmari Formation. Carbonate lithology represents the chief depositional system of the Asmari Formation (Figure 2). Evaporites are only seen in the Lurestan area (Kalhur Member, Figure 1 c and d; see Daraei et al., (2014)) (Table 1). Siliciclastics of the Asmari Formation are seen in hydrocarbon fields of the Dezful Embayment (Ahwaz Member), represented by a quartz arenite petrofacies in the CK oilfield (SF-1; Figure 2). Within the carbonate facies, small and large benthic foraminifera, red algae, and echinoderms are the main faunal elements. The main characteristics of these facies types are summarized and presented in Table 1 and Figure 2. Figure 3 represents an example of composite geologic logs constructed based on integrated sedimentologic, stratigraphic, and sequence stratigraphic aspects of the Asmari.

Mineralogical content inferred from XRD and SEM

17 carbonate samples from the CK field were analyzed with XRD. Results show that dolomite is the major phase in most samples. Anhydrite and calcite occur as both major and minor phase depending on facies type. Quartz, albite, and orthoclase occur in samples from the lower part of the reservoir (Ahwaz Member). Samples also contain clay minerals such as illite and kaolinite. Eight samples were selected for SEM analysis. SEM results indicate that the main pore types are moldic, interparticle, and intercrystalline (Figure 4). The main lithology and minerals are dolostone and dolomite with minor occurrences of anhydrite and quartz. Dolomitization in most samples has created an interrelated network of intercrystalline pores but over-dolomitization has destroyed the reservoir quality in some spaces (e.g., see Figure 4e).

Depositional environment

According to the distinguished facies, carbonates of the Asmari Formation in the studied area were deposited in a homoclinal carbonate ramp system (Figure 5).

Table 1. Characteristics of Asmari sedimentary facies in outcrops and onshore oilfields in Lurestan Salient and Dezful Embayment

Facies Name	Dominant Lithology	Dominant Components	Sedimentary Structure/Feature	Depositional Environment	Reference
EF-1: Evaporites	dominantly gypsum; dolomite & anhydrite as subordinate	fine crystalline, anhedral to subhedral gypsum; small to coarse laths or equant blocky anhydrite crystals; micro-dolomite	poikilotopic anhydrite, alabastrine, fibrous and daisy wheel structures at microscopic scale; massive, laminated, nodular, satin spare, palmate, palisade, chicken wire to enterolithic at macroscopic scale	basinwide evaporites	Amirshahkarami, 2013; Daraei et al., 2015; Abyat et al., 2019; Fallah-Bagtash et al., 2022; Noorian et al. 2021; Omidpour et al., 2021; Sadegi et al., 2021; Khazaie et al., 2022
CF-1: Stromatolite (dolo) boundstone	dolomitic limestone to dolomite	blue-green algae; rarely mollusks, evaporite crystals, peloids and imperforate small foraminifers	lamination, evaporite nodules, fenestral pores	peritidal	Vaziri-Moghaddam et al., 2006; Amirshahkarami et al., 2007; Daraei et al., 2015
CF-2: Bioclastic wackestone	limestone	mollusks, echinoids, miliolids; subordinate porcelaneous and small hyaline benthic foraminifers, ostracods, bryozoan, and peloids	bioturbation and geopetal structures	lagoon	Aqrawi et al., 2006; Vaziri-Moghaddam et al., 2006; Amirshahkarami et al., 2007; Al-Aasm et al., 2009; Allahkarampour Dill et al., 2010; Sadegi et al., 2011; Kavoosi & Sherkati, 2012; Amirshahkarami, 2013; Daraei et al., 2015; Adabi et al., 2015; Abyat et al., 2019; Joudaki et al., 2020; Karami et al., 2020; Omidpour et al., 2021; Khalili et al., 2021; Omidpour et al., 2022; Noorian et al., 2021; Khazaie et al., 2022; Mohammadi et al., 2022; Rahmanizadeh et al., 2022
CF-3: Small hyaline benthic foraminifera mudstone/ wackestone	dolomitic limestone	small benthic foraminifers; minor ostracods, Elphidium, porcelaneous foraminifers and mollusks	bioturbation, pyritization	lagoon	Seyrafian, 2000; Aqrawi et al., 2006; Vaziri-Moghaddam et al., 2006; Amirshahkarami et al., 2007; Daraei et al., 2015; Shabafrooz et al., 2014; Abyat et al., 2019; Sadooni & Alsharhan, 2019; Omidpour et al., 2021; Omidpour et al., 2022;Fallah-Bagtash et al., 2022; Noorian et al., 2021;Isvand et al., 2022; Mohammadi et al., 2022
CF-4: Ostracoda oyster floatstone/rudstone	argillaceous limestone	oysters and ostracods, minor mollusks	partly rudaceous	lagoon	Aqrawi et al., 2006; Vaziri-Moghaddam et al., 2006; Sadegi et al., 2011; Shariatinia et al., 2012; Maghfouri Moghaddam et al., 2013; Daraei et al., 2015; Adabi et al., 2015; Abyat et al., 2019; Fallah-Bagtash et al., 2022; Khalili et al., 2021; Khazai et al., 2022
CF-5: Ooid (dolo) grainstone	dolomite	dominantly ooids; less abundantly peloids, porcelaneous foraminifers, Faverina, red algae, and intraclasts	good sorting, abundant anhydrite cementation, complete micritization	marginal shoal	Aqrawi et al., 2006; Al-Aasm et al., 2009; Kavoosi & Sherkati ,2012; Shariatinia et al., 2012; Amirshahkarami, 2013; Daraei et al., 2015; Joudaki et al., 2020; Omidpour et al., 2020; Falahatkhah et al., 2021; Khalili et al., 2021; Omidpour et al., 2021; Sadegi et al., 2021; Isvand et al., 2022; Khazaie et al., 2022; Rahmanizadeh et al., 2022
CF-6: (Coralline algae) foraminifera (dolo) packstone	limestone/dolomitic limestone to dolomite	common to abundant coralline algae and porcelaneous foraminifera; subordinate mollusks, chinoids, peloids, small benthic foraminifers, green algae, ooids, intraclast, coral debris	rhodoliths; crustose and articulated coralline red algae	subtidal settings (lagoon to off-shoal subtidal)	Seyrafian, 2000;Aqrawi et al., 2006; Vaziri-Moghaddam et al., 2006; Amirshahkarami et al., 2007; Al-Aasm et al., 2009; Allahkarampour Dill et al., 2010; Sadegi et al., 2011; Monjezi et al., 2012; Amirshahkarami, 2013; Daraei et al., 2015; Allahkarampour Dill et al., 2017; Joudaki et al., 2020; Karami et al., 2020; Omidpour et al., 2020; Fallah-Bagtash et al., 2022; Khalili et al., 2021; Noorian et al., 2021; Omidpour et al., 2021; Sadegi et al., 2021; Mohammadi et al., 2022; Rahmanizadeh et al., 2022

CF-7: Coralline algae bindstone	limestone/dolomitic limestone to dolomite	dominant coralline red algae; less abundant porcelaneous foraminifers and echinoids	rhodolith pavement; partly preferential dolomitization	proximal middle ramp	Seyrafian, 2000; Aqrawi et al., 2006; Vaziri-Moghaddam et al., 2006; Amirshahkarami et al., 2007; Allahkarampour Dill et al., 2010; Sadegi et al., 2011; Monjezi et al., 2012; Amirshahkarami, 2013; Daraei et al., 2015; Shabafrooz et al., 2015; Adabi et al., 2015; Allahkarampour Dill et al., 2017; Abyat et al., 2019; Sadooni & Alsharhan, 2019; Joudaki et al., 2020; Omidpour et al. 2020; Omidpour et al., 2021; Falahatkhah et al., 2021; Noorian et al., 2021; Sadegi et al., 2021; Isvand et al., 2022; Maghfouri Moghaddam, 2022; Mohammadi et al., 2022; Rahmanizadeh et al., 2022
CF-8: (Coralline algae) large benthic foraminifera floatstone/bindstone	argillaceous limestone	large/small benthic foraminifers, textularids, and valvulinds as major forms; mollusks, echinoids, bryozoans, ostracods, porcelaneous foraminifers as subordinate particles	rhodoliths and worm tubes	distal middle ramp	Seyrafian, 2000; Aqrawi et al., 2006; Vaziri-Moghaddam et al., 2006; Amirshahkarami et al., 2007; Al-Aasm et al., 2009; Allahkarampour Dill et al., 2010; Sadegi et al., 2011; Monjezi et al., 2012; Amirshahkarami, 2013; Daraei et al., 2015; Adabi et al., 2015; Shabafrooz et al., 2015; Allahkarampour Dill et al., 2017; Sadooni & Alsharhan, 2019; Joudaki et al., 2020; Karami et al., 2020; Omidpour et al., 2020; Falahatkhah et al., 2021; Khalili et al., 2021; Noorian et al., 2021; Omidpour et al., 2021; Sadegi et al., 2021;Isvand et al., 2022; Khazaie et al., 2022; Mohammadi et al., 2022; Rahmanizadeh et al., 2022
CF-9: Planktonic foraminifera wackestone	marl/shale	abundant planktonic foraminifers; less commonly mollusks, echinoids, ostracods, and small benthic foraminifera	pyritization, bioturbation and worm tubes	outer ramp	Seyrafian, 2000; Aqrawi et al., 2006; Amirshahkarami et al., 2007;Al-Aasm et al., 2009; Sadegi et al., 2011; Kavoosi & Sherkati, 2012;Daraei et al., 2015; Adabi et al., 2015; Shabafrooz et al., 2015; Allahkarampour Dill et al., 2017; Abyat et al., 2019; Karami et al., 2020; Omidpour et al., 2020; Falahatkhah et al., 2021; Khalili et al., 2021; Omidpour et al., 2021; Sadegi et al., 2021; Isvand et al., 2022; Mohammadi et al., 2022; Rahmanizadeh et al., 2022;
SF-1: Siliciclastic sands/Quartzarenite	sand (sandstone) along with dolomitic matrix in parts	moderately sorted quartz sand; less abundantly k-feldspars, micas, and shell fragments	mostly homogenous with no specific structure; loose (un-cemented) in nature	marginal marine (siliciclastic delta)	Amirshahkarami, 2013; Avarjam et al., 2014; Joudaki et al., 2020; Sadegi et al., 2021; Isvand et al., 2022; Khazaie et al., 2022

Deposition occurred in a range of sub-environments from sabkha, peritidal, lagoon, and shoal to middle and outer ramp. The inner ramp was a semi-/restricted environment in which microbial mudstones to microbialites/stromatolites were deposited in peri-tidal zone (CF-1), and bioclastic wackestones (CF-2 to CF-4) in the lagoon (CF-2). The seaward margin of the inner ramp is recognized by semi-continuous oolitic shoal bodies (CF-5). The middle ramp was dominated by coralline red algae with diverse porcellaneous benthic foraminifera contributing to shallower sub-tidal euphotic part (CF-6, CF-7; Buxton & Pedley, 1989; Geel, 2000; Pedley, 1998; Pomar, 2001), but being replaced by larger hyaline benthic foraminifera (LBFs) toward distal dysphotic/oligophotic part (CF-8; Amirshahkarami, 2013; Pomar, 2001).

The outer ramp, characterized by marl to argillaceous limestone, was the site of pelagic sedimentation, represented by the domination of planktonic foraminifera (CF-9) with some contributions from reworked materials of shallower parts. The proportions of different facies and sub-environments of the Asmari obtained from petrographic data are shown in Figure 5. CF-1, CF-6, and CF-5 are the most frequent facies types, and inner ramp deposits constitute the majority of the Asmari succession.

