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Effect of diagenetic minerals on gas reservoir porosity of Dalan Formation in a large gas field in northern Persian Gulf

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K E Y W O R D S: Diagenetic minerals, porosity, gas reservoirs, Dalan Formation, Persian Gulf.

ABSTRACT: Diagenetic processes are very important in forming and changing of the secondary porosity. Diagenetic minerals derived from these processes, play the most important role on the porosity, permeability and size variations of porethrout among the reservoir rocks porosities. In this paper, diagenetic minerals include different types of dolomites (Rd1, Rd2, Rd3, Cd1, and Cd2), anhydrites as diverse structure and textures (nodules structure and textures of needle, radial, fibrous, crystalline, amorphous, mixed, etc.), and calcites as cement (fiber/blade, equant, and poikilotopic). Due to the presence of gas within the reservoir rocks, amount and type of porosity and permeability of the rocks also is important. In the studied area, touching-vug porosities (intergranular, intercrystalline) increase the whole porosity and improve the permeability of the reservoir rock and separated-vug porosities (such as moldic, intraparticle and vuggy) increase the whole porosity but have not a large role in the extraction of gas (permeability). In this paper, the effect of diagenetic minerals on types of porosity has been studied based on the study of thin-sections prepared from cores.

Introduction

Sediments and sedimentary rocks are affected by diagenetic processes, especially the last diagenetic processes during different stages of the burial. Some effective diagenetic processes include: dolomitization, anhydritization, cementization, and a variety of mechanical and chemical compactions. Undoubtedly, the diagenetic fluid needs a space (porosity) and suitable permeability to pass through the rock. So depending on the volume of the space (porosity and its variants), their position relative to each other and relative to the position of porosity, diagenetic minerals create various permeabilities for passing the hydrocarbon fluid which this may impact affect the quality of the reservoir rock positively or negatively. In the reservoir rocks, porosity is changed under the influence of sedimentary and diagenetic processes which these changes control the moving of fluid and increasing or decreasing the reservoir quality (Aliakbardoust & Rahimpour-Bonab, 2013).

Here, different types of diagenetic minerals and their effect on the types of porosity (according to Lucia classification) have been studied in a large gas field in the northern of the Persian Gulf.

Methods and Materials

In this study, 554 thin sections (approximately one thin section per 30 cm.) gamma and sonic logs, and more than 200 meters of drilled cores have been studied. All thin sections were examined by Alizarin Red-s for separation of dolomite from calcite. Log-plot (version 6) was utilized for drawing the litho-stratigraphic column.

Persian Gulf Geology

Iran is a hydrocarbon-rich country with giant and supergiant hydrocarbon reservoirs (oil and gas) in the Kopet-Dagh and the Persian Gulf regions. Presence of such gas fields attracts special attention to geological framework and tectonic events of in the two mentioned regions. Accordance to the location of the studied area in the Persian Gulf, it is necessary to take a short look to the geology and dominant tectonicon of the Persian Gulf. This gulf has been formed by the growth of the western edges of the Sea of Oman about 30 million years ago. About 60 percent of the hydrocarbon reservoirs in the Persian Gulf (including the studied gas fields) has been created as a result of salt tectonic (Arian, 2010). In addition of salt tectonic, the African, Arabic, Asian plates, and also the Zagros suture, the Red Sea Rift and the Gulf of Aden Rift, have influenced hydrocarbon reservoirs in the Persian Gulf (Figure 1). Geologically, the Persian Gulf (and the gas fields under discussion), is located in the Alpine-Himalayan Mountains belt and is a part of the tectono-stratigraphy unit of the Zagros Mountains, located in the northern of the Persian Gulf (Stampflietal, 2001; Agardetal, 2001).

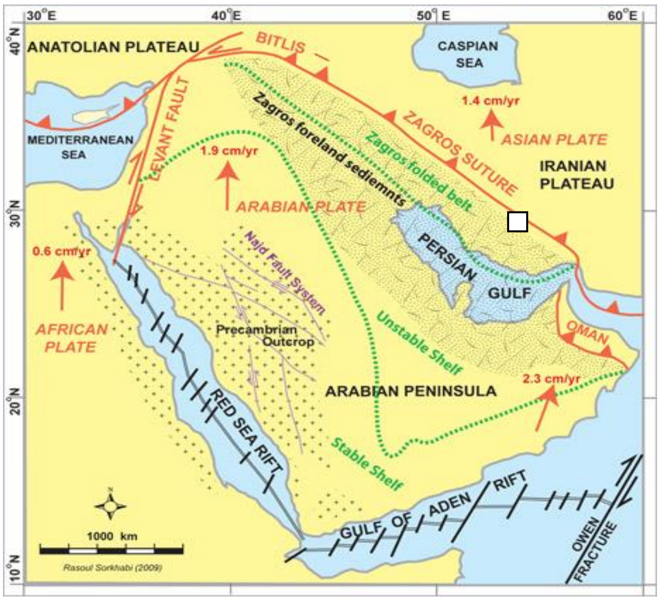

Figure 1: Plates and faults surrounding the Persian Gulf. The Plates and faults have been very effective in the existing structures, especially activity of salt domes. White square shows the position of the studied gas field.

