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Analyzing the Facies, Sedimentary Environment, Sequence Stratigraphy and Diagenetic Processes of Kangan Formation in Kish Gas Field (Kish Well#3)

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Abstract

Background/Objectives: Although many studies have investigated the reservoir formations in Dahrom group including Kangan formation, but most of these studies have been concerned to other hydrocarbon fields. Regarding the great reservoir importance of Kangan formation in Kish Gas field, therefore, it is important to examine these rich gas-condensate reservoirs. This study aims to restore the sedimentation condition and the conditions governing the sedimentary basins during that period (lower Triassic) and detect the factors affecting the reservoir quality. **Methods**: To determine facies, sedimentary environment, sequence stratigraphy and identify the most important diagenetic processes occurring in the evaporate-carbonate depositions of Kangan Formation in Kish Gas Field, a sample of 510 microscopic thin sections were collected out of the core extracted from Kish Well#3 and considered by polarizan microscope. **Results**: Detailed petrographic investigation and well log analysis of the Kangan Formation in Kish gas field led to the recognition of arid tidal-flat (A), back barrier lagoon (B) and barrier/shoal (C) facies belts related to an inner part of a homoclinal ramp platform. The Kangan Formation is mainly composed of dolomite, dolomitic limestone with shale and anhydrite. This formation has been affected by several diagenetic processes which played a significant role in improving reservoir quality. **Conclusions**: Vertical facies changes and cycle stacking patterns demonstrate that the Kangan Formation consists of four depositional sequences of the Third-order in the Kish Well#3, each consisting of transgressive and highstand systems tracts.

Keywords: Analyzing the Facies, Diagenetic Processes, Kangan Formation, Sedimentary Environment, Sequence Stratigraphy

1. Introduction

Kangan Formation is one of the most important reservoir formations in Fars zone of Iran which it belongs to Dehram group and its age is Lower Triassic (Scythian). This formation is mainly composed of dolomite, dolomitic limestone with shale and anhydrite. It is unconformably underlain by the upper Permian Dalan Formation[1] and is conformably overlain by the upper Triassic Dashtak Formation[2]. To investigate the microfacies, sedimentary environment, sequence stratigraphy and diagenetic processes of Kangan Formation, the underground section of Kish Well#3, located offshore approximately 5.5 km from southwestern Kish Island, is chosen. As an oval island, Kish is 15.6 km long and 7 km wide, covering an area of 89.7 sq. km in the Persian Gulf. It is part of Hormozgan Province in Iran, locates at the southwest of Bandar Abbas. The geographical coordinates of Kish are 53˚, 53′ and 54˚, 04′ E and 26˚, 29′ and 26˚, 35′. Moreover, the geographical coordinates of the studied underground section are 53˚ 53′ 24″ E and 26˚ 29′ 42″N and overlies Kish anticline (Figure 1).

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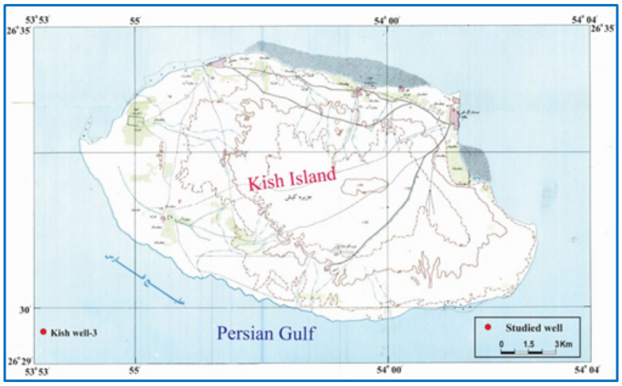

Figure 1. The position of the studied well in the topographic map of Kish island (cited in the map of national Iranian oil company).

To determine facies, sedimentary environment, sequence stratigraphy and identify the most important diagenetic processes occurring in the evaporate-carbonate depositions of Kangan Formation in Kish Gas Field, a sample of 510 microscopic thin sections were collected out of the core extracted from Kish Well#3 and considered by polarizan microscope. To distinguish between calcite and dolomite, moreover, the thin sections are colored by Alizarin Red-S and Dickson's method[3]. Comparative diagrams of Flugel[4] are also employed to calculate the percentage of the components of the rocks. Having identified and determined the percentage of the skeletal, non-skeletal, cement and muddy components as well as the texture of the microscopic sections, Dunham's nomination method[5], developed by Embry and Klovan[6]and revised by Wright[7]was performed. Classification of carbonate microfacies is also performed based on Lasemi and Carozzi[8,9]. Eventually, the determined facies are compared and conformed to those of Flugel[4]and Wilson[10]. Corel Software is also used to draw the facies columns with respect to the vertical changes in them. Flugel[4] and Walker [11] are also employed to present the depositional models. The facies and sedimentary environment in Kangan Formation is compared with the new such as those presented in Purser[12] and Tucker and Wright[13] and old ones such as those in Read[14]. At last, the sequence stratigraphy of the studied sequence and type-3 sedimentary sequences is identified using the ordinary methods[15-17].

