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MICROFACIES, DEPOSITIONAL ENVIRONMENT, AND DIAGENETIC PROCESSES OF THE MAUDDUD MEMBER, IN THE PERSIAN GULF

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ABSTRACT

Mauddud member with the age of late Albian to Cenomanian is equivalent to the lower Sarvak formation in the southern Persian Gulf and adjacent area. In this work, microfacies, depositional environment, and diagenetic processes affected the Mauddud member in a field in the Persian Gulf are investigated. Based on the studies of available cores and thin sections of 3 wells, five types of microfacies, namely MF1 to MF5, have been identified in the Mauddud member. These microfacies have been deposited in 2 facies belt including a vast lagoon and local bioclastic shoal. Based on the lack of great barrier reefs and calciturbidities and gradual change of microfacies into each other, it is concluded that the Mauddud member was deposited on a shallow marine homoclinal ramp. Several diagenetic processes such as bioturbation, micritization, dissolution, cementation, dolomitizetion, and compaction have influenced this member. Among all, dissolution increased porosity and thereby reservoir quality, while cementation and compaction decreased reservoir characteristics. Finally, it was found out that matrix porosity was the main type of porosity in the studied interval.

Keywords: Mauddud Member, Microfacies, Depositional Environment, Diagenetic Processes, Reservoir Quality, The Persian Gulf

INTRODUCTION

Mauddud member is equivalent to the lower Sarvak formation and designated to represent the Orbitolina-bearing limestone of the southern Persian Gulf [1]. It shows different characteristics in neighboring countries. For example, produced oil in Awali field in United Arab Emirates and has no production in some offshore wells, but represents oil shows. In Oman, is hydrocarbon bearing in some central Oman fields, in Iraq produced oil in Jambur and Kabbaz and oil shows in Kirkuk field and in Iran has no production, but represent oil shows in some wells [2].

Many scientists have studied the Sarvak formation in Iran from different points of view [3-7]. This study concentrates on the microfacies analysis, depositional environment, diagenesis, and the effects of diagenetic processes on reservoir properties of the Mauddud member in a field located in the Persian Gulf (Figure 1).

Stratigraphy of the Sarvak Formation

The Sarvak formation which is a part of Bang-estan group is known as one of the giant oil reservoirs in the southwest of Iran and the Persian Gulf.

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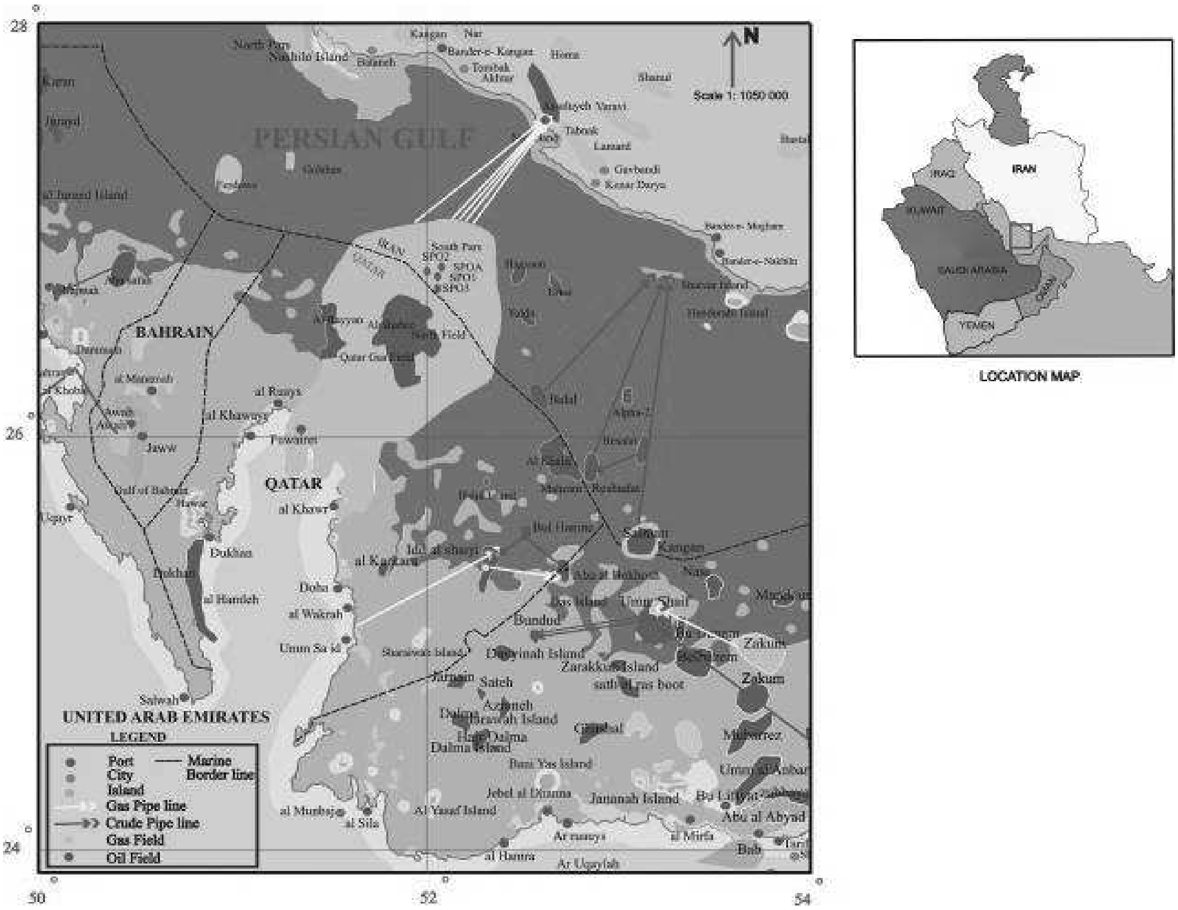