Geology of the studied Gas Field

In the studied gas field, the thickness of the Upper Dalan Member is 229 m, including two subdivisions named K3 and K4 (Figure 2). The base of the Upper Dalan Member with the Nar Member is conformable and its top with the Kangan Formation is unconformable (Permo-Triassic boundary). General lithology of the Member in the gas field is: dolomite, dolomitic limestone, limestone, some anhydrite, and some shale (figure 2).

Diagenetic minerals

During the diagenetic processes, some diagenetic minerals and cements including dolomites, anhydrites, and calcites are formed in the rocks of the Upper Dalan Member. These have caused texture change of the rocks leading to creation of the secondary porosity. These minerals are discussed further.

Dolomites

Dolomites are crystalline carbonate rocks formed in the two-phase system, replacive (Replacive dolomite) and cement (Dolomite cement) (Bazargani-Guilanietal, 2008, 2010).

Replacive dolomite has been formed from replacing of calcite by dolomite as particle-by-particle which is the secondary type. Generally, most of these kinds of dolomites have cloudy center and clear margins (limpid) (Sibly, 1982; Kyseretal, 2002).

Dolomitic cement is chemically or biochemically crystallized from a solution (Choquette & Hiatt, 2008). This dolomite usually has coaxial crystal growth and is clear (limpid), but may also have inclusion and is platy to saddle in shape.

Replacive dolomitization in absence of anhydride or in the presence of patchy anhydrite improves the reservoir quality. Where Anhydritic cement is widespread lading to the plug of rock fabric, reservoir quality is reduced by decreasing porosity and permeability (Lucia, 1999; Rahimpour-Bonab, et al, 2010).

Replacive dolomites

These are usually known as low-temperature dolomites and are formed at temperatures below 60 ° C.

Dolomite the type-1 (Rd1)

This dolomite is the most abundant type. The dolomite is microcrystalline and amorphous with size of about 10 microns (Figure 3a, b, d), so it is known as dolomicrite. Many researchers such as Sibley and Gregg (1987); Warren (2000); Choquette and Hiatt (2008); Bazargani-Guilanietal, (2008, 2010) studied this type of dolomite and considered a sabkha and restricted platform for environment of it. Under the microscope, the crystals usually are euhedral to anhedral and connection attitude of crystals, especially in the euhedral type creates a good porosity in the rocks, but due to the small size of crystals, the created space (intercrystalline porosity) has a high capillary pressure followed by decreasing permeability of the rock. So despite the high porosity it cannot help to improve the quality of the reservoir. In the mentioned gas field, this type of dolomite is converted into dolomite the type 2 (Figures 3b). Rd1 can be seen in mudstone facies and matrix of wackstone, packstone, and grainstone facieses.

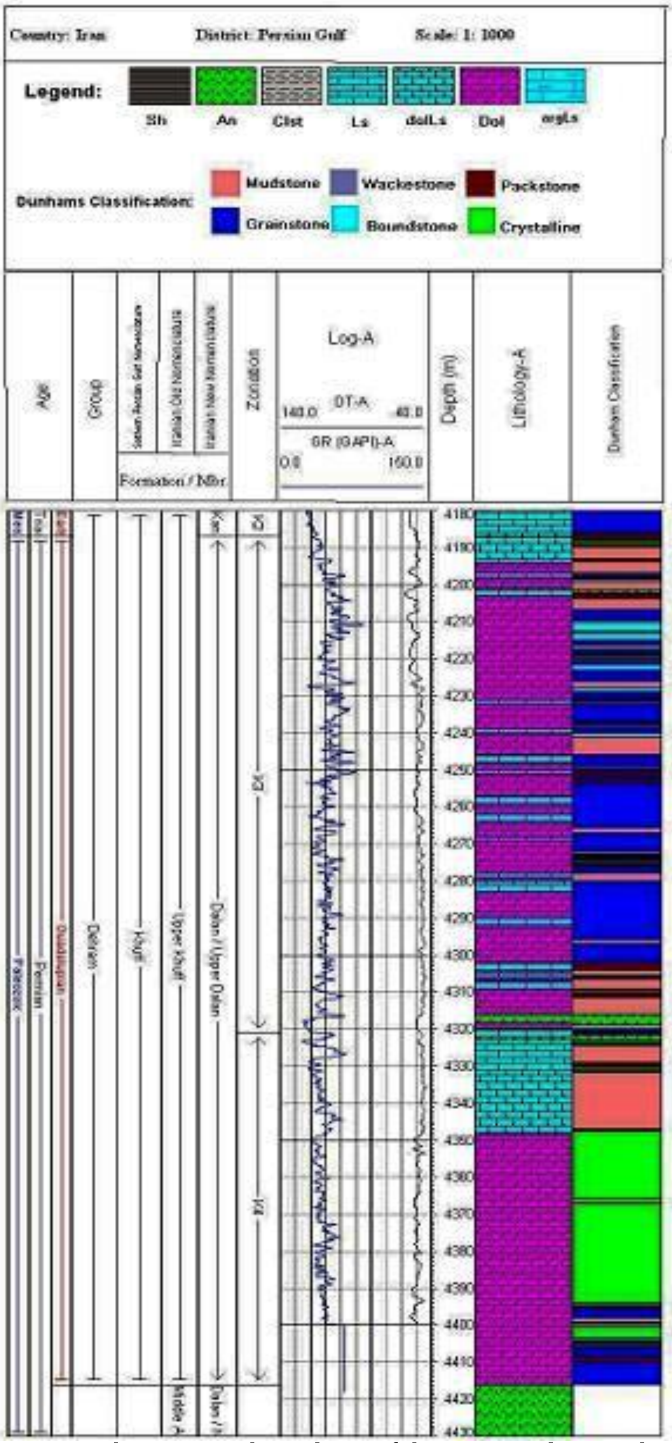

Figure 2: Litho-stratigraphic column of the Upper Dalan member.

