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Reservoir Characterization and Quality Controlling Factors of the Fahliyan Formation Located in Southwest Iran

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Abstract

The Berriasian-Valanginian Fahliyan Formation forms one of the giant reservoirs in the subsurface of the Abadan plain, onshore Iran. A detailed petrographical analysis of the available cores and thin sections revealed that the different diagenetic parameters influenced the reservoir quality of the Fahliyan Formation in this field. The Fahliyan Formation has been influenced by three diagenetic environments, including marine, meteoric and shallow and deep burial environments. The main diagenetic parameters identified in the field under study are dissolution, fracturing, cementation, compaction and dolomitization. Among all, dissolution is the main diagenetic feature improving porosity and reservoir quality. This feature formed as a result of meteoric diagenesis during subearially exposure of the Fahliyan sediments. Fracturing and dolomitization also locally have positive effects on reservoir quality, while compaction, cementation and dolomitization (as cement) have destructive effect on reservoir characteristics. Late stage diagenetic cements such as sparry calcite cement and with lower amount saddle dolomite are the most important and also widespread types of cement decreasing reservoir quality. Based on new genetic classification of porosity, porosity in the Fahliyan Formation are hybrids of three depositional, diagenetic and fracturing, but diagenetic porosity is the most important types of porosity and so Fahliyan reservoir is a type of diagenetic reservoir. Based on this study using petrophysical and petrographical data, the Fahliyan reservoir is not a homogeneous reservoir, so it was divided into eight reservoir zones with different specifications.

Keywords: Fahliyan Formation; Reservoir characterization; Abadan plain; Iran

Introduction

The field under study lies in the southwest of Iran (Fig. 1). This subsurface structure was discovered in the mid 1970's using seismic, and at present it is effectively under production. The structure is a symmetrical

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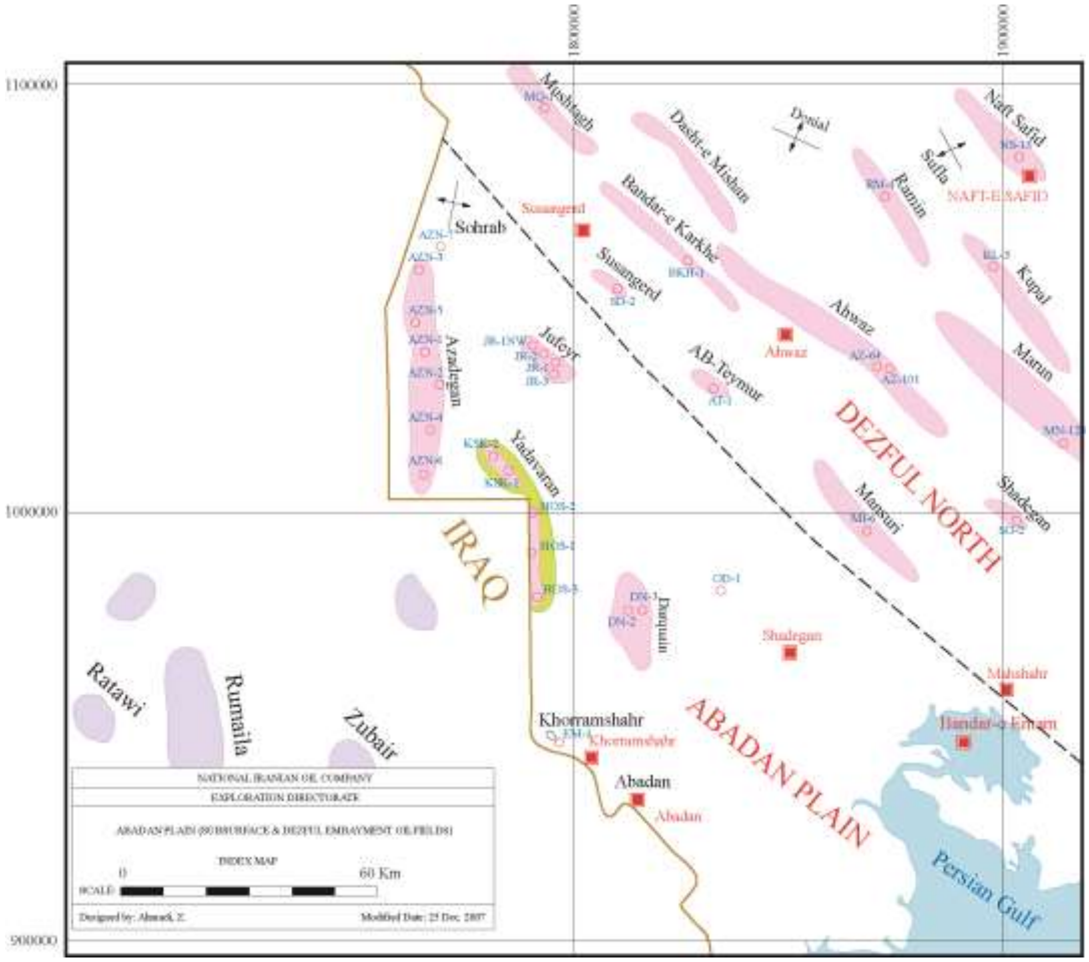

Figure 1. Location map of the field under study.

anticline elongated in N-S direction, about 20 km long and 8 km wide based on seismic lines derived from the top Sarvak contour map. No significant faults were observed. However, the 3D seismic study has highlighted some fracture trends that are currently under investigation.

The structure is part of the Mesopotamian-Persian Gulf lowland [5] and structurally belongs to the stable shelf of the Arabian Platform. Its trend is in contradiction to the Zagros type structures (NW-SE) and considered as an Arabian-type structure. It is parallel to N-trending anticline which extends from Saudi Arabia to Kuwait's Burgan Field [3]. North-trending basement fault systems are expected for such paleo-highs. These N-trending basement fault systems appear to have been formed during the Precambrian after the Amar Collision, about 640 and 620 Myr ago [3] and have been reactivated during the Cretaceous.

Motiei [20] proposed that the particular structure is a part of the Abadan Plain geological zone. This zone is not seismically active, and there is no evidence of geological outcrops for subsurface structures, therefore their exploration is based on geophysical data.

Many wells have been drilled in the studied field, of which the first three exploration wells were drilled by the National Iranian Oil Company (NIOC). The first well penetrated the reservoir for only a few meters. The second well, which is located on the crest of the structure, discovered 400m of oil column in the Fahliyan Formation and the third well located on the flank of the anticline, confirmed the continuity of the structure, but the reservoir layers has low porosity and high water saturation.