Figure 1: Location map of the field under study is shown with the rectangle.

The type locality is in Tang-e-Bang-estan in Khuzestan province and its thickness reaches 832 meters [8,9]. It is equivalent to Mauddud, Ahmadi, and Mishrif formations of the Persian Gulf region [1]. It is conformably overlies the Kazhdumi formation with a grada-tional contact. The upper contact with marl and shale of the Gurpi formation is sharp. This unit is broadly distributed in the Dezful embayment area and the northern Persian Gulf. In the coastal northern Persian Gulf, the Sarvak forma-tion is identifiable by two members, namely Ahmadi and Mauddud. This formation in the field under study consists of three members namely, Mishrif, Ahmadi, and Mauddud [1]; the Mauddud member is described below.

Mauddud Member

This member in the studied field is mainly composed of brown dolomitic limestone. The Mauddud member overlies Kazhdumi formation, and passes upward into Ahmadi member. The cores belonging to Mauddud member is heavily oil stained. The thickness of this member in the studied field is about 50 m.

Materials and Methods

About 60 m available cores related to three wells are described. Different parameters such as lithology, texture, allochems and their fre-quency, diagenetic parameters such as dissolu-tion and cementation, pore types and percent-ages, and sedimentary environments were recorded. The cross matching of visual observa-tions was done by thin sections. The whole cores as well as slab photography were preceded simultaneously. About 160 thin sections of 3 wells were prepared and stained with Alizarin red-s following Dickson [10]. Limestones were classified using Dunham [11] and Carozzi [12] classification. Depositional environment was determined using Wilson [13] and Flügel [14]. The classifications of Gregg and Sibley [15], Sibley and Gregg [16], and Mazzullo [17] were used for the study of dolomites. Seven samples were selected for SEM analysis in order to study microporosity and fine calcite and dolomite crystals. The SEM analysis was done in Tarbiat Modarres University with Phillips XL30. Using all the sedimentological data, a 3D depositional model was prepared for Mauddud member in the area (further discussion is given below (see Figure 3)). Sedimentological log of the studied interval was also prepared (Figure 7).

Microfacies Analysis

Sedimentological studies of both cores and thin sections have been resulted in the identification of five carbonate microfacies (MF) as described below.

MF1: Dolo Skeletal Wackestone

This microfacies is mud-supported and shows wackestone fabric with the amount of about 10-30% bioclasts. *Orbitolina* sp. is the main component of this microfacies. Other skeletal debris are *Trocholina* sp*., Textularia* sp, Echinoderm, Gastropod, Rudist debris, *Ostracod*, and shell fragments. *Lenticulina* (thin walled shell fragments), Pelecypod, Miliolid, and *Chrysalidina* sp. were also observed with a lower amount (Figure 2A). Bioturbation affected some of the samples (Figure 2B). The frequency of this microfacies in the Well 1 and Well 2 is high.

Interpretation: the presence of micrite and lagoonal microfauna revealed that this microfacies was deposited in a low energy lagoonal environment [14,18,19].

MF2: Dolo Skeletal Wackestone to Packstone

This microfacies were abundantly observed in the Mauddud member in all the three wells. The allochems such as *Orbitolina* sp., *Trocholina* sp., Echinoderms both stem and spin, large shell fragments, Gastropod, and *Chrysalidina* sp. were identified in MF2 (Figure 2C).