According to the discussed characteristics, five types of dolomites can be identified in the Dalan Formation. These identifications is based on Sibly and Gregg (1987), Gregg and Shelton (1990), Mazzullo (1992), Chen etal, (2004), Nader etal, (2004) and Bazargani-Guilanietal, (2008 , 2010).
The dolomites include:

Dolomite the type-2 (Rd2)

Dolomite the type 2 can be seen as euhedral (idiotopic-e) crystals with size of about 70 microns. This dolomite is in micritic matrix of rock and is known as dolomicrites. The Dolomites are in suitable size and shape to create porosity among the crystals and the porosity formed by locking of the crystals creates a good permeability to store and product of the hydrocarbons. Under polarized light, these crystals have usually straight extinction. Their large crystals (euhedral to anhedral) have cloudy cores and clear margins (Fig. 3b). In the studied area, this type of dolomite is converted into type 3 (Fig. 3b). Generally, the spaces among the dolomites of the type-2 are filled by dolomite the type-1, calcite, and anhydrite. The dolomite can be seen more in mudstones and matrix of wackstones.

Dolomite the type-3 (Rd3)

It is a mosaic dolomite crystal with dimensions of about 250 microns. Dolomite type-3 includes subhedral to anhedral crystals and Planar-s and Idiotopic-s. Under the polarized light, this type shows straight extinction (Figs. 3a, b, c). Amorphous shape and overgrowth of the crystals led to locking the crystals together and as suture contacts occupy almost all the space around them. Dolomite the type-3 usually is fabric destructive and destroys characteristics of the early diagenesis and depositional environment. The crystals usually have abundant of inclusions, so are cloudy in appearance and sometimes show clear margins.

The order of the formation of replacive dolomites in the gas field is Rd1→ Rd2→ Rd3.

According to the vast dolomitization of type-2 and 3 accompanied with intense anhydritization in the carbonate platform (especially in the lagoon and bar), the mechanism of dolomitization has probably been seepage-reflux.

Dolomite cement

These dolomites are usually known as high-temperature dolomites and are formed at temperatures more than $60^{℃}$, probably during the burial diagenesis. The dolomites in each type are fabric destructive and decrease quality of reservoir.

Dolomite cement the type-1 (Cd1)

This dolomite (type idiotopic-c) has Planar-e crystals and is euhedral to subhedral in shape with size of about 150 microns (Figure 3a). Most of the crystals have straight extinction and zonation. The dolomites are observed as filling materials of the vuggy and moldic porosities in grainstones and along the stylolite veinlets. The nature of the dolomite shows their formation in the empty space of rock, so any kind of porosity is partially or completely filled by this type of dolomite. Thus, the porosity and permeability of reservoir is decreased.

Dolomite cement the type-2 (Cd2)

These dolomites are saddle shaped dolomites which are unplanar and curve shaped with undulatory extinction and dimensions of about 300 microns (Fig. 3d). Due to many inclusions, most of the dolomites have cloudy appearance. The crystals with clear margin are sometimes seen among the saddle shaped dolomites. The dolomites are also growing from the center to the margins of ooids. These dolomites are more seen in the fractures. As in the case Cd1, saddle shaped dolomites are formed in the spaces of rock, having nature of filling materials. So, the porosity and permeability of reservoir is decreased.

Petrography of Anhydrite

The sulfate minerals (gypsum and anhydrite) usually occur as nodular and interbedded structures and also as a series of textures associated with these structures in the carbonate rocks. Anhydritization commonly occur during the evaporation of sea water in the lagoon and the warm sabkha such as the southern coast of the Persian Gulf (when the sea water concentration is 5 to 6 times more than the normal amount) (Qing et al, 2001; Melim and Scholle, 2002 ; El-Tabakhetal, 2004; Warren 2006, 2010).

A few attempts have been done for classification of anhydrite. Until now, three classifications have been presented for anhydrite including Murray (1964), Maiklem et al, (1969) and Meyer (2005). Murray's classification is more focused on morphology of anhydrite. Meiklem's one is aimed on structure (outer shape, relationship between anhydrite and matrix of rock, type of layering and its disorders) and texture (size, shape, and relationship between crystals into anhydritic mass). And finally, Meyer's classification is focused on the shape of anhydrite (Irajian etal. 2014). Unfortunately, we cannot create a good relationship between the morphology of anhydrite and its depositional environment. Perhaps this is the most important reason for the rejection of these classifications among geologists.

Anhydritic structure

The nodular structure is the only structure found in the studied member.

