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Diagenetic Processes Imprint on Reservoir Quality and Hydraulic Flow Units of the Lower Cretaceous Strata (Fahliyan Formation), Izeh and Dezful Zones, Zagros Basin, SW Iran

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Abstract

The Fahliyan Formation, a significant carbonate reservoir in southwestern Iran encompassing the Izeh and Dezful Zones, underwent detailed petrographic investigations. These analyses revealed eight distinct microfacies associated with four different depositional settings within a homoclinal ramp model. From a diagenesis perspective, the formation has undergone various processes, including micritization, dissolution, compaction, cementation, dolomitization, stylolitization, and fracturing. These diagenetic features affected the Fahliyan Formation from early marine–meteoric to late burial diagenetic realms. Notably, dissolution developed as the most effective and widespread diagenetic feature, improving reservoir quality. Likewise, fracture and dolomitization positively impact reservoir quality, while compaction and cementation have destructive effects. Micritization and early isopachous calcite cement have a retentive role in reservoir characteristics. In addition, the Flow Zone Indicator (FZI) approach introduced three Hydraulic Flow Units (HFUs). Ultimately, the correlation between microfacies types and their petrophysical features indicates that the bioclastic peloid packstones and grainstones have better reservoir quality, which resulted from dissolution and initial isopachous calcite types of cement. Also, Planktonic foraminifer's bioclastic mud/ wackestone and Quartz-bearing mudstone, equivalent to HFU1, indicate lower reservoir quality due to the compaction (stylolitization) and cementation.

Keywords: Facies Analysis, Diagenetic Features, Petrophysical Properties, Reservoir Quality, Hydraulic Flow Unit .

Introduction

The Fahliyan Formation is one of the most prolific reserves in the Zagros area and represents a carbonate ramp system that developed during the early Cretaceous period in the central Persian Gulf region [1]. This formation is equivalent to the Sulaiy/Makhul and Yamama strata in Saudi Arabia and Iraq, the Minagish Formation in Kuwait, and the Ratawi Formation in Kuwait and Iraq [2]. The Fahliyan Formation consists of three distinct segments. The lower Fahliyan, equivalent to the Sulaiy/Makhul Formation, exhibits the highest reservoir quality. In contrast, the middle Fahliyan, comparable to the Yamama/Minagish Formation, has moderate reservoir quality. Finally, the upper Fahliyan corresponds to the lower Ratawi Formation and represents a zone with poor reservoir quality [3,4]. Many researchers have studied lithostratigraphy and sedimentology of the Fahliyan successions [1, 5-7]. Moreover, it exhibits varying thicknesses across different locations. It measures approximately 283 meters at the type locality (near Fahliyan village) [1]. However, in areas like the Izeh Zone and Dezful embayment, the thickness ranges from 300 to 600 meters. For example, in the Gachsaran and Garangan oilfields, it reaches 582 and 475 meters, respectively, while in the Eshgar and Lar anticlines, it spans 330 and 655 meters, respectively [8, 9]. It comprises massive, ooid, and peloid carbonate facies with a brecciation process in the lower part [1]. Facies analysis studies revealed that the Fahliyan Formation consists of eight sedimentary facies deposited on the carbonate ramp [10, 11, 12]. Recently, more investigations have been focused on sedimentary characteristics, reservoir rock typing, biostratigraphy, and sequence stratigraphy in the surface and well localities [5, 8-9, 13-19]. In addition, the signature of syn-depositional stretching faults, disconformities, and

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facies variations through the Lurestan area has been studied by Tavani et al. [20]. Noori et al. [9] have suggested that relative sea-level fluctuations and tectonic activities have caused thickness changes and various depositional lithologies of the Fahliyan Formation throughout the Izeh area.

The integration of sequence stratigraphy and diagenesis represents a powerful approach to understanding porosity, permeability distribution, and reservoir quality evolution in carbonate reservoirs [21-27]. The sequence stratigraphic framework could predict the distribution of diagenetic features and reservoir potential. Additionally, this method can provide helpful information about the formation of diagenetic seals and barrier strata, which it may result in the compartmentalization of the reservoirs [28]. Therefore, diagenetic alterations can shape the overall reservoir quality. In addition, diagenetic processes play a crucial role in modifying HFU characteristics as a practical tool used to evaluate reservoir quality. This method groups rocks based on their petrophysical attributes (e.g., porosity and permeability).

Despite many studies, the change in depositional sequences of this formation and the impact of diagenetic processes on reservoir quality remains elusive. Therefore, the primary goal of this research is to establish a clear relationship between major diagenetic features and sedimentary facies and their effects on the reservoir quality of the Fahliyan Formation.

Geological Setting

The Zagros fold-thrust mountain formed in the foreland of the collision between the Arabian Plate and the Eurasian Plate. It is separated into several parts, including Lurestan, Izeh, Dezful Embayment, Fars, and High Zagros [29], which differ in their structural features and depositional properties [29-31]. The Fahliyan Formation is a crucial part of the Khami Group reservoir in the Zagros structural zone, particularly within the Dezful Embayment (Figs. 1 and 2). The Balarud and Kazerun faults distinguished these regions from the Lurestan and Fars regions [29, 31]. The first compressional stage with subduction towards the northeastern of the Arabian Plate occurred from the Jurassic to the Early Cretaceous and was followed by the Late Cretaceous abduction occurrence [32].

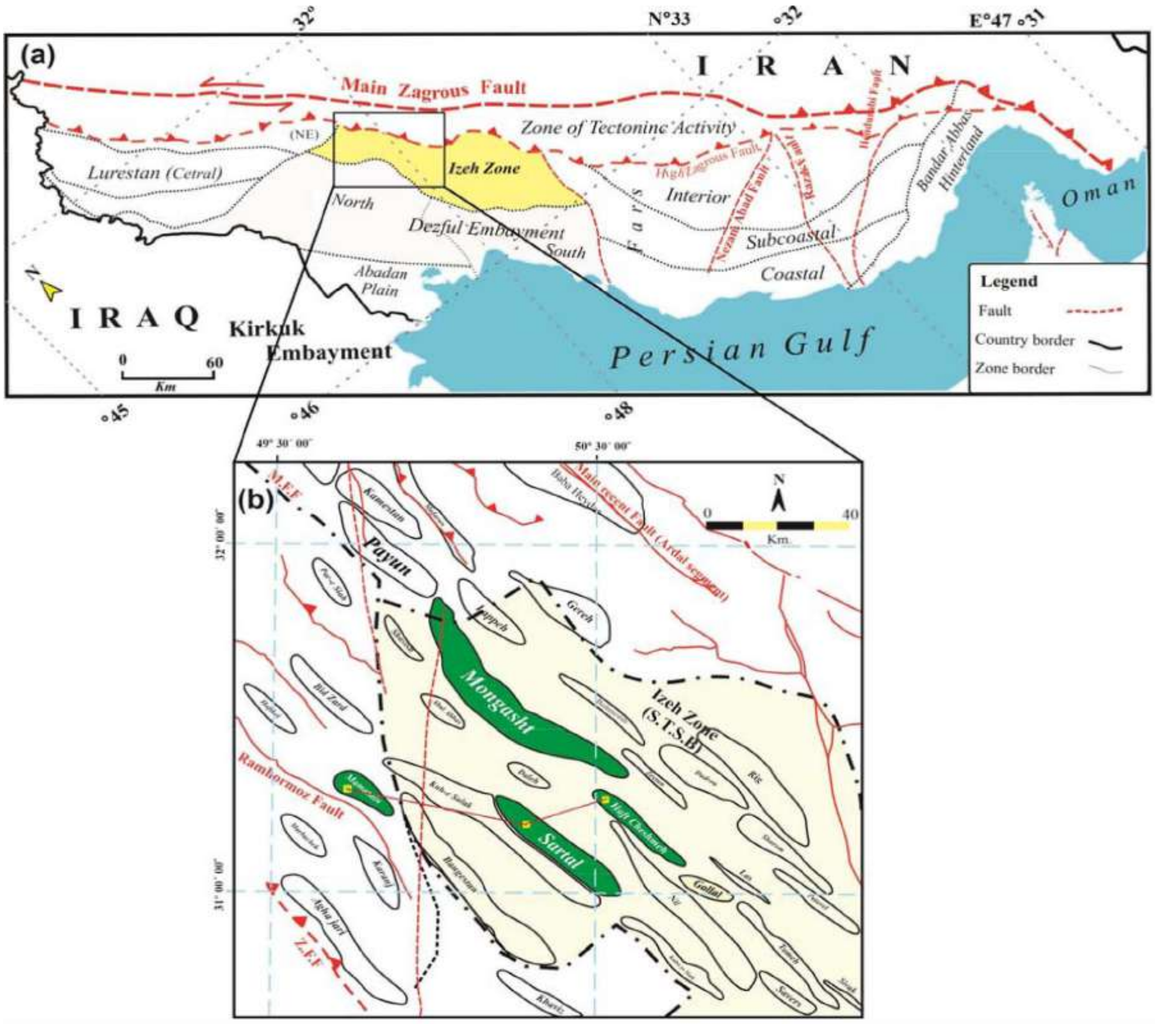

Fig. 1 a) The main structural features and sub-zones of the Zagros Basin, and b) the locations of three studied subsurface sections along with the Mongasht outcrop in the Izeh Zone (adapted from NIOC). Abrr. M.F.F.: Mountain Front Fault, Z.F.F.: Zagros Frontal Fault.