This study tends to achieve the following goals:

- Stratigraphic study of the sediments of Kangan formation in the studied well.
- Identifying the sedimentary facies of Kangan reservoir rock in the studied thin sections.
- Determining facies column and curve of changes in depth, associated with the depositions of Kangan Formation in the studied underground section.
- Interpreting the sedimentary environment of the deposits of Kangan Formation and presenting a sedimentary model consistent with the results of the studies.
- Recognizing the sedimentary sequences, sequence boundaries and comparing them with global sequences.
- Identifying the most important diagenetic processes and investigating their effect on the reservoir quality.

2. Classification of the Facies

Having examined the logs and microscopic sections of the core of the studied well, 15 major facies (14 carbonate facies and 1 evaporative facies) in terms of three facies belts including tidal flat, lagoon and shoal were identified in Kangan formation. These facies groups are discussed as following:

2.1 Facies Group A (Tidal Flat Facies)

This group, covering an area form supertidal to lagoon, consists of seven major facies as follows:

2.1.1 Facies A1 (Layered Anhydrite with Chicken Wire Structure)

This facies consists of layers of anhydrite (Figure 2a, b). These layers are generated in the early stages of the diagenesis through direct deposition of evaporates such as gypsum in hypersaline lagoons. The most important fabric observed in this facies is chicken wire fabric in a micrite matrix. In addition, large anhydrite nodules are sporadically observed in dolomitic intervals. These anhydrite nodules have a blade texture. Anhydrite does not enjoy a good reservoir quality and, as an internal reservoir barrier, acts as a barrier to vertical fluid flow. Regarding the fact that anhydrite results from gypsum dehydration process in a dry and intense evaporation condition [13,18], the upper supratidal zone is an environment where this facies is formed. The major characteristic of this region includes highly intense evaporation (more than rainfall) and long-term exclusion of sediments from sea water. The modern form of facies A1 can be seen in the western part of Persian Gulf [13,19].

2.1.2 Facies A2 (Dolomite Mudstone)

This facies can be found in cream, dark brown and gray colors and includes evaporative nodules. These evaporative minerals in the rocks indicate that they are deposited in a dry and hot climate [20,21]. Dolomitization is one of the most important diagenetic processes of this facies, in which stylolitization and fracturing can be seen as well (Figure 2c). This facies contains crystals, needles and anhydrite fragments, floating in a matrix. In some thin sections, this facies can be seen as fossil-free dolomicrite and anhydrite needles and fragments. Dolomitization process increases porosity and permeability of the mudstones but anhydration of dolomite mudstone, occurring as replacement and pore-filling processes, greatly decreases porosity, and most pores are filled by secondary anhydrite. In comparison to carbonate environments in Persian Gulf, this facies is of hot and dry type in the upper supratidal zone [13,22]. Generally speaking, this facies points to a low-energy and hypersaline environment in a hot and dry climate. Trivial amount of fossils and sometimes lack of it suggest an adverse environmental condition (high salinity) for living creatures.

2.1.3 Facies A3 (Dolomite Mudstone with Evaporative Casts)

This facies includes primary fine-crystalline dolomites as well as lots of evaporative molds and white-to-milky anhydrite nodules in a dark muddy matrix (Figure 2d). Development of anhydrite nodules and evaporative molds may form chicken wire fabric in the Sabkha section[23]. In general, this facies indicates a low-energy and hypersaline environment in a hot and dry climate. Lack of evidence associated with exclusion of water in this facies reveals that the mentioned dolomudstones are formed in a subtidal condition. Given that this facies lies among tidal facies, one can interpret it as small ponds or as small parts of restricted lagoon environments located around the margins of tidal zones [24]. This facies enjoy a trivial primary porosity since secondary anhydration and dolomitization processes, through generating coarse crystals together with the lack or small amount of skeletal fragments prone to dissolution, have caused this facies lose its reservoir quality. Todays, the same facies is seen in some hot and dry carbonate platforms with high evaporation in the sabkha region in Persian Gulf [13,21,22,25].

2.1.4 Facies A4 (Stromatolite Boundstone)

This facies is seen as wavy or striped laminations. Stromatolites are laminated sediments formed as a result of trapping and binding of sediment particles by cyanobacteria (blue-green algae with slimy and rope-like texture). This will form dark and bright laminations [26]. Dark laminations are enriched by organic matter of blue-green algae and the bright ones are sediment particles covering the slimy surface of cyanobacteria (Figure 2d). These stromatolites belong to Autochthonous stromatolites group and can be classified as bindstone [13,27]. This facies contains a large body of fenestral fabric, mud cracks and anhydrite nodules as well as intracrystalline, fenestral and vuggy porosity, most of which filled by anhydrite nodules. Due to the lack of appropriate primary porosity and presence of a lot of anhydrite plugs, this facies enjoys low reservoir quality and permeability. The presences of mud cracks, fenestral fabric and evaporative molds as well as adjacency to lagoon facies imply the development of this facies in the inner parts of platform, around tidal flat especially intertidal zones and hot and dry climate [24].

