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Microfacies, Depositional Environment and Diagenetic Processes of the Mauddud Member, in a Field in the Persian Gulf

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Abstract

Mauddud Member with the age of Late Albian to Cenomanian is a part of Sarvak Formation in adjacent area, shows different characteristics. This study investigates the sedimentological studies and reservoir characterization of the Mauddud member in a field in the Persian Gulf. According to petrographical studies of both cores and thin sections available, five types of microfacies related to shallow marine carbonate ramp has been identified which are deposited in a vast lagoon and local bioclastic shoal. Different diagenetic processes affected this member which is bioturbation, micritization, cementation, dolomitization, dissolution, and compaction. Among all, dissolution increased reservoir quality, while cementation and compaction decreased reservoir characteristics.

Keywords: Mauddud member; Microfacies; Depositional environment; Diagenetic processes; Reservoir Quality; Persian Gulf

Introduction

Mauddud Member is equivalent to Lower Sarvak Formation and designated to represent the Orbitolina-bearing limestone of the southern Persian Gulf. It shows different occurrence in neighboring countries. For example in Bahrain produced oil in Awali Field, in United Arab Emirates has no production but represent oil shows in some offshore wells. In Oman hydrocarbon bearing in some central Oman fields, in Iraq oil in Jambur and Kabbaz and oil shows in Kirkuk field and in Iran has no production, but represent oil shows in some wells [1] This study concentrates on microfacies analysis, depositional environment, diagenesis and the effects of diagenetic processes on reservoir properties in a field located in the Persian Gulf (Figure 1).

Stratigraphy of the sarvak formation

The Sarvak Formation is a part of Bangestan Group which is known as one of the giant oil reservoir in southwest and the Persian Gulf. The type locality is in Tang-e-Bangestan in Khuzestan Province and its thickness reaches to 832 meters [2,3]. It is equivalent to Mauddud, Ahmadi and Mishrif Formation of the Persian Gulf region [4]. It is conformably overlies the Kazhdumi Formation with a gradational 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 coastal northern Persian Gulf, the Sarvak Formation 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 [4]. The Mauddud member is described below.

Mauddud member

This formation in the study field is mainly composed of brown dolomitic limestone. The Mauddud member overlies Kazhdumi Formation, but passes upward into Ahmadi member. The cores belong to Mauddud member is heavily oil stained. Thickness of this formation is 52.3m in well#1 and 53.1m in the well#3 in the field under study.

Material and Method

About 60 m available cores related to three wells have been described. Different parameters such as lithology, texture, allochems and their frequency, diagenetic parameters such as pore types and percentages and sedimentary environment are recorded. The cross matching of visual observations have been done by thin sections that were prepared to confirm all the observations carried out in the core laboratory to minimize the errors on observations. The whole cores as well as slab photography are preceded simultaneously which are the support of all the observations carried out in core lab. About 161 thin sections of 3 wells have been studied. The microfacies, diagenesis and sedimentary environments were studied and interpreted in detail using the classification of Dunham [5] and Carozzi [6]. Depositional environment was determined using Wilson [7] and Flugel [8]. Gregg and Sibley [9], Sibley and Gregg [10], and Mazzullo [11] used for classification of dolomites. Seven samples have been selected for SEM analysis in order to study microporosity and fine calcite and dolomite crystals. This analysis has been done in Tarbiat Modarres University with Phillips XL30. They send to Using the sedimentological data a 3D depositional model will be prepared showing the regional history of deposition of the Mauddud Member in the area.

Microfacies

Sedimentological studies have been resulted in identification of five microfacies (MF) described below.

MF1-Dolo skeletal Wackestone: This Microfacies mainly consists of Orbitolina sp., Trocholina sp., Textularia sp, Echinoderm, Gastropod, Rudist debris, Ostracod, shell fragments, Lenticulina, thin walled shell fragments, Pelecypod, Miliolid and Chrysalidina sp.. Orbitolina sp. is the main component which is mixed with other bioclasts mentioned above. Bioturbation had been affected on some of the samples (Figures 2a,2b). This microfacies represents a low energy, inner ramp, protected lagoonal deposit [12]. The Frequency of this microfacies in the well#1 and well#2 are high but its amount in well#3 is lower than the others. Dolomitization has been affected on this microfacies. The crystallization of dolomites along the stylolites is also seen. Vuggy porosity is a common porosity type with the amount of

