academicJournals

Vol.8(1), pp. 1-10, January, 2017
DOI: 10.5897/JPGE2016.0244
Article Number: FB0E5D062398
ISSN 2141-2677

http://www.academicjournals.org/JPGE

Journal of Petroleum and Gas Engineering

Full Length Research

Petrographic and diagenetic studies of thick transition zone of a middle-east carbonate reservoir

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Received 23 August, 2016; Accepted 10 January, 2017

This work aims to characterize petrographically some of the transition zone plug samples in order to understand the impact of diagenetic processes on the transition zone rock quality. Three carbonate samples were collected from the same well which cuts through a thick transition zone of a heterogeneous cyclic carbonate reservoir of Abu Dhabi with respect to depth. The petrographic analysis was conducted by the thin sections study and scanning electron microscope (SEM) imaging in order to interpret the main depositional facies, diagenetic features and how the poro-perm characteristics were affected by them. SEM analysis is utilized in order to observe and recognize in detail the diagenetic relationships between different mineral phases or cement types and to help in identifying the pore geometry. Diagenesis in the transition zone is very extensive especially affected by micritization and cementation. The diagenetic features are increasing with depth as the zone is having higher water saturations. The importance of this analysis is to better understand the rock fabric heterogeneity and capillary pressure behavior as a function of depth of thick carbonate transition zones.

Key words: Transition zones, diagenesis, petrographic analysis, scanning electron microscope study, carbonate reservoirs.

INTRODUCTION

Tight carbonate reservoirs exhibit thick transition zones which usually contain large quantities of oil and therefore a significant amount of reserve might be left after secondary recovery. Therefore, the proper characterization of transition in terms of depositional facies, diagenesis and structural features are important for improved knowledge of transition zones. The nature of the mixer of the hydrocarbons with water in the transition zones face considerable production challenges, hence, require proper reservoir characterization coupled with advanced completion and stimulation techniques for efficient oil production. Shiekah et al. (2009) defined the transition zone and predict the performance of the transition zone regarding the water saturation changes. It is well known that depositional facies mainly control the pore system geometry and architecture, primary porosity and permeability of the rocks, sedimentology and formation water chemistry near the surface water (Henares et al., 2014; Hartmann and Beaumont, 1999; Morad et al., 2010). Petrographic and diagenetic studies

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of reservoir rock samples are crucial in reservoir quality predictions as well as understanding the relationship between depositional facies and diagenesis (Bloch and McGowen, 1994; Henares et al., 2014). Diagenesis accounts for all the alteration processes which occur in the original rock or group of facies after deposition; it results in the modification of the pore network or pore throat geometries by preservation, loss, or enhancement of rock petrophysical properties. Moreover, diagenesis is used to understand and predict changes in the reservoir pore structure. It is also important to note that the influence of the diagenetic overprint on the determination of the pore system and their impact on the reservoir quality and its flow behavior (Farooq et al., 2014; Wazir et al., 2015; Aliakbardoust and Rahimpour-Bonab, 2013; Rushing et al., 2008; Zhang et al., 2009; Gomes et al., 2008).

Recently, Kolchugin et al. (2016) studied the diagenesis of the paleo-oil-water transition zone in a lower Pennsylvanian carbonate reservoir to document the strengths of a combined petrographic and geochemical study in order to investigate the actual timing of oil migration in carbonate reservoirs and its related cementation dynamics.

A few authors have described the microporosity effect as a diagenesis feature, by using thin sections and scanning electron microscope (SEM) methods (Fullmer et al., 2014; Vahrenkamp et al., 2014). Gale et al. (2005) studied the diageneses especially fractures and cementation in order to predict the fluid flow. Again Ehrenberg et al. (2014) and Major (2014) studied the diagenetic environment and regimes that result on enhancing the quality of the reservoir under investigation. Apart from these studies, it is necessary to work on characterization of transition zone sample in terms of petrographic analysis and diagenesis. Therefore, we hope that the present research work would be able to provide new aspects and information about characterizations of transition zone samples for further study by diagenesis analysis.

During this research, a petrographic study on thin sections was performed by SEM in order to understand the depositional textures, pore types, diagenetic features and visually estimate the porosity and, eventually, the permeability. A detailed analysis of the sample was done on the basis of petrographic and diagenesis features. Before continuing special core analysis (SCAL) of transition zone samples, it is necessary for reservoir quality through diagenesis. Therefore, the present work interacts the attention of reservoir engineers to primary diagenesis analysis of reservoir rock samples.