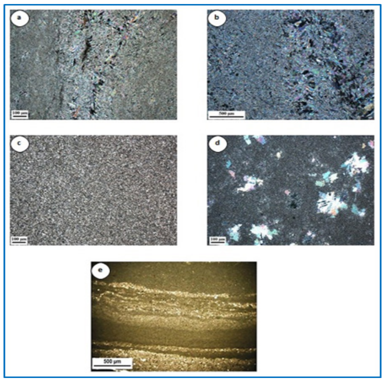

Figure 2. Tidal flat environment microfacies (XPL): (**a, b**) Layered Anhydrite with chicken wire fabric. (**c**) Dolomitic mudstone. (**d**) Dolomite mudstone with evaporate casts. (**e**) Stromatolitic boundstone facies, characterized by laminated texture in the image.

2.1.5 Facies A5 (Thrombolite Boundstone)

Like stromatolite boundstone facies, this facies is made of algal latent structure. However, thrombolite boundstone, characterized by a microscopic clotted fabric, is distinguished from stromatolite boundstone due to the lack of fine lamination (Figure 3a, b). Developing throughout the basin, this facies underlies the lower boundary of Kangan formation[24]. Pelloid texture, bird's eye fabric and mottled and massive form are among the specific characteristics of this facies. Thrombolites are reported from Cambrian, Ordovician, Triassic and even contemporary carbonate platforms[28]. Thrombolite boundstones are mainly developed in different parts of the world in early Triassic era (after the Permian-Triassic boundary). Thrombolite boundstone facies are formed after the mass extinction of living things in Permian-Triassic boundary. Some diagenetic processes such as cementation and compaction have caused a decrease in the reservoir quality of this facies. The paucity of symptoms and various forms of withdrawal from water reveal that this facies was formed in lower tidal flat and subtidal environments.

2.1.6 Facies A6 (Dolomite Pelloid Grainstone with Keystone Pores)

Pelloid, interconnected by anhydrite cement, is the most abundant allochem of this facies, comprising 50% of it. Aside from pelloids, about 5-10 percent intraclast can also be found there. This facies is also characterized by fenestral fabric and keystone or large bird's eye pores, mostly filled by anhydrite cement (Figure 3c, d). These pores distinguish intertidal flats[21] and are mostly formed in micrite sediments due to the withdrawal of air, dissolution of organic materials and emission of gases[25, 29]. Therefore, evidence such as grain-supported fabric, high percentage of pelloid, the peresence of fenestral fabric and keystone pores prove the formation of this faces in the lower intertidal flat.

2.1.7 Facies A7 (Dolomite Pelloid Intraclast Grainstone)

The most abundant non-skeletal grains constituting this facies are intraclasts and pelloid in a sparry matrix. This facies also contains a poikilotopic, pervasive anhydrite cement more than carbonate cement (Figure 3e). It also includes keystone and bird-eye vugs between non-skeletal, intraclast and pelloid grains. These vugs are larger than intragranular vugs and result from decomposition of organic materials and emission of their gases[29-31]. Evaporative mudstones are also found here. Grain-supported fabric, anhydrite cement, evaporative materials, pelloid and bird-eye vugs between non-skeletal grains all point to the formation of this facies in the lower intertidal zone [25,32-34].

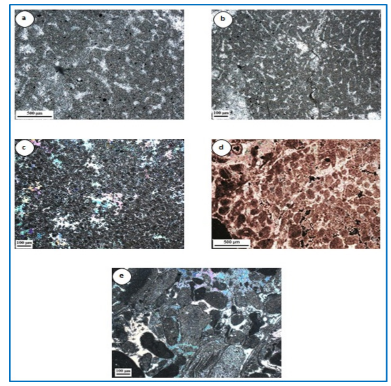

Figure 3. Tidal flat environment microfacies (XPL): (**a, b**) Thrombolitic boundstone facies, characterized by clotted fabric and mottled and massive texture, resulting from cyanobacteria and algal activities. (**c, d**) Dolomitic pelloid grainstone facies with keystone pores, where the fenestral and keystone pores between pelloids are mostly filled by anhydrite non-carbonate cement. (**e**) Dolomitic pelloid intraclastic grainstone facies.

2.1.8 Interpretation

The facies of this group reflect the characteristics of Sabkha and tidal environments and are formed in intertidal and supratidal zones. Evidence such as primary fine-crystalline dolomites, evaporites, bird-eye (fenestral) vugs and stromatolites indicate that these facies are deposited in a hot and dry tidal environment. Due to the low latitude of Persian Gulf in lower Triassic and hot and dry climate of the region, evaporative-hypersaline condition is developed and consequently, results in anhydration and dolomitization[35]. The abundance of evaporites in this facies accounts for higher evaporation rate than precipitation and these facies were formed under the supersaturated conditions of the sulfate-rich solutions. This facies shows remarkably various anhydrite structures and textures including massive, laminated and chicken wire anhydrites in a supertidal environment. Due to the capillary movement of brines through sediments, anhydrite nodules develops in the dolomudstones of supratidal zone[23] and as capillary action of brines through dolomudstones continues, anhydrite nodules, affected by replacive and displacive processes gradually replace the sediments[23] and continue until all muddy deposits are transformed into anhydrite and eventually a chicken-wire anhydrite is formed.Fenestral and thrombolite and stromatolite boundstones formed in an intertidal environment[21] are other characteristics of these facies. Anhydrite is less developed in an intertidal environment than in a supertidal one and most evaporite sediments are observed in the forms of nodule or crystals dispersed in the matrix of the host rock.