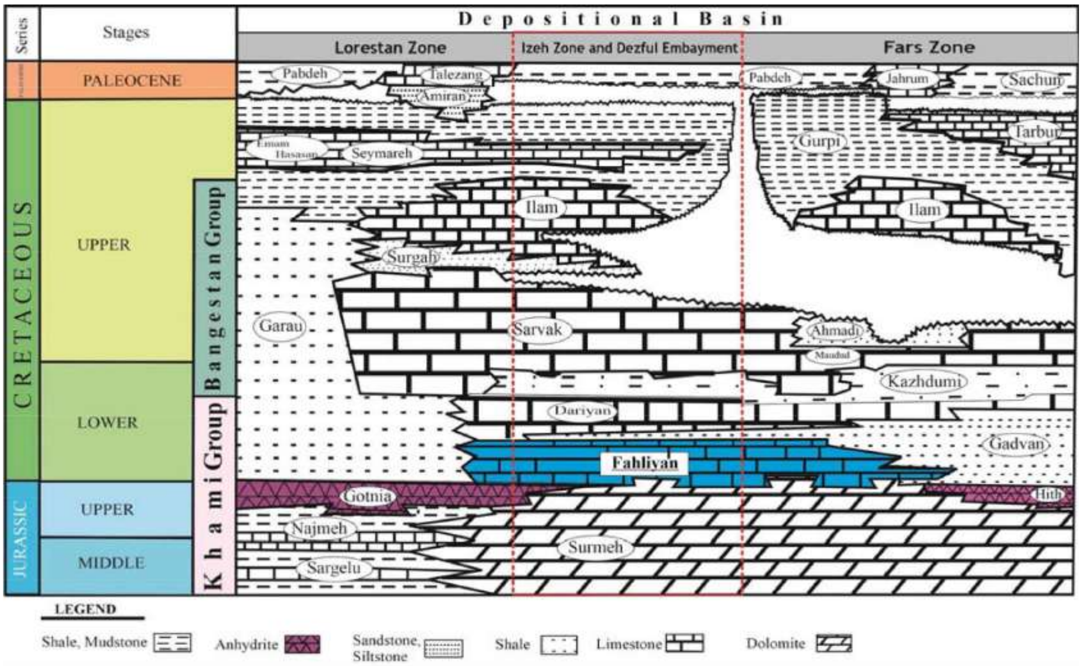

Fig. 2 Stratigraphic columns of the Jurassic and Cretaceous successions throughout the Zagros Basin, including Lorestan, Izeh Zone and Dezful embayment (Red-dashed rectangle), and Fars area (modified from James and Wynd 1965; Rostamtabar et al., 2022). The Fahliyan Formation is marked with a blue hatch.

It represents Lower Cretaceous deposits and consists of carbonate rocks. The formation includes massive oolitic to pelletal limestone, with subordinate brecciation in its basal parts. Sedimentary facies were changed from the southwestern to the northwestern part of the Zagros basin. The main cause of these changes was the reactivation of pre-existing structural features (i.e., Izeh and Kazeroun basement faults) [33]. The tectonic history of the Zagros Basin significantly influenced the deposition and subsequent diagenesis of the Fahliyan Formation. For example, the Zagros Basin was developed as a foreland basin in response to the tectonic loading from the collision, and sediments were deposited in it during various stages of tectonic activity. In the early Cretaceous time interval, the marine, fossiliferous successions of the Fahliyan Formation and the Garau and Gadvan strata deposited on the passive margin along the N-E trend of the Arabian Plate [34, 35]. Therefore, it is possible that tectonic stresses influenced diagenetic processes (such as cementation, dissolution, and dolomitization) within the Fahliyan Formation, affecting reservoir quality. The paleoclimate during the Cretaceous also played a role in sedimentation. This formation was deposited in warm and shallow marine conditions during the Neocomian period [1, 3, 36, 19, 37, 38, 18]. The presence of ooids, peloids, and other carbonate textures reflects these paleoenvironmental conditions.

Materials and Methods

Diagenetic features and their impact on reservoir properties were investigated based on core and cutting data from three subsurface sections. Moreover, sedimentological data, petrophysical logs, and reservoir quality data (porosity and permeability) were used from 120 core specimens in the Haft Cheshmeh subsurface section. Additionally, 800 thin sections (200 from cores and 600 from cuttings) were prepared. Moreover, major diagenetic features were determined through a polarized microscope and Cathodoluminescence (CL) analysis (using a Nikon polarized microscope Model mk8200). In addition, 12 samples from the Mongasht outcrop were analyzed (using Scanning Electron Microscope (SEM) Model LEO 1450VP with a resolution of 2 nm at the Central Laboratory of Ferdowsi University of Mashhad) to identify the crystalline shapes, porosity types, and diagenetic imprints. Also, gamma-ray log responses were applied to determine third-order sequences in the study region according to the Van Wagoner et al. (1990) approach. Furthermore, 125 samples were dyed with blue epoxy resin to identify different pore types. Then, the connection between sedimentological and petrophysical characteristics was evaluated for each microfacies based on poro-perm data from cores in the Haft Cheshmeh section. Finally, reservoir rock types of the Fahliyan Formation were determined using Hydraulic flow units (HFU) and Flow Zone Index (FZI) concepts in the Haft Cheshmeh well.

Results and Discussion

Results

Facies Analysis and Sequence Stratigraphy

In the scholarly work titled “Facies analysis and sequence stratigraphy of the Lower Cretaceous strata (Fahliyan Formation) in Izeh Zone, Zagros Basin, SW Iran” the authors have identified facies and sequences [18]. The article delves into the impact of diagenesis on reservoir quality. Consequently, the concepts of facies and sequences serve as a summary within the mentioned article. The obtained results led to the classification of eight microfacies from MF-1 to MF-8, ranging from open marine to intertidal environments. To describe their sedimentary settings, determined facies are correlated with established standards for carbonate ramp models [39] and previous research on the Early Cretaceous successions in Iran and the Arabian Plate [8, 40, 41]. These facies are described in terms of their depositional textures, main constituents, and sedimentary environment in Table 1. From the sequence stratigraphy point of view, based on the previous studies in the Arabian Plate and Zagros basin [18, 20, 42], three third-order depositional sequences, including FaDS1, FaDS2, and FaDS3 were identified within the Fahliyan Formation in the Izeh area (Fig. 3).

The TST of the FaDS1 sequence is mainly composed of open marine facies (MF-1 and MF-2) in the Mamatain section and shoal facies (MF-3 and MF-4) with intercalations of lagoonal facies in Sartal and Haft Cheshmeh sections. While the maximum flooding surface (MFS-1) consists of open marine facies (MF-1 and MF-2). The HST of this sequence comprises shoal and lagoonal facies and ends with lagoonal facies (MFs 5-7), which is the lower part of the FaDS2. The TST part of the FaDS2 is dominated by open marine facies (MF-1 and MF-2), which results in the maximum development of Radiolarian sponge spicule wackestone (MF-1) (MFS-2). The upper part of this sequence (HST) comprises open marine facies (MF-2) and intercalations of shoal and lagoonal facies. likewise, the upper sequence boundary is characterized by shoal/lagoonal facies. The TST for FaDS3 consists of shallow open marine facies (MF-2). The MFS-3 represents the maximum development of open marine facies. The HST represents a shoaling-upward trend towards the uppermost part of the systems tract and begins with shallow open marine microfacies in the Mamatain section. However, shoal and lagoonal microfacies dominate the upper part of this systems tract in the Sartal and Haft Cheshmeh sections. Therefore, there is a deepening trend of facies from Haft Cheshmeh toward Mamatain. Furthermore, the gamma-ray signature represents an upward cleaning trend in the Mamatain and Sartal sections.