Geological setting and environmental situation of the field

The transition zone under this study is part of a reservoir group from the Early Cretaceous, deposited during the Aptian age. This zone is defined as the interval between the top of one of the reservoir zone and the base of the tight, argillaceous formation and represents the lower part of the Shuaiba Formation (Strohmenger et al., 2006). The field under study (Figure 1A), which is an onshore oil field in Abu Dhabi, is a double-plunging anticline trending NE-SW formed during the Campanian (Al Bloushi, 2013; Vahrenkamp et al., 2014). The thickness varies between the crusts of the structure with 190 to 130 ft at the flank. According to the regional geology, this zone was deposited within the mega sequence AP8 when the Arabian Plate was undergone several tectonic events such as the opening of the Indian Ocean that results in the formation of a new passive margin within the Neo-Tethys as shown in Figure 1B (Sharland et al., 2013). Strohmenger et al. (2006) interpreted the reservoir zone as a third-order sequence, corresponding to the AP3A 18 sequence of the composite transgressive systems tract of a second-order composite sequence. Strohmenger et al. (2006) and Al Bloushi (2013) studied the depositional environment and texture of this zone and they stated that this reservoir zone was deposited on an open platform, subtidal, and depositional environment in a carbonate ramp to basin system. The zone has various porosity ranging from <1 to 38% comprising of intragranular, intergranular, microporosity and moldic porosities. The decrease in porosity with depth from crest to flank represents the transition zone. The permeability ranges from 0.1 to 1000 mD depending on the facies. It was recognized that the permeability depends on the type of porosity and the average pore size. Again Strohmenger et al. (2006) discussed the texture of this zone. The reservoir zone is dominated by shallow marine planktonic foraminifera wackestone/packstone with interbedded (dense) bioturbated, burrowed wackestone to mudstone. The sequences start with the subaerial exposure to a transgressive period of mudstone/wackestone, then ends with a regressive interval of packstone/grainstone cycle (Strohmenger et al., 2006; Vahrenkamp et al., 2014; Van Buchem et al., 2013).

METHODOLOGY

The method is typically based on optical microscope techniques in order to determine the rock texture and composition, pore network, fabrics, and diagenetic events. The main objective of this analysis is to supplement rock properties determination extracted from other methods such as core analysis and NMR. The petrographic analysis allows the determination of the mineralogy, cement and the estimation of the volume of the visible (> 20 µm) pore types. The petrographic analysis is the visual assessment of the rock properties on the pore-scale basis on the microscopic imaging. It is important to define the minimum volume of macroporosity in order to assist the evaluation of the rock quality. The value is determined based on the volume that represents the majority of the rock pores. The SEM analysis will be utilized in order to observe and recognize in detail the diagenetic relationships between different mineral phases or cement types and to help in identifying the pore geometry. The SEM spatial resolution is typically at least 100 times