Skeletal debris was more abundant in MF2 than MF1. In this facies, dolomitization pervasively affected both matrix and allochems particularly the *Orbitolina*.

Interpretation: The presence of lagoonal fauna suggests the deposition in the lagoon environment. A decrease in the amount of mud in this microfacies compared to MF1 indicates a condition of higher energy.

MF3: Dolo Skeletal Packstone to Peloid Skeletal Packstone

The MF3 shows packstone fabric. The main allochems of this microfacies are peloid and bioclasts. Bioclasts mainly consist of *Orbitolina* sp*., Trocholina sp*., Echinoderm stem and spin, Gastropods, Crinoids, *Nezzazata* sp., and coarse rudist fragments. Peloids are the non-skeletal grains which are pervasively observed in thin sections (Figure 2D). MF3 is the main microfacies type observed in Well 3.

Interpretation: The presence of microfauna such as *Orbitolina* sp., *Nezzazata* sp., and Gastropods shows that the deposition was taken place in a lagoonal environment. In some cases the presence of coarse rudist fragments in association with *Trocholina* and *Orbitolina* sp. shows the development of this facies in leeward shoal environments.

MF4: Peloid Skeletal Packstone to Grainstone

The fabric of this microfacies is packstone to grainstone. The main allochems identified in this microfacies are *Orbitolina sp., Trocholina sp., Pseudolituonella* sp., large shell fragments, *Nezzazata* sp*., Chrysalidina* sp., Gastropods, Echinoderm, and Miliolids (Figures 2E and 2F). The skeletal grains reach about 60%. The non-skeletal grains are peloid and rarely intraclast with the total amount of 15%.

Interpretation: Grainstone fabric, low amount of micrite, and the presence of calcite cement indicate the deposition of this microfacies in a high energy leeward shoal and shoal environment.

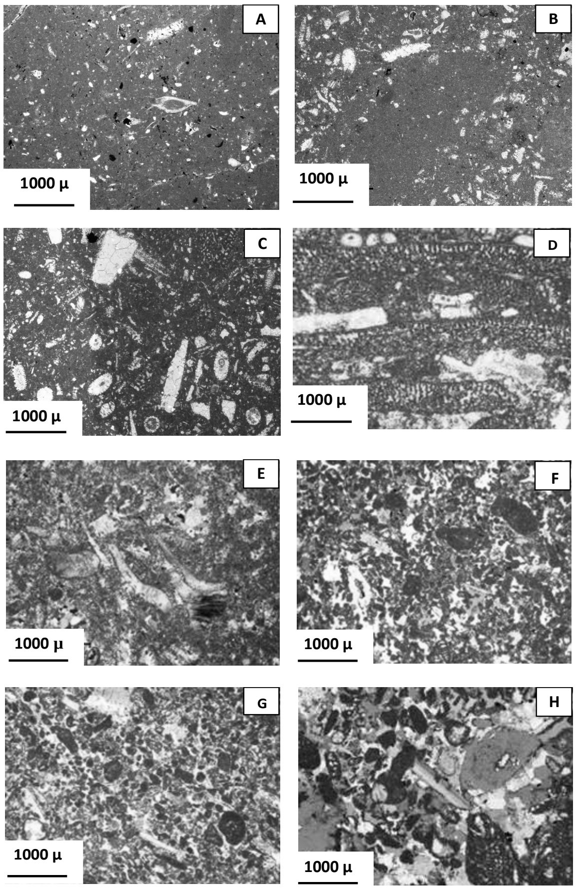

Figure 2: Photomicrograph of different microfacies. A) MF1: Skeletal wackestone, PPL; B) MF1: Skeletal wackestone with bioturbation, PPL; C) MF2: Skeletal wackestone to packstone (thin section stained with alizarin red-s), PPL; D) MF3: Dolo skeletal packstone, PPL; E) MF4: Skeletal packstone with rudist debris, XPL; F) MF4: Skeletal packstone to grainstone, XPL; G) and H) MF5: Skeletal grainstone, XPL.

MF5: Skeletal Grainstone

This microfacies is characterized by grainstone fabric. The main components of MF5 are *Orbitolina* sp., Miliolids, Echinoderm, *Nezzazata* sp., *Chrysalidina* sp. associated with rudist debris and large shell fragments (Figures 2G and 2H). Allochems are coarse grained and rounded to subrounded and calcite cement has filled interparticle porosity. Micrite envelopes were observed around some of the allochems. This microfacies is not observed in Well 1.

Interpretation: Grain-dominated fabric, the presence of calcite cement, and lack of matrix suggest the deposition in the bioclastic shoal environments.