2.2 Facies Group B (Lagoon Facies)

This group includes four major facies:

2.2.1 Facies B1 (Dolomite/Limestone Mudstone with Bioturbation)

This facies enjoys a mud-supported texture and contains a low percentage of skeletal grains and pelloids. It is characterized by bioturbation, found as dark and light brown spots and producing mottled fabric (Figure 4a, b). Bioturbation destroys the early sedimentary arrangement of this facies. This characteristic points to the deposition of the sediments of this facies in the low energy and deep part of lagoon which is a calm environment without displacement of mud[4,13,34]. Due to its mud-supported texture and lack of porosity, this facies lack appropriate reservoir quality.

2.2.2 Facies B2 (Dolomite Pelloid Wackestone/ Mudstone)

This facies consists of mud-supported texture and sporadic pelloids (Figure 4c). The presence of micritic pelloid refers to low-energy and deep sedimentary environments as well as an area with limited water flow in the lagoon environment (back-barrier lagoon). The abundance of micrite implies the lack of enough energy for carrying lime mud[36].

2.2.3 Facies B3 (Dolomite Bioclastic Packstone/ Wackestone)

Enjoying a micrite matrix, this facies is mainly composed of lagoonal bioclastic grains. Gastropod, bivalve fragments as well as some fragments of algae are placed within a dolomicrite matrix (Figure 4d). Pelloids and some intraclastic fragments are also found there. The abundance of bioclastic grains implies an appropriate environment, resulting from more relation and water circulation. This facies is mainly characterized by the processes of micritization and dolomitization. This facies is attributed to lagoon environment due to the abundance of the lagoonal bioclasts, development of micritization and the presence of pelloids in a dolomicrite matrix[4,19].

2.2.4 Facies B4 (Dolomite Pelloid Packstone)

This facies is composed of 40-50% pelloid and 4-5% skeletal fragments such as gastropod and bivalves (Figure 4e). The carbonate cement found in this facies is of Isopachous and equant types while its non-carbonate cement is made of anhydrite and is precipitated in the pore spaces of allochems. Evidence such as grain-supported texture of the facies, abundance of pelloid, presence of cement, lack of evidence on water withdrawal and presence of non-skeletal fragments such as gastropod and bivalves prove that this facies is deposited in the shallow, high energy parts of the lagoon, namely the environment close to bar. Despite the abundance of pelloid as a dominant allochem and considering pelloids as the main components of the shallow carbonates[12,13,21,34] as well as the presence of skeletal fragments of the wetland and comparing them with the previous works[32,34], one can come to this conclusion that this facies is formed in the lagoon environment. The most important porosities of this facies are vuggy, intercrystalline and intergranular porosities, the low amount of which accounts for the medium-to-low quality of the reservoir. On the other hand, pore-filling non-carbonate anhydrite cement plays a key role in decreasing the reservoir quality.

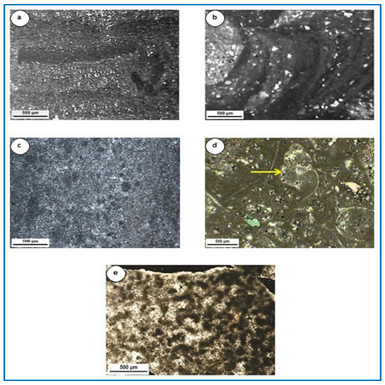

Figure 4. Lagoon environment microfacies: (**a, b**) limestone/dolomitic mudstone facies with bioturbation (PPL), in which the dark stains result from bioturbation. (**c**) Dolomitic pelloid wackestone/mudstone facies, in which pelloids are located within a dolomicritic matrix (XPL). (**d**) Dolomitic bioclastic packstone/wackestone facies (XPL), characterized by gastropod and bivalves, and the gastropod cells (yellow arrow) are filled by dolomite crystals as a result of diagenetic processes of dolomitization. (**e**) Pelloid packstone facies (XPL), in which the vuggy pores between pelloids are filled by dolomitic cement.

2.2.5 Interpretation

The facies of the lagoon environment in kangan formation include wackestone and packstones containing carbonate mud, pelloid and skeletal fragments (gastropod and bivalves). The skeletal fragments of this part are mainly influenced by the process of micritization, pointing to the bacterial and algal activities in this part[10]. Lack of sorting and the presence of carbonate mud in these facies point to the low energy and limited water flow in this region since the carbonate bar acts as a barrier to turbulent waves and protect lagoon against invasive waves[37]. The presence of bioturbation in muddy sediments is another feature of this environment, referring to a calm and low energy sedimentary environment. It is noteworthy that facies B1 enjoys the lowest energy and facies B4 enjoys the highest energy in the deposited lagoon. Most fossil grains observed in facies group B are gastropods and bivalves.

2.3 Facies Group C (Shoal Facies)

Facies belt C, extending from leeward shoal environment towards seaward shoal environment; include four major facies as follow:

2.3.1 Facies C1 (Dolomite Pelloid Ooid Grainstone)

Ooid is the most abundant non-skeletal grain, comprising 30-50% of the allochem. In addition to ooid, 20-25% pelloids as well as a small amount of fine-skeletal fragments of lagoon environments including gastropods and bivalves can be found in a sparry dolomite matrix (Figure 5a). As energy or water flow increase, a number of pelloid is carried from lagoon environment and deposited in the high-energy shoal environment. However, most pelloids are likely to be fractured or micritic aragonite ooids.