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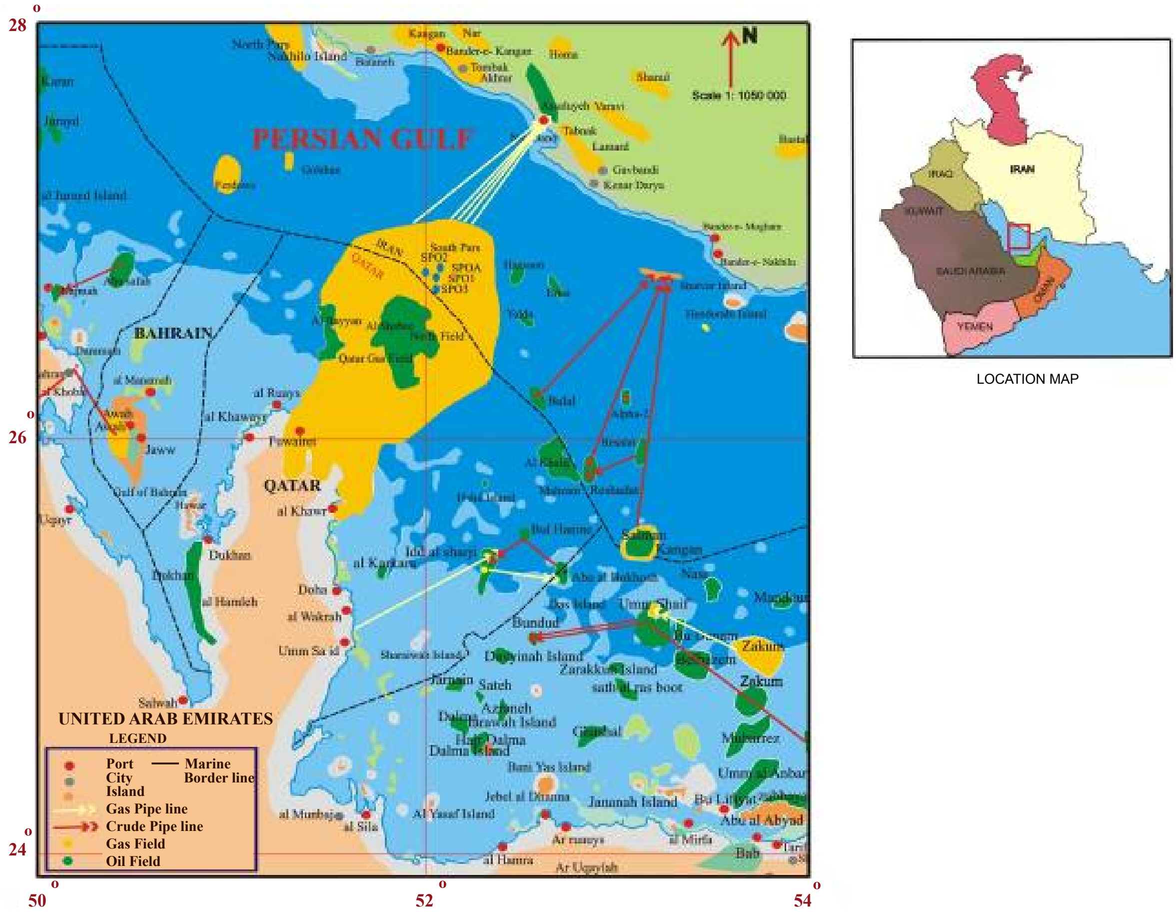

Figure 1: Location map of the field under study is shown with red rectangle.

5-20% (Average-12.5%) in well#3.The calcite cement filled the vugs or replaced the allochem tests.

MF2-Dolo skeletal Wackestone to Pack stone: This microfacies 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. have been identified (Figure 2c). In this facies dolomitization pervasively affected both the matrix and the allochems particularly the Orbitolina. It clearly shows that in some samples dolomitization is fabric selective and allochems is partially replaced with dolomite whereas in others it is not fabric selective and both matrix and allochems are replaced with dolomite. The total porosity ranges between 1-25% (averages 9.95%) in well#2 whereas in well#1 and well#3 it is about 2-18% (average 7.33%) and 4.0-8.0% (average 6.0%) respectively. The main pore types are micro vugs and open fracture types though in rare cases intraparticle and intercrystalline porosities are also observed particularly between the euhedral dolomite crystals which are formed locally in the matrix. The intercrystalline porosity mainly is filled out by dolomicrite cements. The percentage of cement varies between 2-30%. They are mainly of coarse sparry calcite cement. The percentage of allochems ranges between 35-45%. They are mostly coarse grained. The core and thin section show that this facies mainly is deposited in a vast lagoonal environment.

MF3-Dolo Skeletal Pack stone to Peloid Skeletal pack stone: It is the main microfacies type observed in well#3. This microfacies contains Orbitolina sp., Trocholina sp., Echinoderm stem and spin, Gastropods, Crinoids, Nezzazata sp. and coarse rudist fragments. Peloids are the nonskeletal grains that pervasively observed in thin sections (Figure 2d). Dolomitization is the main process affecting the matrix as well as the allochems. Cementation is another process found in two forms; equate micro spars and coarse spars. In some samples the glauconites have also identified. The presence of microfauna such as Orbitolina sp. Nezzazata sp. and Gastropods show that the deposition has taken place in a lagoonal environment. In some cases the presence of coarse rudist fragments in association with Trocholina and especially with Orbitolina sp. show the development of this facies in leeward shoal environments.

MF4-pel skeletal pack stone to grain stone: The main allochems has been identified in this microfacies are Orbitolina sp., Trocholina sp., Pseudolituonella sp., large shell fragments, Nezzazata sp., Chrysalidina sp., Gastropods, Echinoderm and Miliolid (Figure 2e, 2f). The skeletal grains reach up to about 60%. The non skeletal grains are less than 15%. The non-skeletal grains are peloid and rarely intraclast. The main pore type observed is of vuggy type though the intraparticle, interparticle and intercrystalline porosities are also observed in lesser percentages. The cements are mostly of coarse sparry calcite. The thin section observation shows that the calcite cement filling highly decreased the porosity percentage. As seen in previous facies the process of dolomitization highly affected the allochems as well as the matrix. It seems that the porosity (intercrystalline) mainly induced between the micro-rhombic dolomite and calcite matrix. The presence of large