A ramp depositional environment for Asmari carbonates has also been suggested by many other studies (e.g., Abyat et al., 2019; Amirshahkarami et al., 2007; Aqrawi et al., 2006; Ehrenberg et al., 2007; Isvand et al., 2022; Joudaki et al., 2020; Karami et al., 2020; Kavoosi & Sherkati, 2012; Khalili et al., 2021; Moghaddam, 2022; Noorian et al., 2021; Rahmanizadeh et al., 2022; Seyrafian, 2000; van Buchem et al., 2010; Vaziri-Moghaddam et al., 2006). However, some studies have suggested deposition in a nearly distally steepened ramp, at least in part of the Asmari basin or episodes of the Asmari evolution through time (e.g., Allahkarampour Dill et al., 2018; Dabbagh & Kendall, 2021; Shabafrooz et al., 2015).

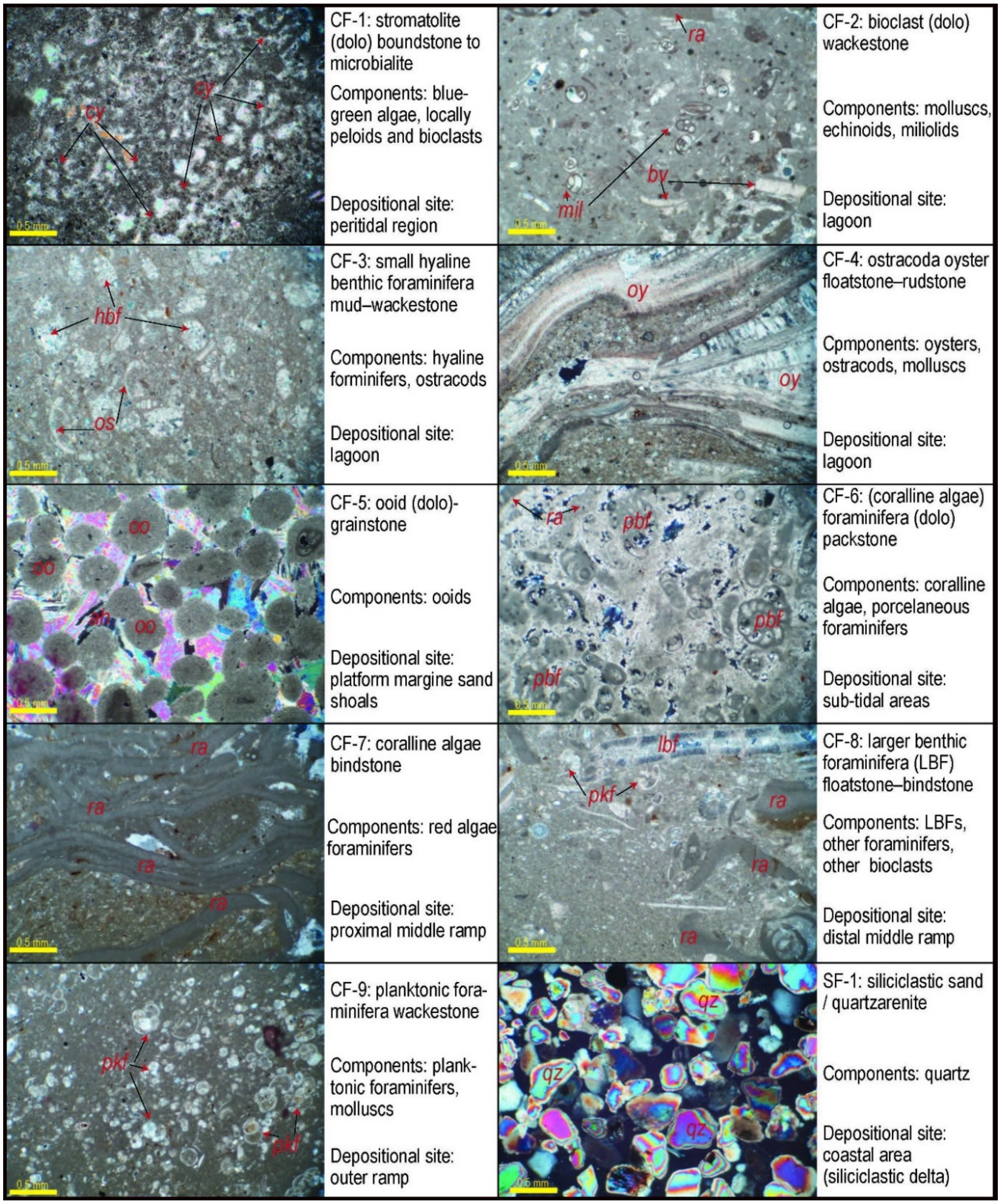

Figure 2. Main microfacies types recognized in this study. Abbreviations: *cy*=cyanobacteria, *ra*=red algae, *bv*=bivalve, *mil*=miliolid, *hbf*=hyaline benthic foraminifera, *os*=ostracod, *oy*=oyster, *oo*=ooid, *pbf*=porcelaneous benthic foraminifera, *pkf*=planktonic foraminifera, *lbf*=larger benthic foraminifera, *qz*=quartz

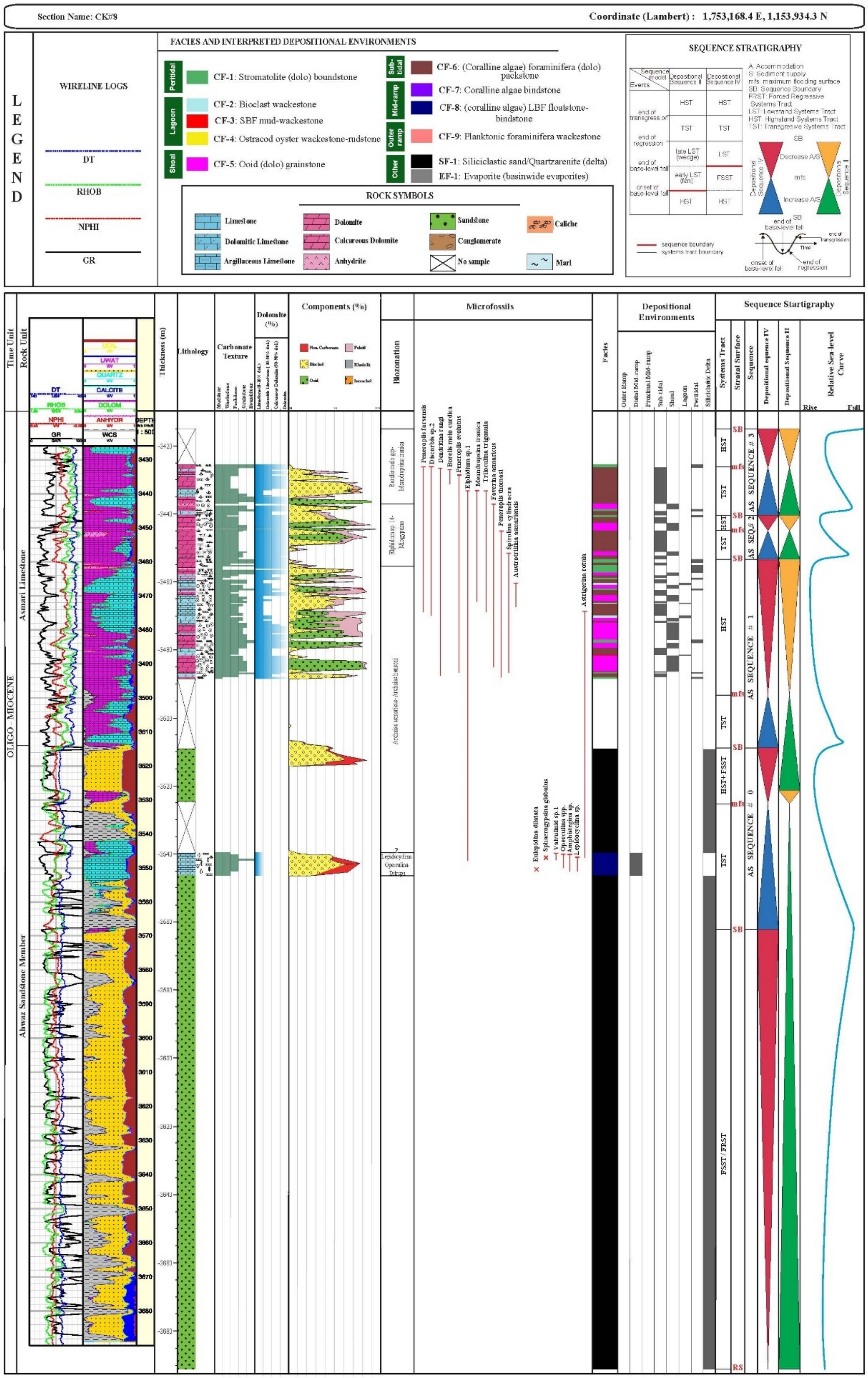

Figure 3. Composite log demonstrating sedimentology, stratigraphy and sequence stratigraphy aspects of the Asmari in CK#8