Depositional Environment of Mauddud Member

Based on the sedimentological studies carried out on the cores and thin sections, 5 microfacies have been identified. By the comparison of these microfacies with Wilson [13] and Flügel [14] standard facies belt, two types of carbonate facies belt were recognized. These facies belts included shallow lagoonal environment and small bioclastic shoal (Figure 3). Based on microfauna such as *Orbitolina* sp. *Trocholina* sp., MF1 to MF3 were deposited in a vast lagoonal environment with different depth and energy [14]. MF4 and MF5 with coarse grained, rounded to subrounded, large allochems, and grainstone texture revealed the deposition in a high energy environment. Therefore, the deposition in the bioclastic shoals environment was suggested.

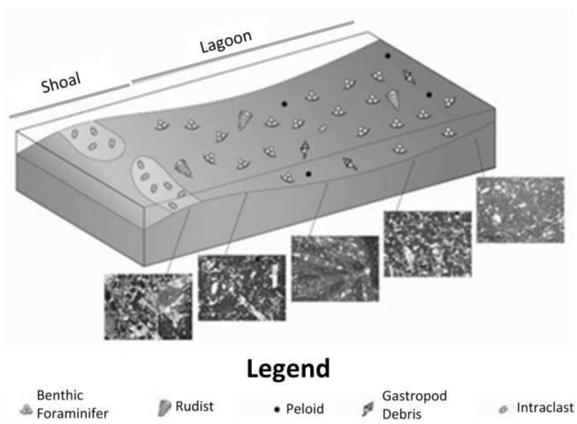

Figure 3: A schematic block diagram of Mauddud member

Based on the lack of calciturbidities, great barrier reefs, and gradual change of microfacies into each other [20], deposition in a gentle homoclinal ramp have been proposed for the Mauddud member. This model also was proposed for the Mauddud formation in Kuwait area (onshore), Abu Dhabi, United Arab Emirates, and Saudi [19,21].

Diagenetic Processes and their Effects on Reservoir Quality

Several diagenetic processes have affected the Mauddud member. These processes include bioturbation, micritization, cementation, compaction, pyritization, dissolution, and dolomitizetion, which are described below.

Bioturbation

Bioturbation is essentially a syn-depositional phenomenon, whereby organisms deform the sediments early in their diagenetic history. This process in the samples has been identified in the form of burrowing which disturbs the original depositional texture and sedimentary structures of the facies (Figure 2B).

Micritization

This is a process whereby bioclastic grains are altered on sea floor or just below by bacteria, fungi, and endolithic algae in quieter-water areas, leading to the formation of micritic envelops around bioclasts [18]. Micritization, which is an early diagenetic process, and formed in a shallow marine environment [22-24], may decrease permeability by filling pore throats or decreasing their sizes. However, early micritization might help to prevent porosity reduction due to burial compaction [4]. This phenomenon is widespread and some of the bioclastic grains such as echinoderm debris are bored around the margin and the holes filled with micrite and cause to form micrite envelope (Figure 4A). Since the action of endolithic algae is intensive, most of the skeletal grains and other allochems are completely micritized.

Cementation

Various types of cement, as described in the following section, were formed in the studied field.

Sparry Calcite Cement

Sparry calcite cement was formed in the late stage of diagenetic history and was pervasively distributed in the samples. This type of cement usually plugged or reduced different types of porosity especially vuggy type. Cementation found to be of two different types. Microspares mainly cemented the spaces between the grains and caused a tight and dense structure, which reduced the porosity and the coarse sparry formed due to the recrystallization of micrites and microsparites to coarse sparite. This phenomenon occurred between the allochems and interspaces of some allochems (Figure 4B). The core observation showed that coarse sparry calcite cements mostly filled the fractures and vugs.

Syntaxial Cement

Syntaxial overgrowth cement grows in optical continuity with echinoderm grains. In skeletal grainstones with abundant echinoids, the overgrowth cement may partially fill primary intergranular pores, while this type of cement is formed around echinoderm debris. The amount of this cement in the studied interval is low and observed up to 1% in some samples (Figure 4C). Hence the effect of this type of cement on reservoir quality is negligible.

Neomorphism

Neomorphism is one of the major diagenetic processes effected both the structure within the allochems and the matrix background. As a result of this process, aragonitic allochems such as gastropods or some shell fragments are replaced with calcite (Figure 4D).

The aggrading neomorphism is another process occurred chiefly in fine grained limestone such as microcrystalline carbonate and forms microspare and coarse sparry calcite.

