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Sedimentary Environment and Sequence Stratigraphy of the Kangan Formation in Kish Gas Field (Kish Well A1 Subsurface Section)

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Abstract

Kangan formation is one of the most important gas reservoirs of south and southwest Iran which it belongs to Dehram group and its age is Lower Triassic (Scythian). It was formed in an extensional basin in the expanded Neotethys Ocean. The basin was formed as a result of the Late Permian continental drift between Cimeria and Gondwana. The Kangan Formation is mainly composed of dolomite, dolomitic limestone with shale and anhydrite. It is unconformably underlain by the upper Permian Dalan formation and is conformably overlain by the upper Triassic Dashtak formation. In order to study facies, sedimentary environment and sequence stratigraphy in the Kish gas field, subsurface section of well A1 have been studied.

Based on microfacies analysis, three facies belts include Tidal flat (A), Lagoon (B) and Shoal (C) were recognized in the Kangan formation. Facies analysis and those comparisons with modern and ancient environments indicate that the Kangan formation was deposited in an inner part of a homoclinal ramp platform.

The sequence stratigraphy studies on the Kangan formation in this gas field led to assessment of three main sedimentary sequences of the Third-order in the Kish Well A1. 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). The main diagenetic processes in this formation are dissolution, cementation, micritization, anhydritization, dolomitization, recrystallization, physical and chemical compaction which played a significant role in improving reservoir quality. The dominantly ooid grainstone facieses with intercrystalline, moldic and Fracture porosity comprise the main reservoir facies of the Kangan Formation.

Keywords: Dehram Group, Homoclinal Ramp, Kangan Formation, Scythian, Sequence Stratigraphy, Unconformity Boundary

1. Introduction

Iran has been divided into several structural-sedimentary zones, the most important of which is Fars zone. Owning to the absence of igneous activities, presence of organic-rich source rocks and porous and permeable reservoir rocks with suitable cap rock, this zone is characterized by a unique situation for producing and accumulating hydrocarbons, and known as one of the most prolific gas resources among the sedimentary basins all over the world. Kangan Formation is one of the most important formations in this zone, belonging to Dehram Group and Lower Triassic period. Correlatable with upper part of Khuff formation in south of the Persian Gulf[1,2]. This rock unit is composed of carbonate and evaporative rocks, and unconformably overlies Dalan Formation[3] and conformably underlies Dashtak Formation[4].

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To investigate the microfacies, sedimentary environment and sequential stratigraphy of the depositions of Kangan Formation in Kish Gas Field, the underground section of Kish Well A1 is chosen. The Kangan formation in the study site is composed of dolomites, evaporites, limestones and shales with an overall thickness 185.5m. 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 Island are 53°, 53′ and 54°, 04′ E and 26°, 29′ and 26°, 35′. Moreover, the geographical coordinates of the studied underground section are 53° 57′ 54.9″ E and 26° 32′ 25.7″ N and overlies Kish anticline (Figure 1).

This research is based on petrographic studies of 170 thin sections obtained from cuttings in Kish Well A1 as well as sedimentological interpretations of gamma ray log for this section. Carbonate rocks were classified according to the Schemes of Dunham[5]. Facies analysis and, vertical and lateral changes carried out based on[6,7,8]. The results were compared with recent and pale depositional environments to determine sedimentary environment of the Kangan Formation[7,9–11]. Sequence stratigraphy concepts developed by pervious workers e.g.[12–17] were extended to the current study.

This study tends to achieve the following goals:

1. Identifying the sedimentary facies of Kangan reservoir rock in the studied thin sections.
2. Determining facies column and curve of changes in depth, associated with the depositions of Kangan Formation in the studied underground section.