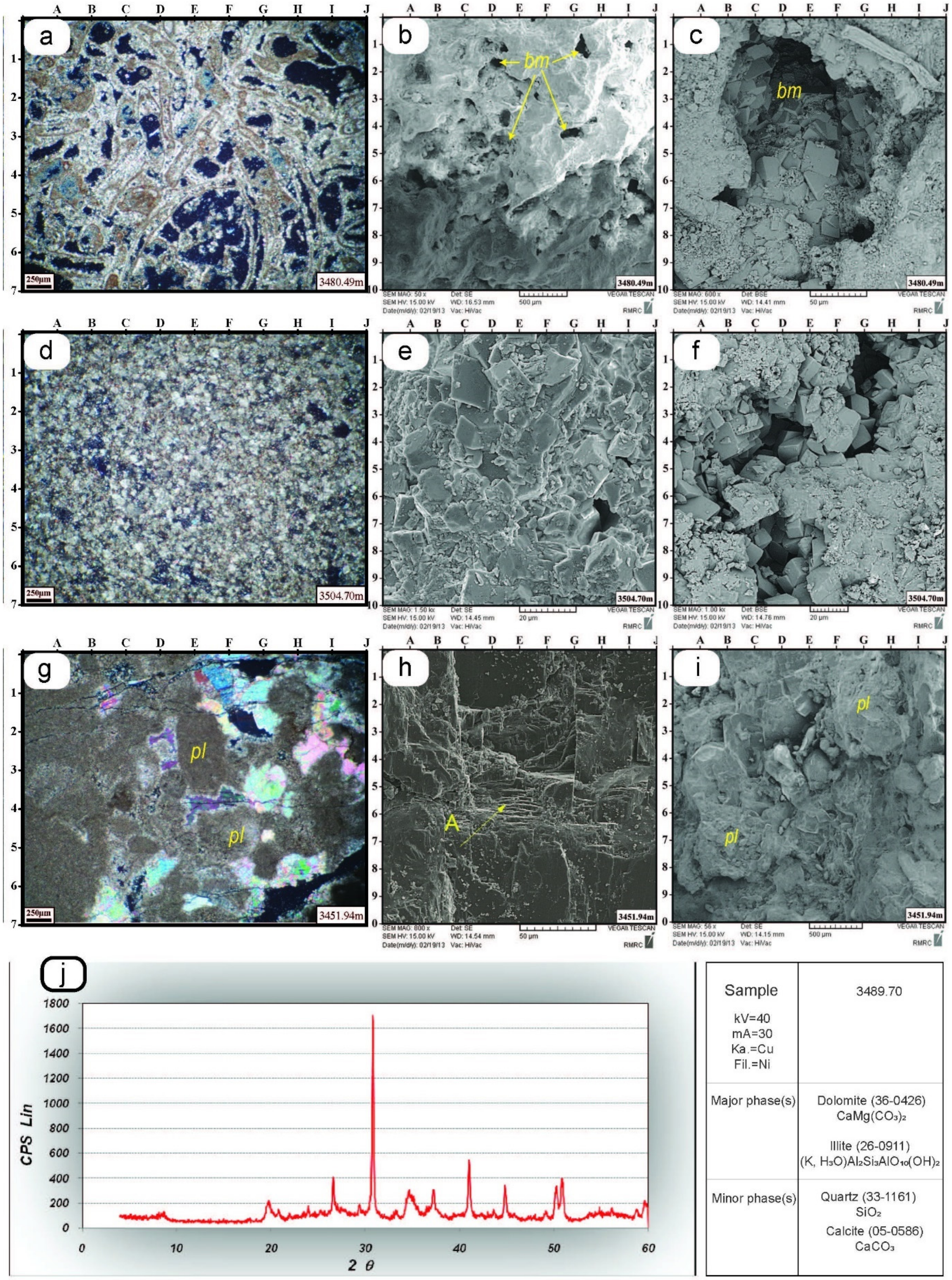

Figure 4. *a–c*) different views of a bioclastic sample with biomoldic pores (*bm*) lined by early diagenetic dolomite cement. *b*) high moldic porosity. *d–f*) different views of a dolomite sample with intercrystalline pore spaces. *e*) over-dolomitization has destroyed most of the porosity. *g–i*) different views of a peloidal sample with anhydrite-filled intergranular pores. *J*) an XRD result of a carbonate sample with illite (clay mineral) as a major phase. A: anhydrite, *pl*: peloid

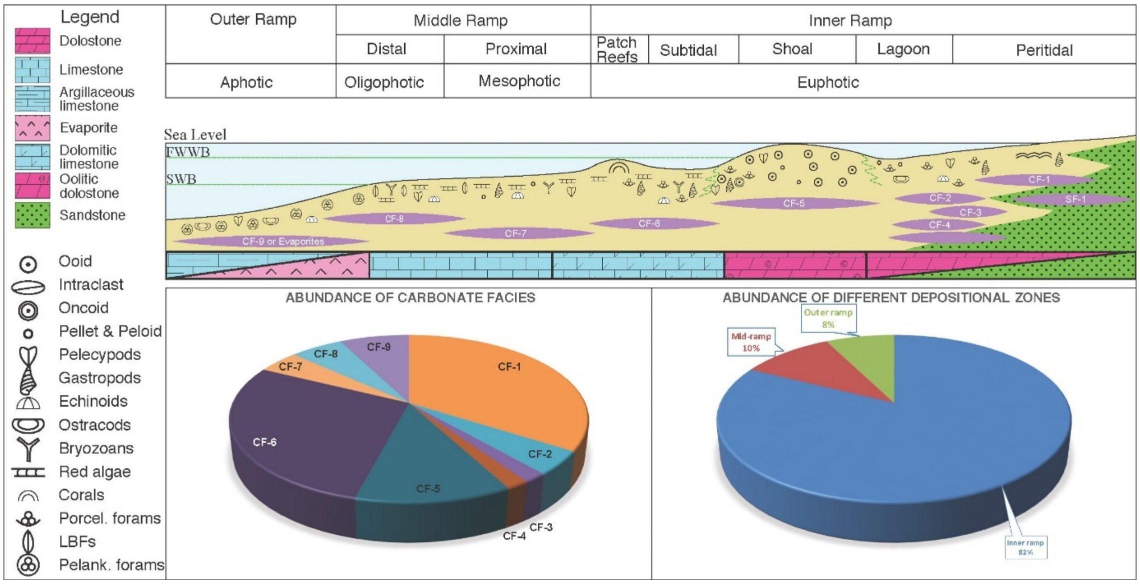

Figure 5. Model proposing Asmari depositional system in study area

Diagenesis

Diagenetic processes and products

Petrography along with XRF, XRD and SEM results indicate that the Asmari Formation has undergone various diagenetic processes leading to local variations in reservoir properties. The main diagenetic processes include micritization, dolomitization, dissolution, cementation, mechanical compaction, and chemical compaction (Figures 6 and 7). Different diagenetic processes are described and discussed with emphasis on porosity evolution of the reservoir. The relative timing of these processes is illustrated in Figure 8.

A) Micritization. Micritization is a common process affecting grains in oolitic shoal facies and lagoon facies of the Asmari Formation. In the shoal facies (CF-5), many ooids have lost their primary fabric turning into bahamite peloids (sensu Flügel, 2004) (Figure 6a). This alteration has determined their later diagenetic path where micritized ooids have survived meteoric dissolution whereas non-micritized aragonitic ooids have been mostly dissolved out. Micritized ooids have been mostly transformed into fine to medium crystalline dolomitized ooids (Figure 6b). In lagoon bioclastic facies, micritization has affected the margins of bioclasts leading to their preservation during later diagenesis (Figure 6d). Micritization commonly occurs in low-energy shallow-marine environments by endolithic and other microbes (microborers) indicating the presence of intense microbial activity within the depositional environment (Bathurst, 1975; Flügel, 2004).

B) Dolomitization. Dolomitization is the most pervasive diagenetic process of the Asmari carbonates (Figure 6e), commonly associated with anhydrite precipitation (Figure 6f, g). The dolomite partially to completely replaces calcite in the landward facies (CF-1 to CF-5) and is mostly seen as pervasive fine- to medium-crystalline dolomite mosaics ("microcrystalline replacive dolomite" and "pervasive micro-medium crystalline dolomite" of Al-Aasm et al., (2009)). These fine- to medium-crystalline dolomites range in shape from anhedral to euhedral and are mostly fabric-selective and fabric-retentive (Figure 6h; Sibley & Gregg, 1987). However, fabric-destructive dolomites are also present (Figure 6i), particularly in facies of more proximal areas. Spatiotemporal relationship of stacked facies of the Asmari Formation in the study area shows a proximal–distal gradient in the tendency of the Asmari limestones to retain their primary fabrics where distal facies are less affected by dolomitization. Dolomitization and crystal growing led to the creation of intercrystalline porosity (Enayati-Bidgoli & Navidtalab, 2020). Based on petrographic evidence, this process mostly pre-dates compaction features and fracturing, and probably occurred in association with early diagenetic processes such as dissolution.

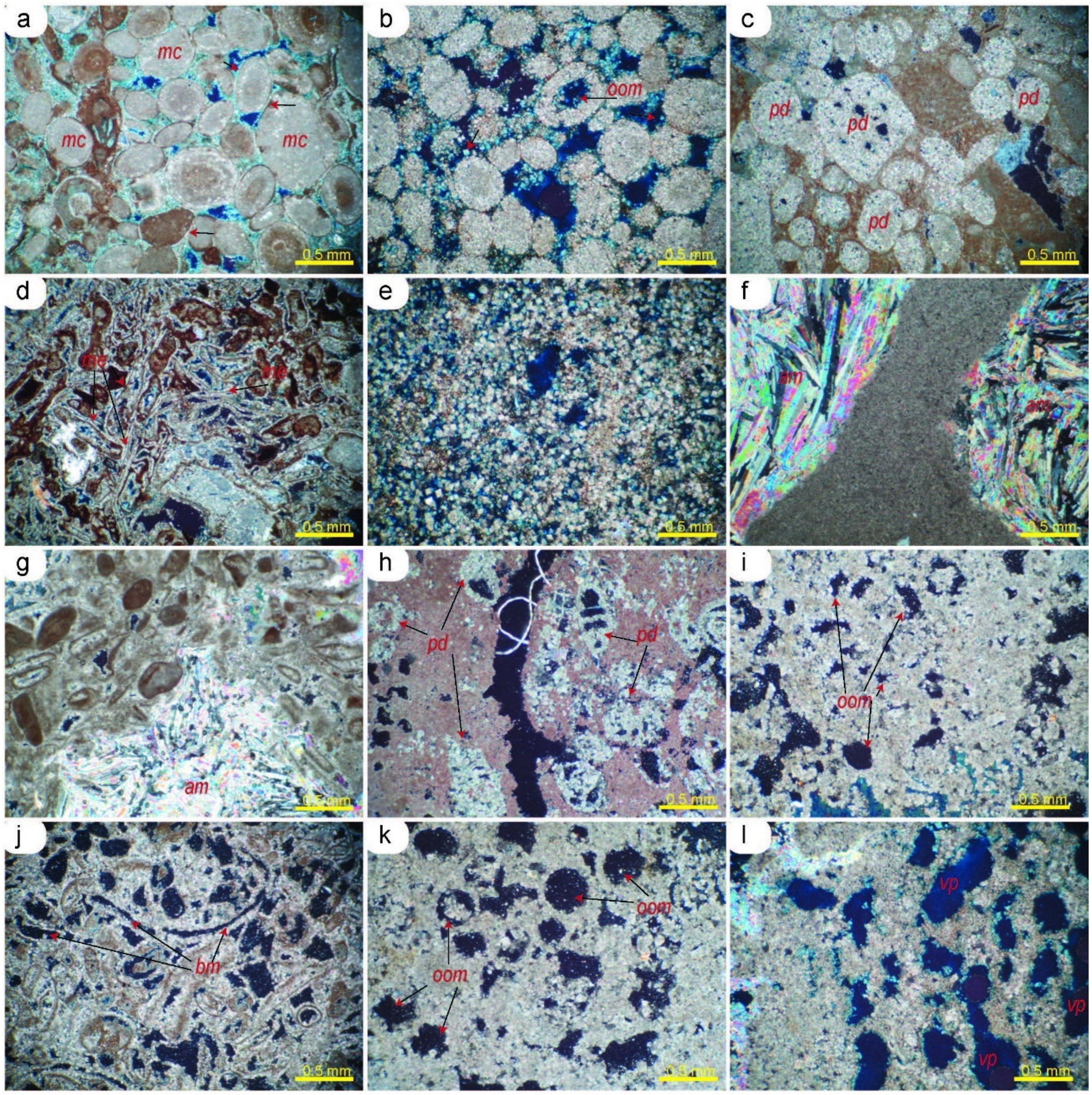

Figure 6. Main diagenetic products and processes of the Asmari in the CK Field. a) micritization (*mc*) in an ooid grainstone sample with fine crystalline calcite cement (arrows) possibly of marine origin around the grains. b) dolomitization in micritized ooids postdating micritization with an oomold (*oom*) and sparse rhombs (arrows) of dolomite cement. c) preferential dolomitization (*pd*) in micritized ooids with surrounding micrite left intact. d) micritization in a bioclastic facies of lagoon creating micrite envelopes (*me*) around bioclasts, making them more resistant to later dissolution. e) Medium crystalline replacive dolostone resulted from dolomitization of a precursor peritidal mudstone. f–g) anhydrite mineralization (*am*) in dolomitized facies. h) preferential fabric-selective dolomitization (*pd*) in foraminifera wackestone. Foraminifers are dolomitized, also partly dissolved out, but micrite (purple stained) left intact. i) fabric-destructive dolomitization in ooid grainstone with signs of selective dissolution of ooids (*oom*). j–l) development of biomoldic (*bm*), oomoldic (*oom*), and vuggy porosity (*vp*) due to early dissolution