Nodular structure

This type of anhydrite is formed from nodules with different morphology (Figure 4a) which has subtle and complex of internal textures, so it is known as felted texture. Generally, in the sabkha environment, these nodules have been formed due to injection of evaporate brines into the porosity of the carbonate rocks (dolo-mudstones). Nodule diameters are changed from a few millimeters to a few centimeters and are white to milky in colors. According to Lucia (2007) because of distribution of nodules in the dolomite rocks under attack of brines, nodules have no significant effect on reservoir properties.

It should be noted that the nodular structure is formed during the early diagenesis but its formation has been reported during the burial diagenesis (Machel, 1993; Amadietal, 2012).

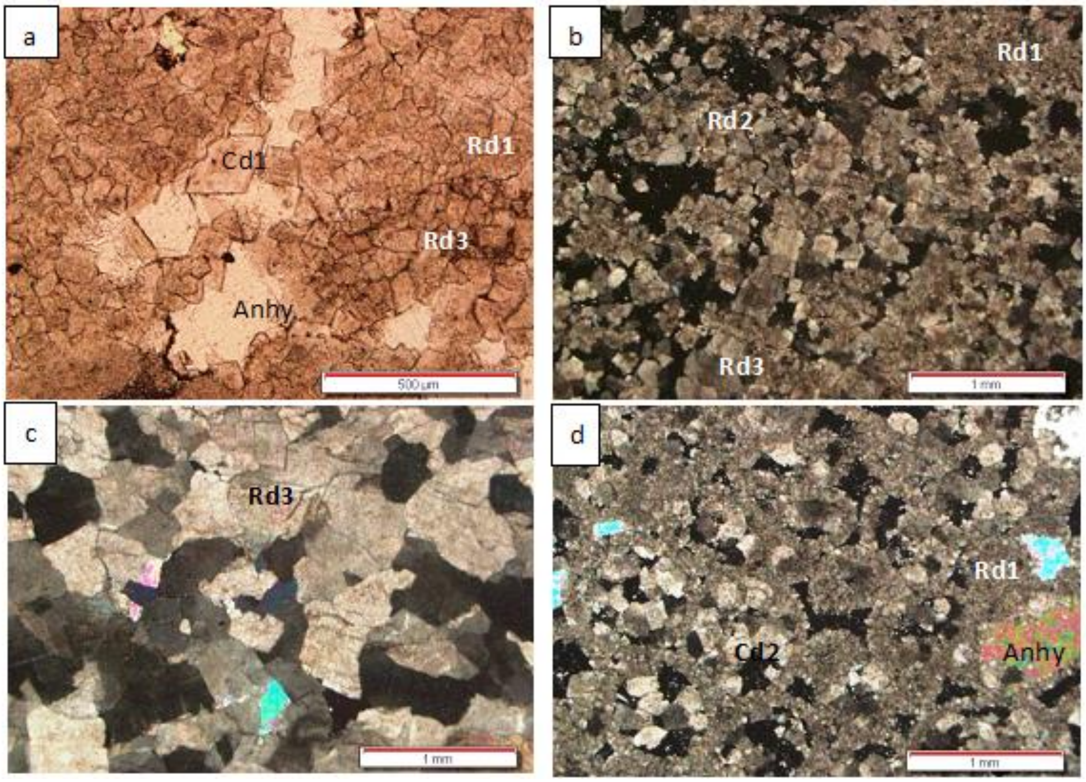

Figure 3: types of dolomites. a: dolomite the type-1 in matrix of a crystalline carbonate. Cd1 filled part of a fracture. Whole the fracture filled by Anhydrite. b: dolomites the type-2 (Rd2). On feature of the dolomites is cloudy core and clean margins that shown in the picture. c: dolomite the type-3 (Rd3) with subhedral to unhedral crystals. Usually this type of dolomite can be porosity and fabric destructive. d: saddle dolomite with curve structure and undulatoryextinction that filled all of vuggy porosity (it seems be ooid). Surround of ooids filled by Rd1.

Like the research of Hadjian-Barzietal, 2011, the anhydrite in the Upper Dalan Member has nodular structures and a series of textures associated with these structures.

Anhydritic textures

In this section, a number of anhydrite textures related to anhydrite nodules are mentioned.

Needle shape texture

In this texture, length the crystal is much greater than its width (Figure 4b). The needles are usually parallel to semi-parallel with each other. The needle texture is seen within a nodular structure of anhydrite (Figure 4b). In the studied area, the texture has been occurred during the early diagenesis in the tidal environment.

Crystalline shape texture

In this texture, length/width ratio of crystals is close and it has a variety of shapes and sizes (Figure 4c). Since the anhydrite crystals are cut by stylolite (as seenin figure 4c) the texture has been formed during the early diagenesis in the tidal flat or sabkha. However, the texture can be seen in each environment and diagenesis conditions that are under control of anhydritization fluids. Usually the crystals are monochromatic and multi-colored nature cannot be seen in a crystal.

Radial shape texture

This type of texture can be seen within nodular structure or moldic porosity (Figure 4d) but the texture is observed within all porosities of rocks and all environments that are under control of anhydritization fluids. In the mentioned gas field, the texture has been occurred during different conditions and different environments from sabkha (dolo-mudstone) to shoal (ooid grainstone).

Disordered shape texture

The texture is generally seen within nodular structure (Figure 4e) and is similar to the needle texture, but the needle has not specific orientation.