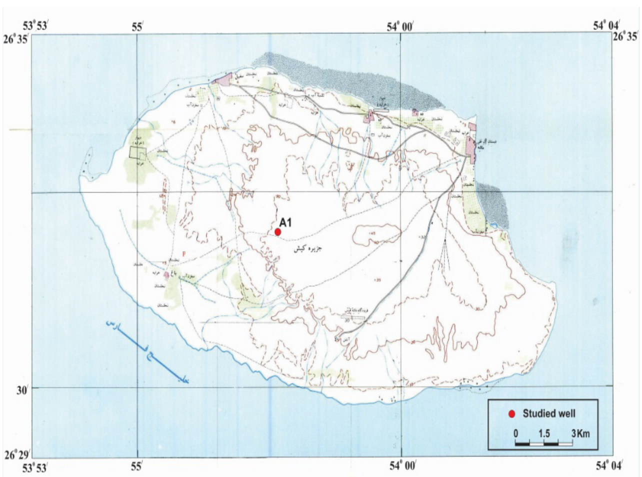

Figure 1. Situation of studied well on topography map of Kish Island.

3. Interpreting the sedimentary environment of the deposits of Kangan Formation and presenting a sedimentary model consistent with the results of the studies.
4. Recognizing the sedimentary sequences, sequence boundaries and comparing them with global sequences.

2. Facies Classification

Facies groups of Kangan Formation, covering an area from shore towards the deeper parts of the carbonate platform, include:

- Facies group A (Tidal flat facies)
- Facies group B (lagoon facies)
- Facies group C (shoal facies)

Each of the above facies is examined thoroughly as follow:

2.1 Facies group A (Tidal flat facies)

This facies group is characterized by the following five major facies:

2.1.1 Facies A1 (Layered Anhydrite)

This facies consists of layers of Anhydrite (Figure 2a). 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[11,18], 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 [11,19].

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 2b, c, d). 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 an hydration 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[11,22]. 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 2e, f).

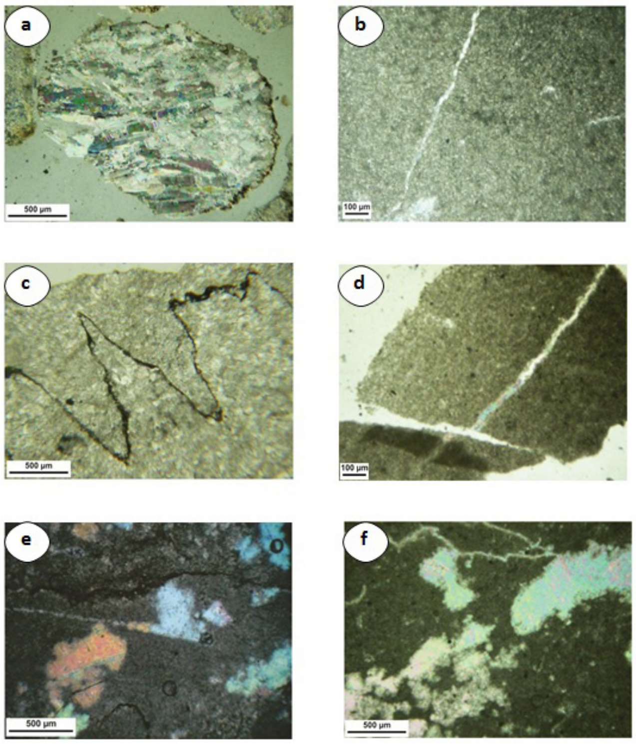

Figure 2. Tidal flat environment microfacies (XPL): a-Layered Anhydrite with chicken wire fabric, b,c,d-Dolomite mudstone, e, f-Dolomite mudstone with evaporate casts.

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 [11,21,22,25].

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 3a, b). These stromatolites belong to Autochthonous stromatolites group and can be classified as bindstone[11,27]. 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].