Diagenesis

Detailed microscopic investigations indicated that the Fahliyan Formation was influenced by several diagenetic realms, including marine, meteoric, and burial diagenetic environments. The most common diagenetic features observed are micritization, bioturbation, micritization, neomorphic, cementation, compaction, dolomitization, fracturing, and dissolution, represented in Fig. 4 to 10. These processes have shaped the reservoir quality and influenced its overall characteristics. Micritization: Micritization has affected the Fahliyan Formation carbonate as an earlier diagenetic process (Fig. 4a, b, e). Furthermore, carbonate particles such as bioclasts and non-skeletal grains (peloids) were partially or completely micritized, by endolithic/ epilithic and other microbes (microborers) on the sea floor.

Table 1 Main facies characteristics, diagenetic features, and proposed depositional sub-environment for the Fahliyan Formation in the study area.

Facies code	Facies	Lithology	Main constituent		Depositional environment	Main Diagenetic feature
			Skeletal	Non-skeletal		
MF-1	Radiolarian sponge spicule wackestone	Limestone	Sponge spicules, radiolarian, echinoderm	Peloid	Open marine	Neomorphism, bioturbation
MF-2	Planktonic foraminifera bioclastic mud/ wackestone	Limestone	Echinoderm, planktonic froaminifera, sponge spicules, rare bivalve	-		Neomorphism, syntaxial cement
MF-3	Intraclastic ooid grainstone	Limestone	Benthic foraminifera, green algae	Intraclast, ooid	Shoal	Micritization, isopachous rim cement, dissolution
MF-4	Bioclastic peloid grainstone	Dolomitic limestone	Benthic foraminifera, green algae, lithocodium, echinoderm, bivalve	Intraclast, peloid		Micritization, isopachous rim cement, equant sparry calcite cement, dolomitization, fracturing
MF-5	Bioclastic peloid packstone	Limestone	Benthic foraminifera	Peloid	Lagoon	Micritization, equant sparry calcite cement, dolomitization, fracturing
MF-6	Benthic foraminifera wackestone	Limestone	Benthic foraminifera, green algae, Lithocodium, bivalves, gastropods	Rare peloid		Equant sparry calcite cement, dolomitization
MF-7	Fossiliferous mudstone	Dolomitic limestone	Benthic foraminifera, green algae	Peloid		Equant sparry calcite cement, blocky cement,dolomitization, fracturing
MF-8	Quartz-bearing mudstone	Limestone	-	Quartz	Intertidal	Neomorphism

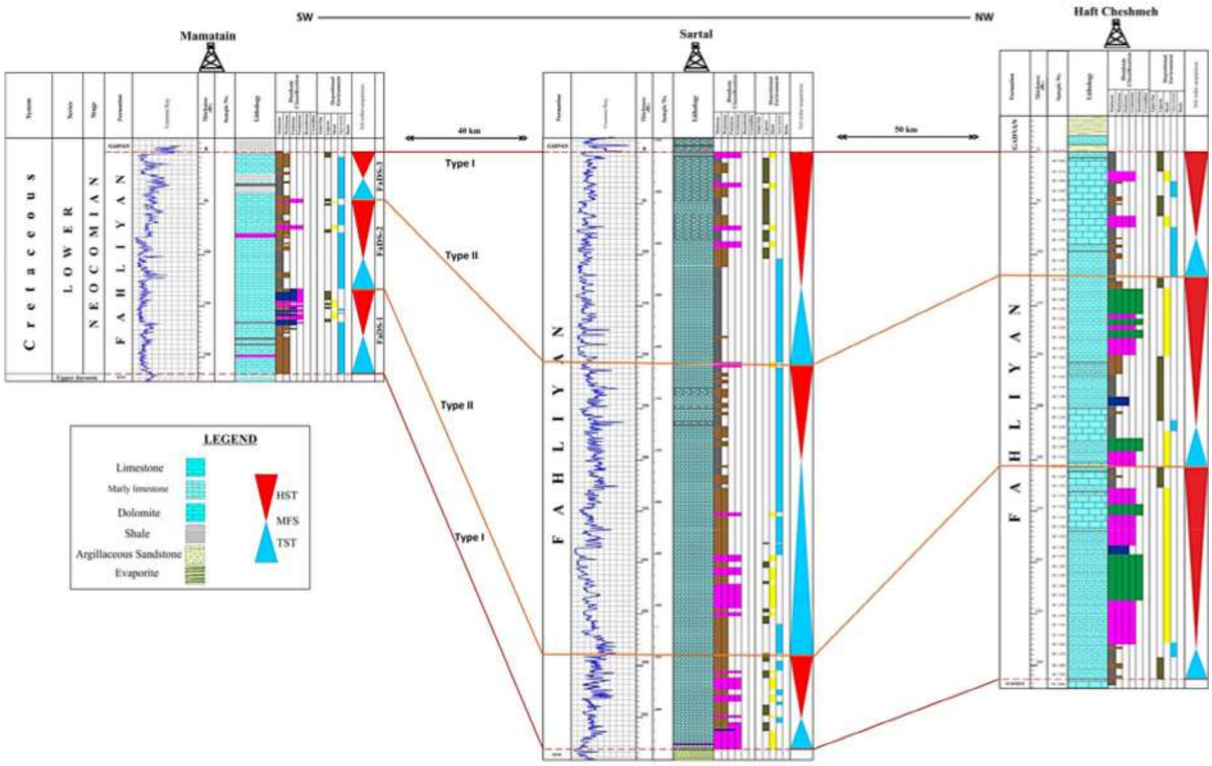

Fig. 3 Sedimentological characteristics and sequence stratigraphic correlation among three studied sections in the Izeh Zone. The available core interval of the Haft Cheshmeh is marked with a grey vertical rectangle (Rostamtabar et al., 2022).

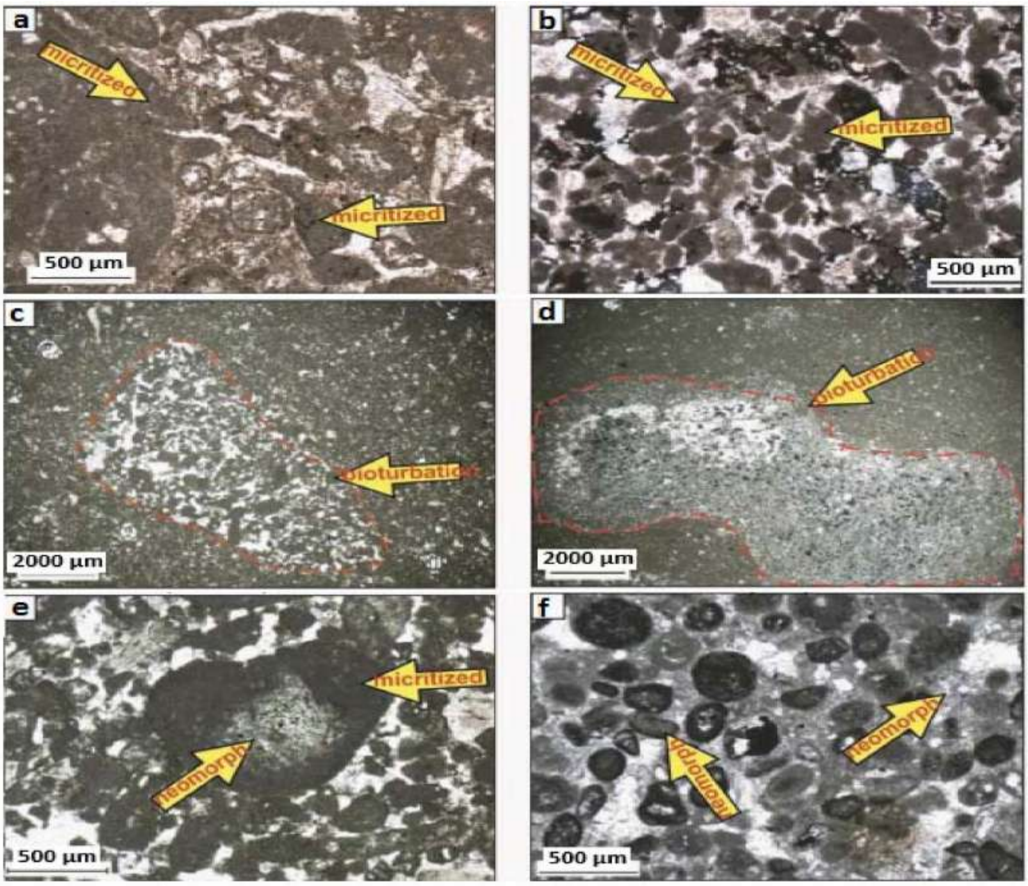

Fig. 4 Photomicrographs of thin sections representing diagenetic features of the Fahliyan Formation; a, b) Micritization of skeletal and non-skeletal grains, and b) Cementation associated with bioturbation in bioclastic peloid grainstone (Sartal section, depth: 1475.35 m), c, d) Bioturbation in bioclastic peloid packstone (Sartal section, depth: 1520.46 m), e) Recrystallization of micrite to microspar, and f) Recrystallization of skeletal grains and transformation of micrite to microspar in bioclastic peloid grainstone (Sartal section, depth: 1890.25 m).