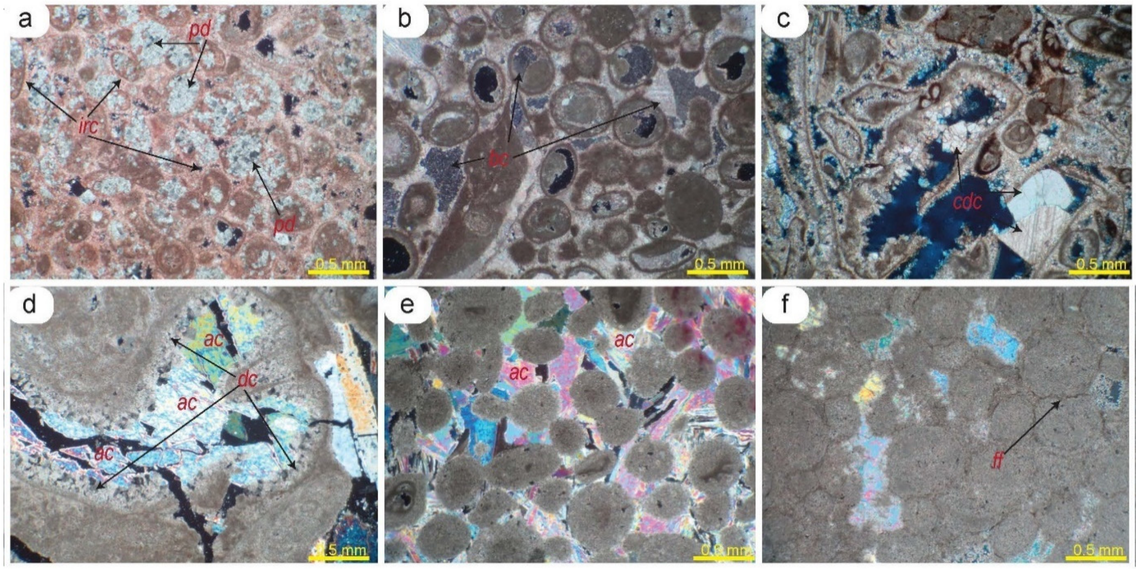

Figure 7. Main diagenetic products and processes of the Asmari in the CK Field. a) evidence of precursor isopachous rim cement (*irc*; pink- to pale red-stained) around ooids with preferential dolomites (unstained; *pd*) within some ooids. b) burial blocky calcite cement (*bc*) filling space between ooids in an ooid grainstone sample. c) burial coarse crystalline dolomite cement (*cdc*) with twinning (partly blue stained). d) anhydrite cement (*ac*) succeeding an earlier dolomite cement (*dc*) generation. e) anhydrite cementation (*ac*) with displacive behavior in an ooid grainstone sample. f) development of fitted fabric (*ff*) due to chemical compaction

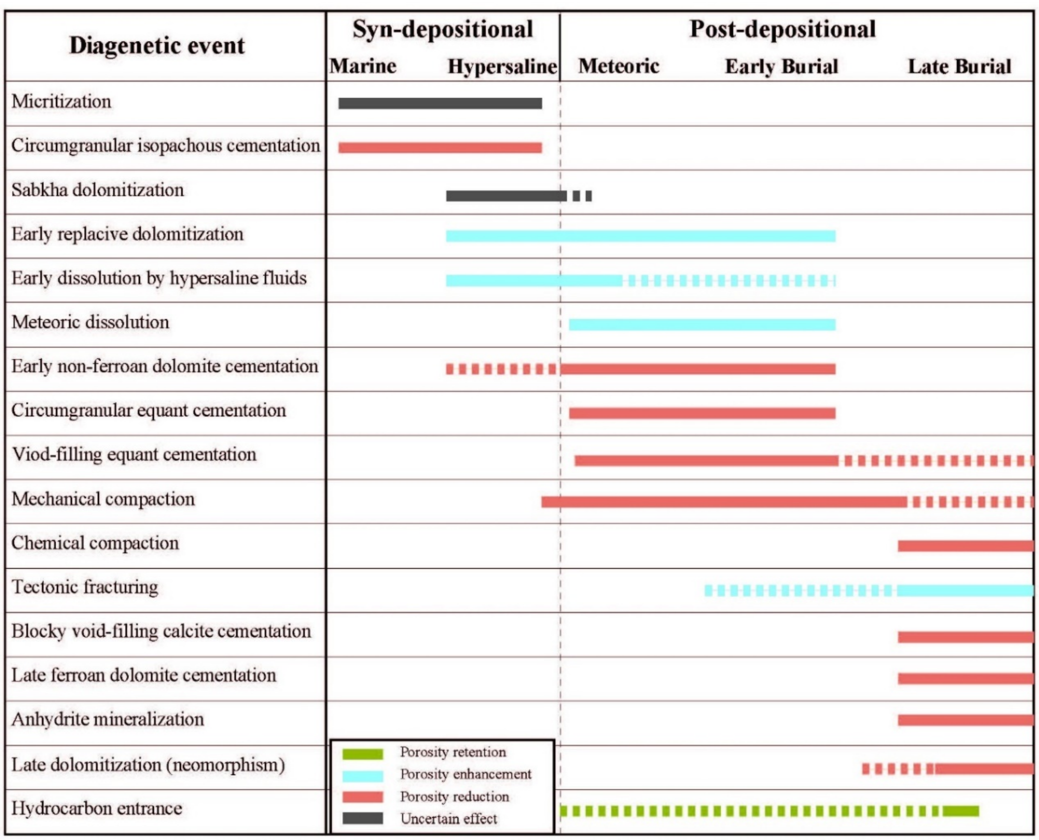

Figure 8. Sequence of Asmari Formation's diagenetic events and processes from petrographic observation of cross-cutting relationships and cement morphology and fabrics

C) Dissolution. Dissolution is a key diagenetic process in the Asmari Formation, increasing porosity. Unstable particles such as aragonite grains have been dissolved, creating oomoldic (CF-5: shoal facies), vuggy and biomoldic pore spaces (Figure 6j–l). Fine cements (dolomite/calcite) line these pores (Figure 6d and Figure 4a–c), indicating an early diagenetic origin. This dissolution phase predates compaction features.

D) Cementation. Cementation in the Asmari Formation of the CK field includes several generations of cements filling pore spaces. Dolomite and anhydrite are the main cement types, with minor calcite and clay. Dolomite cement is the most abundant one, lining primary and secondary pore spaces (Figures 6d and 4a–c) and predating compaction features. Anhydrite cement is the most effective pore-filling product, occluding whole pore spaces and succeeding earlier dolomite cements (Figure 7d). In most places, it has patchy poikilotopic distribution, but 'pore-filling even distribution' also occurs, particularly in oolitic shoal facies (CF-5; Figure 7e) (cf., Lucia, 2007).

Calcite cement is a minor pore-filling cement in the Asmari Formation. It occurs as fibrous circumgranular, equant mosaic and coarse blocky fabrics (Figure 7a-b). Fibrous circumgranular cement follows marine isopachous aragonite cement (James & Choquette, 1983). Coarse blocky calcite spar postdates dissolution and early cements (Choquette & James, 1987; Moore & Wade, 2013). Clay content is detected as illite (Figure 4j) and may be authigenic (Aqrawi et al., 2006).

E) Compaction. The Asmari carbonates are greatly compacted during and after burial (depth >3 km) in the studied wells. This is represented by stylolites, solution seams, and other petrographic evidence (concave/convex grain contacts, grains deformation or breakage). Specifically, the process is observed in the bioclastic facies as broken allochems (Figure 6d), and in the oolitic facies as fitted fabrics and stylolites (Figure 7f). These features dominate in less porous intervals.

F) Fracturing. Fracturing (in the form of open and filled fractures and micro-fractures) is rarely observed and recorded in the studied wells. Based on petrographic observations and the geophysical report of the studied field (unpublished), fracturing in the CK field has played a negligible role on modifying the reservoir quality.

Diagenetic path

A schematic model illustrating diagenetic evolution of the formation during its burial is presented in Figure 9. The burial history of the Asmari Formation shows a path from marine to meteoric to burial diagenetic realms. In the marine realm, micritization and local cementation were the most influential processes. Restricted lagoon and peri-tidal areas were prone to evaporation under arid climate conditions resulting in the production of hypersaline brines with the potential of triggering evaporative dolomitization (sabkha and seepage-reflux) (Figure 9: Phase I). Dolomitization of the Asmari has mostly occurred in landward facies in association with evaporite mineralization pointing to evaporative dolomitization mechanisms such as seepage refluxion and sabkha dolomitization (Jones et al., 2002; Machel, 2004). The dolomite formation predates compaction and fracturing and hence, occurred together with early diagenetic processes. Similar observations and interpretations have been documented for the Asmari Formation by Aqrawi et al., (2006) and Al-Aasm et al., (2009). Mg-saturated fluids derived from the underlying shale-bearing Pabdeh Formation as well as "dense brine refluxing" from the overlaying Gachsaran Formation may also account for developing some dolomitic intervals in the Asmari Formation (Aqrawi et al., 2006; Luo et al., 2019). The presence of minor fabric-selective dolomitization in deeper-marine strata of the lower Asmari supports the idea of some local dolomitization from the underlaying Pabdeh shales. Brines generated by evaporite precipitation during sea level falls in the basin center (Kalhur evaporites) might have affected rocks just next to the basinal evaporites of the Kalhur Member, that is platform margin oolitic shoal facies (CF-5). Intense dolomitization and evaporite mineralization in the sand shoal facies may support this intrinsic dolomitization mechanism.

Petrographic evidence suggests that dolomitization and dissolution in the Asmari occurred contemporaneously. Petrographic study suggests that the major dolomitization phase of the Asmari Formation occurred during the early diagenesis stage. This is because it mostly predates compaction features and fracturing. Additionally, the dominant dolomite cements, which are a major diagenetic product within the Asmari Formation, line primary and secondary pore spaces that are of early diagenetic origin (see previous section). Studies of the geochemical signature of the Asmari dolomites have also indicated a near-surface origin for most of the dolomitization (e.g., Aqrawi et al., 2006). Therefore, it is likely that dolomitization of the Asmari Fm. and early diagenetic processes such as dissolution occurred simultaneously.

Two main possible explanations can be proposed for this co-occurrence. The simplest scenario considers initial replacive dolomitization in near-surface environments by evaporated seawater, shortly followed by dissolution (Aqrawi et al., 2006). Dissolution of carbonates typically occurs in the meteoric zone, but it is also possible in the mixing zone between fresh water and saline seawater (Moore & Wade, 2013). Some researchers suppose that extensive dissolution in anhydrite–dolomite successions may occur as a result of hypersaline brines, those also account for dolomitization (Qing Sun, 1992). The absence/scarcity of meteoric calcite cements in secondary pore spaces created by dissolution but the presence of dolomite cement in these moldic and vuggy pore spaces supports this possibility (Aqrawi et al., 2006; Mohammadi et al., 2022). Similar hypothesis has been discussed for the origin of dissolution in other dolomitic reservoirs of the world (e.g., Al-Saad & Sadooni, 2001; Saller & Henderson, 1998). It can be concluded that those dolomitizing brines produced by evaporative mechanisms were also responsible for the dissolution of unstable allochems soon after the Asmari deposition when the sediment was still experiencing near surface diagenesis (Figure 9: Phase II-a). Early diagenetic dolomite cement was also precipitated in pore spaces by these fluids (Phase II-b; Figure 9).