Fibrous shape texture

In this texture, length/wide ratio of crystals is less than of ratio of needle crystals, so the crystals are wider (Figure 4f). In the texture, fibers are usually parallel to semi-parallel to each other. The crystals are scattered in the matrix of dolosparites. This texture is occurred more in the tidal flat to the sabkha environments, during the early diagenesis.

Mixture shape texture

This is a texture that occurs due to neighboring of two or more textures described above (figure 4g).

Moderate and burial anhydritic textures

Various textures of anhydrite are formed during the mesogenetic stage (meso to burial diagenesis) when the carbonate rocks affected by the anhydritic brines. These textures are explained below:

Anhydritic texture filling fractures

Most of the textures pointed above can be followed within the fractures during mesogenetic stage such as crystalline and fibrous textures (figures 4h, i).

Anhydritic textures filling vugs

Intergranular shape texture (Poikilotopic)

In this texture, one or more large anhydritic crystals encompass allochems or fossils (figure 4k).

Moldic shape texture

The texture occurs when anhydritic brines fill the molds. The textures formed within these vugs include: crystalline and fibrous textures (figure 4k).

Anhydrite filling vugs has destructive effect on the reservoir quality and decreases porosity and permeability. With increasing depth, the sequence of formation of anhydritic structure and textures is:
Nodules→ Layers→ Cements

Calcite cement

In a different diagenetic area, within the carbonate rocks, calcite (calcite cement) is seen as the various forms which all act as filling materials of porosity but some forms decrease permeability. In the studied gas field, the calcite can be divided in the following two general categories: 1- Calcite cement (spary) filling porosity among the allochems and fossils (interparticle calcite cement), acts as decreasing of porosity and permeability. 2- Calcitecement (spary) filling moldic porosity, applied as decreasing of porosity but not necessarily permeability.

Interparticle calcite cemen

The spary cements have filled the primary space among the allochems and fossils with different forms:

Fibrous/bladed cement

It seems that this cement to be the first cement formed in the Upper Dalan Member (Figure 5a). The cement, which is usually known as marine phreatic cement encompasses ooids and fossils. According to the dimensions and spread of cement in the Member, it can be said that fiber /bladed cement cannot have a significant role in decreasing porosity and permeability. This cement is formed in the eogenetic stage and is certainly affected during the different stages of diagensis. It can be seen as a ghost under the microscope. The volume of the cement is low and occupies less than 10% of the pore space.

Equant and Poikilotopic cements

After fiber/bladed cements, the equant and Poikilotopic cements are the next generations that fill the remaining space among the allochems (Fig. 5 b, c). Regarding to distribution of these types of cements and the occupied space, it can be said that they have the most negative effect on the porosity and permeability. The mentioned cements have been formed during the early and late diagenesis, so at any time they have been able to reduce the residual space. However these types of cements have been replaced by a variety of dolomite and anhydrite during shallow and burial diagenesis (eogenetic and mesogenetic) that were previously mentioned. In terms of the effect, these cements occupy more than 90 percent of the porosity space.

Calcite cement (spary) filling moldic porosity

The creation of moldic porosity can be signed as domination of meteoric diagenesis and development of secondary porosity after removing of the early porosity. It can be linked to the eogenetic and telogenetic areas, provided by high water flow and continues contact of calcium carbonate saturated water with allochems and fossils. Fractures usually occur during the tectonic movements and usually occur in the telogenetic area.

Calcite cement filling moldic porosity

The moldic porosity is widely spread in the Upper Dalan Member. Generally, the porosity of the formation is filled by dolomite and anhydrite cements but there is a little calcite cement filling the most space of molds (figure 5d). Commonly, the moldic porosity itself cannot help to increase the reservoir permeability and production but it increases the storage of