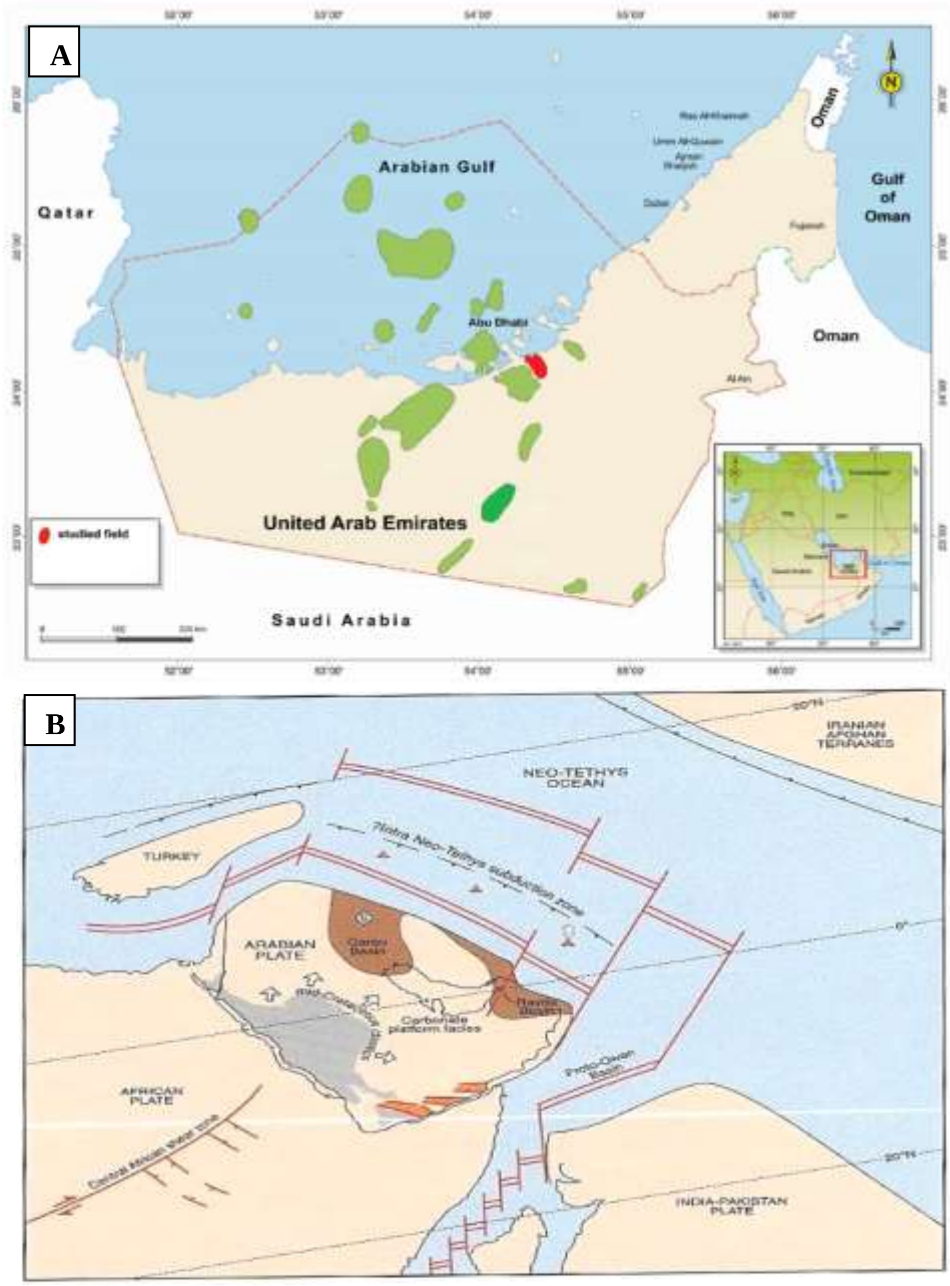

Figure 1. (A) Location of the field of the present study, the “Arabian Gulf” is also known as “Persian Gulf” (reproduced from Vahrenkamp et al. (2014) and (B) AP8 megasequence of the Late Jurassic to Late Cretaceous (149-92 Ma) showing the tectonic events including opening of the Indian Ocean’s southern extension and passive margin post-rift thermal subsidence (Sharland et al., 2001).

greater compared to a standard optical microscope. Scanning electron microscopes commonly have an X-ray spectrometer tool used to detect the characteristic X-rays of a selected mineral that can be used to identify the mineral composition. Ortenzi and Carmela (2014) emphasized the importance of these methods on the characterization of the carbonate reservoirs.

Gas porosity measurements of the samples were conducted by helium gas expansion method. The permeability of the samples was assessed with the Darcy equation, Equation 1, used with fluid flow in porous media. For a horizontal linear system, flow rate is related with permeability as follow:

$$q = \frac{kA}{\mu}\frac{dp}{dx} \quad (1)$$

where q is volumetric flow rate (cm^3/s), A is total cross-sectional area of the sample (cm^2), μ is the fluid viscosity (cP), dp/dx is the pressure gradient (atm/cm) and k is permeability in Darcy.

Table 1. Conventional core analysis (CCA) results of the used three plugs in this work

Sample No.	Zone in oil column	Permeability (mD)	Porosity (%)
1	Upper Structure	12.660	20.9
8	Mid Structure	7.846	15.4
12	Down Structure	7.096	4.7