After near surface diagenetic realm, the Asmari Formation entered the burial realm. Mechanical and chemical compaction features such as deformed and broken grains and fitted fabrics created in this realm. It is also where the strata were affected by later diagenetic cementation (anhydrite and coarser dolomite cements) as well as fracturing (Phase III in Figure 9). Petrographic evidence indicates that the main part of the Asmari porosity was destroyed during burial through compaction as well as cementation. Development of pressure solution features requires a depth more than 500 m (Dunnington, 1967). Currently, the studied formation in the CK Field has reached a depth of 3.5 km where experiencing a temperature more than 100°C. As a result of the relatively moderate burial depth, most of the porosity is destroyed during compaction. Although fracturing in the studied field played a negligible role on reservoir quality, it is one of the main aspects contributing to global reputation of the Asmari Formation as a highly productive reservoir. Strong dolomitization supposedly made the formation more brittle and hence, more susceptible to fracturing (Haynes & McQuillan, 1974; McQuillan, 1973, 1974, 1985). Fractured Asmari reservoirs have been reported in several fields such as Ahwaz, Gachsaran, Marun, Bibi Hakimeh, Agha Jari, Pazanan, Haft Kel, Rag-e Sefid, Karanj, Kabud, Parsi and Qaleh Nar oilfields (Esrafili-Dizaji & Rahimpour-Bonab, 2019).

Sequence stratigraphy and dynamic depositional model

Depositional sequences

In the CK Field and Lurestan Zone, three depositional sequences have been identified based on fieldwork data, petrographic analysis, and other criteria such as spatio-lateral depositional trends, facies stacking, major stratigraphic surfaces, and biofacies (Figure 10). These sequences correspond with those found by Ehrenberg et al., (2007) and van Buchem et al., (2010). In this study, we re-examined and expanded upon the findings of Daraei et al., (2015) to include the entire study area, encompassing both the Lurestan and Dezful Embayment zones. This allowed us to gain a more comprehensive understanding of the sequence stratigraphic framework and basin-fill history of the Asmari Formation in these two distinct structural zones. The absence of certain sequences in our study compared to those identified by Ehrenberg et al., (2007) and van Buchem et al., (2010) can be attributed to the time-transgressive nature of Asmari deposition across the basin. According to this sequence stratigraphic framework, the sequences identified in the Asmari Formation of the Lurestan region span from 25.1 Ma to 18.5 Ma (cf., van Buchem et al., 2010), indicating a time range of about 6.6 million years for Asmari deposition. However, it should be noted that Asmari deposition in the Dezful Embayment began earlier.

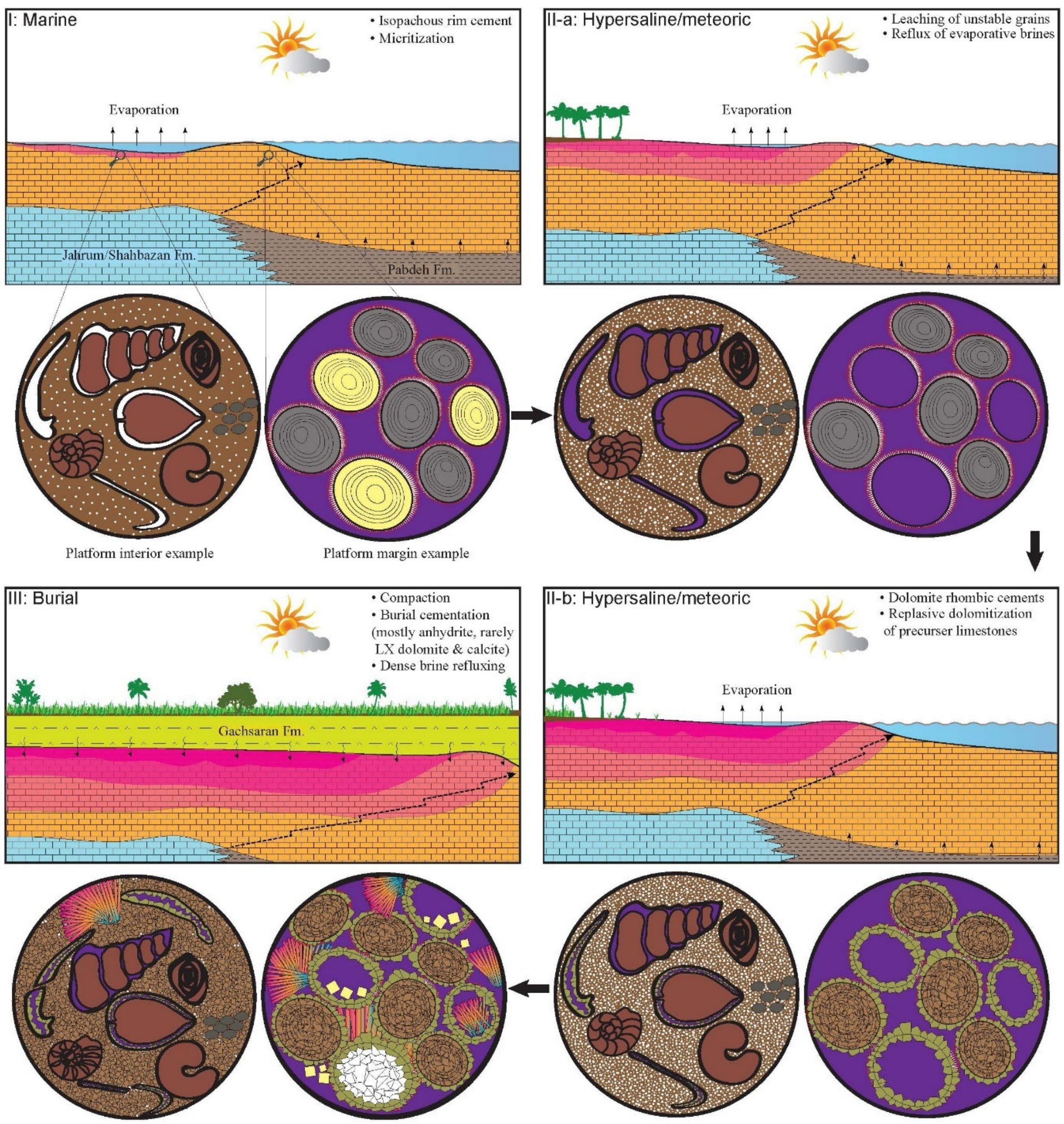

Figure 9. A diagenetic evolutionary scheme highlighting the succession of main diagenetic processes of the Asmari in different realms

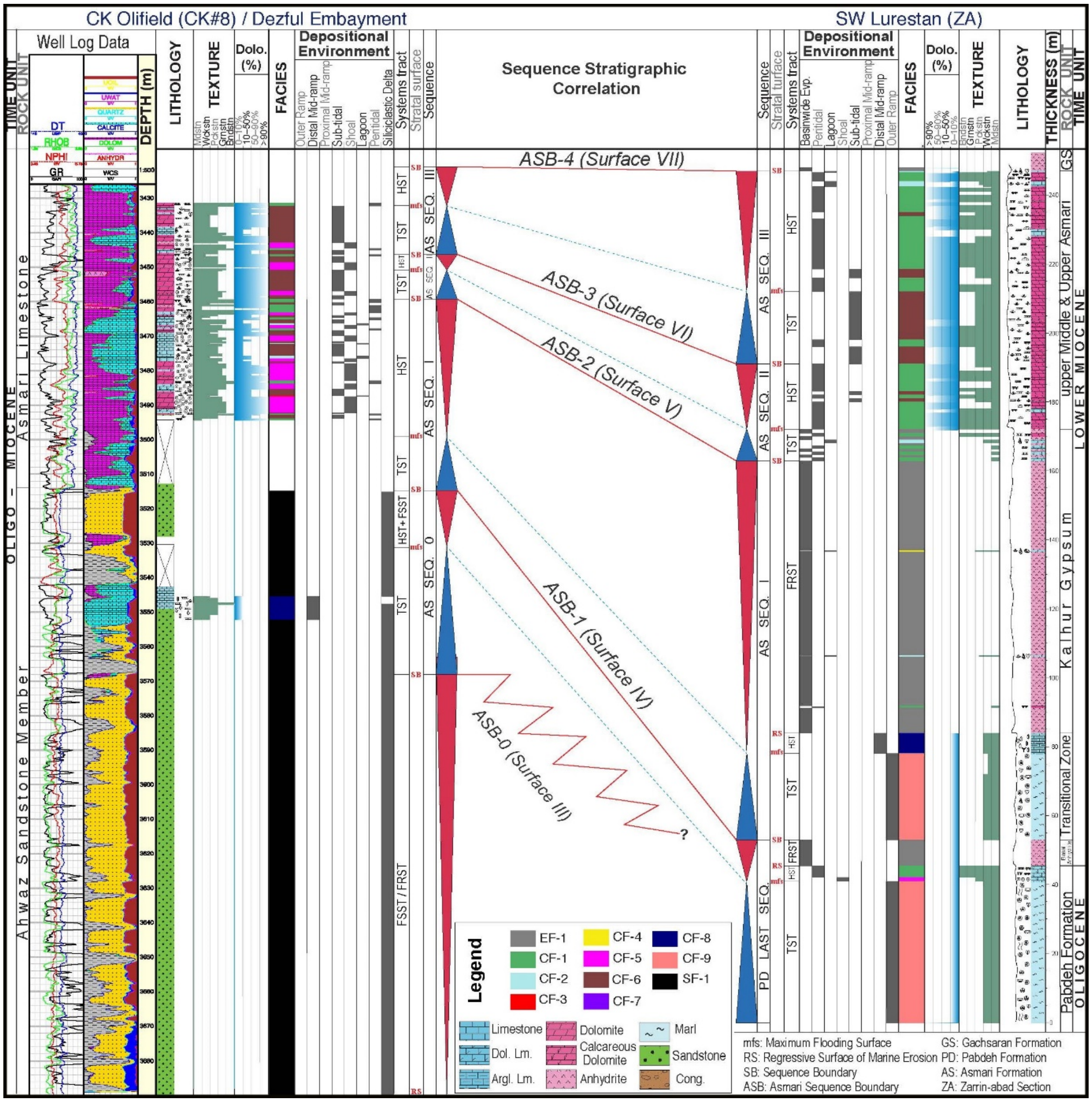

Figure 10. A sequence stratigraphic correlation between two representative sections: one from the Dezful Embayment with siliciclastics of the Ahwaz and one from the Lurestan with evaporites of the Kalhur Member (modified from Daraei et al., 2017)

AS Sequence-1. This sequence consists of a transgressive systems tract (TST) and a highstand systems tract (HST) in the CK field, as well as a falling stage systems tract (FSST) in SW Lurestan, represented by the Kalhur evaporites. The TST displays a retrogradational stacking pattern of outer ramp facies (CF-9) with a marl to argillaceous limestone lithology. In contrast, the HST is composed of aggradationally to progradationally stacked facies, primarily of mid-ramp to platform margin origin. The FSST is only present in SW Lurestan and comprises the Kalhur evaporites deposited during a sea-level fall (Daraei et al., 2015). The lower sequence boundary of this sequence (ASB-1) is marked by a lithologic change from siliciclastics (in the CK Field) or Asmari basal anhydrite (in SW Lurestan) to pelagic marlstone or argillaceous limestone of the lower Asmari with a sudden deepening trend. The upper sequence boundary (ASB-2) is characterized by a subaerial exposure surface at the top of peritidal facies (CF-1) in the CK Field and by a significant facies change from the basinwide Kalhur evaporites to overlying shallow-marine carbonate-evaporite alternations in SW Lurestan. These two bounding surfaces correspond respectively with “Surface IV” (23.1 Ma) and “Surface V” (21.4

to 20.8 Ma) as described by van Buchem et al., (2010).