Moldic, vuggy, intragranular, intergranular and intracrystalline porosities are among the most frequently seen porosities in this facies, mostly influenced by diagenetic process of dissolution and dolomitization. The carbonate cements of this facies are of isopachous and equant types, pointing to the formation of this facie in a marine environment while noncarbonated anhydrite cements mostly fill the pore spaces between allochems. Lack of micrite and filling intragranular pore spaces by sparry cement are considered as other characteristics of this facies. Pelloids and skeletal fragments particular to wetland as well as high percentage of ooid as the specific allochem created in shoal environments[13,32,34,38] indicate that this facies is formed around a leeward shoal environment. It is reported that this facies is developed in the upper Khuff Formation (southern coastlines of Persian Gulf)[19,38,39]. This facies shows various transformations and inconsistencies in the reservoir quality, affected by secondary anhydration process (anhydration process can cause an intense reduction in porosity, especially primary porosity such as intragranular porosity) and cementation. Accordingly, the reservoir quality of this facies varies from weak to good.

2.3.2 Facies C2 (Ooid Grainstone)

This facies contains about 80% ooids and 10-20% skeletal fragments and pelloids (Figure 5b, c). Most ooids are 0.2 to 1 mm. This facies can be found either in dolomite or in lime forms. Aragonite ooids are greatly dissolved and pore spaces are filled by calcite and dolomite or can be seen as moldic porosity, known as oomoldic porosity. Dissolution of ooids and dolomitization phenomenon have created a great reservoir quality in this facies and named it as the most important facies in the reservoir facies. Intragranular, intergranular, vuggy and intercrystalline porosities can also be observed here. The intergranular carbonate cement of this facies is of isopachous, equant and drusy types while its noncarbonated pore-filling cement is anhydrite cement, accounting for reduction in the porosities and reservoir quality.

Dolomitization, anhydration, micritization, cementation, dissolution, mechanical and chemical compaction and recrystallization are the diagenetic processes occurring in this facies. The most important diagenetic process is micritization, determining the preservation of the primary framework of the allochem and creation of moldic porosity[4]. Ooids are formed in shallow (lower than 2 m), hot and hypersaline environments, saturated with calcium carbonate[13]. The presence of ooid and various marine cements and lack of matrix indicate that this facies is deposited in a high energy shoal environment and above the wave effect line, and high evaporation can also account for formation of ooids[9,32,40-42]. The presence of rounded-grain ooids and cross lamination, formed in a place where tidal energy can be found as reciprocating streams can account for development of this facies in the shoal environment[32,38]. The allochems of this facies is composed mostly of dissolved or replaced aragonite ooids. Aragonite and high-magnesium calcite ooids are unstable and are precipitated when Mg/Ca ratio is high and Co_2 pressure is low[43,44]. Formation of aragonite ooids during Triassic period is related to eustatic and relative fall in sea level during late Permian and early Triassic[45,46]. It is noteworthy that sediments resembling facies C2 are now depositing in some parts of Persian Gulf[12,19] and Bahamas[47,48].

2.3.3 Facies C3 (Intraclastic Bioclastic Ooid Grainstone)

As an ooid grainstone, this facies is composed chiefly of coarse skeletal fragments and intraclasts (Figure 5d). Skeletal fragments are mainly derived from bioclastic parts of shoal environment and contain gastropods and bivalves. Ooids are relatively well-sorted. Most of these allochems are carried from various parts of shoal dunes. Cementation, as a diagenetic process occurring in this facies, fills the intergranular vuggy spaces by isopachous fringe carbonate, equant, blocky and drusy cements. Dissolution is another diagenetic process, creating vuggy and moldic porosities especially in aragonite and unstable grains such as ooids and reduces reservoir quality. The presence of intergranular and intragranular porosities has increased the porosity rate. Evidence such as lack or paucity of mud, remarkable development of marine cements, coarse bioclasts, ooids and intraclasts proves that this facies belong to open marine carbonate shoal environment. Due to the lack of protective wall against marine waves and storms, a turbulent and high energy environment governs this facies[42,49-51].

2.3.4 Facies C4 (Ooid Intraclastic Grainstone)

Intraclasts (30-35%) and ooids (25-30%) constitute the most abundant allochems in this facies. In addition to these, some skeletal fragments (less than 5%) including bivalves can also be found in a sparry matrix there (Figure 5e). Since the intraclasts are carried from their place of origin by a high energy flow and redeposit in the basin, the intraclasts of this facies followed by ooids seems to be derived from inlet channels[13]. Regarding the abundance of non-skeletal grains of intraclast and coarse ooids as well as the presence of sparry and dolomitized matrix and lack of micrite, this facies is likely to be deposited in a carbonate shoal sub-environment. The above-mentioned evidence and comparing them with previous studies [19,39], sedimentary environment of today's Persian Gulf [12,13] and standard facies[4] point to the deposition of this facies in the inlet channels. Lack of protective wall against marine waves and storms has caused a turbulent and high energy environment govern this facies[42,49-51]. Intergranular, intragranular, intercrystalline and moldic porosities are the major porosities of this facies and it shows high reservoir quality. However, the low development and thickness of this facies account for its trivial effect on the reservoir quality.