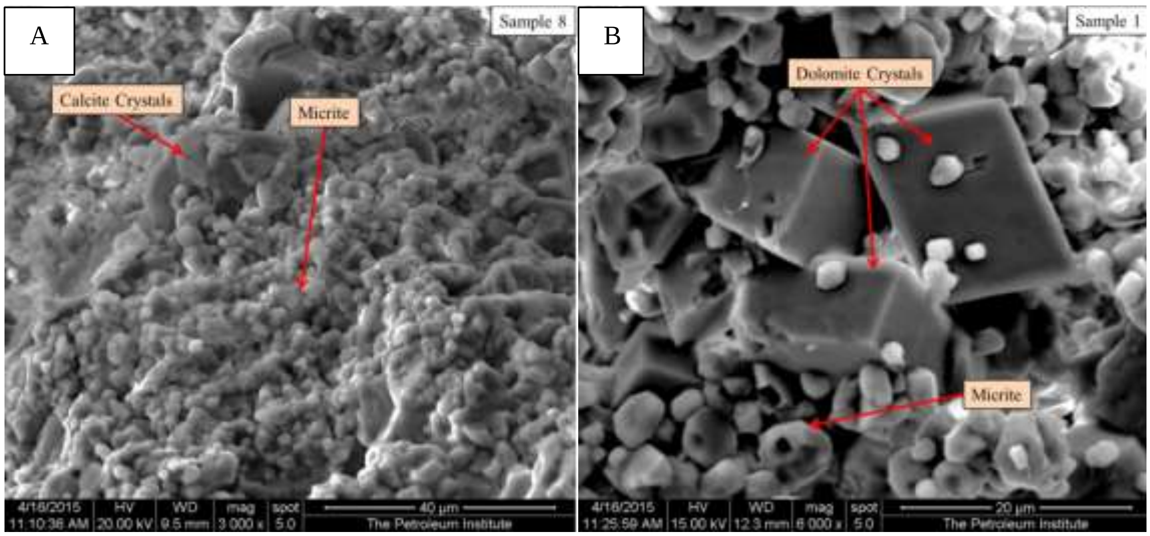

Figure 2. SEM images of (A) Calcite and (B) Dolomite crystals.

Table 1 shows the conventional core analysis (CCA) results of the three samples used in this study at ambient conditions.

RESULTS AND DISCUSSION

Petrographic/Petrology study (Depositional textures)

The majority of the zone comprises limestones, while the dolomite is observed with the SEM only at the bottom of the zone (Figure 2A and B). There are four major textural classifications, namely wackestone, packstone, grainstone and floatstone available. There are five major types of bioclasts within the samples studied, which are thin-shelled bivalves, brachiopods, planktonic foraminifera, gastropods and echinoderms. Some of the bioclasts are aggregated bioclasts that form the grainstone texture.

Diagenetic process and features

Four major diagenetic processes have affected the transition zone including micritization, cementation, dissolution and compaction.

Micritization

Micritization in this transition zone is extensive in the bioclasts. These micritized bioclasts can form the matrix during deposition (depositional micrite) (Figure 3A). According to Alsharhan and Nairn (1990), micrite underwent recrystallization (to form microcrystalline calcite) as shown from the SEM imaging (Figure 3B). Micritization is the earliest diagenetic event in this transition zone. It destroys the internal features of the skeletal grains and thus it degrades the reservoir quality.

Dissolution

Dissolution is the leaching of the metastable bioclasts due to the presence or circulation of the meteoric waters (Tucker and Wright, 2009; Flügel, 2004). However, partial dissolution of the bioclasts is common in the upper zone of the well, which depends on the original bioclasts composition stability as shown in Figure 4A and B. The pore shape will have the shape of the originally dissolved fossil. Dissolution of carbonate rocks occurs thus leading to an enhancement of the reservoir porosity in the form of solution moldic voids. The moldic porosity along with

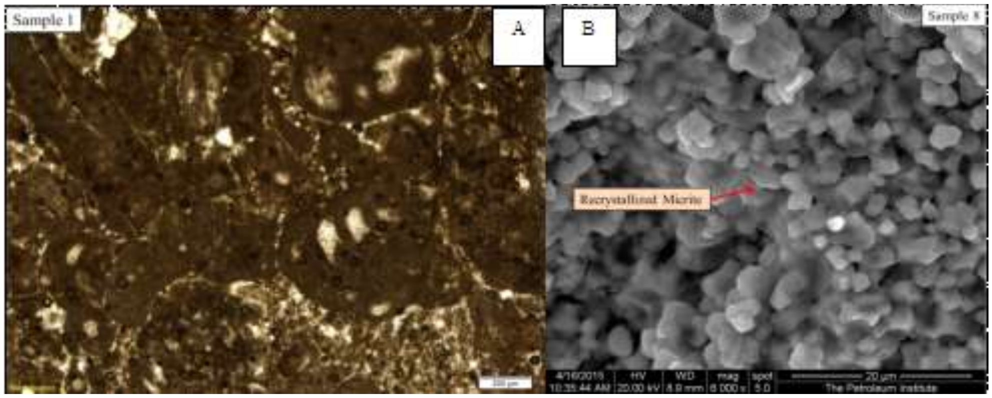

Figure 3. (A) Micritized bioclasts filled with cement and (B) Micro-porosity within subhedral to euhedral micrite.