Moreover, micritized bioclasts are frequent in the lagoonal facies but also occur in the shoal facies (fossil fragments). Some of the uncertain grains have been produced during the whole micritization. This feature frequently happens in relatively low-regime, shallow-marine settings (stationary marine phreatic environments), confirming severe microbial occurrence [39, 43, 44]. This diagenetic process is mainly observed in the MF-3, MF-4, and MF-5.

Bioturbation: Bioturbation is a common feature in lagoonal and open marine sedimentary facies of the Fahliyan Formation. It is mainly recorded as boring structures within the large skeletal particles filled by peloids, micrite, and cement (MF-1) (Fig. 4c, d).

Neomorphism: Calcification of aragonitic components and micrite (formation of pseudo-sprite) usually occurred in the inner ramp facies of the Fahliyan studied interval (MF-1, MF-2, MF-8) (Figs. 4e, f and 9d, f). Also, this process may alter the micrite partially or totally to micro-spar or pseudo-sparite (crystal size > 4 μm). Occasionally, differentiating ortho-sprite (sparry cement) and pseudo-sprite (neomorphic sprite) is difficult. In some cases, the primary texture of facies is completely obliterated during neomorphism.

Cementation: This process is one of the most frequent diagenetic features in the Fahliyan studied succession that filled primary and post-depositional pore spaces (MF-2, MF-3, MF-4, MF-5, MF-6, MF-7). In many cases, interparticle, intra-skeletal, moldic, and fracture pores have been entirely or partially occluded by types of cement. From a mineralogy point of view, calcite (DLMC) is the dominant cement phase (Figs. 5 and 6b-d). Dolomite remains present (Fig. 6a). At least four main cement generations were observed in the Fahliyan Formation. These include interparticle, intraparticle calcite spars, and mold/ fracture filling types of cement. They are drusy and blocky (Figs. 5a, c-e, 6c, 9c, 10d, e) in form and may derive from various diagenetic realms.

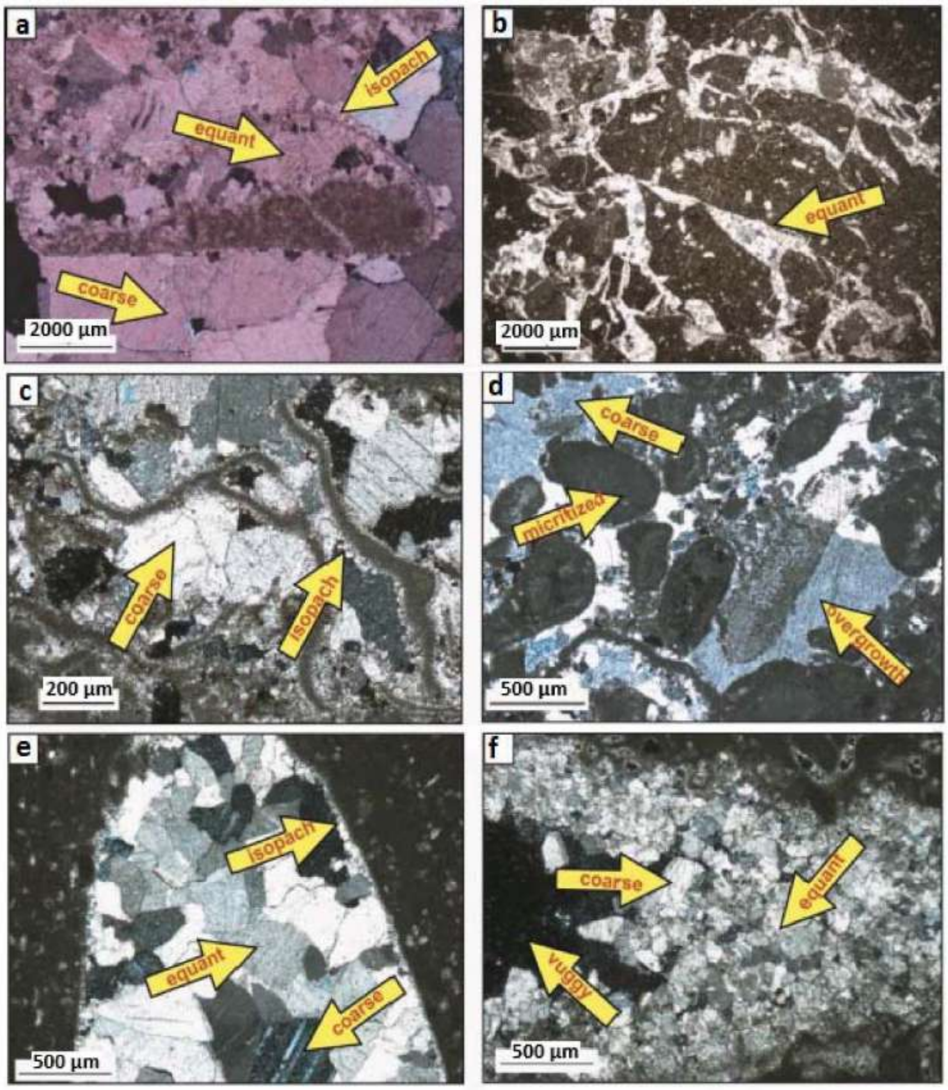

Fig. 5 Photomicrographs of thin sections representing diagenetic features observed in the Fahliyan Formation; a) Isopachous calcite cement on the skeletal substrate, coarse-grained blocky calcite cement within a bioclast along with pore-filling coarse-grain calcite cement, and b) Brecciation and coarse-grain calcite cement and dissolved vugs in bioclastic peloid grainstone (Sartal section, depth: 1475.35 m), c) Isopachous high-Mg calcite cement on the skeletal substrate and coarse-grained calcite cement within dissolved vugs, and d) Overgrowth and intergranular coarse-grain crystalline calcite cement in Intraclastic ooid grainstone (Sartal section, depth: 1970.56 m), e) Isopachous calcite cement in the internal substrate along with coarse-grained blocky calcite cement within a bioclast, and f) Coarse-grain equant calcite cement filling a dissolved vug in benthic foraminifera wackestone (Sartal section, depth: 1960.30 m).