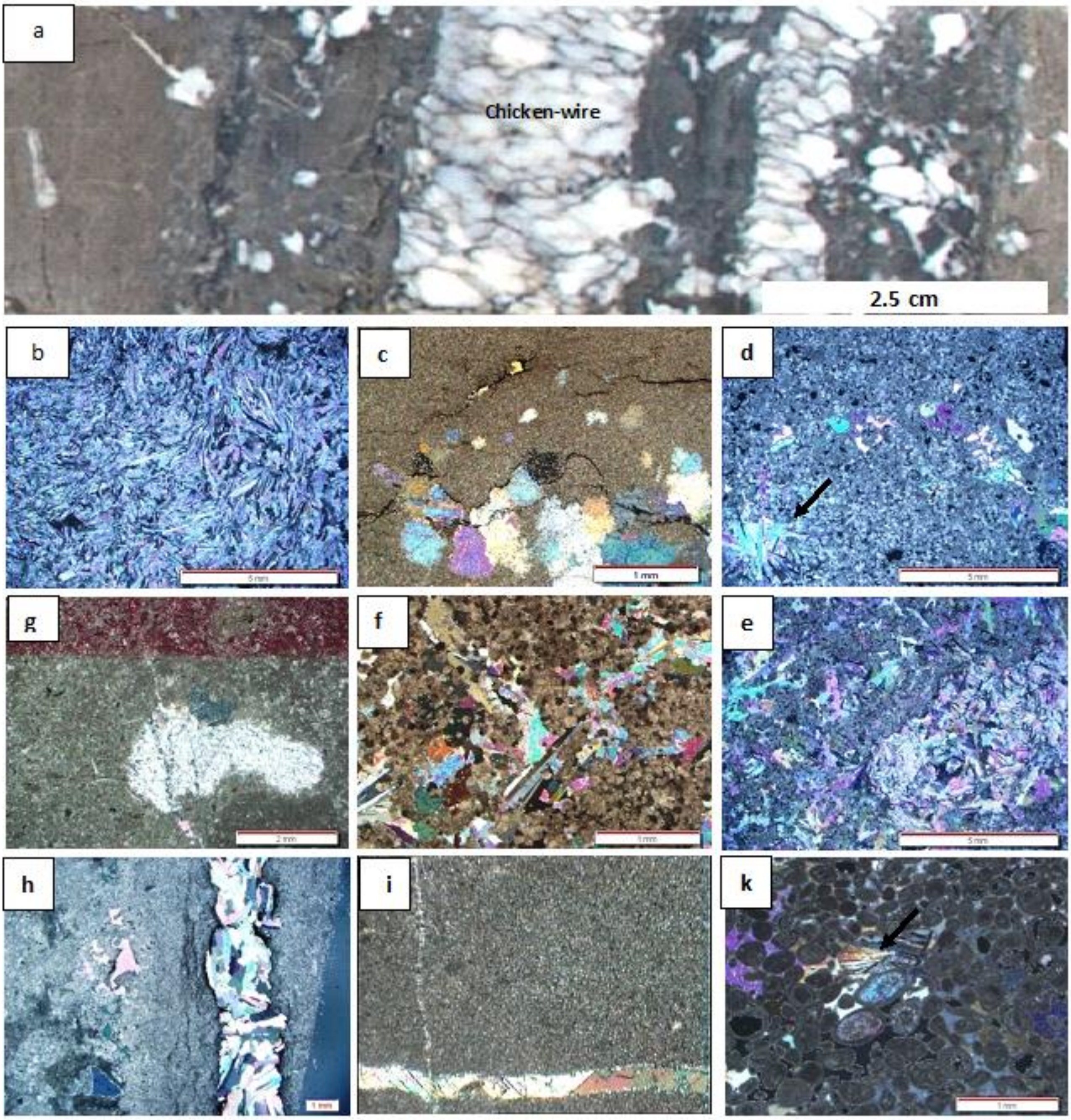

Figure 4: Anhydritic structure: a. Nodular structure (chicken wire) in the Upper Dalan Member.Anhydritic textures: b. Anhydritic needle within the nodular structure. c. Crystalline shape texture. The texture has been occurred within a dolo-mudstone. Usually the crystals are monochromic and cannot be seen multi-color in a crystal. d. Radial shape texture, bottom left (flash). e. disordered texture within a nodule in dolo-mudstone. f. fibrous shape texture in a dolosparite. g. mixture shape texture in a dolosparite. Anhydritic texture filling fractures: h,i. Fibrous and crystalline textures in dolo-mudstones. Anhydritic textures filling vugs: k. Poikilotopic texture encompasses ooids, fibrous shape texture within an ooid (flash) and crystalline shape texture occupied within some of ooids in a grainstone.

hydrocarbon. Thus filling the porosity cannot also play a significant role in decreasing permeability. The volume of the cement is low and less than one percent.

As seen in Figure 5 (b), the orders of formation of diagenetic minerals during the deep burial are as follows:
Poikilotopic calcite cement→ dolomite cement→ Poikilotopic anhydrite cement