To understand carbonate rocks at reservoir scale, one first has to understand them at pore scale. Carbonate reservoirs are porous and permeable rocks that contain hydrocarbons. Carbonate porosity includes three end - member genetic categories: purely depositional pores, purely diagenetic pores, and purely fracture pores. Intermediate types exist, of course, but the point is that there are three main types of carbonate porosity that represent distinctly different geological processes. Before one can fully appreciate these differences and be proficient at distinguishing between the varieties of carbonate reservoir types, one must understand what carbonates are, how and where they form, and how they become reservoirs. In order to identify and map flow units, barrier and baffles, understanding the origin of porosity is necessary (Ahr, 2007) so Fahliyan Formation has been studied by Kavoosi et al. (2006) [16] and Nourafkan and Lasemi (2008) [17].The objective of this investigation is the study of diagenetic parameters affected on this formation, porosity types and percentage and reservoir zonations and to determine the reservoir quality of the Fahliyan Formation based on sedimentological investigation and petrophysical logs.

Stratigraphy

The Fahliyan Formation Berriasian-Valanginian in age forms a prominent limestone within the Khami Group. This formation consists of shallow water massive limestones with a predominance of very thick-bedded strata [13]. The type section with the thickness of 365,7m was measured close to the Fahliyan village on the south flank of Kuh-e-Dul.

Generally the Fahliyan Formation is defined as a limestone between the Hith and Gadvan Formations (Fig. 2). Both the upper part of the Fahliyan Formation and the lower part of the overlying Gadvan Formation are marly and argillaceous. The boundary between these two units appear conformable. This formation has the major distribution in the Fars province but also it is observed northwest of the Dezful Embayment and Lurestan. In these areas, the Fahliyan Formation laterally changes to argillaceous limestone and shale of the Garau Formation. In coastal Fars it is separated from the Surmeh by the Hith Formation. In places where the Hith is absent, the lower boundary lies at the junction between the limestones of the Fahliyan and the dark colored Surmeh dolomites. The carbonate lithofacies and fauna of the Fahliyan Formation indicate that it was deposited in a shallow carbonate shelf environment. It is sealed by the Gadvan and sourced by Garau and/or the Jurassic Sargelu Formations [13]. The Fahliyan Formation is equivalent of the lower Ratawi and Minagish Formation of Kuwait and southern Iraq, and the Sulaiy and Yammama Formations Valvulinella zone [19].

Geological Setting

In SW Iran the Berriasian-Valanginian Fahliyan Formation is subdivided into two parts. The lower part is equivalent to the Yamama-Minagish in Kuwait and SE Iraq. The Berriasian-Valanginian Minagish Formation in an oilfield in north Kuwait, which was

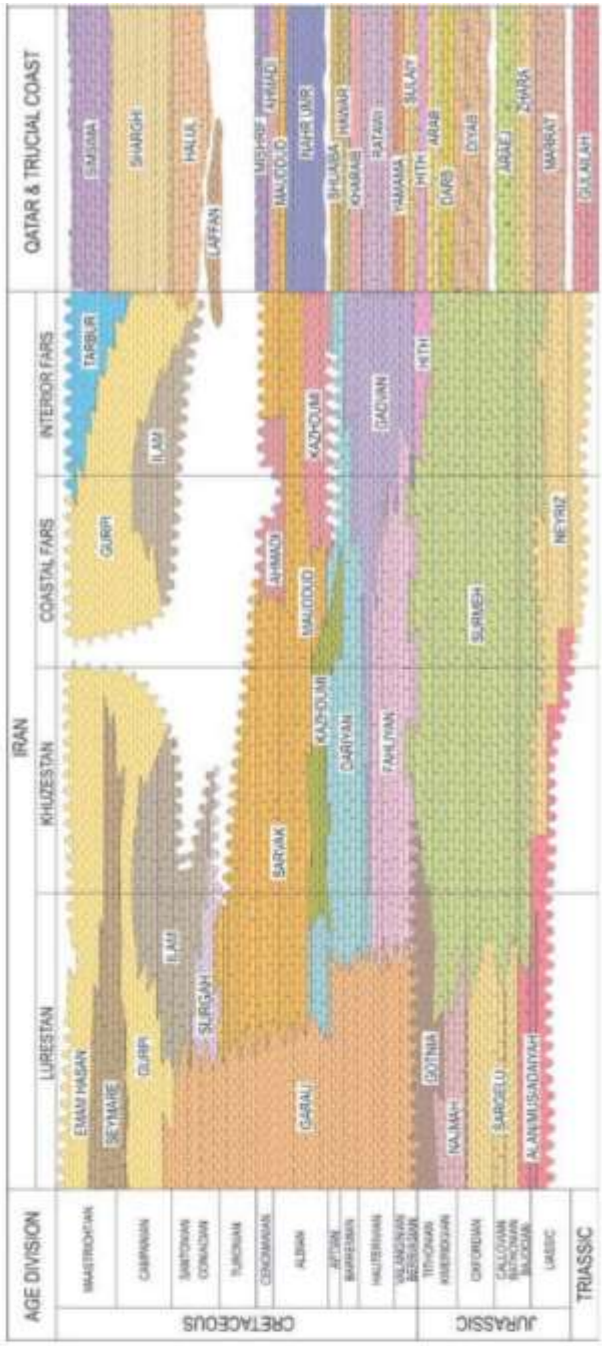

Figure 2. Rock units correlation chart in middle east.

deposited on a homoclinal carbonate ramp [9]. The same depositional setting is supposed for the lower Fahliyan Formation in the study area [9]. Ziegler (2001) [31] suggested a shelf platform of the Arabian Plate that was covered by shallow-water carbonates "Yamama" Formation during the Berriasian to Valanginian. Sadooni (1997) [24] proposed sedimentation of the Yamama Formation in SE Iraq on a leeward ramp on the gentle slope of the Arabian Platform.

The Early Cretaceous Garau intra-shelf basin inherited much of the differential topography from the upper Jurassic Gotnia intra-shelf basin in the Abadan Plain and Dezful embayment [26]. Later on, progressive uplift of the western Arabian Plate (including Abadan Plain) commenced, possibly as a result of the opening of the south and central Atlantic Ocean and most of the area was dominated by shallow water deposition of carbonate ramp [26]. At the beginning of the Cretaceous period, SW Iran was located just north of the Equator, and the large scale basin configuration had just changed from one of a differentiated passive-margin of shallow shelves and deeper, intra-shelf basins which characterized the Jurassic [21] to that of a very low relief passive-margin ramp setting, with the stable Arabian shelf passing northeastwards into the deeper water realm of the Mesopotamian-Northern Gulf Basin [2].

Material and Methods

About 260,9m of available cores in three wells were aligned and studied. The different parameters mainly lithology, texture, allochems, sedimentary structures, bioturbation etc. were described. To carry out the petrographic and sedimentological studies, 256 thin sections were prepared. The diagenetic parameters such as dissolution, fracture type (orientation and intensity), bioturbation, cementation, compaction and dolomitization were studied. In order to classify dolomite types, classification of Sibley and Gregg [27] and Mazzullo [18] were used Visual porosity types were studied using Choquette and Pray classification [8]. All identified parameters are demonstrated in form of a sediment-logical log (Fig. 3). Finally these observations were used to define and introduce the different rock types and also to categorize the different reservoirs and non-reservoir intervals using the petrophysical logs.