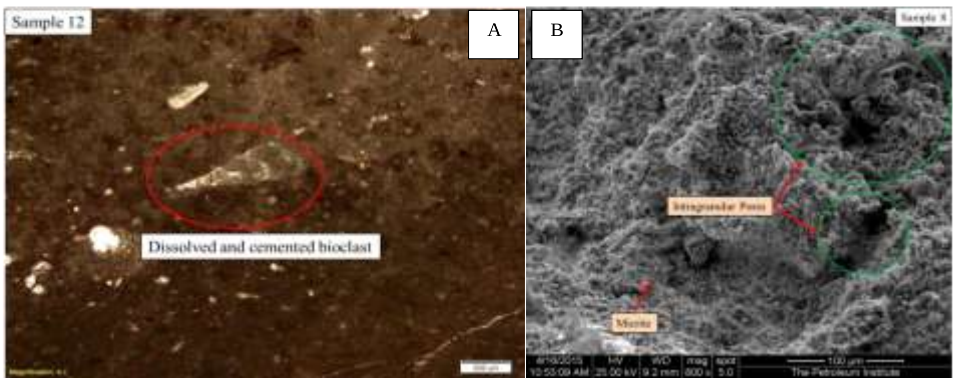

Figure 4. (A) Partial dissolution of the bioclas and (B) Intragranular pore in a bioclast (might be a gastropod).

intergranular porosity is the most common type of porosity found in the upper zone of the well.

Cementation

Based on our earlier study, it can be stated that cementation is a very important factor for controlling porosity and permeability in rock (Bera and Belhaj, 2016). Figure 5A and B shows drusy and blocky calcite in the present sample analysis. Saddle dolomite (Figure 5C and D) and fluorite cement (Figure 5E and F) are also present in the sample which indicates the diagenetic environment where it was precipitated and the timing of the cementation. Calcite, saddle dolomite and fluorite (CaF_2) are the main cement phases in this zone. In general cementation reduces the porosity and permeability as it plugs the pores. Cement precipitation can fill the pores fully or partially based on the situation. Cement precipitation (drusy or blocky) and/or by matrix during deposition or post-deposition by compaction processes can clog the pores resulting in lower permeability (Tucker, 2009; Lucia, 2007). Drusy calcite cement is thought to be a sign of early diagenesis in a meteoric environment, whereas the saddle dolomite and the fluorite mineral are believed to be formed by circulation of hydrothermal fluids at a deep (Flügel, 2004; Tucker, 2009; Lambert et al., 2006; Hollis et al., 2010; Alsharhan and Nairn, 1990). It is also believed to have occurred after reaching burial depth of around 600 m at temperatures of around 65.6°C (Cox et al., 2010). This is considered to be a late diagenesis stage, where it replaces calcite.

Compaction

In this zone, mechanical compaction is very limited and it appears in some sections which are fractured. Fractures can enhance overall reservoir quality if they are not cemented (open fractures) (Figure 6A and B), however, some open fractures could be induced while coring or plugging the core. Most of the fractures are partially cemented (Figure 6C and D) or closed fractures due to