AS Sequence-2. This thin sequence consists of a TST followed by an HST. The TST is marked by a sudden facies change compared to the underlying package of facies. In the CK Field, the TST begins with a deepening turnover from peritidal to open marine facies, while in SW Lurestan it is characterized by a change from the Kalhur evaporites to carbonate strata (ASB-2 surface). The HST follows the TST with a progradational stacking pattern of facies, dominated by peritidal facies of shallower marine origin. The upper sequence boundary (ASB-3) is represented by a regional unconformity known as the “Burdigalian transgressive surface” (Adams & Bourgeois, 1967; Adams, 1969; Ehrenberg et al., 2007). This hiatal surface is recorded as a conglomerate lag deposit with carbonate clastic particles in some sections of SW Lurestan, as reported by Daraei et al., (2015) (see their Fig. 12c). However, in the CK Field, the presumed exposure surface is recognized by a subtle facies shift across the surface, indicating changes from peritidal to shoal facies. ASB-3 corresponds to Surface VI (20.2 Ma) as described by van Buchem et al., (2010).

AS Sequence-3. The final sequence of the Asmari Formation consists of a TST and an HST. The TST follows the “Burdigalian transgressive surface” and is composed of deeper marine facies compared to the underlying strata. The HST displays a progradational stacking pattern of facies associations, ending to a paleo-caliche horizon in some localities of SW Lurestan (Daraei et al., 2015; see Fig. 12f therein). In other parts of the Zagros Mountains, the boundary (ASB-4) corresponds to the contact between the Asmari Formation and overlying Gachsaran Formation, where an abrupt lithologic change from Asmari carbonates to Gachsaran evaporites occurs. This contact is equivalent to “Surface VII” (18.5 Ma) as described by van Buchem et al., (2010).

Dynamic depositional model

Results of this study show that the two locally occurring members of the Asmari Formation (Ahwaz siliciclastics and Kalhur evaporites; represented by EF-1 and SF-1 in Table 1) were deposited episodically into parts of the tectonically-compartmentalized Asmari basin during the same stage of sea-level changes (sea-level fall). Three interrelated depositional systems (carbonate–evaporite–siliciclastic) formed within the Asmari Basin during the Oligo–Miocene as a result of combined tectonics and sea-level changes under arid climatic conditions.

Based on the results of this study and previous research on the formation (e.g., Aqrawi et al., 2006; Joudaki et al., 2020; Kavoosi & Sherkati, 2012; Moghaddam, 2022; van Buchem et al., 2010; Vaziri-Moghaddam et al., 2006), it can be concluded that Asmari deposition occurred in a carbonate-dominated, NW-SE trending foreland basin. The physiography of this basin was largely inherited from the Eocene depositional system, with shallow marine carbonate deposition occupying the peripheral parts of the basin and pelagic sedimentation occurring in the center of the basin (Figure 11: Episode I) (Adams & Bourgeois, 1967; Adams, 1969; Ehrenberg et al., 2007).

During the Oligocene, the entrance of siliciclastics into the SW margin of the basin, derived from the erosion of thermally-uplifted peri-rift heights of the Red Sea combined with a sea-level fall, resulted in the development of a siliciclastic deltaic system (Ahwaz sands) (Wang et al., 2021; Ziegler, 2001). Meanwhile, other parts of the basin retained their carbonate depositional conditions similar to those that prevailed during the Eocene (Figure 11: Episode II). In the latest Oligocene-Early Miocene, major changes occurred in the basin configuration due to the reactivation of Zagros basement faults (Bahroudi & Koyi, 2004; Farzipour-saein et al., 2009), creating an intrashelf shallower sub-basin in the N part of the Asmari Basin (Kalhur Sub-basin). In this restricted sub-basin, sea-level fluctuations resulted in alternating evaporite and carbonate precipitation (Daraei et al., 2014; Moghaddam, 2022).

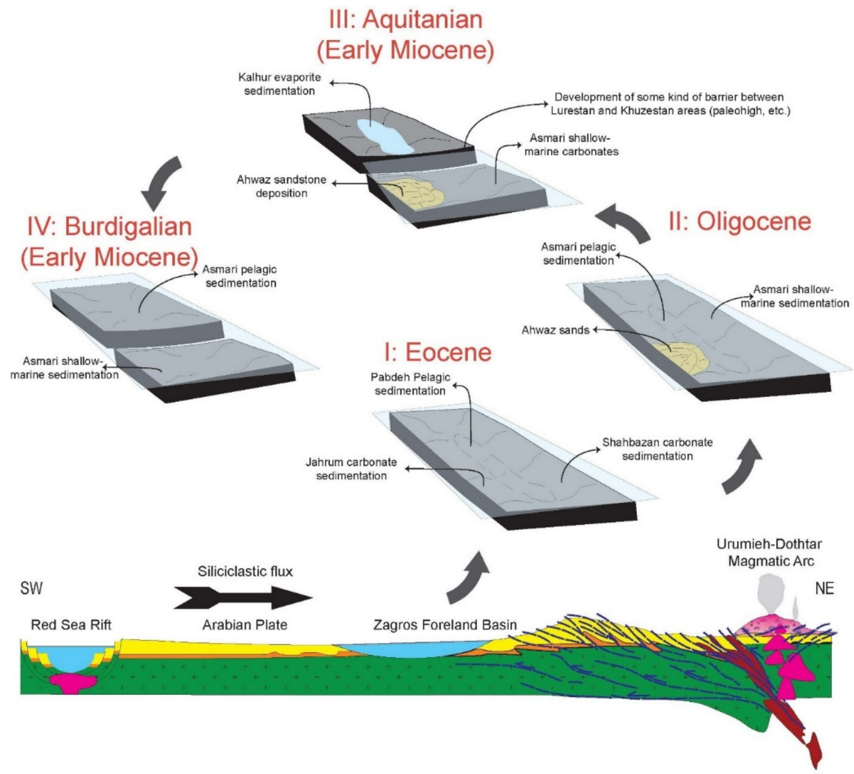

Figure 11. The Asmari basin evolved over time and was occupied by three inter-related depositional systems in the NW-SE trench between the Arabian and Iranian plates

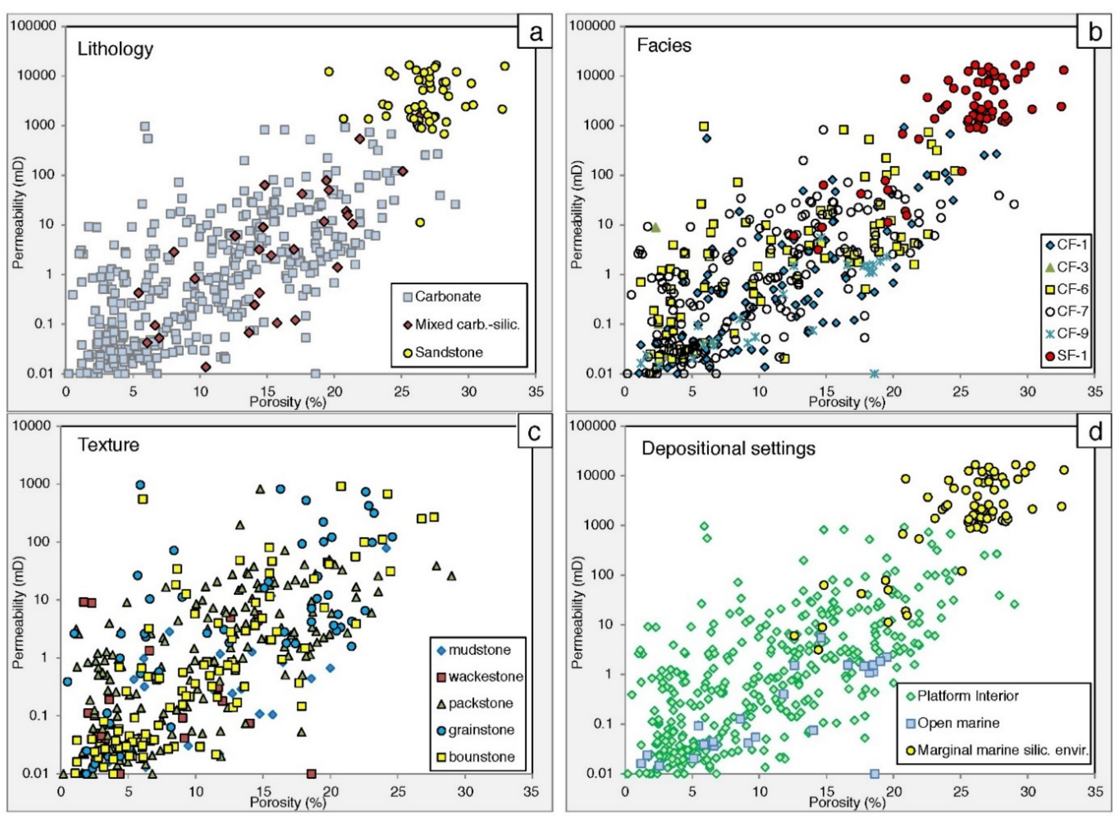

Figure 12. Cross-plots of porosity vs. permeability for depositional controls on reservoir quality in CK Field including lithology (a), facies (b), texture (c), and depositional settings (d). See Table 2

When sea level was high enough to immerse the sub-basin, it would have acted like other parts of the basin with dominant carbonate deposition. However, during sea-level falls, the sub-basin was separated from the rest of the basin and turned into a lake-like evaporitic depositional system with evaporite precipitation (compare Episode III with Episode IV in Figure 11). It should be noted that simultaneous with this evaporite deposition in the N during sea-level falls, siliciclastics entered into the S part of the basin (Dezful Embayment).

Reservoir Quality

Controlling factors

Each controlling factor on reservoir quality would have its own specific effect on petrophysical properties of reservoir rock. Petrography, advanced techniques, and statistical approaches are used to examine heterogeneity of a reservoir or the role of different factors on variations in reservoir quality within a rock unit (e.g., Gharechelou et al., 2022; Gharechelou et al., 2018; Khazaie et al., 2022; Moradi et al., 2017; Sadeghi et al., 2021). Petrographic data and petrophysical properties are statistically considered to inspect the role of each primary or secondary parameter in shaping the reservoir quality of the Asmari. Table 2 shows the statistical analysis of petrophysical data for some primary and secondary parameters of the Asmari core samples. Cross-plots of porosity versus permeability for these controls are illustrated in Figures. 12 and 13.

A) Lithology**.** Lithology of reservoir exerts a major control on the reservoir quality of the Asmari Formation (Table 2 and Figure 12a). Siliciclastics of the Ahwaz Sandstone Member (SF-1) represent the best rock unit with respect to reservoir quality (mean porosity value: 26.57% and mean permeability value: 5244.4 md; Table 2). Carbonates of the Asmari Formation in the CK field show moderate reservoir quality (mean porosity and permeability values of 10.37% and 42.28md, respectively) (North, 1985). Evaporite facies recognized in the outcrop sections of the Lurestan are tight rocks acting as intraformational barriers to any spatial fluid flow. The Kalhur Member may act as a seal for hydrocarbon traps.

B) Facies. Facies type and texture may control reservoir quality to varying degrees. Among the nine carbonate facies comprising the Asmari Formation in the study area, five facies (CF-1, CF-2, CF-5, CF-6, and CF-8) make the building blocks of the reservoir (Table 2 and Figure 12b). CF-1 (peritidal facies) and CF-5 (oolitic shoal facies with intergranular and/or oomoldic porosity) demonstrate relatively good reservoir quality (Table 2). Petrographic observations indicate that CF-1 is a porous facies with dominant fenestral/vuggy pore spaces owing to the presence of cyanobacteria. Pervasive dolomitization may have created a network of interrelated intercrystalline pores. CF-5 contains considerable intergranular and/or secondary oomoldic porosity. However, standard deviations of porosity-permeability values show that original petrophysical properties may have been altered due to post-depositional modifications.