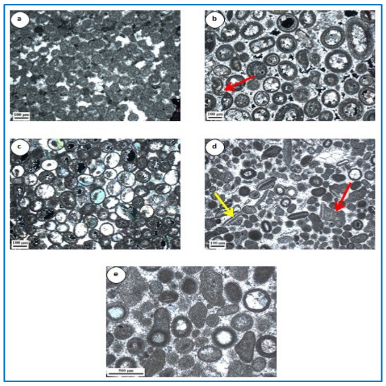

Figure 5. Shoal environment microfacies: (**a**) Pelloid ooid grainstone facies (PPL). (**b, c**) Ooid grainstone facies (XPL), the dissolved, dolomitized, superficial, S-like (red arrow) and transformed ooids can be seen in figure b and in figure c, most of the dissolved ooids are filled by anhydrite cement. (**d**) Intraclastic bioclastic ooid grainstone facies (XPL), characterized by bioclastic bivalves (yellow arrow) and intraclasts (red arrow). (**e**) Ooid intraclastic grainstone facies (PPL).

2.3.5 Interpretation

The facieses of this group are greatly developed in Kangan Formation and is recognized as the best reservoir facies of this formation with respect to porosity, permeability and reservoir quality. Regarding sedimentation situation, the facies of this group are deposited within leeward shoal, central shoal and seaward shoal sub-environments. This facies group is characterized by grain-supported facies, development of marine cements, lack of or low volume of micrite and abundance of ooids, all accounting for a high-energy sedimentary environment. Facies C1, formed in a low-energy leeward shoal environment includes higher carbonate mud content, more pelloids and less ooids than another facies. Ooids are the major components of the facieses in this group, connected by sparry cement to each other. Development of moldic and intergranular porosities in ooid grainstone is provided by intermittent deposition of the sediments near the meteoric waters and dissolution of unstable ooid grains in this facies.

3. Depositional Model of Kangan Formation

Studies on the facies, classification of the facies groups and examining their lateral and vertical patterns based on standard facies belts[4,10] reveal that the sedimentary environment of the carbonate sediments of this formation is a homoclinal ramp (Figure 6.) and development of tidal zones (together with stromatolite and thrombolite boundstone facies) in the studied sequence points to the shallowness of a large body of this basin and its hot and dry climate, resembling today's climate in Persian Gulf [4,19,52]. This conforms to the climate dating back upper Permian and lower Triassic.

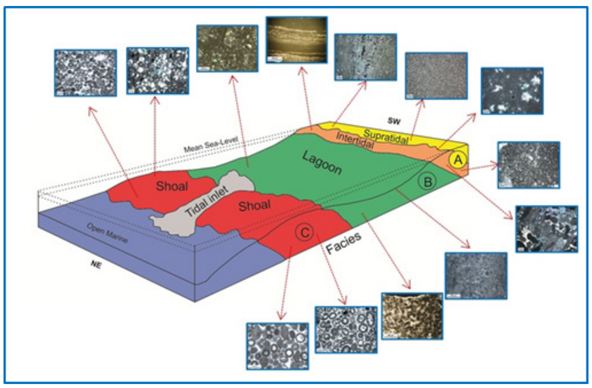

Figure 6. Depositional environment model of Kangan Formation in the studied well.

4. Interpretation of Sedimentary Sequences

Investigating the vertical changes of the microfacies identified in Kangan Formation, determining their stacking patterns, separating the sedimentary phases and primary and secondary unconformities and finally equivalence of the facies with gamma ray curve lead to recognition of four third-order sedimentary sequences in Kish well#3 (Figure 7). These sedimentary sequences are comparable by the Upper Absaroka A supersequence[53]. These third-order sequences belong to TST and HST facies groups. TST facies group, lying under each sedimentary sequence consists of one or more transgressive parasequences. Transgressive Surface (TS) and Maximum Flooding Surface (MFS) constitute the lower and upper boundaries of this facies group respectively. HST, consisting of one or more transgressive or regressive parasequences overlies TST. The lower boundary of the facies group is characterized by MFS while its upper boundary with sequence boundary. The boundary between the Third-order sequences with each other and also the boundary between Third-order sequences with Dashtak formation were unconformity boundary of type 2 (SB2) and the boundary between Third-order sequences with Dalan formation which is the Permian-Triassic boundary is an unconformity boundary of type 1 (SB1). Generally speaking, TST facies group observed in the studied sedimentary sequences mostly starts with tidal and lagoon zones and terminates in the facies deposited in a high-energy shoal environment. This facies is formed in the facies belt of inner ramp and MFS is achieved in the ooid intraclast grainstone facies of the shoal environment (C4 facies). The initial facies of TST represent a shoal environment and then major facies of shallow lagoon and tidal environments are regressively formed and finally terminate along the sequence boundaries. The upper TST and lower HST are of important reservoir quality due to holding grain-supported facies such as ooid grainstone. However, the lower TST and the upper HST is of low importance as a result of having anhydrite and anhydrite cements. Studying the reservoir zones in Kangan Formation indicates that the best gaseous zones of this formation can be found in HST facies group.