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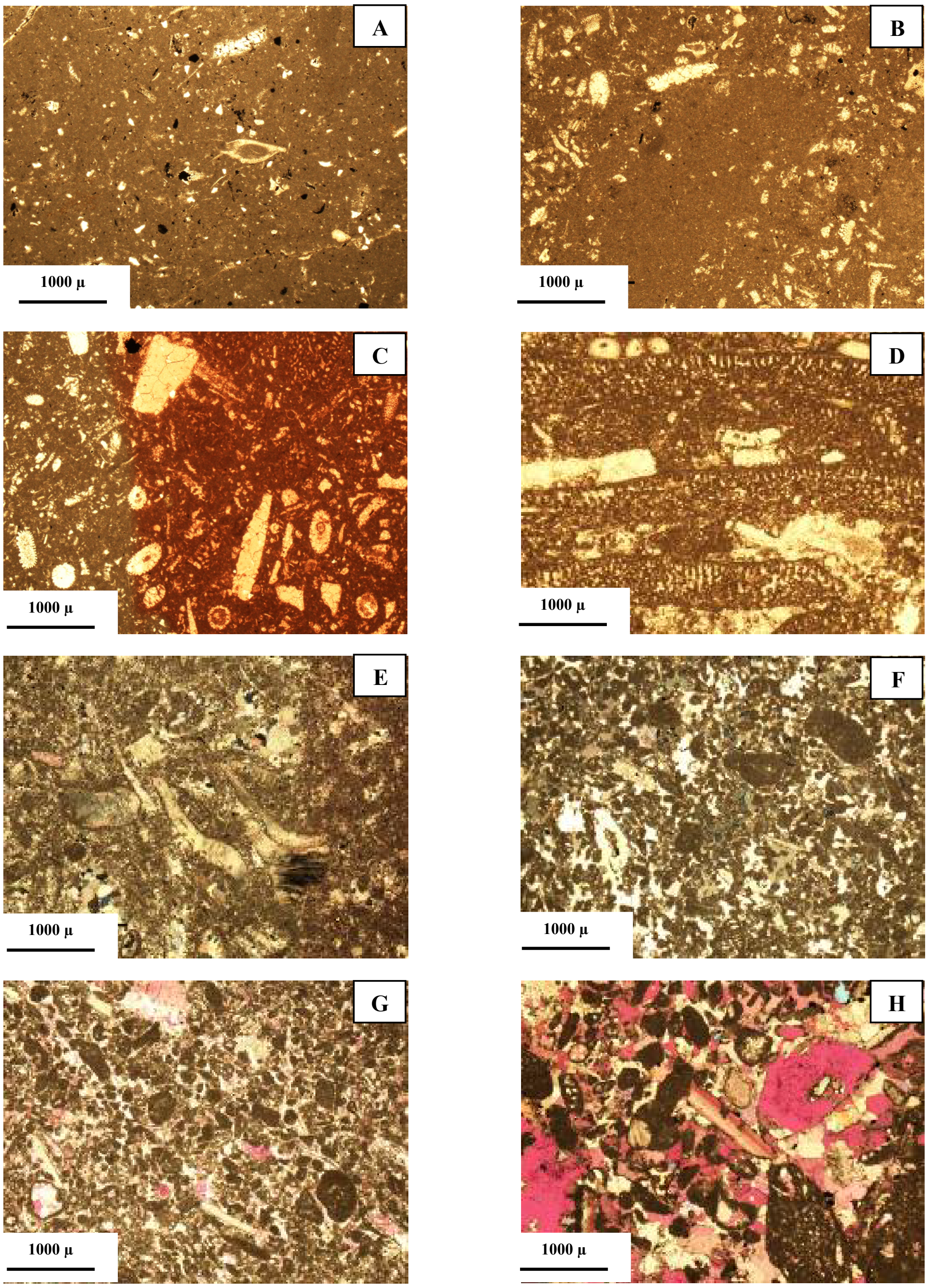

Figure 2: Photomicrograph of different microfacies. A: MF1- skeletal wackestone. PPL. B: MF1- skeletal wackestone with bioturbation. PPL. C: MF2- skeletal wackestone to packstone (thin section stained with alizarin red-s). XPL. D: MF3- dolo skeletal packstone. XPL. E: MF4- skeletal packstone with rudist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

number of allochems indicates the deposition of this microfacies has taken place in shoal and leeward shoal environments.

MF 5-skeletal grain stone to peloid skeletal grain stone: The main components of MF5 are Orbitolina sp., Miliolid, Echinoderm, Nezzazata sp., Chrysalidina sp., associated with rudist debris and large shell fragments (Figure 2 g, 2h). This microfacies does not observe in the well#1. Sparry calcite cement filled the interparticle porosity.

Micrites envelop, neomorphism, filled fracture and mechanical compaction have been observed. The amount of calcite cement is between 7-30%. Dolomite percentage in the well#2 is very low (1%) and in the well#3 is between 15-30%. This microfacies was deposited in the shoal environments. In different microfacies of Mauddud Member up to 1% quartz grains (sand size) and phosphatic debris also observed.

Depositional Environment of Mauddud Member

Based on petrographic studies carried on cores and thin sections,

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two types of carbonate facies belt [7] have been recognized. These facies belts include shallow lagoonal environment and small bioclastic shoal (Figure 3).According to this study, and based on microfauna such as Orbitolina sp. Trocholina sp., the microfacies MF1 to MF4 were deposited in a vast lagoonal environment with different depth and energy [8]. While MF5 with coarse grained, rounded to sub rounded, micritized large allochems revealed deposition in a high energy environment. So the deposition in bioclasitc shoals environment has been suggested. Based on the lack of calciturbidites and open marine fauna, a gentle carbonate ramp platform proposed for the Mauddud member. Many studies carried out by several researchers on the Sarvak Formation are from Abu Dhabi, United Arab Emirates and Saudi Arabia. For example, the Mauddud Formation in Kuwait area (on shore) was deposited along a gently northward and northeastward direction dipping homoclinal ramp [12,13].

Diagenetic Processes and Their Effects on Reservoir Quality

Diagenesis in rocks is generally taken place as any process that acts upon sediment or rock that alters chemical, physical, or textural character. This is more important in reservoir quality evaluation after textural facies determination to find the reservoir characteristics. Several diagenetic processes affected the Mauddud Member. Among them, bioturbation, micritization, cementation, compaction, pyritization, dissolution and dolomitization are the most significant. Reservoir quality is generally diagenetically controlled. Diagenetic processes have greatly influenced the reservoir quality of Mauddud Member of the Sarvak Formation.

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 disturbing the original depositional texture and sedimentary structures of the facies destroyed the reservoir quality (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 a quieter-water areas, leading to the formation of micritic envelops around bioclasts [14]. Micritization, which is an early diagenetic process characteristics of the shallow marine environment [15-17], May decrease permeability by filling pore throats or decreasing their sizes. However early micritization might help to prevent porosity reduction due to burial compaction [18]. 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 caused to form micrite envelope (Figure 3a). Since the action of endolithic algae is intensive, most of the skeletal grains and other allochems are completely micritized.