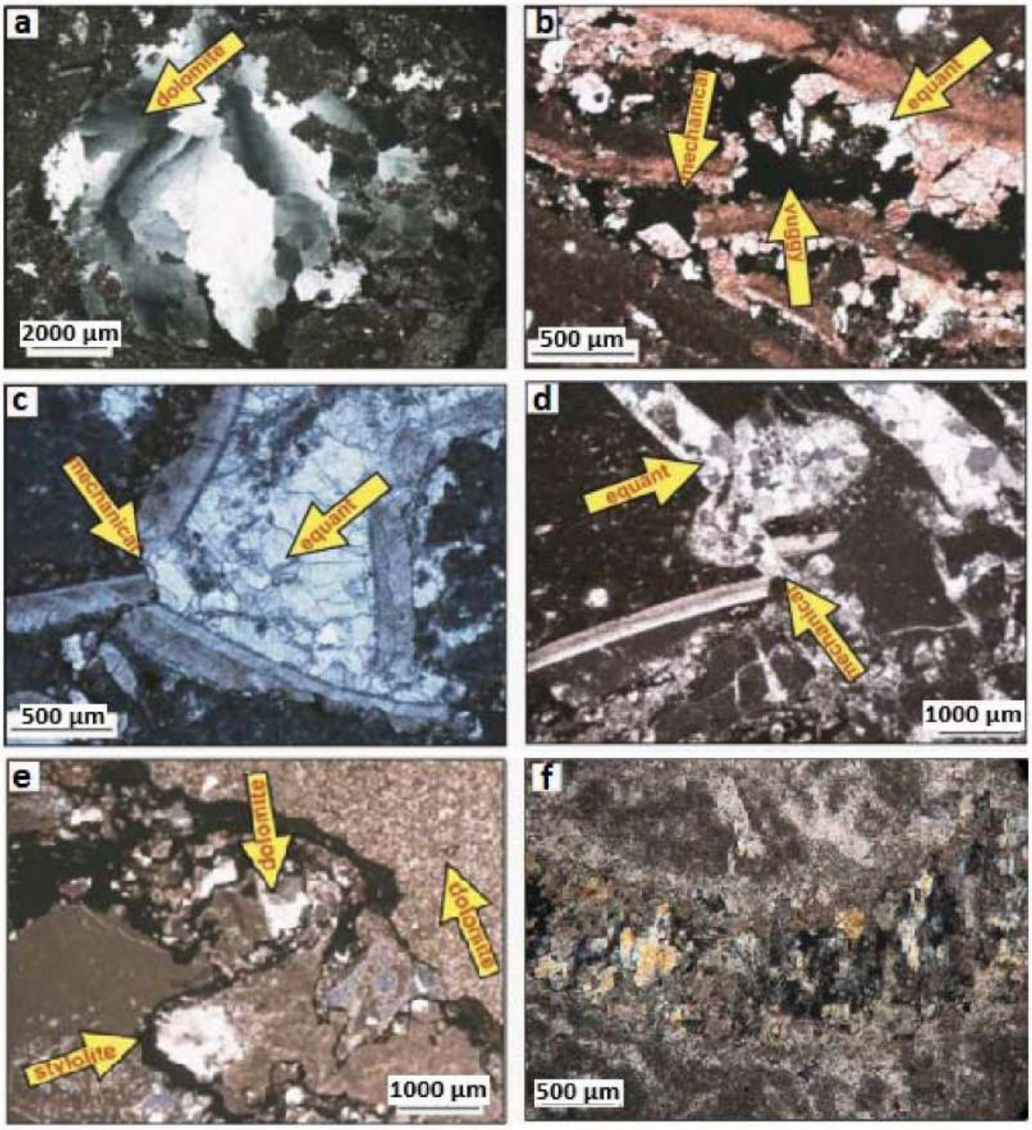

Fig. 6 Photomicrographs of thin-sections representing diagenetic features of the Fahliyan Formation in bioclastic peloid packstone, Sartal section; a) Pore-filling saddle dolomite cement with undulose extinction, b) Mechanical compaction and over-packing of the skeletal grains along with pore-filling equant calcite cement, and residual hydrocarbon (depth: 1475.35 m), c) Physical compaction and crushing of fossils along with pore-filling equant calcite cement, d) Physical compaction and crushing of fossils along fracture-filling equant calcite cement within bioclasts (depth: 1520.46 m), e) Saddle dolomite cement with undulatory extinction, dolomitization in the matrix (upper-right corner of the image), close-up view of stylolitization and solution seam, and f) Fracture filled with silica cement (depth: 1960.30 m).

The intergranular calcite cements are common in the high-regime shoal facies (MF-3 and MF-4) and seldom occur in other facies associations. Fracturing and subsequent cementation of fractures (by blocky coarse-grained calcite) are recorded in thin sections. The main recognized cement types in the Fahliyan Formation are shown in Figs. 5 and 6.

Compaction: The studied interval of the Fahliyan Formation has been significantly influenced by compaction during and after the burial (present burial depth 2.5-3 km) in the studied sections. Compaction features of this formation can be classified into two main physical and chemical compactions (Fig. 5c-f).

Mechanical compaction applies to grain packing, deformation, and breakage due to stress increasing in burial realms [26]. Chemical compaction forms features, including solution seams, wispy seams, and stylolites. In the studied interval, both stylolites and solution seams are recorded as important diagenetic features (Fig. 6e). However, solution seams are more common and primarily formed in mud-dominated facies (mudstones and wackestones). Stylolites are mainly recorded within grain-supported facies.

Dolomitization: This diagenetic process has not been well developed in the studied interval of the Fahliyan Formation (Figs. 6e, 7a, b). Occasionally, the dolomitization caused the formation of intercrystalline porosity in a few samples. It was commonly observed as saddle dolomite pore-filling.

cement (Fig. 6a). The source of magnesium for this extensive dolomitization is assigned to ophiolite obduction on the continental margins of the Arabian Plate and Central Iran during the Late Cretaceous [45, 46, 47, 48]. Dissolution of large echinoderm bioclasts (with HMC mineralogy), which is concentrated along the stylolites (Figs. 8c, 10b, f), supplied a partial source of magnesium for dolomitization.

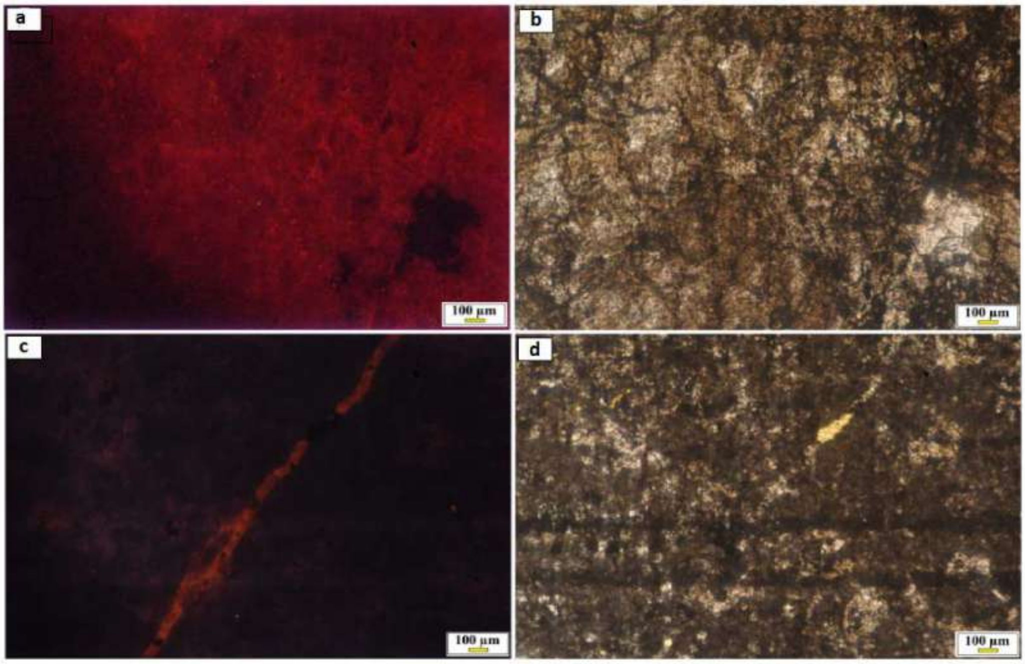

Fig. 7 Cathodoluminescence microscopy images representing diagenetic features from the Fahliyan Formation in Mongasht section; (a, b) Dolomitization in dolostone facies, (c, d) Fracture filled with calcite cement in peloidal wackestone facies. a, c: Cathodoluminescence, b, d: polarizing light.