Objectives

Fahliyan Formation in the field under investigation consists of 10 microfacies, which is deposited in vast shallow marine lagoon (MF1 and MF2), leeward lagoon (MF6), shoal (MF7), shelf margin (MF8 and MF9) and proximal open marine environments (MF10). This studies concentrated on the different diagenetic processes affected this formation in different diagenetic environment. Diagenetic history of this formation in the filed under study is defined. The effects of diagenetic processes on reservoir characterization have been studied. In order to get a good imagination of reservoir quality in the whole Fahliyan Formation, we identified all the diagenetic processes and their effects on reservoir quality and then we subdivided it into different reservoir and nonreservoir zones.

Diagenetic Features in the Fahliyan Reservoir

The petrographic examination of cores and thin sections revealed different kinds of diagenetic features as described below:

Micritization

As a result of this process, most of the allochems such as skeletal grains and ooids in coarse grained textures are altered while on the seafloor or just below by endolithic algae, fungi and bacteria [29] (Fig. 4a). Micritization, is an early diagenetic process characteristic of the shallow-marine environment [4, 14, 25]. It may decrease permeability by filling pore throats or decreasing their sizes. However, early micritization might help to prevent porosity reduction due to burial compaction [28].

Bioturbation

Bioturbation in the form of large and thick burrowing is well developed in the cores of the different wells in different intervals. Because of the large size of burrowing, only variation of color from dark to light color can be observed in thin section.

Cementation

Since the majority of the encountered microfacies in this field are mud-supported, the formation of early stage of marine cements is very rare, but the late stage diagenetic cements are frequent. Based on the petrographical investigation, lithologically two types of cements are observed including calcite and dolomite though calcite cements are more abundant. Based on the time of formation, the following types of cement are recognized.

Isopachous Bladed Cement

This type of cement is mainly observed in grain-supported microfacies (MF7, MF8 and MF9) and is limited to lower part of the drilled well. It is a type of

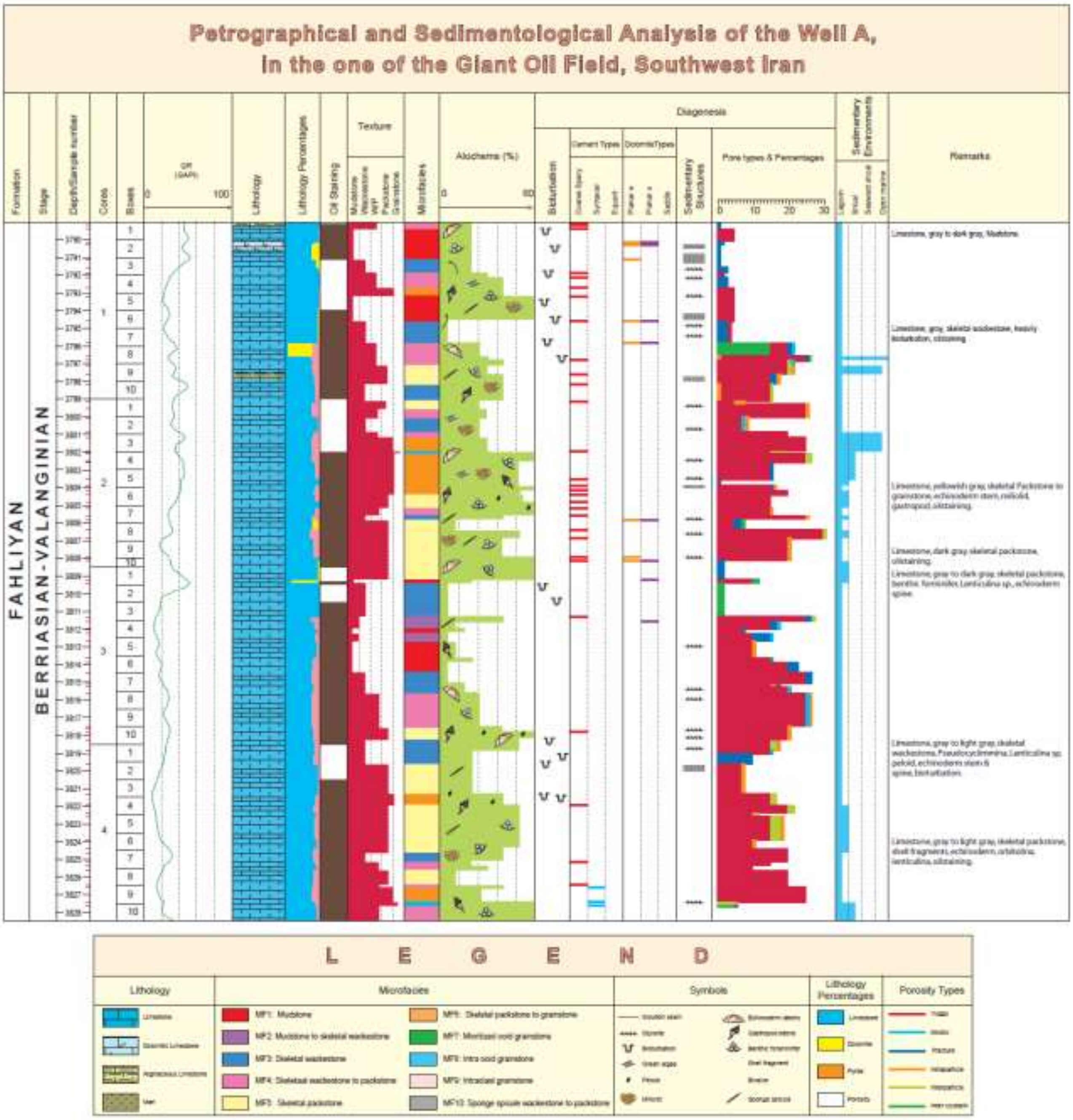

Figure 3. Petrographical and sedimentological analysis of the well A, in the field under study.

marine cement formed around allochems after deposition at the early stage of diagenesis. When this type of cement forms prior to compaction, it forms a rigid framework and thus reduces the effect of mechanical compaction (Fig. 4a, b and c).