Cementation

Various types of cement were formed in the field under study are as follows.

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 types. Cementation found to be of two

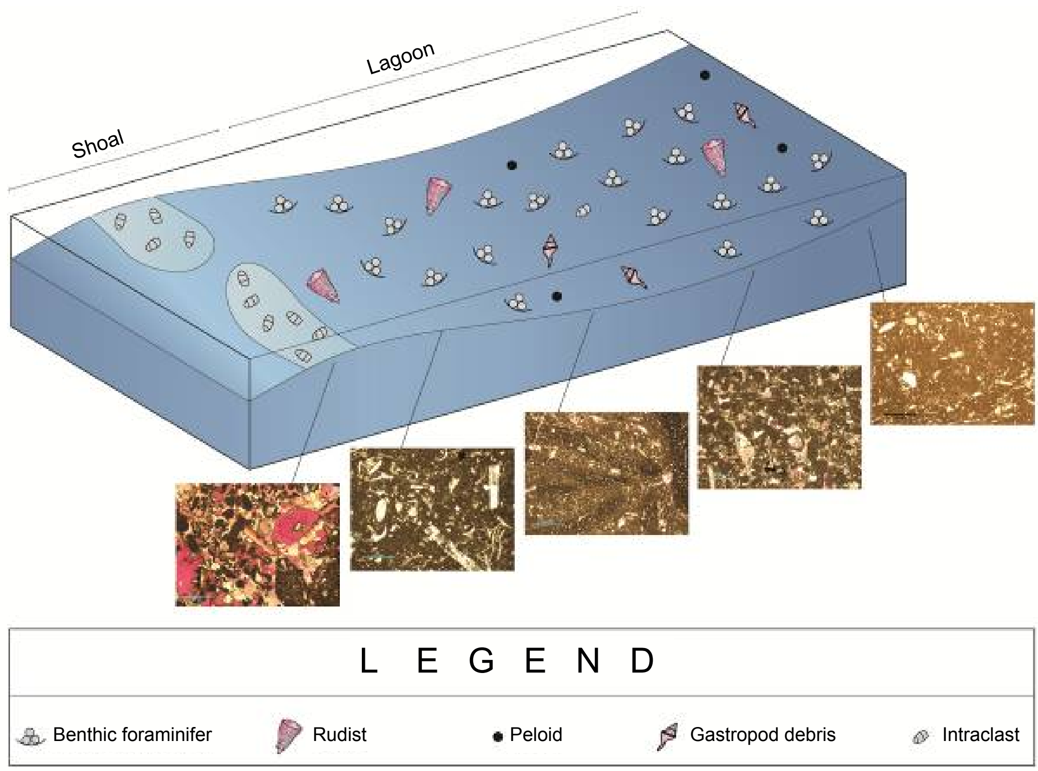

Figure 3: Schematic block diagram of Mauddud member.

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different types. Micro spares mainly cemented the spaces between the grains and cause a tight and dense structure decreasing the porosity and the coarse spary which forms due to recrystallization of micrites and microsparites to coarse sparite. This phenomenon occurred between the allochems and interspaces of some allochems (Figure 3b). The core observation shows 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 fills primary intergranullar pores, while this type of cement formed around echinoderm debris. The amount of this cement in studies interval is low and observed up to 1% in some samples (Figure 3b). So the effect of this type of cement on reservoir quality is negligible.