2.1.5 *Facies A5 (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 3c, d, e). It also includes keystone and bird-eye

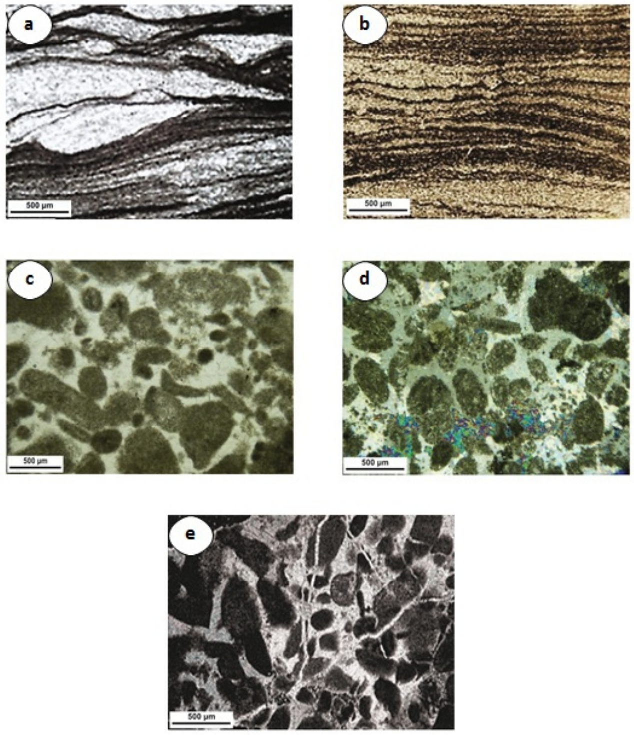

Figure 3. Tidal flat environment microfacies: a, b-Stromatolite boundstone (XPL), c (PPL), d, e (XPL) - Dolomite pelloid intraclast grainstone.

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[28,29,30]. 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[7,25,31,32].

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[33]. 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.

2.2 Facies group B (Lgoon Facies)

This group includes two major facies:

2.2.1 Facies B1 (Dolomite Pelloid Wackestone/ Mudstone)

This facies consists of mud-supported texture and sporadic pelloids (Figure 4a, b). 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[34].

2.2.2 Facies B2 (Dolomite Pelloid Packstone)

This facies is composed of 40–50% pelloid and 4–5% skeletal fragments such as gastropod and bivalves (Figure 4c, d). 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

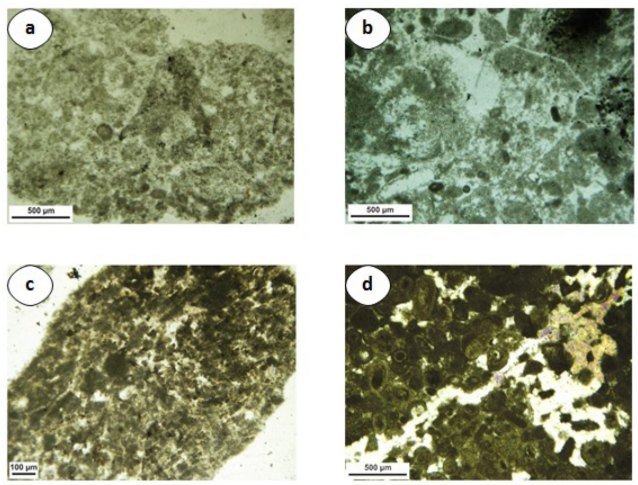

Figure 4. Lagoon environment microfacies: a, b-Dolomite pelloid wackestone/mudstone (PPL), c-Dolomite pelloid packstone with fenestral fabric(PPL), d-Dolomite pelloid packstone with poikilotopic anhydrite cement (XPL).

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[10,11,21,32] as well as the presence of skeletal fragments of the wetland and comparing them with the previous works[7,32], 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.