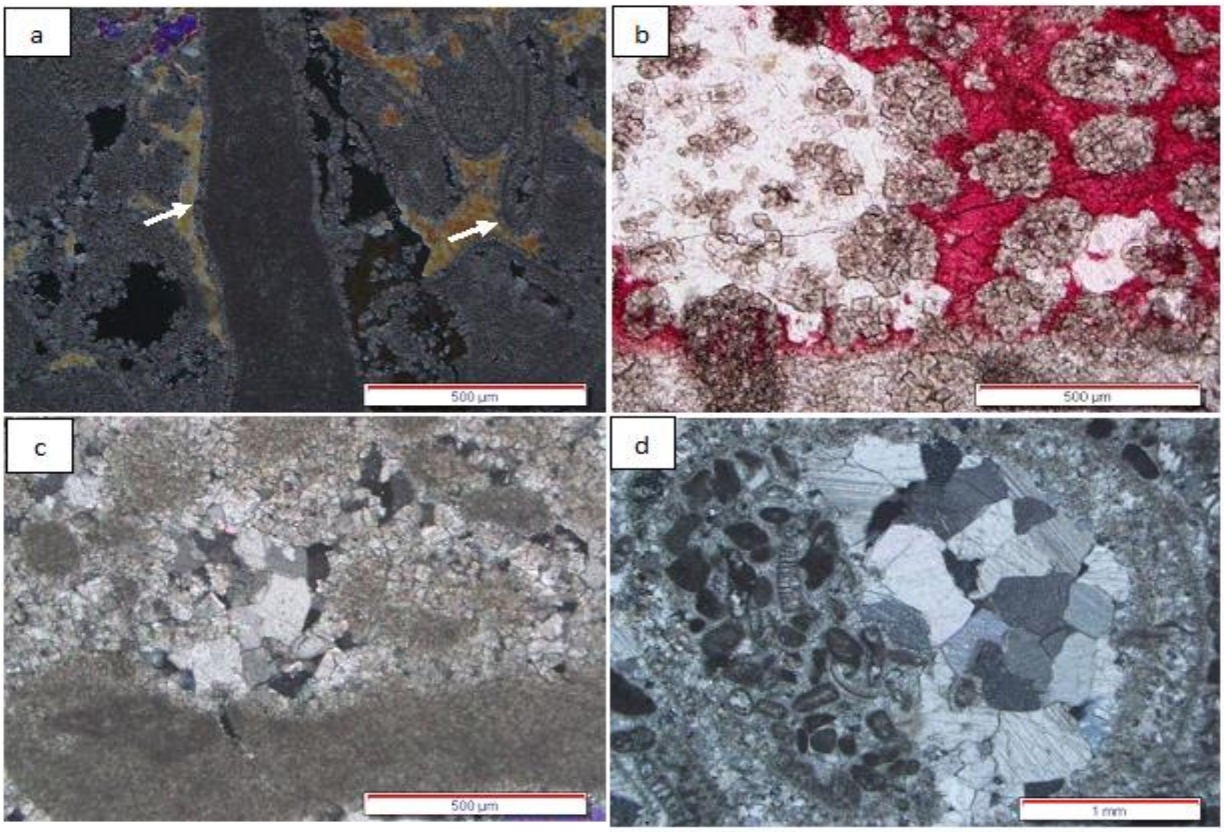

Figure 5: Types of calcite cements: a. fibrous/bladed spary cement (flash) in a grainstone, spaces between alochems and fossils is occupied by anhydrite. b. the ooids all dolomitization and destroyed and porosity between thems is occupied by poikilotopic spary cement (red color) and anhydritic poikilotopic cement. c. mosaic spary cement (equant) filling porosity between fossils ghost. d. spary cement filling more than half of moldic porosity that created by a alge.

Porosity in the Upeer Dalan Member

There are various classifications of porosity in sedimentary and petroleum studies, among which three classifications are more common. Classification of Choquette and Pray (1970) is more used by sedimentologists but classifications of Archie (1952) and Lucia (1995) are utilized by petroleum geologists and petrophysist. The Choquette and Pray classifications have been more related to sedimentary fabric and evolution of rock during different diagenetic processes and consequently change of reservoir quality. So it can be used for exploration of oil and gas reservoirs. The Archie and Lucia classifications is applied for oil specialists and petrophysist because it is directly related to the pore geometry and fluid properties (Irajian et al. 1393b).

Based on porosity classification of Lucia (1995), porosity in the reservoir rocks of the Upper Dalan Member can be divided into two major groups as follow: 1- interparticle porosities and 2- vuggy porosities. The vuggy porosities are divided into two sub-groups, touching-vug porosity and separated-vug porosity.

Interparticle porosities

During deposition, carbonate sediments without mud cause interparticle porosity. Interparticle porosity is divided into two types including intercrystalline and Intergranular. This porosity group is very useful for permeability of the reservoir (Lucia 1995).

Intercrystalline porosity

This type of porosity is formed in the space among the dolomite crystals (Fig. 6a) and its geological setting is the sabkha to open marine. The porosity creates one of the best places to store the gas in the studied gas field.

Intergranular porosity

This type of porosity usually is developed among ooid allochems and skeletal grains in sequences of K3 and K4 subdivisions (Figure 6b).

Vuggy porosities

Touching-vug porosity

This porosity consists mostly of fracture, brecciate, cavity, and Fenestral porosities. The group is usually non-fabric selective. The porosity is usually formed a continuous network and can be useful for gas reservoirs permeability (Lucia 1995). In this Member, brecciate porosity is more important (figure 6c).

Separated-vug porosities

Generally, these porosities include moldic, intraparticle, and shelter porosities. In this Group, porosity is as isolated or as slightly connected pores (Lucia 1995). These porosities are fabric selective. This group increases the porosity rather than permeability in the reservoir (Lucia 1995). In the studied Member, moldic porosity is abundant and more important than the others.

Moldic porosity

The porosity is the most common type in the Dalan Formation. It is usually seen in the facieses of ooid and skeletal (oomolds and biomolds) (Figure 6 d). The formation of this porosity is usually a selective process of the selective dissolution and occurs with dissolution of the allochems or fossils. The porosity may occur during the early diagenesis, but it generally occurs in the secondary diagenesis in a meteoric environment under water saturated from calcium carbonate ion and the abundant flow (Simoetal, 1994).

Conclusion

Since the beginning of the sedimentation and also during the different diagenesis stages (early to burial diagenesis) minerals and the porosities existing in the sedimentary environments are frequently changed. In terms of creating suitable conditions for a hydrocarbon reservoir, these changes are sometimes useful and sometimes destructive. So the last diagenetic stage dominated the depositional environment determines the quality of the reservoir of a sedimentary rock (here carbonate rocks).