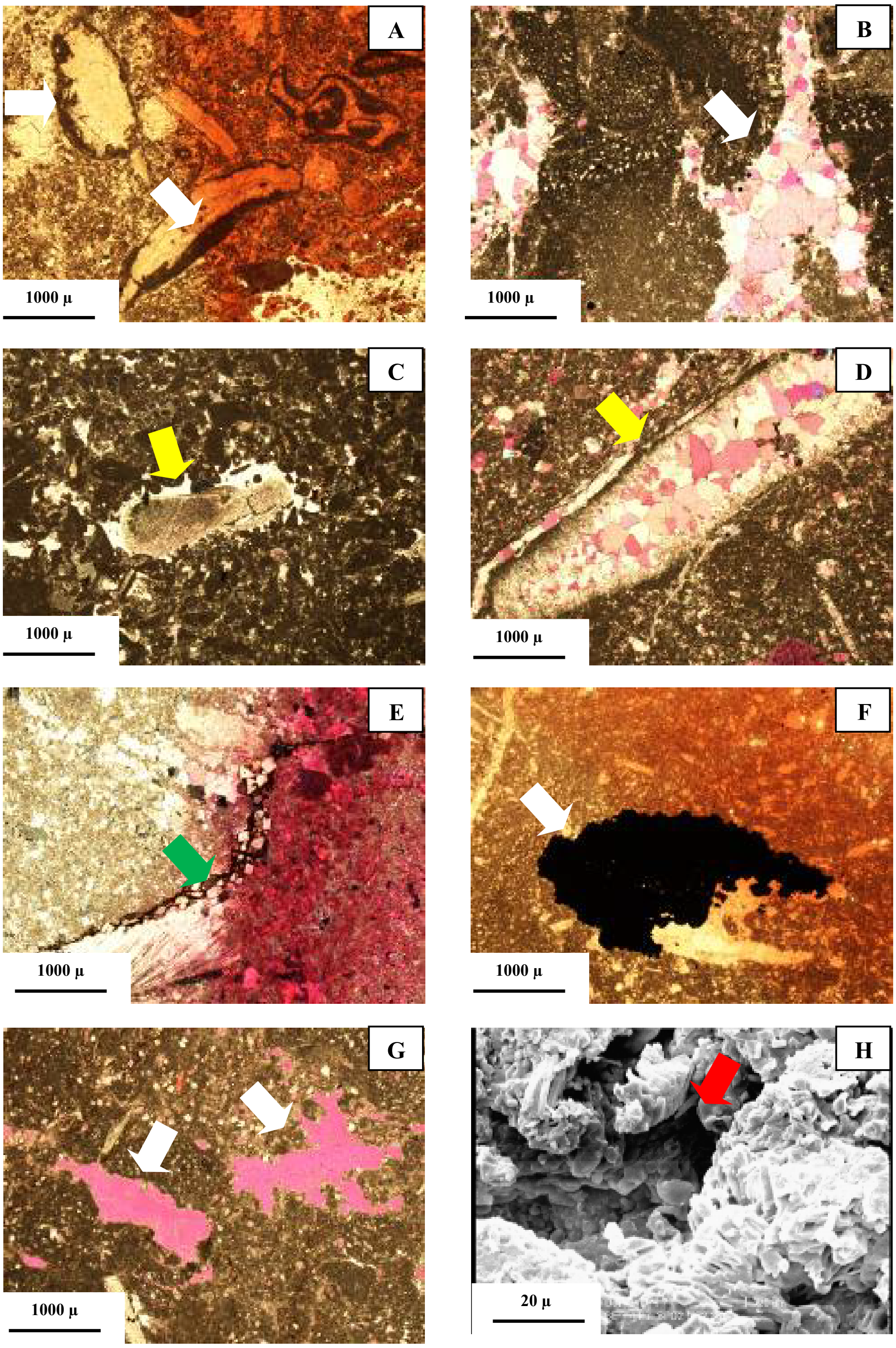

Figure 4: Photomicrograph of different diagenetic processes. A: micrite envelope around rudist debris. PPL. B: spary calcite cement. XPL. C: syntaxial cement around echinoderm debris xpl. D: neomorphism in a skeletal debris, XPL. E: solution seams with crystals of dolomite around it. XPL. F: partial fabric selective pyritization in a shell fragment.ppl. G: vuggy porosity (in purple). XPL. H: SEM photo of microporosity.

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Neomorphism: Neomorphism is one of the major diagenetic processes that is effected both the structure within the allochems as well as the matrix background. As a result of this process aragonitic allochems such as gastropods or some shell fragments are replaced with calcite (Figure 3d).

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

Compaction

Compaction in the Mauddud Member of the Sarvak Formation is due to mechanical and chemical processes and ordinary depending of 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 cores and thin sections (Figure 3e). They are in 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 presents of dolomite crystals along the solution seams indicate that the brines were flowing along them.

Pyritization

Pyrite most abundantly observed in two forms either scattered in the matrix or local accumulation. They are either in the amorphous form or in the homogeneous shape of tetragonal or pentagonal forms. In some samples shell fragments such as pelecypods selectively are replaced with pyrite (Figure 3f). Also they are seen crystallized along the fractures. In some samples the pyrite replacements have been partially altered to hematite (reddish), probably during exposure weathering.

Dissolution

Dissolution is the main diagenetic process that improves porosity and permeability and therefore leads to improved reservoir quality after [18]. Dissolution depends of the solubility of the minerals; for example, the solubility of calcium carbonate increases form low