The high level of carbonate production, an increase in the grain size and a decrease in micrites in this facies group account for distribution of carbonate reservoirs in this facies group.

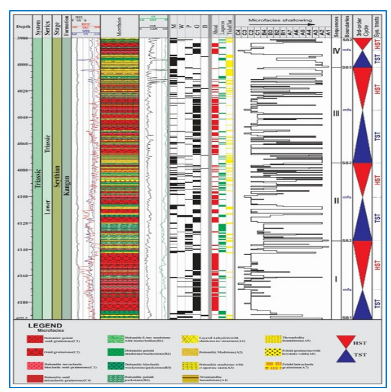

Figure 7. Sequence stratigraphy column of Kish Well#3 section.

5. Diagenetic Processes

The most important diagenetic processes occurring in Kangan formation include dissolution, micritization, cementation, dolomitization, compaction, fracturing and bioturbation. These processes are briefly discussed below:

6. Dissolution

Dissolution is one of the most important diagenetic processes causing porosity in carbonate rocks. This process occurs under the influence of interstitial fluids and mineralogical composition of the rocks so that minerals are dissolved without displacement (Figure 8a, b). The process of dissolution occurs simultaneously with uplift of carbonate sediments and can be found in a near-surface atmospheric zone as well as a burial environment[4].

7. Micritization

Micritization is one of the diagenetic processes, resulting from the activities of living things especially bacteria and fungi. These creatures cause microscopic pores in the fringe of skeletal grains, filled subsequently by micritic fine-grained sediments (Figure 8c, d) so that these grains are covered by these sediments or the whole grain or shell are converted into micrite[4,42] (Figure 8c, d). The micritization of the sediments mostly occurs in lagoon and calm environments. The micritization of the grains impedes their dissolution and dolomitization in subsequent diagenetic processes and eventually, decrease reservoir quality[13].

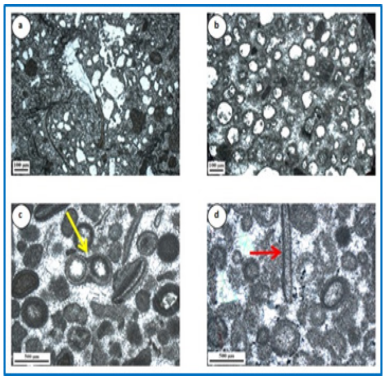

Figure 8. (**a, b**) The microscopic images of the porosities left by dissolution of allochems (PPL). (**c, d**) The microscopic image of micritization process. A compound ooid (yellow arrow), coated by micrite and secured against its complete dissolution can be seen in the center of figure c (PPL). Ooids and bivalves (red arrow) in figure d are completely micritizated and the vuggy pores between them are filled by anhydrite cement (XPL).

8. Cementation

Cementation is a diagenetic process by which authigenic minerals are deposited in the vuggy pores of the sediments and convert the sediments into rock[4]. Cementation may cause a reduction in porosity and compaction of the rock or impede the development of the compaction[54]. Cementation includes all processes triggering deposition of minerals in the major and minor pores of the rocks and requires supersaturated interstitial fluids[4]. The cements found in the studied sections are mainly of anhydrite, dolomite and calcite sparry types and are basically observed in the form of isopachos, blocky, drusy, microcrystalline, equant and poikilotopic cements (Figure 9 a, b, c, d, e).

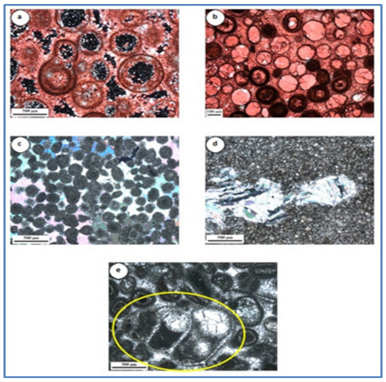

Figure 9. The microscopic images of cementation process. (**a**) Microscopic image of the calcite isopachus cement with isopachus fine-grained crystals around ooid grains (XPL). (**b**) The microscopic images of blocky calcite cement within dissolved ooids (PPL). (**c**) The intragranular porosities are filled by pervasive anhydrite cement (XPL). (**d**) The presence of anhydrite cement with acicular fine-grained cement and chicken wire fabric within dolomitic mudstone facies (XPL). (**e**) The gastropod cells are filled by dolomitic cement (within yellow area) (PPL).

9. Dolomitization

Dolomitization is one of the most important diagenetic processes, rooting in displacement and resulting from dolomitization of the calcite (Figure 10 a, b). Dolomitization has largely increased the reservoir quality in the carbonate formations and then, as dolomite increases, the reservoir quality decreases[4,55]. Fine to coarse dolomite crystals are found in various sections. The fine-grained dolomites result from percolation, refluxion and pumping processes while coarse-grained dolomites result from burial dolomitization model, in which magnesium ions, as a result of increase in depth and temperature, are derived from source rocks and as magnesium increases in intergranular water, dolomitization occurs. Pressure dissolution and the presence of fluids resulting from hydrothermal deformation are among other sources for supplying magnesium ions[4].