With regard to facies textures, the statistical analysis of petrophysical properties of different textures of Asmari carbonates (Table 2, Figure 12c) shows that grainstone generally represents the highest reservoir quality, followed by mudstone, boundstone, packstone, and wackestone, respectively. Grainstone in the Asmari Formation is mostly observed as oolitic facies (CF-5) with good intergranular and oomoldic pore spaces. Exceptionally high reservoir qualities are observed in mudstone and boundstone textures of the Asmari carbonates. Petrography indicates that these rocks are mostly dolomitic and/or microbialites, and contain intercrystalline and/or fenestral/vuggy pores. Original textures are influenced by post-depositional modifications without obliterating the fingerprint of the rock fabric.

Table 2. Statistical analysis of petrophysical properties of various parameters controlling reservoir quality of the Asmari Formation in the CK Field

Parameter	Sub-parameter	Data count	Phi (%)			K (md)		
			Max. & Min. phi	Mean phi	Stand. Dev.	Max. & Min. K	Mean K.	Stand. Dev.
Lithology	Carb.	397	29.01&0.20	10.37	6.67	6377.9770.00	42.28	338.28
	Mixed Carb. & Silic.	31	26.40&0.00	14.91	6.15	16.36&0.00	84.27	304.05
	Silici.	56	32.70&19.60	26.57	2.46	16632&11.20	5244.4	4830.1
Facies	CF-1	120	28.31&1.07	11.15	6.58	6377.97&0.01	82.06	591.72
	CF-2	5	3.40&2.30	2.84	0.45	8.90&0.02	1.82	3.95
	CF-3	1	Poor data	Poor data	Poor data	Poor data	Poor data	Poor data
	CF-4	1	Poor data	Poor data	Poor data	Poor data	Poor data	Poor data
	CF-5	91	24.60&1.20	11.34	7.09	966.00&0.00	53.86	168.37
	CF-6	168	29.01&0.20	9.86	6.34	819.00&0.00	12.16	65.34
	CF-7	1	Poor data	Poor data	Poor data	Poor data	Poor data	Poor data
	CF-8	28	19.50&1.20	10.28	6.74	5.50&0.00	0.73	1.18
	SF-1	70	32.70&0.00	24.7	5.22	16632&0.00	4232.35	4773.8
Texture	Mdst.	28	28.31&1.90	11.65	6.23	6377.97&0.01	231.39	1204.71
	Wkst.	28	18.60&1.70	6.36	4.6	9.20&0.00	1.14	2.61
	Pkst.	171	29.01&0.20	10.52	6.49	819&0.01	11.82	64.73
	Grst.	66	24.60&0.50	11.72	7.65	966&0.00	73.04	194.64
	Bndst.	105	27.70&1.07	10.12	6.49	922.29&0.00	32.66	127.05
Depo. Setting	Inner platform	386	29.01&0.20	10.49	6.63	6377.97&0.00	43.52	343
	Open marine	28	19.50&1.20	10.28	6.74	5.50&0.00	0.73	1.18
Dolomite percentage	Lime. (0–10% dol.)	102	21.58&0.20	7.78	6.28	27.71&0.00	1.28	3.53
	Dol. Lime. (10–50% dol.)	40	21.26&1.20	8.25	5.75	71.58&0.01	4.38	11.83
	Calc. dolo. (50–90% dol.)	40	29.01&1.74	12.03	7.91	819&0.00	27.91	129.13
	Dolo. (90–100% dol.)	211	28.31&1.07	11.81	6.31	6377.97&0.00	72.78	458.88

C) Depositional setting. Depositional setting exerts a noticeable control on the reservoir quality of the Asmari Formation (Table 2 and Figure 12d). Open marine carbonates of the CK Field generally show less reservoir quality (mean porosity: 10.28%; mean permeability 0.73 mD) than that of inner platform facies (mean porosity 10.49%; mean permeability: 43.52 mD). Open marine facies of the Asmari Formation are commonly mud-dominated rocks that were kept away from dolomitizing fluids of proximal evaporative mechanisms, thus showing no/minor dolomitization effects. This protection from dolomitization prohibited those rocks from developing intercrystalline pore spaces as a reservoir quality enhancing factor in the Asmari Formation (Lucia & Major, 1994; Saller & Henderson, 1998).

D) Dolomitization. Dolomitization is the most pervasive and effective factor affecting the reservoir quality of the Asmari Formation (Aqrawi et al., 2006; Jafari et al., 2020; Khazaie et al., 2022; Omidpour et al., 2022). This diagenetic process affected the reservoir quality to varying degrees, leading to modification of reservoir properties in some intervals. There is an increase in the intensity of dolomitization from base to top of the Asmari Formation. Also, as mentioned earlier, there is a proximal–distal gradient in the dolomitization intensity of the Asmari facies as distal facies are less affected by dolomitization. In general, the dolomitized facies in core samples of the studied field show relatively more visible porosity than limestones, which means dolomitization generally may increase the reservoir properties of the Asmari. As such, Table 2 and Figure 13a show a strong causal relationship between reservoir quality and dolomitization intensity. Overall, carbonate rocks with more dolomite content show better reservoir quality. In Table 2, limestone, dolomitic limestone, calcareous dolomite and dolomite point respectively to 0–10%, 10–50%-50–90% and 90–100% dolomite content within the rock. There is an increase in reservoir quality with increase in dolomite content (Enayati-Bidgoli & Navidtalab, 2020).

E) Dissolution. Dissolution is an important process enhancing reservoir quality in some intervals of the Asmari reservoir (e.g., Jafari et al., 2020). Results of reservoir rock classification of the CK Field (Figure 13b) show that secondary porosity is the dominant pore type in approximately 34% of the carbonate samples (Daraei et al., 2017) (see also Bahrami et al., 2017; Wang et al., 2021). Petrography reveals that these pores are majorly of oomoldic, biomoldic, and vuggy types created by early diagenetic dissolution of unstable aragonitic grains. However, the created secondary pores are mostly not-connected to each other, incapable of producing an interconnected pore network. Although dissolution is an important diagenetic process in carbonates of the CK oilfield, it has essentially resulted in developing a network of isolated pores with low flow capacity (e.g., Aghli et al., 2020; Esrafili-Dizaji & Rahimpour-Bonab, 2019; Fallah-Bagtash et al., 2022; Wang et al., 2021).

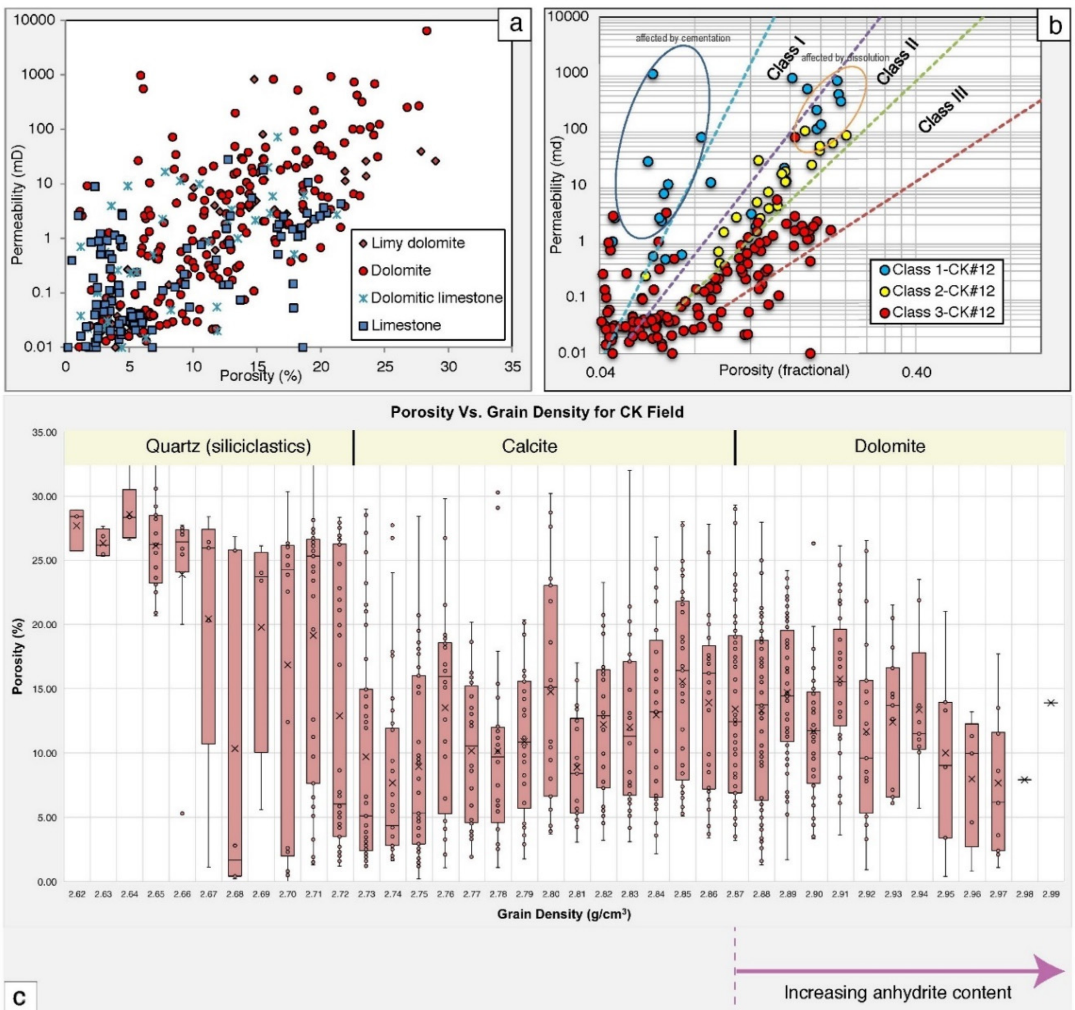

Figure 13. a) cross-plots of porosity vs. permeability for Asmari rocks with various dolomite percentages in the CK Field. b) results of reservoir rock classification of the Asmari in the studied field (modified from Daraei et al., 2017). c) distribution of porosity for each grain density value

F) Cementation. Most effective cement phase in the studied field is anhydrite cementation (cf., Khazaie et al., 2022). Other cements have minor effect on reservoir quality because of their low abundance or pore-lining nature. Figure 13c illustrates a correlation relationship between porosity and grain density of the Asmari rocks in the two wells of the CK field. With increasing density of the carbonates, a clear decrease in porosity value can be seen, attributed to concomitant increase in anhydrite content of the rock in the form of cement (cf., Saller & Henderson, 1998; Wang et al., 2021). Anhydrite has significant effect in decreasing reservoir quality only where it fills interparticle pore spaces. Wherever the cement has poikilotopic or replacive nodular habit, it has little/no effect on permeability (cf., Lucia, 2007; Lucia & Ruppel, 1996; Saller & Henderson, 1998).