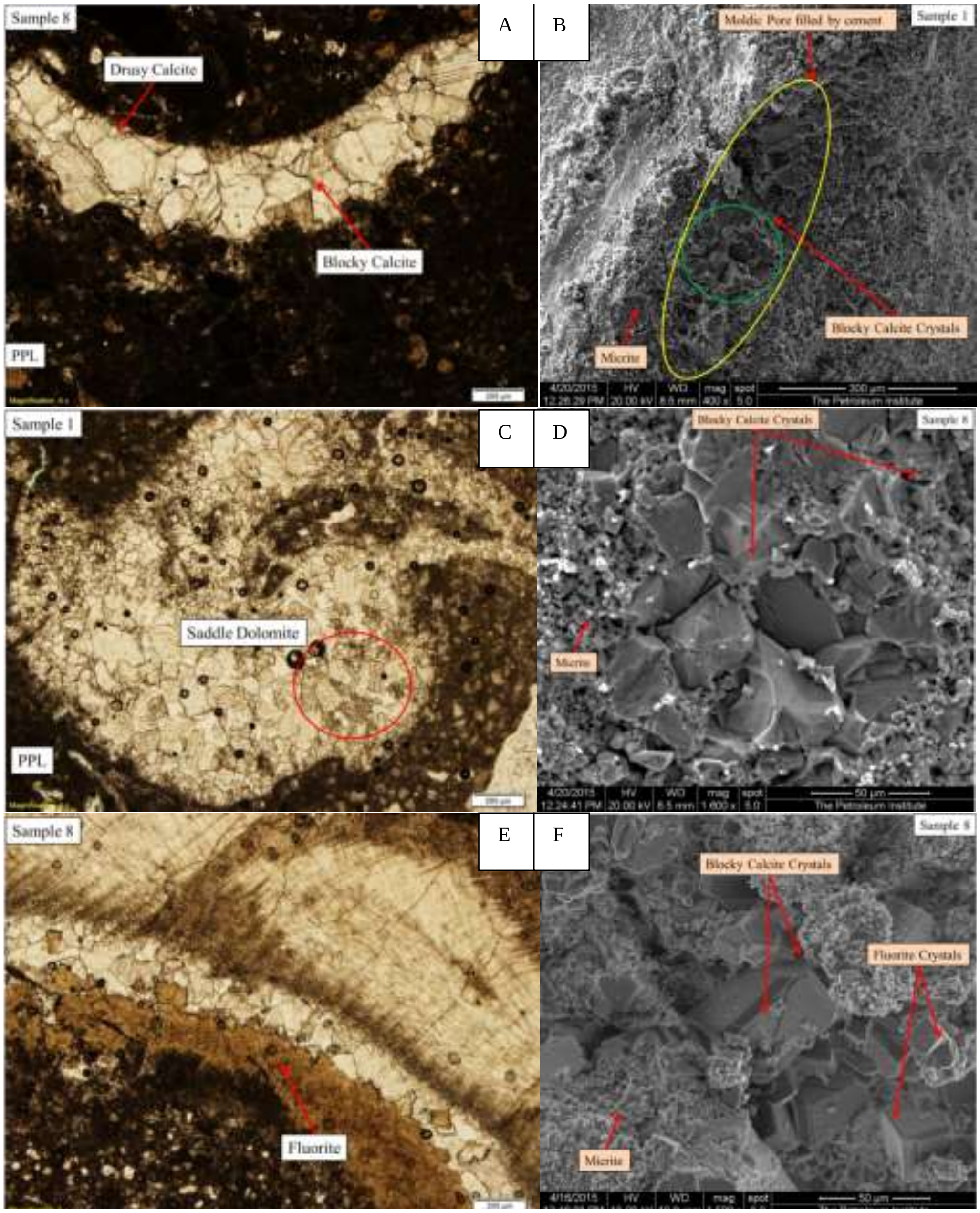

Figure 5. (A) Blocky calcite fully filled the pores, (B) Enlarged view of the blocky calcite cement filling the pore, (C) Saddle dolomite, (D) blocky and drusy calcite cement filling the pores with micrite, (E) Fluorite (light orange-brown color) filling the pore, (F) The cubic fluoride crystals along with the calcite crystals (Bera and Belhaj, 2016).

the precipitation of the cement or compaction which reduces the porosity and the permeability.

Paragenesis

In this zone, the timing is divided into two main events such as Eogenesis and Mesogenesis and telogenesis is not observed in this study.

Eogenesis

After the shallow burial of sediments, they are subjected to endolithic bacterial action that bore into such components and produces a dark micritic seam around grains. This was followed by precipitation of drusy calcite as it commonly occurs in the intergranular pore spaces (Figure 7). The water chemistry was supersaturated with