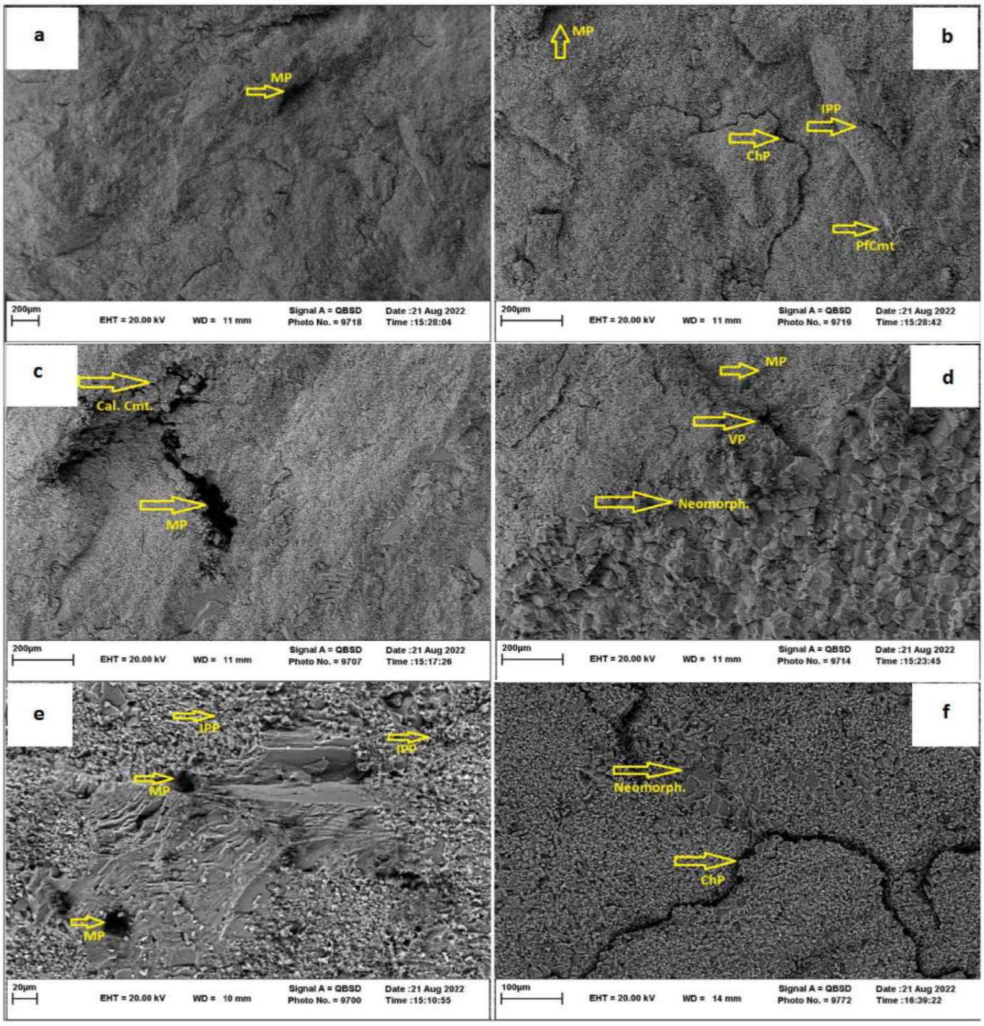

Fig. 8 Photomicrographs representing diagenetic porosity and dissolution features observed in the Fahliyan Formation; a) Interparticle and vuggy porosities in bioturbated context along with matrix porosity, b) Moldic and vuggy porosities within algae along with channel porosity in bioclastic peloid packstone (Sartal section, depth: 1520.46 m), c) Channel porosity resulted from dissolution along solution seams in Fossiliferous mudstone (Sartal section, depth: 1468.20 m), d) Moldic, and vuggy porosities in bioclastic peloid packstone (Sartal section, depth: 1520.46 m), e) Interparticle porosity in bioclast peloid grainstone (Sartal section, depth: 1890.25 m), and f) Formation of moldic and vuggy porosities in bioclastic peloid packstone (Sartal section, depth: 1520.46 m).

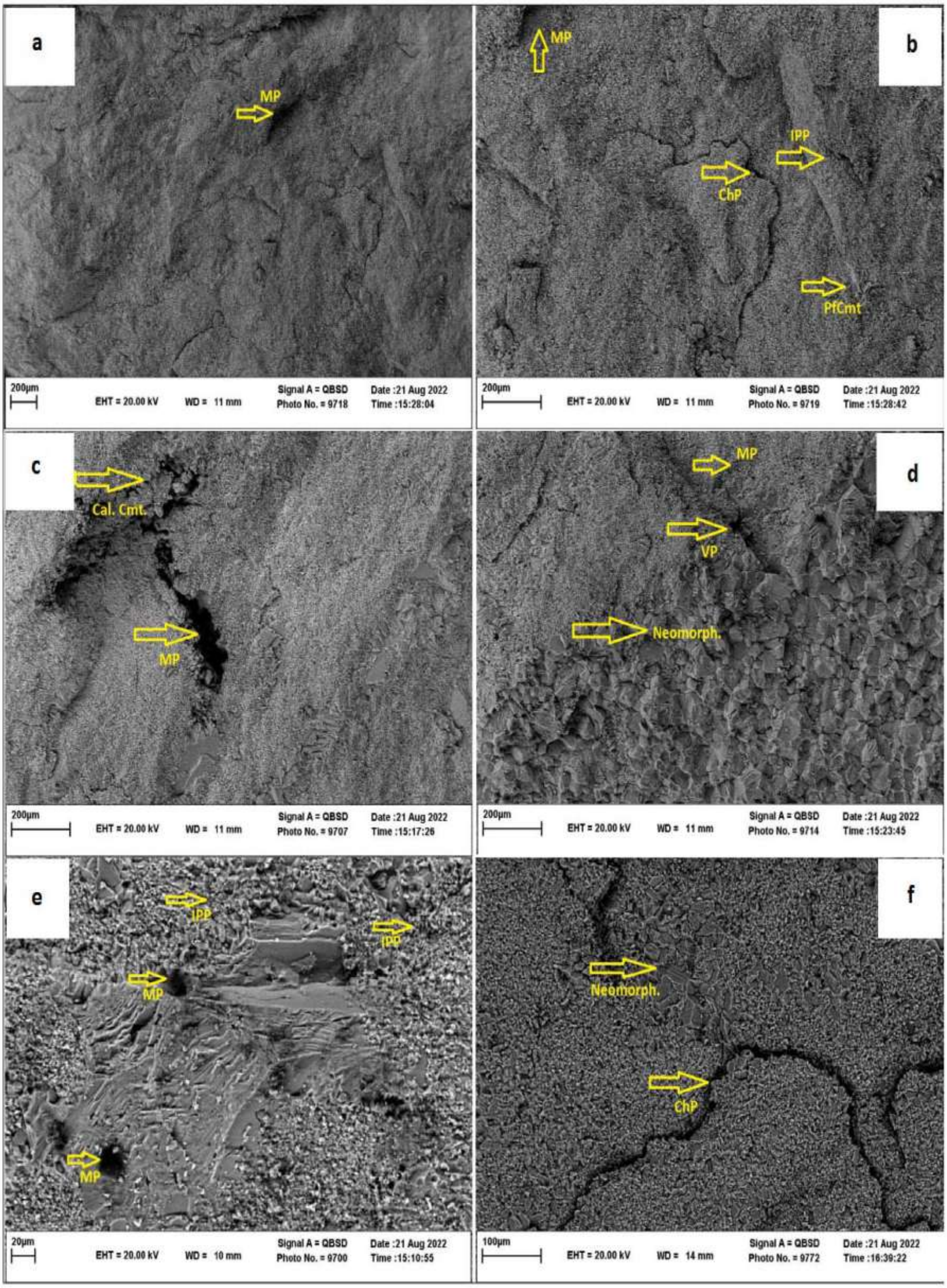

Fig. 9 Scanning Electron Microscope (SEM) images from common diagenetic features and porosity types in the studied interval of the Faliyan Formation in Mongasht section; a) Moldic porosity (MP) and dissolution in intraclastic ooid grainstone (depth: 2160.42 m), b) Moldic porosity (MP), Channel porosity (ChP) along the stylolite, Intraparticle porosity (IPP), and calcite pore-filling cement (PfCmt) in ooid grainstone (depth: 2160.42 m), c) Moldic porosity (MP) and pore-filling calcite cement in bioclastic peloid grainstone (depth: 2159.81 m), d) Matrix porosity (MP), vuggy porosity (VP), and neomorphism in bioclastic peloid grainstone (depth: 2159.81 m), e) Interparticle (IPP) and moldic (MP) porosities in benthic foraminifera wackestone (depth: 2159.20 m), f) Neomorphism and channel porosity (ChP) along the microstylolite in fossiliferous mudstone (depth: 2159.20 m).

Fracturing: Micro-fractures (filled and open fractures) are observed in the studied intervals (MF-4, MF-5, MF-7) (Figs. 6f, 7c, d). In many samples, calcite cement has filled fractures completely or partially. This feature is the last diagenetic phase in many samples, so fractures truncate other diagenetic products (e.g., solution seams).
Dissolution: Selective dissolution of unstable particles is evident in the Fahliyan intervals. Algal and mollusk bioclasts are frequently dissolved (MF-3) (Figs. 8b, d, 9a, c, e, 10c, d, e).

Paragenetic Sequence
The Fahliyan Formation has been influenced by three diagenetic realms: marine, meteoric, and shallow to deep burial (Fig. 11).