Compaction

Compaction in the Mauddud member of the Sarvak formation is due to mechanical and chemical processes depending on the overburden pressure (mechanical compaction by means of grain resistance in grain supported facies). Stylolites and solution seams are the products of chemical compaction. These features are frequently observed in the cores and thin sections (Figure 4E). Stylolites are in the form of high and low amplitudes developed locally in all the wells. They are mostly oil stained and it seems that these are acting as a passage for hydrocarbons. The presence of dolomite crystals along the solution seams indicates that the brines were flowing along them.

Pyritization

Pyrites are most abundantly observed in two forms either scattered in the matrix or local accumulation. They are either in the amorphous form or in the euhedral shape of tetragonal or pentagonal forms. In some samples, shell fragments such as pelecypods are selectively replaced with pyrite (Figure 4F). They are also crystallized along the fractures. Also, in some samples, the pyrite replacements have been partially altered to hematite (reddish), probably during exposure and weathering.

Dissolution

Dissolution is the main diagenetic process that improves porosity and permeability, and therefore leads to improved reservoir quality [4].

Dissolution depends on the solubility of the minerals; for example, the solubility of calcium carbonate increases from low magnesium (LMC) to aragonite and high-magnesium calcite (HMC).

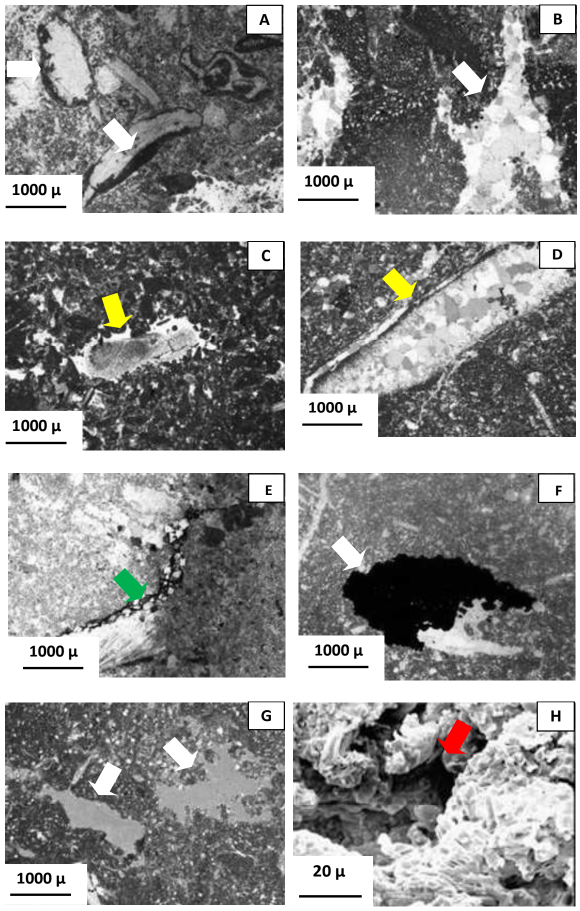

Figure 4: Photomicrograph of different diagenetic processes; A) Micrite envelope around rudist debris, PPL; B) Sparry calcite cement, XPL; C) Syntaxial cement around echinoderm debris, PPL; D) Neomorphism in a skeletal debris, XPL; E) Solution seams with crystals of dolomite around it, XPL; F) Partial fabric selective pyritization in a shell fragment, PPL; G) vuggy porosity (in purple), XPL; H) SEM photo of microporosity.

Dissolution generates three types of porosity, namely vuggy, moldic, and enlarged intergranular porosity, of which vuggy porosity is the main dissolution type. The formation of vuggy porosity appears to be non-fabric selective [25], involving the dissolution of all components (matrix, cement, and grains). The amount of dissolution depends mainly on the length of time that the sediments are exposed to meteoric water. In this study, vugs and micro-vugs were recognized in wackestone and packstone lithofacies of upper Mauddud, which was deposited in a lagoonal environment (Figures

4G and 4H). Microvugs were also recognized in dolomitized wackestone and pack-stone microfacies. Dissolution is thought to have taken place in the meteoric fresh water zone and occasionally in the mixed marine-fresh water zone [4].

Dolomitization

Generally two phases of dolomitization, which are described below in details, have influenced the studied intervals.

Microcrystalline Dolomite

This type consists of very fine grained, unimodal, anhedral crystals of dolomite (Figure 5A). It is classified as nonplanar dolomite based on Sibley and Gregg's classification [16] and xenotopic-A in Gregg and Sibley's classification [15]. Based on the classification of Folk [26], this type of dolomite size is categorized as dolomicrite. The microcrystalline dolomite partially replaced the precursor limestone either in fabric selective form or non-fabric selective one. It means that in some samples, dolomite replaced precursor limestone and only some of the allochems such as agglutinated shells of *Orbitolina* sp. remained unchanged, and in others, both allochems and matrix were dolomitized. They were originated during the early diagenetic history.