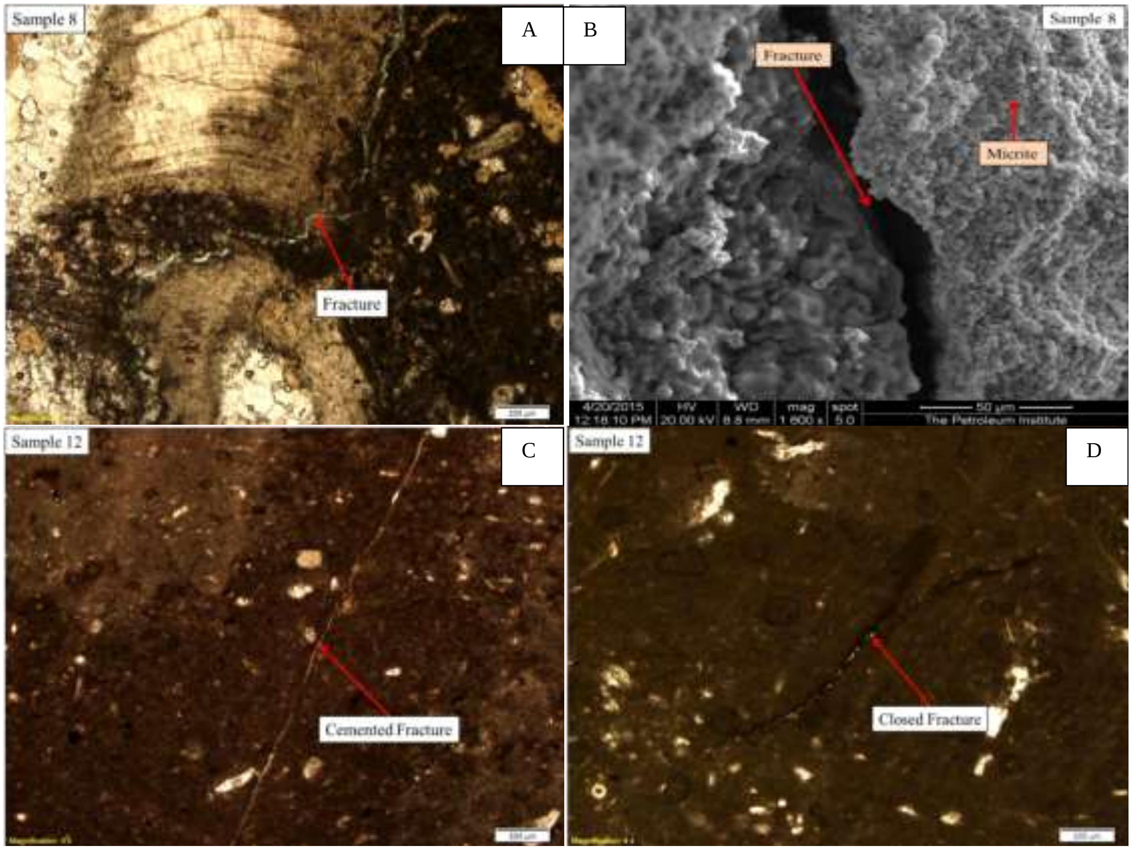

Figure 6. (A) Open fracture that enhances the porosity and permeability, (B) Open fracture, (C) Fracture partially filled with cement, and (D) Closed fracture due to mechanical compaction.

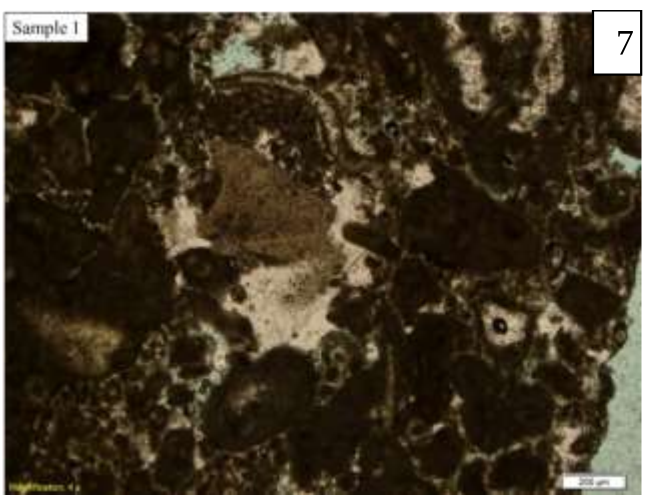

Figure 7. Micritization of the bioclasts and pores are filled by drusy and blocky calcite.

respect to low Mg calcite, which enabled most of the drusy calcite crystals cementation, followed by blocky calcite cement. This occurs in meteoric and marine environments and proceeds on to burial environments.

Mesogenesis

During mesogenesis, there was an increase in pressure-temperature gradients, which allowed for compressional features such as fractures to occur. The second generation of cementation can occur in the remaining pores where saddle dolomite precipitates as a result of this higher temperature and pressure regime. These dolomitic precipitations are likely to be a result of the hydrothermal fluid circulation (Tucker, 2001). Blocky calcite cement is also an evidence of the late diagenetic regime, along with the presence of the fluorite minerals. After attaining an overall understanding of the diagenetic processes affecting the transition zone, by identifying the features that characterize each one, a summary of the overall diagenetic realm can be formulated by placing the occurrence of each event in order of occurrence. Figure 8 summarizes the list of events and their related effects over time.