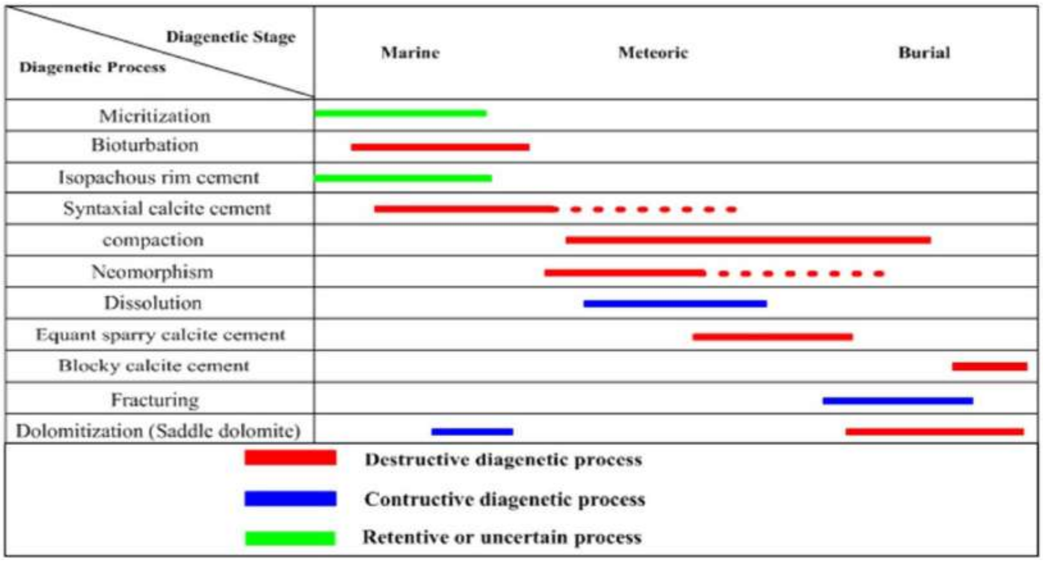

Fig. 11 The paragenetic sequence of the most common diagenetic features, and their effect on the reservoir quality of the Fahliyan Formation.

Micritization has affected the Fahliyan Formation carbonate successions as an earlier diagenetic process. In addition, the pore-filling calcite spars are interpreted as marine [50], freshwater-phreatic [44], and burial-diagenetic products [49]. The intergranular calcite cements are common in the high-regime shoal facies (MF-3 and MF-4) and seldom occur in other facies associations. These cements formed before compactional processes (particle packing and solution seams). They are typical features of marine diagenesis in high-energy shoals, beach rocks, and hardgrounds [51, 52]. However, blocky coarse-grained calcite cement precipitated during burial diagenesis (after fracturing). Dissolution is mainly related to the penetration of under-saturated fresh waters during sea level falling stages. Consequently, this process is supposed to have occurred in the undersaturated zones of the meteoric phreatic and vadose realms [39, 44]. Compaction is a diagenetic process that occurs from the first stage to the last. In the case of fracturing, as it occurred in other kinds of diagenetic processes, it is put at the burial stage. In general, the paragenetic sequence of diagenetic features and diagenesis history of this formation are given in Fig. 11.

Reservoir Quality
The current study applied an integrated approach for rock typing (120 poro-perm data) in the Haft Cheshmeh well locality. HFUs combine FZI and RQI, incorporating both geological and petrophysical aspects. This integration allows for a more holistic assessment of reservoir quality compared to single-parameter methods. HFUs help classify rocks with similar petrophysical and flow characteristics into distinct units. This kind of zonation helps better reservoir characterization, which is essential for accurate field management and production optimization [53]. HFUs are closely related to permeability. The FZI method, which considers pore-scale flow physics and geological parameters, provides accurate correlations between permeability and porosity when the FZI of the reservoir rock is known [54]. In this approach, hydraulic flow units (HFU) were first distinguished using a flow zone indicator (FZI) [55, 56]. The relationship between the reservoir quality indexes (RQI), FZI, and the pore ratio can be stated by the following equations [55].

$$\varepsilon = \frac{\varphi_e}{1-\varphi_e} \tag{1}$$

$$\mathrm{FZI} = \frac{RQI}{\varepsilon} \tag{2}$$

$$RQI\ (\mu m) = 0.0314\sqrt{\frac{k}{\varphi_e}} \tag{3}$$

where k is the permeability in mD, ε is normalized porosity, and φ_e is effective porosity in fraction.
Three different rock types as HFUs were classified based on the above-integrated approach, poro-perm data, determined depositional facies, and diagenetic features (Table 2 and Figs. 12 and 13). Here, the relationship between primary textures and diagenetic processes is investigated for characterization and rock typing of the Fahliyan Formation. Based on poro-perm values, these rock types are ranked in various reservoir qualities from poor to fair and moderate, considering diagenetic effects on depositional microfacies (Table 3).

Table 2 The ranges of logarithmic FZI values in the different HFUs and their reservoir property.

HFU	Log FZI	Average Porosity (%)	Arithmetic average Permeability (mD)	Facies code	Reservoir quality
1	< -0.5	9.56	0.07	MF2, MF5, MF-8	Poor
2	-0.5_0.5	5.62	0.32	MF1, MF3, MF4, MF5, MF6	Fair
3	> 0.5	1.58	1.63	MF3, MF6, MF7	Moderate

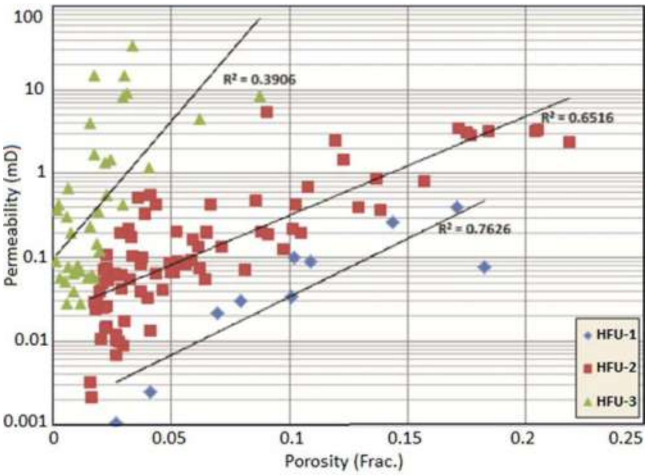

Fig. 12 Cross-plot of Porosity versus permeability for different HFUs defined in the studied interval of Fahliyan Formation.

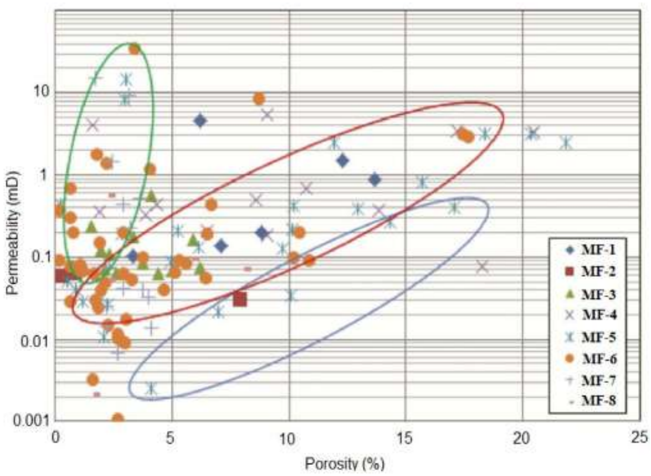

Fig. 13 Relationships between various microfacies and HFU's in the studied interval of Fahliyan Formation.

Table 3 Porosity and permeability mean values of different microfacies in the Fahliyan interval in the Haft Cheshmeh section.

Facies code	Microfacies name	Average Porosity (%)	Arithmetic average Permeability (mD)
MF-1	Radiolarian sponge spicule wackestone	7.75	0.5
MF-2	Planktonic foraminifera bioclastic mud/ wackestone	1.3	0.05
MF-3	Intraclastic ooid grainstone	3.2	0.11
MF-4	Bioclastic peloid grainstone	0.55	6.63
MF-5	Bioclastic peloid packstone	4.5	0.2
MF-6	Benthic foraminifera wackestone	2.45	0.11
MF-7	Fossiliferous mudstone	2.85	0.14
MF8	Quartz-bearing mudstone	3.35	0.05

The relationships between petrographical characteristics and petrophysical data are established based on this section's correlation of facies and proper values (Table 3, Figs. 13, 14, and 15). The diagram of porosity versus permeability for various facies is presented separately in Figs. 13 and 14.

Discussion

Facies studies indicate that this formation was deposited in various environments, from deep to shallow (including open marine, shoal, lagoon, and intertidal zones). The formation consists of eight microfacies labeled MF-1 through MF-8. This study's primary emphasis lies in investigating the diagenetic processes linked to each microfacies, aiming to comprehend their influence on reservoir quality.