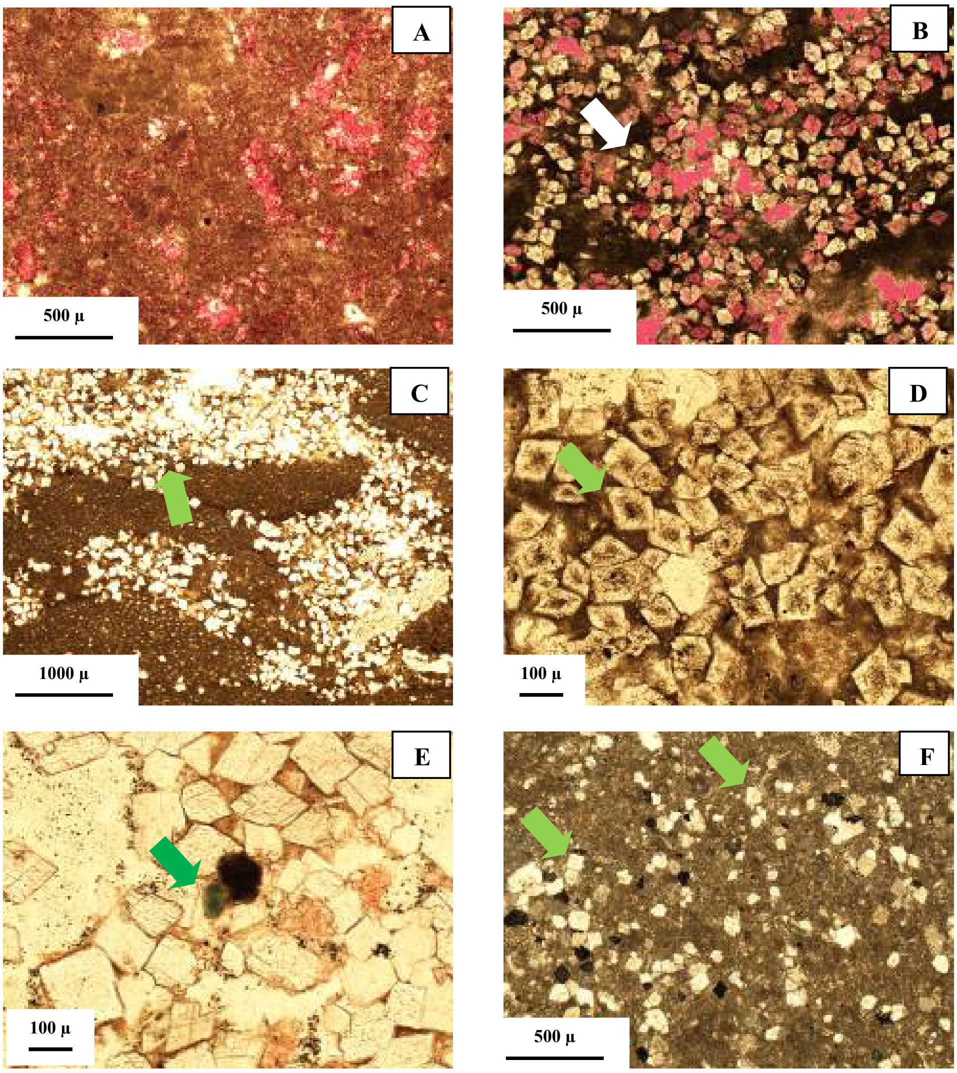

Figure 5: Photomicrograph of different types of dolomite. A: microcrystalline dolomite, note that crystals of dolomite scattered between microcrystalline calcite. PPL. B: coarse crystals of planar-e dolomite with vuggy and a few intercrystalline porosity (in purple). XPL. C: Photomicrograph of planar-e dolomite in skeletal packstone. Dolomitization is fabric selective and only matrix dolomitized. XPL. D: Photomicrograph of cloudy centre and clear rim dolomite (CCCR). PPL. E: Photomicrograph of dolomite in pel skeletal packstone, glauconite also can be observed. PPL. F: scatter rhomb of dolomite in the matrix (planar-p dolomite). XPL. B.

magnesium (LMC) to aragonite and high-magnesium calcite (HMC). Dissolution generates three types of porosity: 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 [19], involving the dissolution of all components (matrix, cement and grains). The amount of dissolution depends mainly on the length of time that the sediments were exposed to meteoric water. In this study, vugs and microvugs is recognized in wackestone and packstone lithofacies of upper Mauddud deposited in lagoonal environment. (Figure 3g, 3h). Microvugs are also recognized in dolomitized wackestone and packstone microfacies. Dissolution is thought to have taken place in the meteoric fresh water zone and occasionally in the mixed marine-fresh water zone [18].

Dolomitization

Dolomitization in the Mauddud Member is related to the host microfacies. In the lagoonal environment the dolomite crystals are mainly microcrystalline, euhedral and characteristically patchy or massive in occurrence.

Generally two phases of dolomitization have been affected on the studied interval. One phase of dolomitization affected some of the samples of the Mauddud Member with different percentage. The second phase of dolomitization has local distribution and was observed in some samples in the Mauddud Member. Both types of dolomite are described below in details.

Microcrystalline dolomite: This type consists of very fine grained, unimodal, unhedral crystals of dolomite (Figure 4a). It is classified as nonplanar based on Sibley and Gregg classification [10] and xenotopic-A in Gregg and Sibley [9]. Based on the classification of Folk [20] this type of dolomite size categorized as dolomicrite. The microcrystalline dolomite partially replaced the precursor limestone either in fabric selective form or nonfabric selective one. It means that in some samples dolomite replaced precursor limestone and only some of the allochems like agglutinated shells of Orbitolina sp. remained unchanged, and in others both allochems and matrix has been dolomitized. They are originated during the early diagenetic processes.

Euhedral to subhedral dolomite: This type consists mostly of limpid, euhedral to subhedral crystals of dolomite (Figure 4b, 4c). In some samples replacement dolomite has a zoning with cloudy center and clear ream (CCCR) (Figure 4d). Center of dolomite crystals are cloudy because of high calcite inclusion. Probably the supper-saturation of dolomitizing fluid was low during the replacement [10]. They are mostly crystal supported with intercrystalline area filled with calcite and /or are porous (Figure 4e). They classified as planar-e (Figure 4f) Sibley and Gregg [10], and idotopic-e Gregg and Sibley [9]. Some of the crystals distributed in the matrix form with a texture of planar-p or porphyrotopic. This type formed as post-stylolites or post-fractures. In post-fracture mode, dolomite rhombs followed fractures that may provide ions and water necessary for their formation [1]. In post-stylolite mode, stylolite seams act as channels instead of permeability barriers. The dolomite may have formed by Mg released during pressure solution [21]. The term "styloreactate" has been introduced by Logan and Semeniuk [22] to describe minerals that form by reaction in or along the stylolite seams.

Porosity types

Mauddud Member shows low porosity in both core and thin sections investigation, whereas the porosity reported from routine analysis is much higher than the visible porosity. It means that major porosity appears in the form of matrix porosity and in not visible under microscope. The core and thin section observation show the