Diagenesis and reservoir quality

The visual porosity of the reservoir is within the range of 0.1 to 1 5%. The porosity types range from moldic,

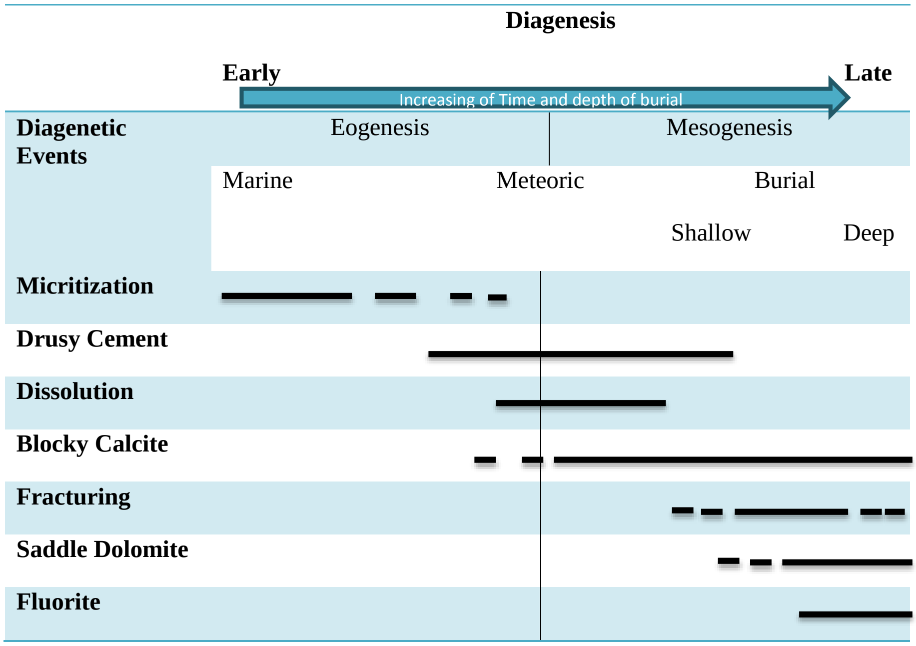

Figure 8. The overall sequence of the diagenetic features and processes in their order of occurrences.

Table 2. Summary of the impact of the diagenetic events on the overall reservoir quality

Diagenetic Process	Reservoir Quality
Micritization	Diminished the quality
Compaction	Diminished the quality
Dissolution and Fracturing	Enhanced the quality
Cementation	Diminished the quality

intergranular, intragranular, microporosity and fracture porosity. Intercrystalline porosity is less frequent. Some fluorite minerals were observed. The main diagenetic features are micritization, dissolution of bioclasts, cementation and compaction. Saddle dolomite was obtained in only one thin section study of sample 1.

In Eogenesis zone, there is extensive micritization observed in the sections, which contributes to the degradation of reservoir quality by diminishing primary porosity and permeability. Aside from micritization, cementation also occurred in the eogenesis in marine, mixed, and meteoric phreatic zones, which contributed to the degradation of the reservoir quality in terms of porosity and permeability. Certain events contributed to enhancing reservoir quality such as dissolution as shown in Table 2.

Mesogentic events mainly contributed to destroying porosity and permeability from the precipitations of the saddle and rhombic dolomite in pores and fractures. Diagenesis in the transition zone is very extensive especially the micritization and cementation due to the presence of the water that is responsible for the diagenetic overprint. The porosity is very low as cement is filling the pore spaces. We observed that in the upper zone, the diagenesis is less intense compared to the deeper intervals due to the presence of more oil that prevents the diagenetic processes. The diagenetic features are increasing with depth as the zone is having higher water saturations.

Conclusions

The main lithology is limestone with some dolomite at the bottom of the transition zone. The dolomite is observed by the SEM imaging only as the scale of investigation is different than the thin sections. A depositional facies ranging from wakestones to floatstones were found. It was also seen that while some diagenetic features such as fracturing and dissolution enhanced reservoir quality, others such as micritization, cementation and compaction led to a reduction in the porosity and permeability. Three types of fractures like opened, partially closed and closed are observed and therefore permeability is affected. The paragenetic sequences are mainly occurring during the eogenesis and the mesogenesis regime.

Conflict of Interests

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Abu Dhabi National Oil Company (ADNOC) Oil Subcommittee (OSC) and its Group of Companies including Abu Dhabi Company for Onshore Oil Operations (ADCO) and Abu Dhabi Marine Operating Company (ADMA-OPCO) for supporting the work on Transition Zones in Carbonate Reservoir project (Project No. OSC13001). Special thanks are due to the Petroleum Institute, Abu Dhabi, for hosting this research work. The authors also thank the other individuals those who directly or indirectly associated with this project.

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