Equant Cement

Calcite cement in the form of equant formed around grains adjacent to bladed cements. This type of cements is mostly made up of coarse-grained transparent calcite crystals. They occlude the pre-existing interparticle

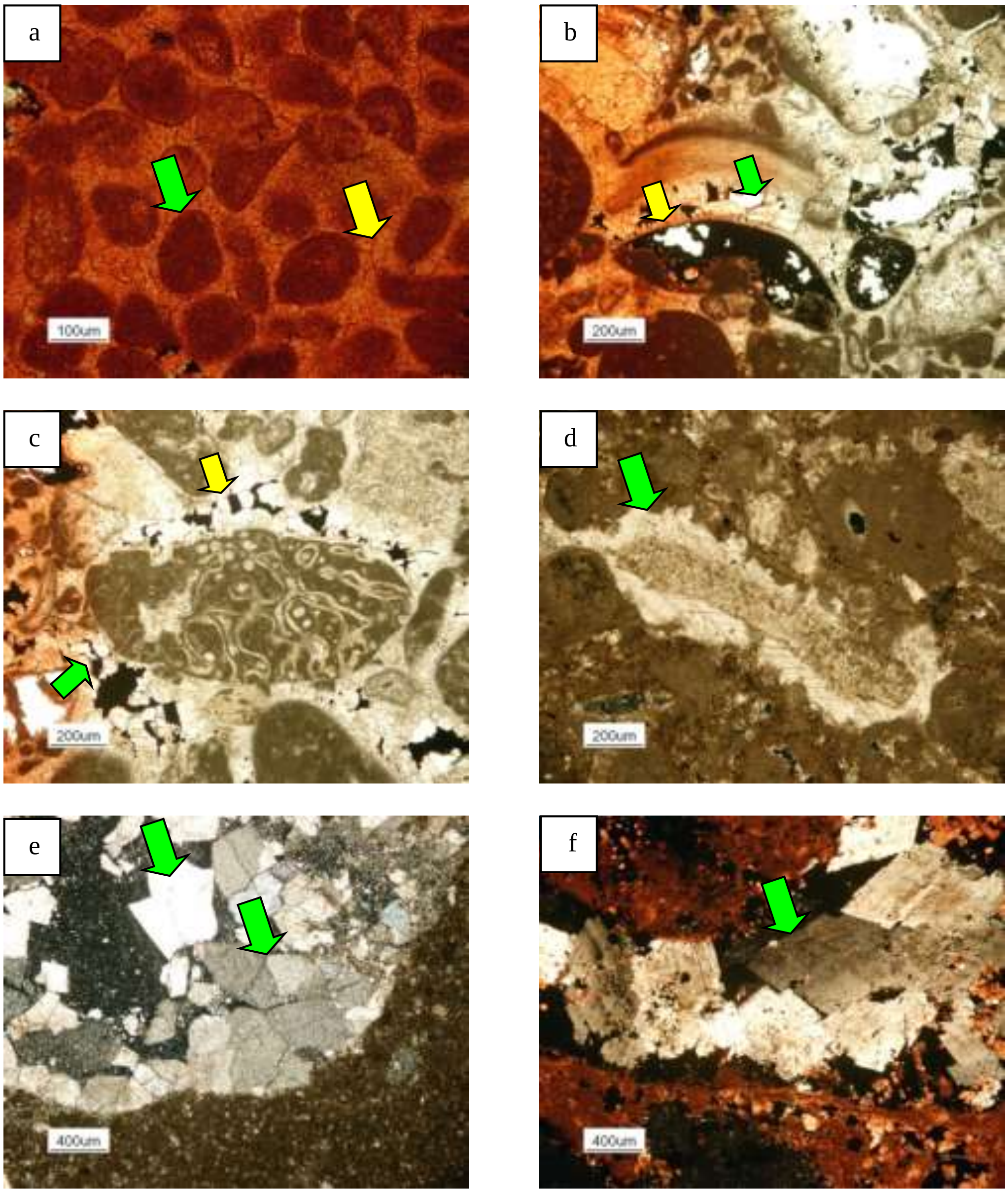

Figure 4. Micritization and cementation. (a) Micritization of ooid in ooid grainstone (MF7) (green arrow). Equant cement is also observed (yellow arrow). PPL. (b) Bladed (green arrow) and equant cement (yellow arrow) in intraclast grainstone (MF9). PPL. (c) Bladed and equant cement. MF9. PPL. (d) Syntaxial cement around echinoid debris. PPL. (e) Coarse sparry calcite cement in vuggy porosity. XPL. (f) Saddle dolomite cement as a fracture filling. XPL.

pores in grain-supported facies (MF7). Occasionally the effect of dissolution in calcite crystals creates the opening and causes the formation of secondary porosity (Fig. 4b and c).

Syntaxial Cement

This type of cement is calcitic in composition. It formed around echinoid fragments and is observed in different microfacies (Fig. 4d).

Coarse Sparry Calcite Cement

This late-diagenetic cement makes up 20% of bulk rock volume in some samples. It seems that this type of cement formed as the result of recrystallization of microcrystalline calcite present within the rock matrix (Fig. 4e). It has a wide distribution in MF 7, MF8 and MF9.