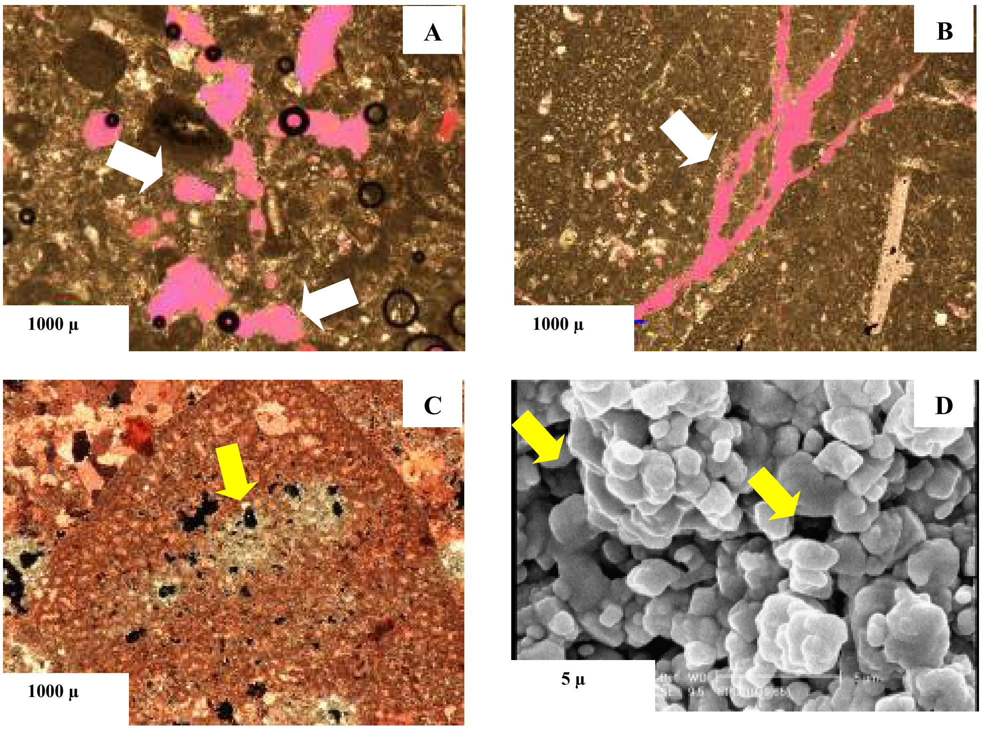

Figure 6: Photomicrograph of different types of porosity. A: vuggy porosity in pel skeletal packstone (in purple) XPL. B: Fracture porosity (in purple). XPL. C: Photomicrograph of intraparticle porosity in Orbitolina sp.. XPL. D: SEM of matrix porosity.

low percentage of visual porosity. The main porosities observed in the Mauddud Members are:

Vuggy porosity: The thin section study shows that the vuggy porosity observed are either in the forms of micro vugs or vugs (Figure 5a). The Vuggy porosity is dominant type of porosity observed ranges between 1-20% with the average amount of 5-7%.

Fracture porosity: It is the second major type of porosity observed in core as well as thin sections (Figure 5b). The frequency of the fractures is not abundant in cores. They are mostly in form of hairy fractures. They are locally developed and are not showing any continuity. The study of cores show the presence of filled fractures (aperture-1-2 mm) mostly filled with calcite cements. However in thin section both the open and filled fractures were observed.

Intraparticle porosity: Intraparticle porosity observed in Orbitolina sp. (Figure 5c, 6) which is the main allochem found in most of the microfacies. This type of porosity is rarely observed in Textularia sp. and algae's like Lithocodium aggregatum. They mostly plugged with 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, which cannot be observed in thin section. So by help 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 micro rhombic porosity between the crystals of calcite and also microcrystalline dolomite (Figure 5e).

Interparticle porosity: Similar to intraparticle porosity, this type of porosity also rarely observed in thin sections. They are found to be developed in packstones and grainstones assigned to leeward shoal or shoal facies.

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

Para Genetic Sequence

Diagenetic processes in three diagenetic environments affected the samples. The first diagenetic environment is marine environment. Micritization of the allochems as a result of the activity of algae, bacteria and fungi have taken place in the early stage of the diagenesis on the sea floor. At first, micrite envelope formed around the allochems. By developing the action, all the allochems replaced with micrite. Bioturbation in the form of burrowing are another diagenetic process which has taken place in the marine environment. Syntaxial cement is a type of cement formed around the echinoderm debris in this environment. Although syntaxial cement can form in other diagenetic environments, which needs cathodoluminesence to determine the precise depositional environment.

After the deposition of the Mauddud Member an unconformity had taken place and as a result, the formation affected by meteoric diagenesis. Dissolution as a result of under saturated meteoric water affected the carbonate rocks of this formation and formed vuggy porosity (Figure 6).

In the burial environment different diagenetic process has been affected the formation. These processes include compaction, fracturing, spary calcite cement and dolomitization. In shallow burial environment, overburden pressure caused to form fitted fabric and shell breakage. By increasing the depth of burial, solution seam and stylolites have been formed. Fracturing also formed under the pressure in this environment. The probable source of the calcite cement is the carbonates which are dissolved during the formation of solution seam and stylolite as a result of overburden pressure.

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

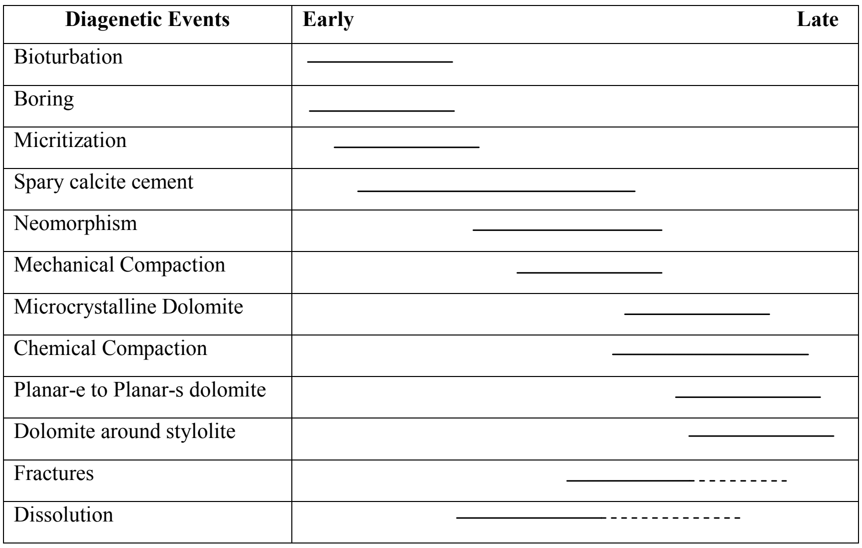

Figure 7: Paragenetic sequence of diagenetic processes of the Mauddud Member in the studied field.

It seems that the dolomitization of phase two, which consist of coarse crystals of euhedral dolomite, has a local source, and does not well developed in the whole part of the formation. One of the probable sources for this type of dolomite is hydrothermal phase after the ophiolite of Oman which formed in the Turonian unconformity [1]. Paragenetic sequence of diagenetic processes demonstrated in the diagram (Figure 7).