Euhedral to Subhedral Dolomite

This type consists mostly of limpid, euhedral to subhedral crystals of dolomite (Figures 5B and 5C). In some samples replacement, dolomite has a zoning with cloudy center and clear ream (CCCR) (Figure 5D). Because of high calcite inclusion, the center of dolomite crystals seems cloudy. Probably the supper-saturation of dolomitizing fluid was low during the replacement [16]. They were mostly crystal supported with intercrystalline area filled with calcite and/or porous (Figure 5E). They were classified as planar-e (Figure 5F) [16] and isotopic-[15].

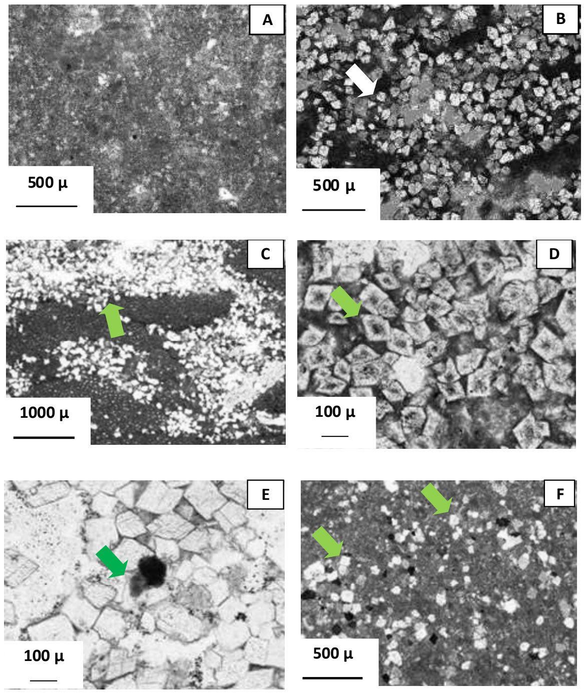

Figure 5: Photomicrograph of different types of dolomite; A) Microcrystalline dolomite (note that crystals of dolomite scattered between microcrystalline calcite) PPL; B) Coarse crystals of planar-e dolomite with vuggy and a few intercrystalline porosity (in purple), XPL; C) Photomicrograph of planar-e dolomite in skeletal packstone, XPL; D) Photomicrograph of cloudy center and clear rim dolomite (CCCR), PPL; E) Photomicrograph of dolomite in peloid skeletal packstone (glauconite can also be observed) PPL; F) Scatter rhomb of dolomite in the matrix (planar-p dolomite), XPL.

Some of the crystals distributed in the matrix with a texture of planar-p or porphyrotopic; this type was formed as post-stylolites or post-fractures. In post-fracture mode, dolomite rhombs followed fractures that might provide the ions and water necessary for their formation [2]. In post-stylolite mode, stylolite seams acted as channels instead of permeability barriers. The dolomite might have been formed by Mg released during pressure solution [27]. The term "styloreactate" was introduced by Logan and Semeniuk [28] to describe minerals formed by reaction in or along the stylolite seams.

Porosity Types

Mauddud member shows low porosity in both core and thin section investigations, whereas the porosity data reported from routine analyses are much higher than the visual porosity. It means that the main porosity appears in the form of matrix porosity and is not visible under microscope. The main types of porosity observed in the Mauddud members are as follows:

Vuggy Porosity

The thin section study shows that the vuggy porosity observed is either in the form of microvugs or vugs (Figure 6A). The vuggy porosity is the dominant type of porosity observed in the ranges between 1-20% with an average amount of 5-7%.

Fracture Porosity

It is the second major type of porosity observed in core as well as thin sections (Figure 6B). The frequency of the fractures is not abundant in cores. They are mostly in the form of hairline fractures and locally developed, and they do not have continuity. Some of the fractures in core examination (aperture: 1-2 mm) are filled with calcite cements.

Intraparticle Porosity

Intraparticle porosity observed in Orbitolina sp. (Figure 6C) is the main allochem found in most of the microfacies. This type of porosity is rarely observed in *Textularia sp*. and algae like lithocodium aggregatum. It is mostly plugged into calcite cements. Intraparticle porosity is not very frequent in thin sections.