Saddle (Baroque) Dolomite Cement

Saddle dolomite filled some of the voids and

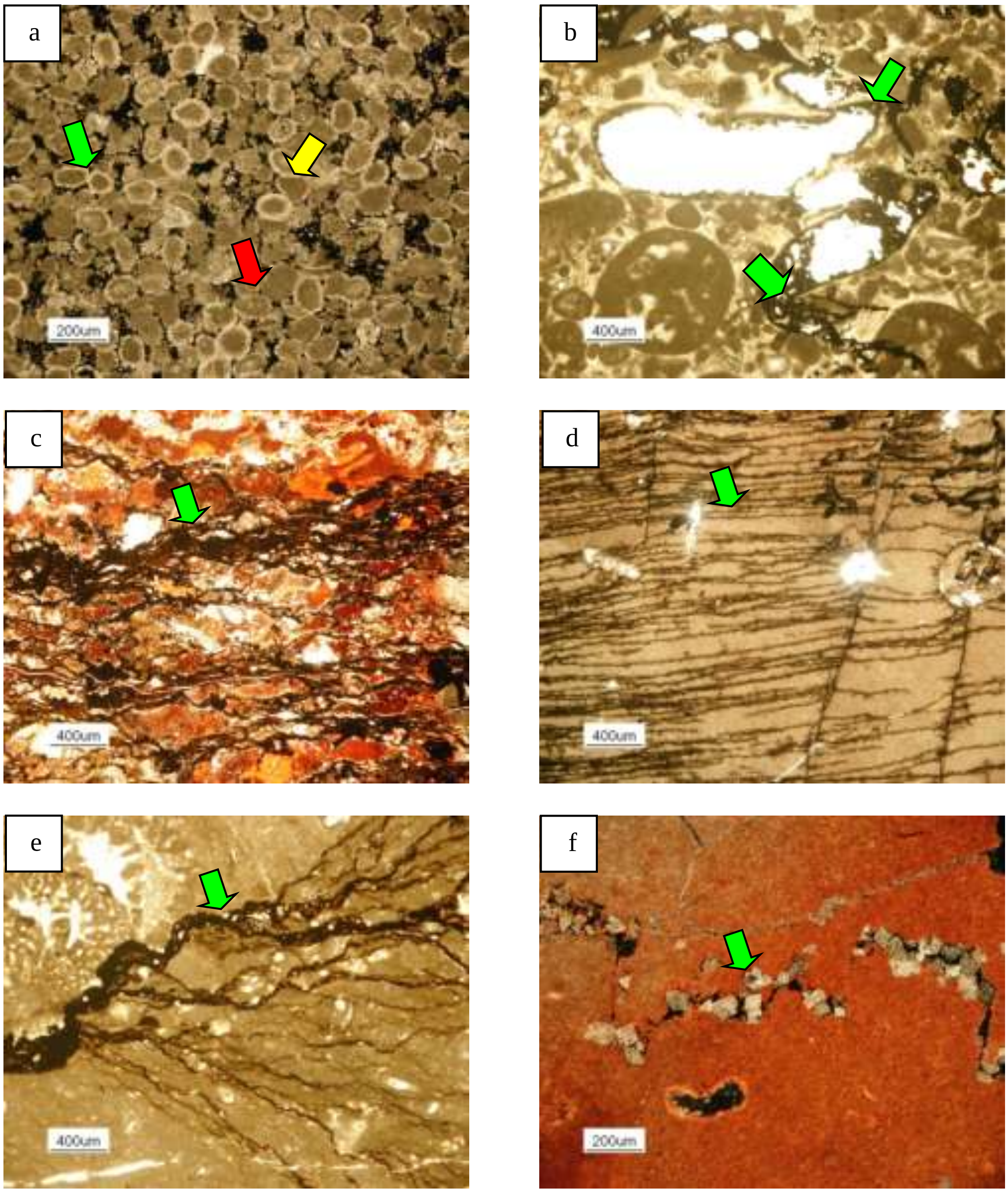

Figure 5. Mechanical and chemical compaction (a) Point (green arrow), tangential (red arrow) and concavo-convex (yellow arrow) contact of grains in ooid grainstone. PPL. (b) Shell breakage in intraclast ooid grainstone as a result of mechanical compaction. PPL. (c) Low amplitude stylolite and solution seam with oil staining. PPL. (d) Pseudobedding in mud-supported microfacies. PPL. (f) Horse tail stylolite with oil staining. PPL. (e) Low amplitude stylolite with dolomite around it. XPL.

fractures; the abundance of this cement is up to 5% of bulk rock volume and has pervasive distribution on the wells of this field (Fig. 4f). This type dolomite formed particularly in the burial environment where water temperatures are 60° C and higher [23].

Compaction

The cores as well as thin sections observation reveals that the compaction generally can be observed in two forms of mechanical and chemical compaction. The products of this process in samples are reorientation of grains, point, tangential and concavo-convex contact of grains (Fig. 5a). In mud-supported limestone (mudstone and wackestone the compaction resulted in shell breakage, change in the textures and overall reduction of porosity and rock volume (Fig. 5b). In grain-supported samples the compaction includes the point as well as tangential grain contacts reducing the overall pore volume and pore throat size. Chemical compaction observed in the form of solution seams, stylolites (Fig. 5c) and pseudobedding (Fig. 5d). High- and low-amplitude stylolites as well as horse-tail features are observed (Fig. 5e). Most of the stylolites and solution seams are oil stained and associated with dolomite rhombs (Fig. 5f). It seems that these features act as a passage for the fluid flow in the reservoir.

Dissolution

Dissolution is the main diagenetic process that improves porosity and permeability. It is the most effective mechanism in the formation of secondary porosity. Dissolution generated vuggy, moldic and interparticle porosity as a result of cement dissolution. This feature is identified in all microfacies. Most of the vuggy porosities are in form of connected and touching vugs (Fig. 7a). These vugs mostly are found in matrix background in variable sizes, the maximum of which reaches about 1 cm. These vugs play an important role in enhancing the reservoir quality. However, some of these pores have subsequently been cemented, thereby reducing the reservoir quality. Dissolution is thought to have taken place in the meteoric-fresh-water zone and occasionally in the mixed marine fresh-water zone.

Dolomitization

Pervasive dolomitization did not taken place in this formation but four types of dolomites have been identified in the studied interval which described below.

- Cream to brown unimodal euhedral to subhedral, compact crystals of dolomite, which are cloudy and full of inclusions. This type of dolomites partially replaced limestones. Sibley and Gregg [27] classified this type of dolomites as planar-e to planar-s (Fig. 6a). This type of dolomite is fabric selective and the matrix is dolomitized and some of the allochems such as *Pseudocyclammina lituus* are preserved and have not been dolomitized (Fig. 6b).
- Limpid euhedral crystals of dolomites formed within and around the stylolites (Fig. 6c). This type of dolomite formed after the formation of the stylolites. It can be concluded that stylolites act as conduits for passing dolomitizing fluids.
- Cream, euhedral, unimodal and cloudy rhombs of dolomite scattered in a micritic matrix. According to Mazzullo [18] this type is called planar-p or porphyrotopic fabric (Fig. 6d).
- Xenotopic, limpid, coarse crystals of dolomite with undulate extinction (Fig. 6e). Based on classification of Mazzullo [18] this dolomite variety is called non-planar-c or saddle dolomite. Saddle dolomite is frequently observed in the wells of this field. This type of dolomite fills the pores and fractures (up to 5%) and thus has a negative impact on reservoir quality. Saddle dolomite is formed in the deep burial environment in the temperature of 50-160°C [23]. It is a good indicator for the oil window.

Neomorphism

Neomorphism is a term summarizing all transformations taking place between one mineral and itself or a polymorph [11]. Neomorphism in thin sections creates micrite enlargement. The product of this process is pseudospar. It is a mosaic of neomorphic crystals having diameters >10-50 μ.

Porosity

The different types of visual porosity observed in cores and thin sections are described hereafter.

Vuggy Porosity

Non-fabric selective dissolution causes formation of vuggy porosity, which is commonly observed in all facies of the Fahliyan Formation (Fig. 7a). In packstone, wackestone and even mudstone of lagoonal and shallow open marine environment, dissolution affected and formed vuggy porosity. The visual observation shows the abundance of vuggy porosity up to 30% of the bulk rock volume.

Intraparticle Porosity

This type of porosity which is primary and fabric selective [8] occurs within individual bioclastic particles such as *Pseudocyclammina lituus* and *Textularia* sp. (Fig. 7b). The amount of this porosity ranges from 1-3%, and was observed in most facies.

Interparticle Porosity

Interparticle porosity fabric-selectively formed between allochems such as ooids, intraclasts and bioclasts (Fig. 7c). This type of porosity is most common in grain-supported microfacies related to high energy shoal environments (MF 7, 8, 9). The amount of this porosity ranges from 3-20%.