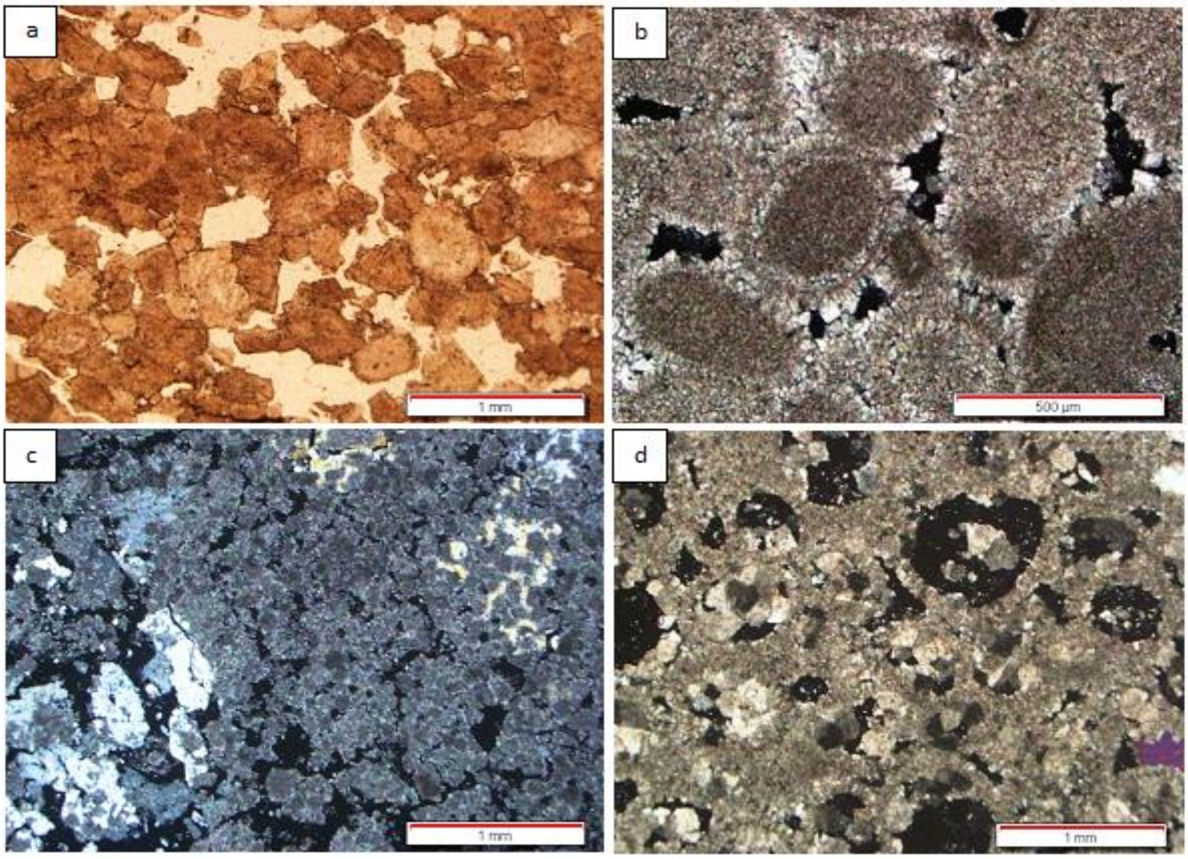

Figure 6: Types of porosity: a. intercrystalline porosity. The porosity occurred in the space between the dolomite crystals in a dolostone. b. Intergranular porosity that occurred in between ooids. Considering dolomitization of rock, the primary porosity continues to be preserved. c. Brecciate porosity in a bioclastic-oolithic grainstone Probably occurred under the influence of salt tectonics. c. Porosity created by the dissolution of the ooids in a ooid grainstone. Some of the porosities occupied by ddolomite the Cd2 type.

Diagenetic minerals and cements studied in this paper can be divided into three main groups as follows: 1- diagenetic minerals improving porosity, 2- neutral diagenetic minerals and cements (those have not significant effect on the pore space) and 3- Diagenetic minerals and cements destroying porosity. It should be mentioned that in the carbonate rocks, the combination of these minerals can be a interstitial effect.

Diagenetic minerals improving porosity: Among the diagenetic minerals in the Upper Dalan Member, the dolomite type-2 (Rd2) has only created the porosity between crystals and helped in forming a suitable permeability for hydrocarbon production.

Neutral diagenetic minerals and cements: Among the studied diagenetic minerals and cements we can be point to the fibrous/blade calcite cement, calcite cement filling vuggy porosity, anhydrite with nodular structure and textures associated with this structure. In terms of volume and/or distribution, the anhydritic textures and cements have no significant effect on the permeability and porosity of the rock and are not considered as a barrier to hydrocarbon production.

Diagenetic minerals and cements destroying porosity: In this case we can point to types of dolomites (Rd1, Rd3, Cd1, and Cd2), Poikilotopic calcite cement, anhydritic textures filling fractures and anhydritic textures filling vugs.
It should be noted that this division can be ideally applied and usually combination of three groups mentioned above affects the porosity, permeability and the early fabric of rock in a diagenetic environment. Therefore, the results are depended on effectiveness and abundant of each three groups illustrated above. By examining the data obtained from this study, it seems that diagenetic processes destroy the quality of a reservoir rather than improve it.

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