Matrix Porosity

The result of core porosity (routine analysis) of the studied interval is much higher than the visual porosity. These differences are related to matrix porosity, which cannot be observed in thin section. Therefore, by means of complementary methods such as SEM and impregnation with blue epoxy resin, this type of porosity has been identified. As a result, matrix porosity is the main porosity. Most of the matrix porosity consists of intercrystalline microrhombic porosity between the crystals of calcite and microcrystalline dolomite (Figure 6D).

Interparticle Porosity

Similar to intraparticle porosity, this type of porosity is rarely observed in thin sections. It is found to be developed in packstones and grainstones assigned to leeward shoal or shoal facies.

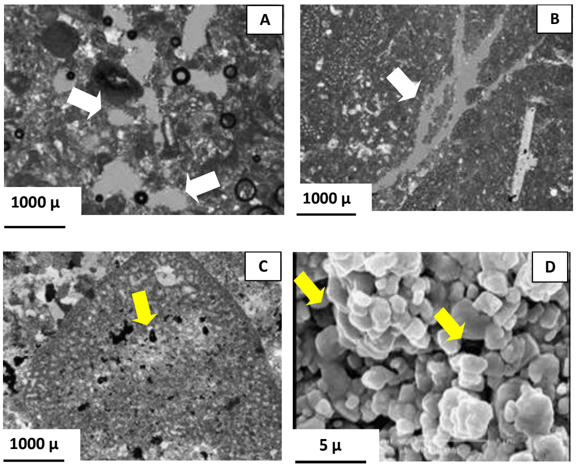

Figure 6: Photomicrograph of different types of porosity; A) Vuggy porosity in peloid skeletal packstone (in purple), XPL; B) Fracture porosity (in purple), XPL; C) Photomicrograph of intraparticle porosity in Orbitolina sp., XPL; D) SEM of matrix porosity.

Moldic Porosity

Moldic porosity formed after the dissolution of unstable shell fragments like *Trocholina* sp., bivalves, etc. The amount of moldic porosity is up to 5% in some samples; however, most of them is reduced or completely plugged into calcite cement.

Paragenetic Sequence

Diagenetic processes of three diagenetic environments affected the Mauddud member.

The first diagenetic environment was marine environment. The micritization of the allochems as a result of the activity of algae, bacteria, and fungi was taken place in the early stage of the diagenesis on the sea floor.

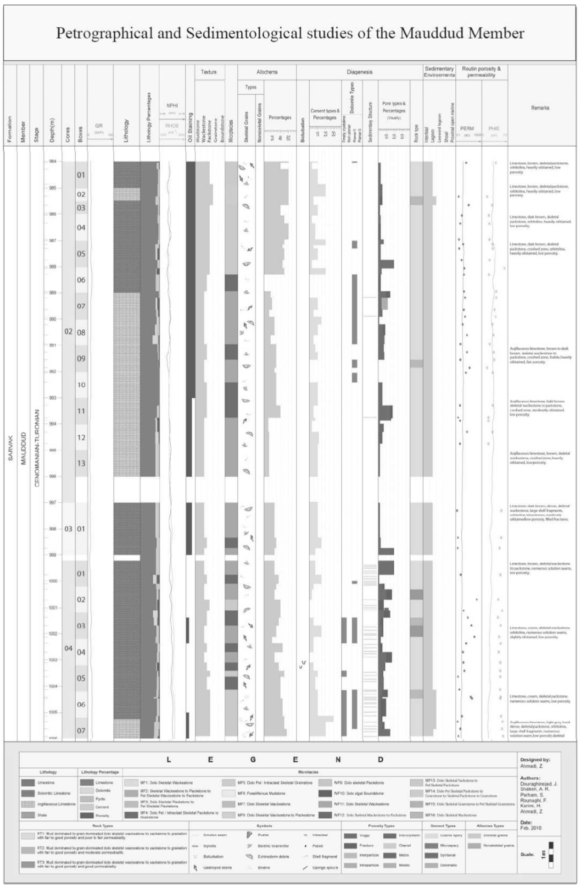

Figure 7: Petrographical and sedimentological logs of the Mauddud member in the studied field

At first, micrite envelope was formed around the allochems. By developing the action, all the allochems were replaced with micrite. Bioturbation in the form of burrowing was another diagenetic process which happened in the marine environment. Syntaxial cement was a type of cement formed around the echinoderm debris in this environment. Moreover, syntaxial cement can form in other diagenetic environments and cathode-luminescence is required to determine the precise depositional environment.

After the deposition of the Mauddud member, an unconformity occurred and, as a result, the formation was affected by meteoric diagenesis. Dissolution as a result of undersaturated meteoric water influenced the carbonate rocks of this formation and formed vuggy porosity.