Moldic Porosity

Moldic porosity formed as a result of selective dissolution of some bioclasts like large shell fragments, echinoid spines, sponge spicules, etc. Molds of

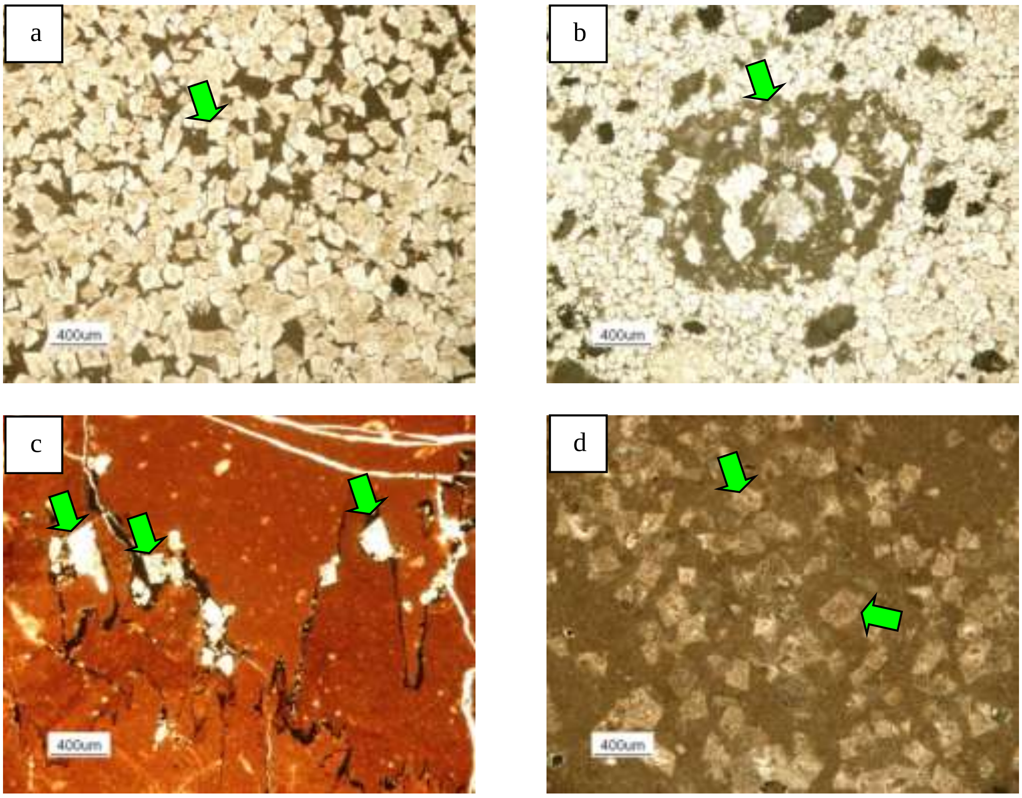

Figure 6. Different types of dolomite. (a) Planar-e to planar-s dolomite in MF1. PPL. (b) Planar-e to planar-s dolomite, dolomitization is fabric-selective and the fossil did not dolomitized. PPL. (c) Limpid euhedral crystals of dolomite around stylolite. PPL. (d) Scattered rhombs of dolomite in micritic matrix (planar-p) -XPL.

Trocholina sp. has been identified in lagoonal microfacies such as skeletal wackestone and packstone. In open marine microfacies (MF10), the molds of sponge spicules are abundance (Fig. 7d and e). This porosity ranges from 1-3% in thin sections.

Fracture Porosity

Fractures identified in this formation may be opened, semi-filled and filled. Although the open fractures are more dominant (up to 4%) (Fig. 7f). The dominant filling material is calcite; however saddle dolomite is also observed.

Diagenetic History

Based on detailed petrographic observation three diagenetic environments have affected the Fahliyan Formation. The first diagenetic environment is marine environment. Micritization of the allochems by algae, bacteria and fungi have taken place in the early stage of the diagenesis in the sea floor. At first, micritic envelope formed around the allochems. By developing the action, all the allochems were replaced by micrite. Bioturbation in the form of burrowing occurred in the marine environment. Syntaxial cement formed around the echinoderm debris in this environment. Although syntaxial cement can form in other diagenetic environments, which needs cathodoluminesence to determine the precise depositional environment. Further sedimentation pushed the Fahliyan Formation to shallow burial environment. Mechanical compaction as a result of overburden pressure had taken place in this condition. As a result of regression or drop of sea level, an unconformity surface developed in the upper Fahliyan Formation. Dissolution by undersaturated meteoric water affected the carbonate rocks of this formation and formed vuggy porosity. After the formation of vuggy porosity, coarse sparry calcite cement precipitated and reduced some of the vuggy porosity. The most probable source of the calcite cement is the materials formed as a result of dissolution of carbonates in meteoric environments. Sea level rise or transgression resulted in the deposition of new sediments. This sediment pushed the Fahliyan deposits