G) Fracturing. McQuillan (1973, 1974) conducted the first detailed study on fractures in the Asmari Formation and concluded that small-scale fractures are controlled by bed thickness and lithology without any relation to tectonic structure. These fractures were thought to have developed prior to Zagros folding due to diagenetic processes. In contrast, larger-scale fractures were found to be related to tectonic structure, although they may be superficial phenomena absent in buried oil fields. However, subsequent studies indicated that there is a strong structural control on fracture distribution, orientation, and development within the Asmari Formation, particularly for larger-scale fractures. Several fracture parameters are the result of Zagros folding (in the late Oligocene to early Miocene according to Al-Aasm et al., 2009) and/or reactivation of basement faults (e.g., Aghli et al., 2017; Noorian et al., 2022; Shariatinia et al., 2013), as well as physical stratigraphy controls such as lithology, texture (mud- versus grain-supported), fabric, degree of dolomitization, mineralogy, bed thickness, depositional environment, and cyclicity (Nemati & Pezeshk, 2005; Wennberg et al., 2007; Wennberg et al., 2006). Despite the poor primary reservoir properties of Asmari limestone, its productivity is thought to have been significantly enhanced by fracturing (Aqrawi et al., 2006; Esrafili-Dizaji & Rahimpour-Bonab, 2019; McQuillan, 1985). Fractured reservoirs of the Asmari Formation are found in several oil fields including Shadegan, Ramshir, Gachsaran, Ahwaz, Marun, Agha Jari, Bibi Hakimeh, Pazanan, Haft Kel, Karanj, Rag-e Sefid, Kabud, Qaleh Nar, and Parsi (Esrafili-Dizaji & Rahimpour-Bonab, 2019; Motiee, 1995; Omidpour et al., 2021; Sadeghi et al., 2021). However, there are exceptions across the Zagros area such as the Cheshmeh Khush (current study) and Ramin fields (Bahrami et al., 2017), where fracturing plays a negligible role in production. Therefore, it can be concluded that wherever fracturing is present in the Asmari Formation, it has played a significant role in enhancing reservoir quality.

H) Larger-scale factors. Larger-scale factors such as tectonic activities, climate and sea-level changes (e.g., Milankovitch-forced eustatic sea-level fluctuations; see Falahatkhah et al., (2021)) have exerted superior influences on the Asmari Formation deposition and its diagenetic pathway (Mohammadi et al., 2022; Noorian et al., 2022; Omidpour et al., 2021). The major effects include: 1) influence on depositional aspects such as developing various facies stacking patterns, 2) combined effects of climate and sea-level changes causing hypersaline conditions controlling diagenesis pathway through pervasive dolomitization, dissolution and cementation, and 3) tectonically induced fracturing enhancing production from many Asmari reservoirs. Further studies are necessary to comprehensively rationalize the role of these allogenic controls on spatiotemporal basin fill history and later modifications of the Asmari reservoirs.

Reservoir quality variations in the context of sequence stratigraphy

The Asmari Formation is a time-transgressive rock unit (Ehrenberg et al., 2007; van Buchem et al., 2010) and its deposition in the Dezful Embayment began before deposition in the SW Lurestan. The lower siliciclastic-dominated sequence (AS Sequence-0 in Figure 10) and its underlying sequence were deposited in the CK oilfield before the beginning of Asmari deposition in the SW Lurestan. These sequences are differentiated based on lithologic and well log responses along with correlation with van Buchem et al., (2010).

Deposition of evaporites of the Kalhur Member and siliciclastics of the Ahwaz Member occurred during the falling stage systems tract (FSST/FRST; Figure 10) in a basin compartmentalized by tectonic movements into at least two sub-basins. In the S part of the basin, lowered base-level and tectonic movements led to delivery of siliciclastics into the Asmari Basin (Ahwaz sands) (Noorian et al., 2022). In the N part of the basin, an intrashelf basin was created due to reactivation of basement faults and creation of structural barrier(s), turning it into an evaporative system (Daraei et al., 2015). Succeeding rise in sea level re-established the carbonate factory across the basin. Such cycle probably occurred twice during the Early Miocene (Figure 10) leading to development of two geographically restricted cycles in the Asmari Formation.

Sequence stratigraphic framework of the Asmari Formation defines a pivotal vertical change in reservoir quality. The Asmari Formation in the study area has an upward trend of overall progressive shallowing, also recorded in other places of the Dezful Embayment (e.g., Aqrawi et al., 2006; Ehrenberg et al., 2007; Omidpour et al., 2022). This trend is comprehendible from the stratigraphic position of the formation where it overlies the pelagic open marine/basinal facies of the Pabdeh and underlies the evaporite- and clastic-bearing facies of the Gachsaran (Alsharhan & Nairn, 1997; Gill & Ala, 1972).

Based on petrographic observations, the progressive trend of decreasing accommodation space resulted in more dolomitization and evaporite mineralization from base to top of the Asmari Formation. The lower half contains more open marine facies where dolomitization and evaporite mineralization modified original rocks to a smaller degree. The upper half is composed of more inner platform facies, vastly affected by dolomitization and evaporite mineralization (Figure 14) (Luo et al., 2019; Omidpour et al., 2022).

These upward changes are attributed to consecutive filling of the Zagros Foreland Basin (Aqrawi et al., 2006; Ehrenberg et al., 2007). These variations reveal the significance of knowledge of sequence stratigraphic framework in comprehending the regional configuration of the Asmari Formation across the Zagros area.

In summary, this study supports the results of previous works on the Asmari Formation and highlights the influence of primary facies types and secondary processes such as dolomitization, dissolution, cementation, and fracturing on enhancing the reservoir quality of the Asmari Formation in the Zagros area (e.g., McQuillan 1973, 1974; Aqrawi et al., 2006; Jafari et al., 2020; Khazaie et al., 2022; Omidpour et al., 2022). However, this study also sheds light on some less studied aspects of the formation that might have had regional effects on its reservoir configuration. Notably, regional variations in the lithologic configuration of the formation, reflected in siliciclastics-carbonate to the south and evaporite-carbonate configuration to the north of the Zagros area (implicitly, spatial configuration of contemporaneous depositional systems during deposition), and the general path of diagenesis are two significant determinants of Asmari reservoir quality that seem to have been controlled by allogenic effects from relative sea-level changes, climate, and tectonic structural style. This study suggests that further research should focus on these allogenic controls to better understand their role in the spatio-temporal basin fill history and establish a regional framework for the distribution of flow, barrier, and baffle units within the rock unit.

Conclusions

This study found that both primary (depositional) and secondary (post-depositional) factors have influenced the reservoir quality of the Asmari Formation in the studied area.

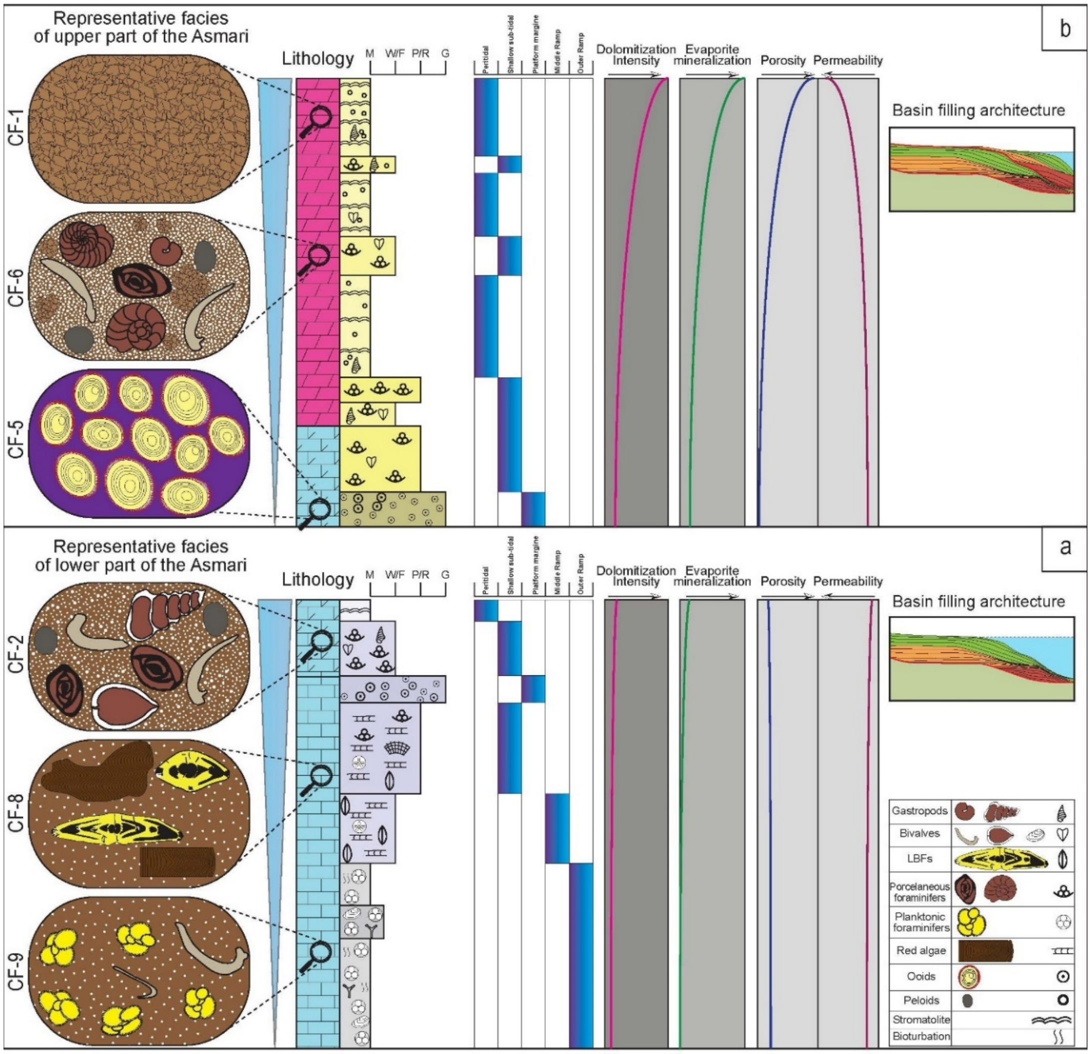

Figure 14. Comparing a hypothetical sequence in the lower half of the Asmari (a) with that in the upper half (b). The Asmari shows a trend of shallowing facies from base to top with an increase in dolomitization and anhydrite mineralization

Lithology is the main control on petrophysical properties of the reservoir. The siliciclastics of the Ahwaz Member have higher poroperm values than carbonates and make the main reservoir pay zone of the Asmari in the Dezful Embayment. In Lurestan Province, the lithology changes to evaporite-carbonate, where evaporites act as regional barriers to fluid flow.

In the subsurface, primary controls such as facies, depositional setting, and texture affect the reservoir quality of the Asmari carbonates. However, diagenetic processes such as dolomitization, dissolution, and cementation significantly alter the carbonates petrophysical properties, resulting in a highly heterogeneous reservoir rock.

Dolomitization has a dual effect on porosity. In the lower Asmari succession, it has a neutral effect, but in the upper formation, it greatly enhances reservoir quality. As dolomitization increases, reservoir quality improves.

Dissolution increases the total porosity of about one-third of the carbonate rocks. However, this secondary porosity mainly consists of isolated moldic and vuggy pores that only increase storage capacity. These pores can be connected through fracturing to produce an interconnected network of pore spaces, as in many petroleum fields in the Dezful structural embayment. In the studied field, fracturing is absent/minor and does not contribute to reservoir quality.

Anhydrite cementation is the main process that reduces porosity in the Asmari reservoir. It locally alters the porosity-permeability characteristics of some facies, notably the oolitic shoal facies.

This study demonstrates that the most prolific zones of the Asmari Formation in hydrocarbon fields of the Zagros area are likely in the Ahwaz Sandstone Member siliciclastic horizons. The best pay zones of the Asmari carbonates are concentrated in the upper part of each depositional sequence where rocks are more affected by dolomitization and in fractured Asmari reservoirs. Further regional sequence stratigraphic and basin analysis studies are necessary to locate the most productive zones on a regional scale.

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