In the burial environment, different diagenetic processes affected the formation. These processes included compaction, fracturing, sparry calcite cement, and dolomitization. In a shallow burial environment, overburden pressure caused to form fitted fabric and shell breakage. By increasing the depth of burial, solution seams and stylolites were formed. Fracturing was also formed under the pressure in this environment. The probable source of the calcite cement was the carbonates which were dissolved during the formation of solution seams and stylolite as a result of overburden pressure.

Calcite cement was deposited in the vuggy fracture or any other types of porosity and therefore clogged and/or decreased the voids. Neomorphism of some of the aragonitic allochems to calcite and replacement and formation of pyrite happened in this environment. The absolute time of dolomitizetion cannot be determined, but it seems that fine crystalline dolomite (phase 1) was formed prior to the coarse crystalline euhedral dolomites (phase 2). Some of the dolomite rhombs were formed around the stylolite and so the relative time of the formation of this type was after the formation of stylolite in the burial environment.

It seems that the dolomitization of phase two, which consists of coarse crystals of euhedral dolomite, has a local source and is not well developed in the whole part of the formation. The paragenetic sequence of diagenetic processes is demonstrated in the diagram. This diagram shows the relative time of different processes.

Table 1: Paragenetic sequence of diagenetic processes of the Mauddud member in the studied field

Diagenetic Events	Early → late
Bioturbation	———
Boring	———
Micritization	————
Sparry calcite cement	—————
Neomorphism	————
Mechanical Compaction	————
Microcrystalline Dolomite	————
Chemical Compaction	————
Planar-e to Planar-s dolomite	———
Dolomite around stylolite	———
Fractures	——- - - - - -
Dissolution	——- - - - - - - -

Diagenesis and Reservoir Quality

Diagenetic processes involved in Mauddud member were responsible for the modification of reservoir quality. From the point of view their effect on reservoir quality, these diagenetic phenomena are compartmentalized into three groups, including increasing reservoir quality, decreasing reservoir quality, or having no effect on reservoir characterization, as described below:

Processes Enhancing Reservoir Quality

1- Dissolution formed different types of porosity including vuggy and moldic porosity; thus dissolution had a positive effect on reservoir quality;

2- Fracturing occurred in the studied interval; although the frequency of fractures was not high and the amount of fracture porosity was between 0-4%, it had a positive effect on reservoir quality;

3- Dolomitization by forming intercrystalline matrix porosity locally enhanced reservoir quality.

Processes Decreasing Reservoir Quality

1- Cementation is the most important diagenetic feature which reduced porosity. Calcite cement in the form of sparry calcite had the most negative effect on reservoir quality. The distribution of sparry calcite cement was high and observed almost in all of the samples; it reduced or occluded different types of porosity including vuggy, fracture, and intraparticle porosity.

2- Chemical compaction by forming solution seems and stylolite had different effects on reservoir characterization. Parallel to the orientation of solution seam, it acted as a conduit for hydrocarbon passage, while perpendicular to the solution seams and stylolite it behaved as a barrier. Mechanical compaction produced fitted fabric and formed a packed texture. Hence, it was a process with negative effects on reservoir characterization.

Process with No or Negligible Effect on Reservoir Quality

Bioturbation, micritization, pyritization, and neomorphism were different diagenetic features which had no or a negligible effect on reservoir quality.

CONCLUSIONS

According to the results obtained, the following conclusions can be drawn.

1- Based on sedimentological investigation of cores and thin sections of the Mauddud member in the studied field, five types of microfacies were identified. These microfacies were deposited in two facies belt related to lagoon and bioclastic shoal;

2- Based on the lack of calciturbidities, great barriers, and the gradual change of microfacies, the Mauddud member was deposited in a homoclinal ramp platform;

3- Different diagenetic processes, including bioturbation, micritization, cementation, dolomitization, dissolution, and compaction, affected this member. Among all, dissolution and dolomitization increased reservoir quality, while cementation and compaction had a negative effect on reservoir characteristics;

4- Matrix porosity was the main type of porosity in the studied interval;

5- Although the Mauddud member showed the effect of dissolution during meteoric diagenesis, it was not subaerially exposed for a long period of time. Therefore, the dissolution, which was one of the most important factors improving reservoir quality in the southern Persian Gulf, was not well developed in this member;

6- Dolomitization, which was one of the most important processes of improving reservoir quality of the Mauddud member in the southern Persian Gulf, was not well developed in the Iranian marine border either;

7- Finally, reservoir characterization was not facies selective and different microfacies related to different environments showed similar reservoir properties.

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