Interpretation

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[35]. 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 B2 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 two 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, b). 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[7,9,11,32] 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)[2,19]. 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 5c, d). 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

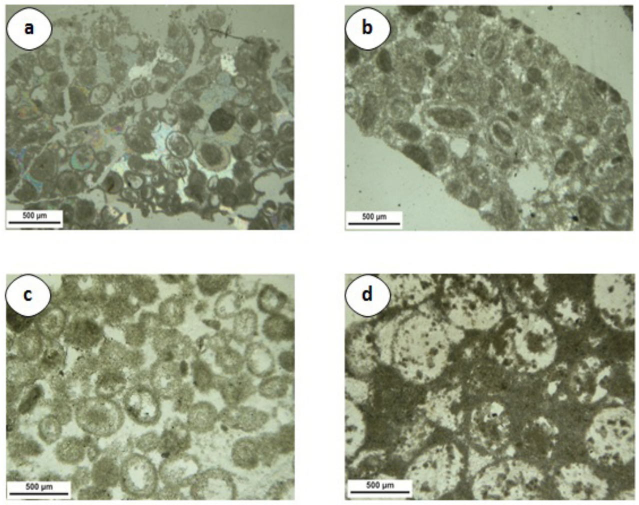

Figure 5. Shoal environment microfacies: a (XPL), b (PPL)–Dolomite pelloid ooid grainstone, c, d-Dolomite ooid grainstone (PPL).

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[36]. Ooids are formed in shallow (lower than 2 m), hot and hypersaline environments, saturated with calcium carbonate[11]. 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[6,7,37,38,39]. 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[7,9].

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[40,41]. Formation of aragonite ooids during Triassic period is related to eustatic and relative fall in sea level during late Permian and early Triassic[42,43]. It is noteworthy that sediments resembling facies C2 are now depositing in some parts of Persian Gulf[10,19] and Bahamas[44,45].

Interpretation

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. 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. 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[36,46] 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 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[19,36,47]. This conforms to the climate dating back upper Permian and lower Triassic. Since carbonate ramps are largely developed in shallow and low-slope beds such as foreland and intercratonic basins, and along the passive margins[9], studies show that Kangan Formation is formed along the passive margins of Neotethys Sea.

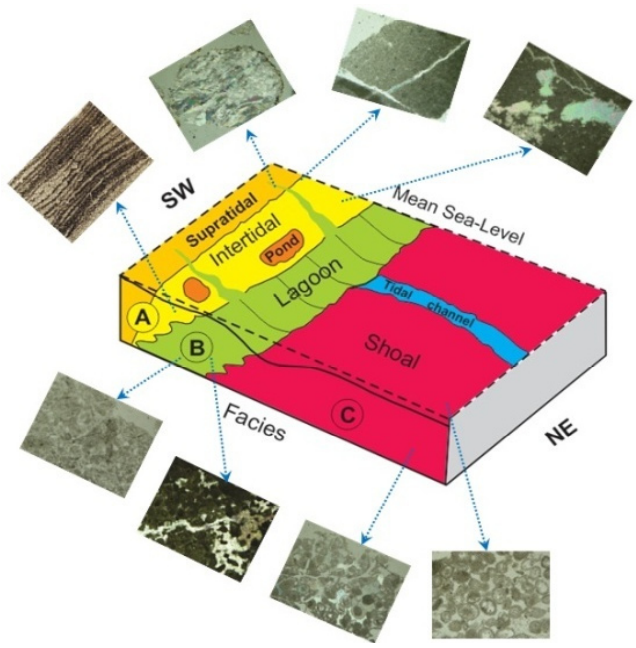

Figure 6. Depositional environment model of Kangan Formation in Kish gas field (Kish well A1 section).

4. Interpretation of Facies Column

Studies on the thin sections of drilling fragments have identified nine major facies in the sedimentary rocks of Kangan Formation, created in tidal, lagoon and shoal environments. Having conducted the microscopic studies and identified the characteristics of these facies, the researchers nominated the facies and then depicted the facies column of the studied underground section (Figure 7).