To facilitate reservoir quality assessment, all facies are categorized into three HFUs. The first HFU corresponds to the poor class and includes MF-2, MF-5, and MF-8. These microfacies exhibit common diagenetic features such as neomorphism, sparry calcite cement, and dolomitization. The Planktonic foraminifera bioclastic mud/wackestone (MF-2) and quartz-bearing mudstone (MF-8) microfacies represent poor reservoir properties due to compaction imprints, particularly stylolites. These units may act as reservoir barriers (seal facies) within the studied interval of the Fahliyan reservoir.

On the other hand, the bioclastic peloid packstone to grainstone facies (MF-4 and MF-5, as shown in Fig. 14) exhibit better reservoir quality in the lower part of the Fahliyan Formation. These facies demonstrate moderate reservoir properties, primarily associated with dissolution and first-generation calcite cement (Isopachous rim high magnesium calcite cement).

In contrast, HFU-3, the best hydrocarbon flow unit (HFU) regarding reservoir quality, comprises MF-3, MF-6, and MF-7. Furthermore, these specific microfacies (MFs) were predominantly influenced by fracturing, dissolution, and dolomitization.

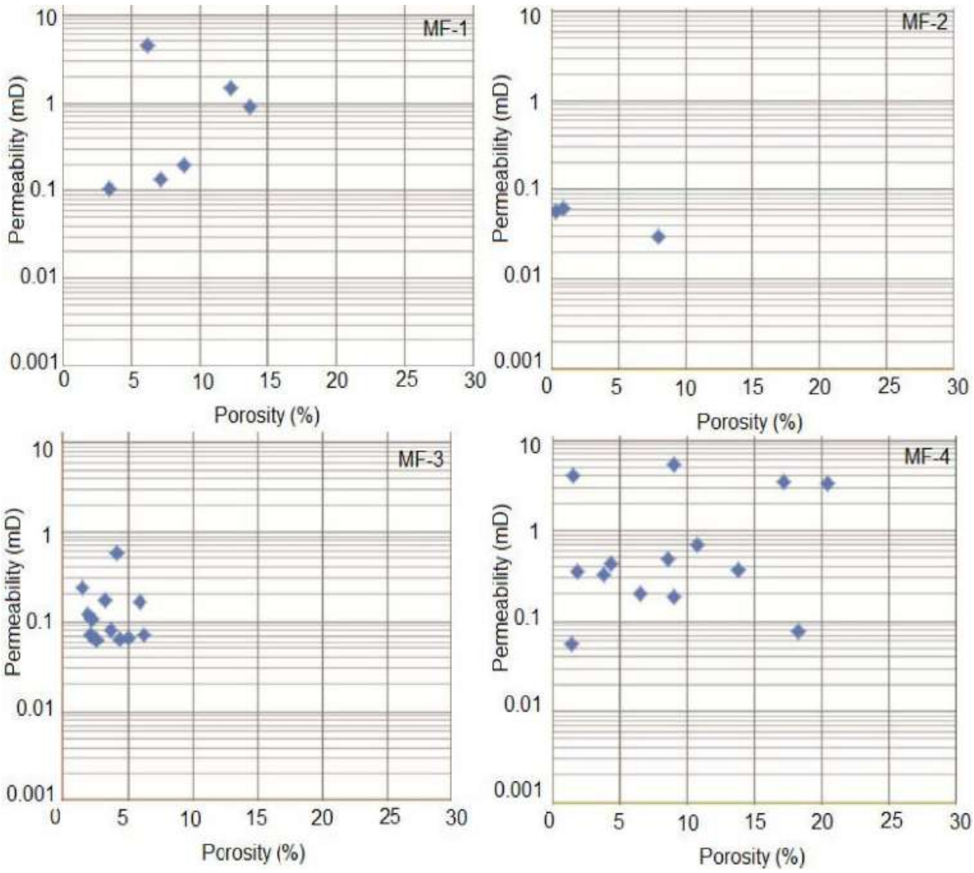

Fig. 14 Porosity vs. permeability cross-plots of MF-1 to MF-4 in the Fahliyan Formation.

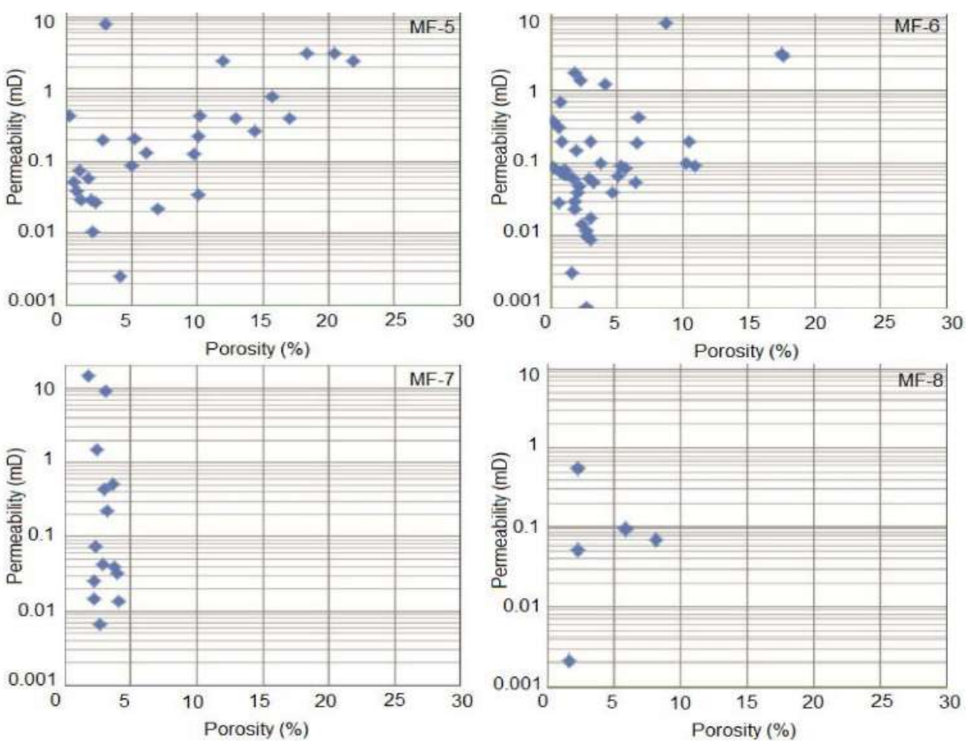

Fig. 15 Porosity vs. permeability cross-plots of MF-5 to MF-8 in the Fahliyan Formation.

As revealed in this study, the key diagenetic processes impacting reservoir quality include micritization, cementation, dolomitization, fracturing, and dissolution. Micritization and the presence of isopachous cement around grains (as seen in Fig. 5a and c) act as porosity-preserving mechanisms, preventing grain compaction and positively affecting the reservoir quality of the Fahliyan Formation. In addition, although dolomitization was not fully developed, it did create intercrystalline porosity in certain areas, thereby enhancing reservoir quality within HFU-3. Conversely, the dolomitization process often manifested as pore-filling cement, leading to reduced reservoir quality in HFU-1 (as depicted in Fig. 6a). Also, fractures play a crucial role as post-depositional (diagenetic-tectonic) features within the Fahliyan Formation, specifically in HFU-3. Interestingly, fracturing seems to impact reservoir quality in this formation positively. Additionally, the dissolution process in the Fahliyan Formation contributes to increased porosity, further enhancing reservoir quality within HFU-3 (as depicted in Figs. 8a-f, 9a, c, and e).

Conclusions

Eight microfacies were recognized based on petrographic investigations. All facies have been categorized into four facies belts of a ramp setting: intertidal, lagoon, shoal, and open marine. Therefore, a homoclinic ramp model was suggested for the Fahliyan succession in the Izeh area.

This formation has experienced three diagenetic stages: marine, meteoric, and burial. Dissolution, as the most significant feature of meteoric stage, which has increased reservoir quality. On the other hand, micritization and isopachous rim types of cement acted as retentive processes, preventing grain compaction and preserving pore spaces. Also, compaction, calcite (both blocky and equant sparry) and dolomite cements filled the pore spaces, which resulted in reservoir quality reduction.

Ultimately, the correlation between depositional facies and their petrophysical characteristics represents that the bioclastic peloid packstones and grainstones (equivalent to HFU3) have higher reservoir quality, which resulted from dissolution and initial isopachous calcite cement. Also, planktonic foraminifera bioclastic mud/ wackestone and Quartz-bearing mudstone (equivalent to HFU1) indicate lower reservoir quality due to the compaction (stylolitization) and cementation.

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