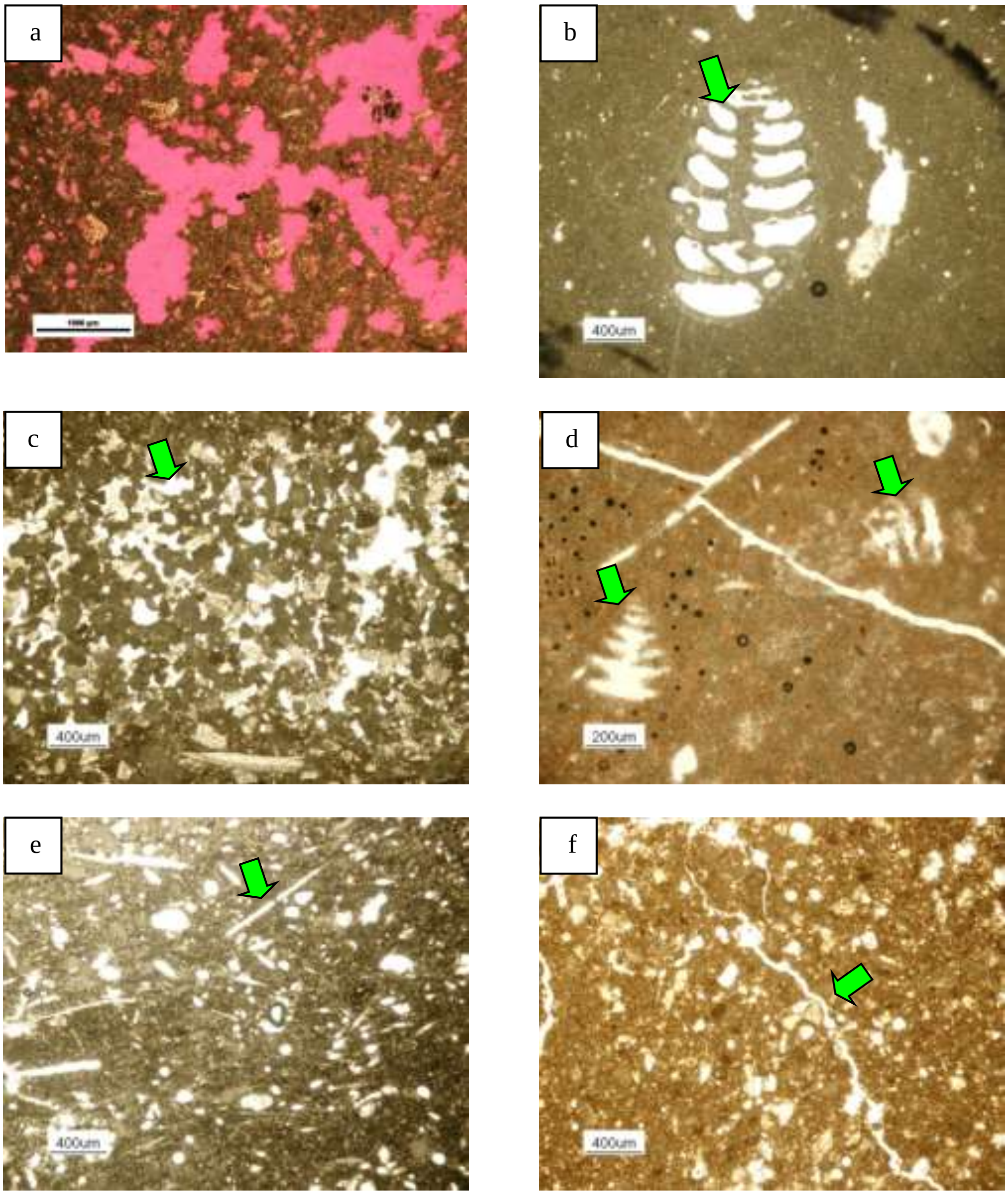

Figure 7. Different types of porosity. (a) Vuggy porosity in skeletal packstone. PPL. (b) Intraparticle porosity in *Cuneolina sp.* PPL. (c) Interparticle porosity in ooid grainstone. PPL. (d) Moldic porosity after *Trocholina sp.* in skeletal wackestone. PPL. (e) Moldic porosity after sponge spicule. XPL. (f) Open fracture observed in skeletal packstone. PPL.

to burial environment. In burial environment different diagenetic processes affected the formation. These processes include compaction, fracturing, sparry calcite cement and dolomitization. By increasing the depth of burial and increasing the overburden pressure, solution seams and stylolites formed. Fracturing also developed under the pressure in this environment. Sparry calcite cement deposited in the vuggy, fracture and any type of porosity and clogged or decreased the pore volumes. The probable source of the calcite cement is the carbonate which dissolved during the formation of solution seam and stylolite as a result of overburden pressure. Replacement and formation of pyrite happened in this environment. Dolomite around stylolites formed in burial environment. Saddle dolomite formed during deep burial environment. The paragenetic sequence and relative timing of diagenetic processes is demonstrated in the Table 1. This diagram showed relative time of different processes.

Table 1. Paragenetic sequence of diagenetic processes of the Fahliyan Formation in the field of study

	Digenetic Environments		
Diagenetic Process	**Marine**	**Meteoric**	**Burial**
Bioturbation			
Micritization			
Syntaxial Cement			
Mechanical Compaction			
Neomorphism			
Dissolution			
Sparry calcite cement			
Chemical Compaction			
Dolomitization			
Fractures			
Saddle dolomite			

The Effect of Diagenesis on Reservoir Characteristics

Among all of diagenetic processes, dissolution is the most important factor in porosity and permeability enhancement and reservoir quality. In this process the allochems as well as matrix are affected intensively, thereby causing the formation of interconnected vugs.

Fracturing is another process which has a positive effect on improving the reservoir quality. In our observation in the high permeable zone (zone D8) the open fractures have a positive role in improving the permeability and therefore the reservoir quality.

Dolomitization did not well developed, but occasionally the dolomitization caused the formation of intercrystalline porosity in a few samples and locally improve reservoir quality.

Some diagenetic processes, such as cementation and compaction, also have negative effects on reservoir quality. Coarse sparry calcites, equant and saddle dolomite cements filled the pore cavities and resulted in a reduction of pore space.

Based on Ahr classification, 2008 the Fahliyan reservoir is a type of diagenetic reservoir. Because the main factor of improving reservoir quality is dissolution. This feature is formed as a result of a regional unconformity, which cause to affect the meteoric diagenetic environment on the Fahliyan sediments.

Reservoir Zonation

The identification of reservoir and non-reservoir zones is a crucial step for future planning and field development. To differentiate the various reservoir and non- reservoir zones the parameters such as lithology, routine analysis and petrophysical logs were used. In general, 5 wells from the particular field were used for detailed zonation. The identification finally resulted in defining 8 reservoir and non-reservoir units (namely D1, D2, D3, D4, D5, D6, D7 and D8) based on the classification of North [22]. The range of porosity and qualitative description of each zone are tabulated below (Table 2). In the zone D8 which is the best reservoir zone of this formation, dissolution has affected more. This zone maybe below the water table in phreatic meteoric environment and indicates a paleowatertable [1].

Results and Discussion

Based on the detailed sedimentological investigations, Fahliyan sediments have tolerated three diagenetic environments including marine, meteoric and

Table 2. reservoir zonation, porosity range and qualitative description of each zone

Zone No.	Porosity Range (%)	Qualitative Description
D1	0.68-4.55	*Poor*
D2	4.66-7.82	*Poor to fair*
D3	1.13-4.74	*Poor*
D4	14.81-19.71	*Good to excellent*
D5	2.12-3.84	*Poor*
D6	9.57-14.59	*Fair to good*
D7	1.12-5.53	*Poor*
D8	8.22-18.33	*Good to excellent?*