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 three third-order sedimentary sequences in Kish well A1 (Figure 8). These sedimentary sequences are comparable by the Upper Absaroka A super sequence[48]. These third-order

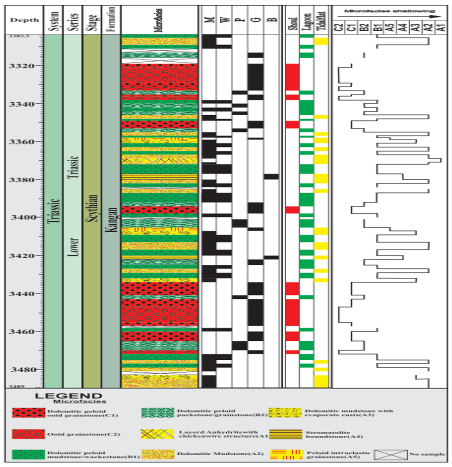

Figure 7. Facies column of Kish well A1 subsurface section.

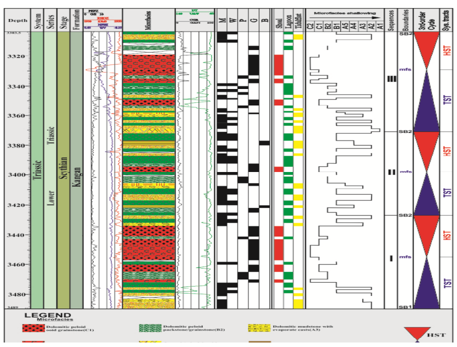

Figure 8. Sequence tratigraphy column of Kish well A1 subsurface section.

sequences belong to TST and HST facies groups. TST facies group, lying under each sedimentary sequence consists of one or more transgressive Para sequences. 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 Para sequences overlies TST. The lower boundary of the facies group is characterized by MFS while its upper boundary with sequence boundary.

5. Interpretation of Sedimentary Sequences

Deposits of the first sedimentary sequence, unconformably overlying the upper Dalan Formation, are equal to the lower Triassic Kangan formation. This sequence starts with TST facies group which overlies the Permotriassic boundary and after reaching MFS, TST finishes and HST starts and continues until the formation of the second sedimentary sequence and complete regression.

The second sedimentary sequence also consists of lower TST facies group and upper HST facies group, and it has type 2 sequence boundary with the first and second sedimentary sequences. The third sedimentary sequence with SB2 overlies the second sedimentary sequence and its upper boundary, lying between Kangan and Dashtak Formations, is SB2.

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 grainstone facies of the shoal environment (C2 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.

6. Conclusion

1. Having studied the microscopic thin sections, the researchers identified nine major facies in Kangan Formation. According to Walter's law, these sediments are deposited in tidal flat, lagoon and shoal environments.
2. The lateral and vertical changes in facies and comparing them with old and today's sedimentary environments suggest that these sediments are deposited in homoclinal carbonate ramp at the passive margin of Neotethys Sea.
3. Dolomitization is the most dominant diagenetic process in Kangan Formation, causing intercrystalline porosity, increase in effective porosity and consequently, an increase in the reservoir quality of this formation. Moreover, cementation phenomenon can be found in the form of carbonate cement (calcite and dolomite) and non-carbonate anhydrite cement. Micritization, neomorphism, bioturbation, compaction and dissolution (especially in aragonite ooids) are among common diagenetic processes in this formation.
4. 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.
5. Examining the microscopic thin sections together with considering the gamma curve indicate that Kangan formation is composed of dolomite, lime, evaporative and shale stones.
6. 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.
7. 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).
8. Development of tidal zones (together with stromatolite 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.
9. Sequential stratigraphy of Kangan formation show that it includes three third-order sedimentary sequences so that the boundary among the third-order sequences as well as the boundary between Kangan and Dashtak formations, namely the upper boundary of the third sedimentary sequence is SB2 while the boundary between Kangan and Dalan formations, namely the lower boundary of the first sedimentary sequence is SB1.

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