The diagram showed relative time of different processes (Figure 7).

Digenesis and Reservoir Quality

Diagenetic processes involved in Mauddud member were responsible for the modification of reservoir quality. At the point of view of affecting on reservoir quality, these diagenetic phenomena have been compartmentalized into three groups: processes enhancing, decreasing and having no rules or effects on reservoir quality (Figure 7). These processes can be described as follows:

Processes enhancing reservoir quality

- Dissolution formed different types of porosity includes vuggy and moldic porosity. So dissolution had positive effect on reservoir quality.
- Fracturing occurred in the studied interval, although the

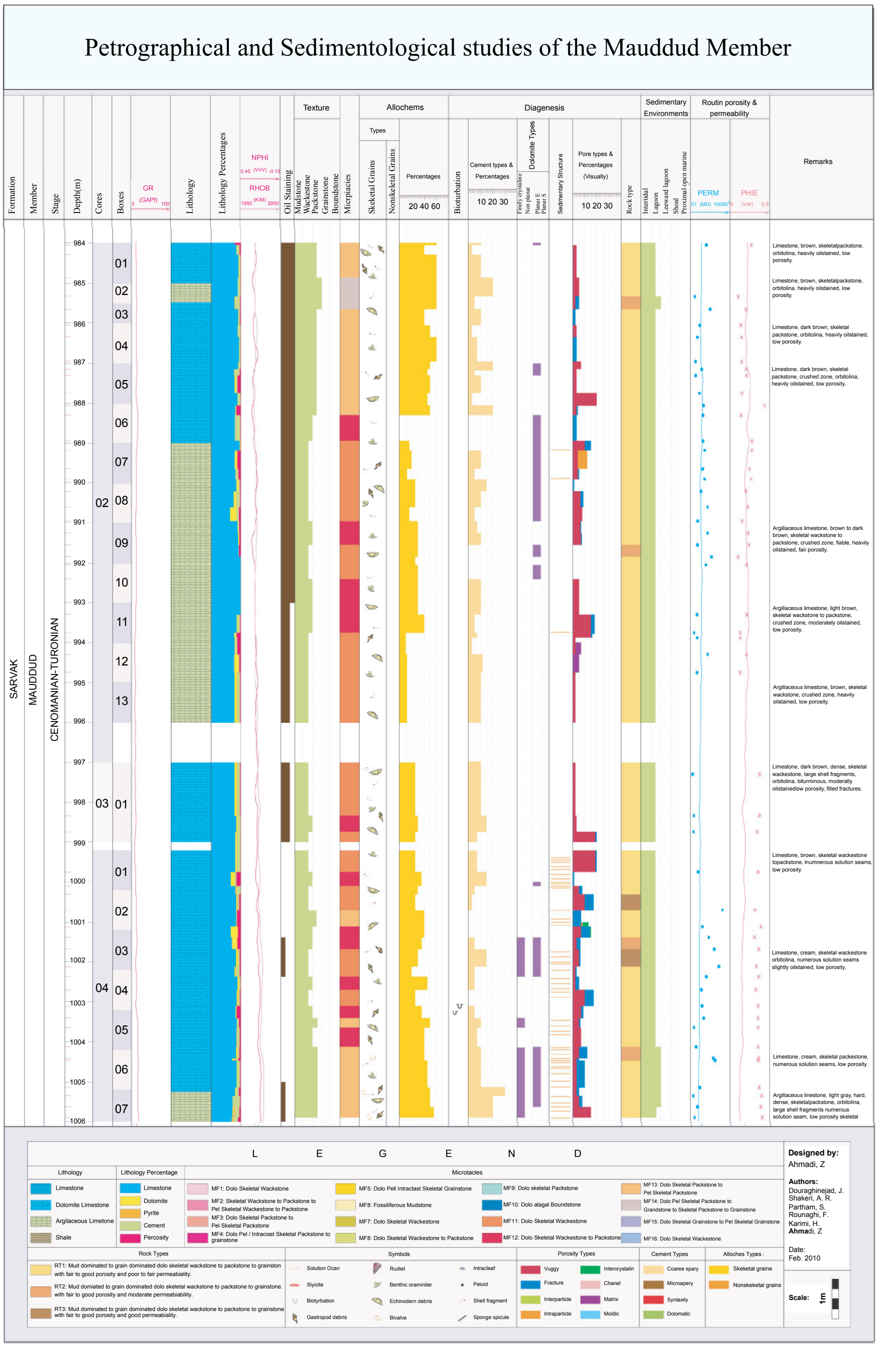

Figure 8: Petrographical and sedimentological logs of the Mauddud Member in the studied field.

frequency of fractures is not high and the average amount of fracture porosity is between 0-4%, but it seems that it has positive effect on reservoir quality.

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

Processes decreasing reservoir quality

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

- Chemical compaction by forming solution seems has different effect. Parallel to the orientation of solution seam, it acts as conduit for hydrocarbon passage, while perpendicular to the solution seam it acts as a barrier. Mechanical compaction produced fitted fabric and form a packed texture is another negative process.

No or negligible effect on reservoir quality

Bioturbation, micritization, pyritization, neomorphism are different diagenetic features which have negligible effect on reservoir quality.

Conclusions

- Based on petrographical investigation of the Mauddud member in the field under study, five types of microfacies have been identified (Figure 8). These microfacies have been deposited in two facies belt related to lagoon and bioclastic shoal. They are related to shallow marine carbonate ramp.

- Different diagenetic processes affected on this member which are bioturbation, micritization, cementation, dolomitization, dissolution and compaction. Among all, Dissolution and dolomitization increased reservoir quality, while cementation and compaction decrease reservoir characteristics.

- Although the Mauddud member shows the effect of dissolution during meteoric diagenesis, but it did not subearially exposed for a long period of time. So dissolution which is one of the most important factors on improving reservoir quality in southern Persian Gulf did not well-developed in this member.

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

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