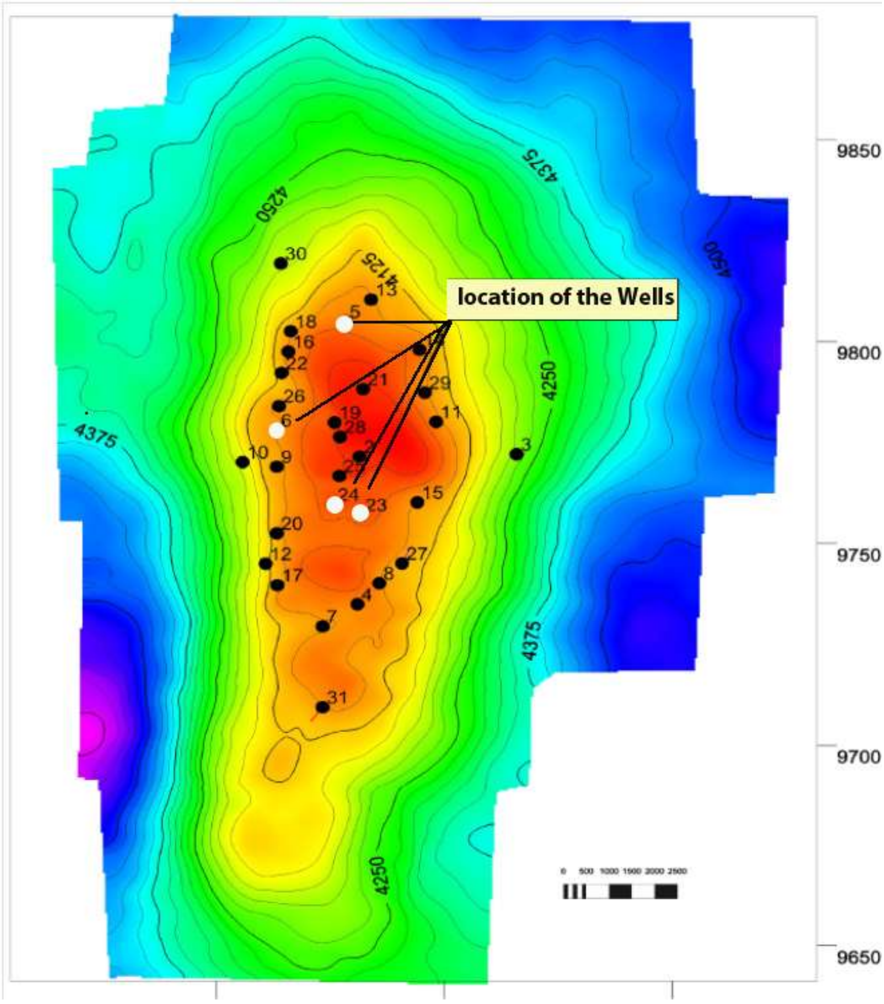

Figure 8. Location of the wells used for correlation.

burial diagenetic environments. Different diagenetic parameters affected on the Fahliyan Formation are dissolutions, fracturing, cementation, compaction and dolomitization. Amongst all, dissolution which is formed as a result of exposure in meteoric environment, fracturing and locally dolomitization have positive effects on reservoir quality; while, cementation, compaction and dolomitization (saddle dolomite as a cement) have negative effects on reservoir quality. Generally it can be concluded that the Fahliyan reservoir mainly is a type of diagenetic reservoir.

In order to get a good imagination of reservoir quality using petrographical and petrophysical data, Fahliyan Formation has been compartmentalized into different subzones. Thereby 8 zones of different characteristics were identified. Amongst all the zones identified, the zone "D8", particularly its lower interval, is considered to be the best and thickest reservoir unit which formed as a result of intense dissolution.D4 also have good porosity data but it is a thin layer and so it has less importance.

Based on studies carried out on Fahliyan Formation this formation also shows lateral facies change toward west and northwest (Yadavaran and Azadegan). Toward the northeast of the studied field there is a deepening of the sedimentary basin and the Fahliyan Formation gradually has been replaced by deep marine shale of Garau Formation. Therefore the development of Fahliyan Formation from south east toward northwest considered as a high exploration risk. The intensity of diagenetic processes are also different, so the reservoir quality decreases toward west and northwest. However toward the north and north east the scenario is changed (the Juffeyr and Susangerd and Ab-Teymur) the reservoir quality increased (Figs. 8 and 9).

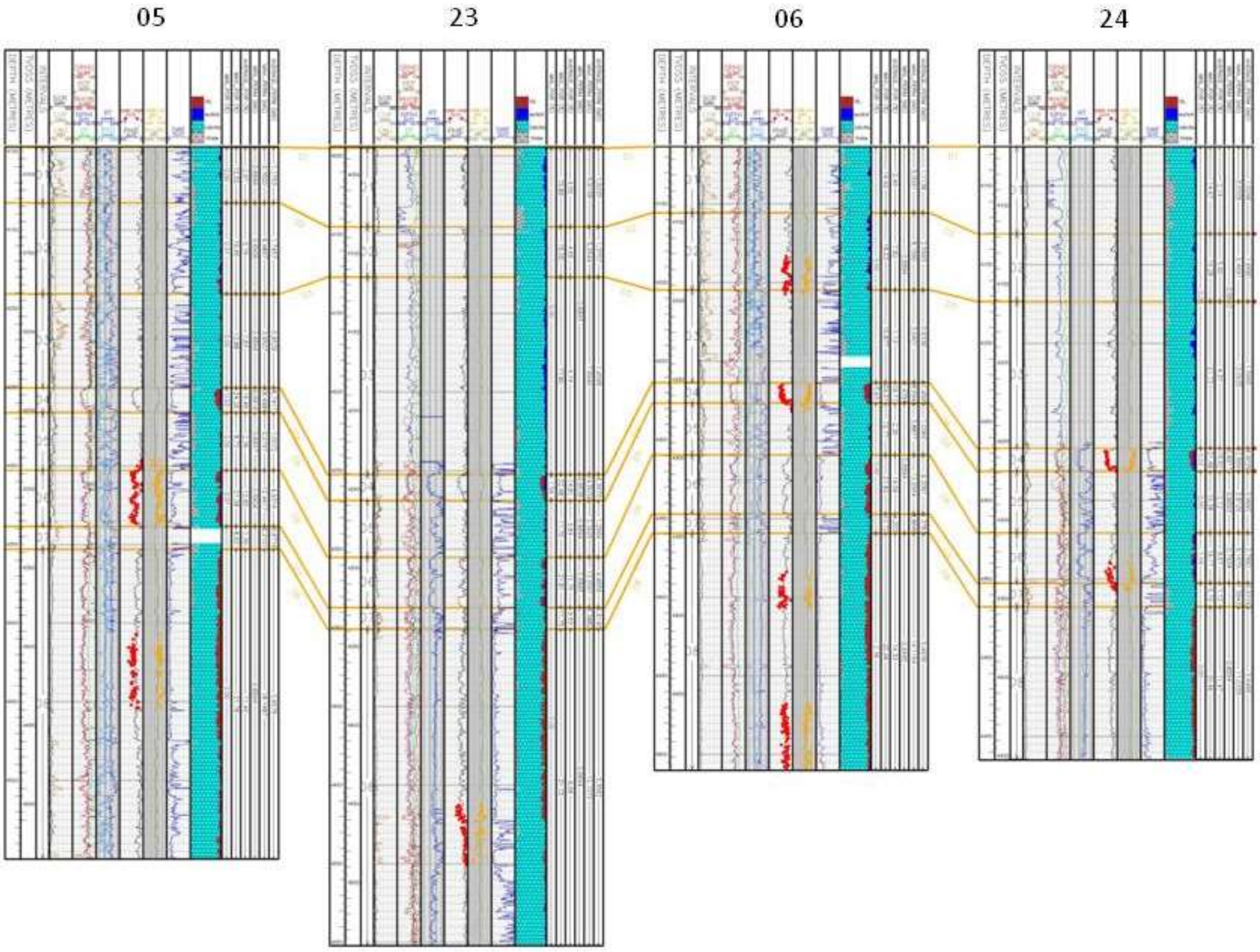

Figure 9. Correlation chart between the wells in the field under study.

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