10. Compaction

Compaction can be found in either chemical or physical forms and is buried as the upper-level pressure increases. This pressure may cause a decrease in the size of vuggy pores of the rocks, penetration of the grains into each other, distortion and fracturing of the grains and dissolution veins and stylolite formation (Figure 10c, d, e, f). The effect of compaction on decreasing porosity in mud-supported carbonate rocks is higher than in grain-supported rocks, but all in all compaction, either in physical or chemical forms, has an important role in decreasing the vuggy pores of the rocks. With increasing depth of burial, this effect will tend to be increased as well[4,13].

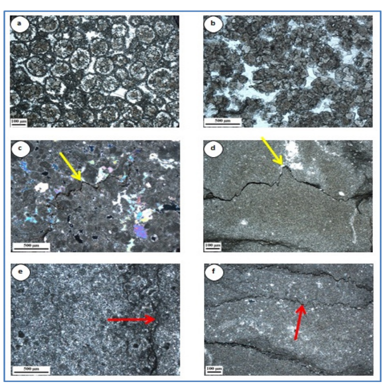

Figure 10. (**a, b**) The microscopic images of the dolomitization process (PPL). In figure a, ooids are affected by dolomitization while the early fabric of the facies is preserved. In figure b, however, dolomitization is considerably intense and the early fabric is destroyed and just a ghost of allochems can be found. (**c, d**) The irregular and jagged surface of stylolite in figures c (XPL) and d (PPL) have result from the effect of compaction on the facies (yellow arrows). (**e, f**) Dissoluble veins, resulting from chemical compaction are found smooth and in the form of indissoluble materials (red arrows) (XPL).

11. Bioturbation

This process is one of the most salient characteristics of subtidal zones and mostly occurs in marine phreatic environment. Plants' roots and burrowing animals account for this kind of process[13]. Bioturbation by burrowing animals results in boring form in coarse sediments while, as caused by mud-eating creatures, it is found in burrow form in fine sediments. This process is mostly developed in carbonate mudstones, relating to lagoon environments (Figure 11a).

12. Fracturing

This process can cause many changes in the reservoir quality especially in its permeability[13]. Most fracturing has tectonic origin while some show diagenetic origin[55]. The vuggy pores caused by fracturing remains in the form of porosity and in other cases, it is filled by calcite and anhydrite cements or saddle-shaped dolomite (Figure 11b, c, d).

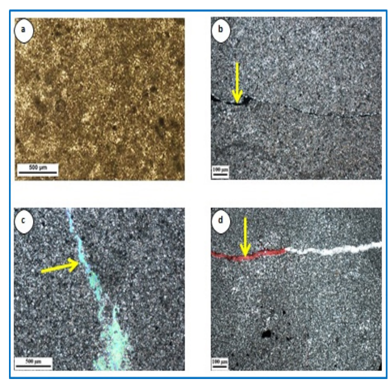

Figure 11. (**a**) Bioturbation in a wackestone/mudstone facies, characterized by a mottled fabric (as can be seen in the image) (PPL). (**b, c, d**) The microscopic images of fracturing process in dolomitic mudstone facies (XPL). The fracturing seen in figure b is open and not filled while it is filled by anhydrite cement in figure c and by sparry coarse-grained calcite cement in figure d (yellow arrows).

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14. Conclusion

Having investigated the microscopic thin sections collected from the core of Kish Well-3, this study recognized 15 major facies (14 carbonate facies and 1 evaporite facies) in Kangan formation. According to Walter's Law, these facies are deposited in three facies belts including tidal flat, lagoon and shoal. Vertical changes of the facies and comparing them with old and contemporary sedimentary environments indicate that these sediments are deposited in a low-slope homoclinal ramp. Destruction of the microfabrics of allochems in most samples and replacing them with dolomite or anhydrite crystals, or their dissolution (especially in ooids) as well as the development of moldic porosity refer to the primary aragonite mineral for ooids. Therefore, the sea water has been an appropriate environment for developing aragonite and high-magnesium calcite during the early Triassic period. Examining the microscopic thin sections together with considering the gamma curve indicate that Kangan formation is composed of dolomite, lime, evaporative and shale stones. Based on factors including development and effective porosity, the facies in shoal facies group, especially ooid grainstone facies is the best reservoir facies of Kangan formation. According to the curve of depth changes in the facies environment and comparing them with sea-level changes curve on a global scale, one can estimates that Kangan Formation dates to early Triassic period (Scythian). Development of tidal zones (together with stromatolite and thrombolite boundstone) in the studied sequence implies the shallowness of a vast area of this region and hot and dry climatic conditions similar to that of today's Persian Gulf, conforming to that of upper Permian and lower Triassic. The sequence stratigraphy of Kangan Formation reveals that this formation includes four type-3 sedimentary sequences, in which the boundary between type-3 sequences as well as the boundary between Kangan and Dashtak formations, i.e. the upper boundary of the fourth sedimentary sequence are SB2 while the boundary between Kangan and Dalan formations, i.e. the lower boundary of the first sedimentary sequence is SB1. The most important diagenetic processes occurring in Kangan formation is dolomitization, creating intercrystalline porosity, increasing effective porosity and consequently, improving the reservoir quality of this formation. Aside from this process, other diagenetic processes including cementation, micritization, compaction, bioturbation and dissolution (especially in aragonite anhydrite) are also seen.

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