



ORIGINAL PAPER

DETAILED DIAGENETIC INVESTIGATIONS OF THE CARBONATE CEMENTS OF THE LOWER CRETACEOUS YAMAMA FORMATION, RIYADH, SAUDI ARABIA

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ABSTRACT

The evaluation of the diagenetic processes is essential in order to comprehend the heterogeneities of the carbonate reservoirs. Different diagenetic processes, especially the carbonate cements, have drastically changed the Yamama Formation, a large reservoir formation in the Saudi Arabian region. The current study aims to assess several calcite cements by using field, petrographic and geochemical analyses. Field studies from three outcrops show that the formation is thin to thick bedded limestone with small amount of shale and marl units. According to petrographic analyses, the cements are primarily composed of dolomite, blocky, drusy, granular, isopachous rim, and syntaxial overgrowth. According to the cathodoluminescence studies, diagenesis primarily occurred in a closed system with no major and trace element fluctuation or exchange. Carbon isotopic values show positive values ($\delta^{13}\text{C V-PDB} = 0.23\text{‰}$ to 3.19‰) falling within the range Cretaceous marine signatures suggesting no influence from the meteoric water. Oxygen isotope show negative values ($\delta^{18}\text{O V-PDB} = -12.32\text{‰}$ to -1.31‰) showing depletion from the Cretaceous marine seawater suggesting diagenetic alteration in different environments. Three stages of evolution—eogenetic, mesogenetic, and telogenetic—are included in the paragenetic sequence. Although their permeability is modest because of limited pore interconnectivity, intraparticle microporosity and intrafossil porosity have improved the overall quality of the reservoir.

1. INTRODUCTION

The world's 50-60 % reservoirs are carbonate units that accounting for 40 % of today's hydrocarbon production (Roehl and Choquette, 1985). Countries in the Middle East hosts around 40 % of the world hydrocarbon reserves of which 60-80 % are found in the carbonate rocks. Moreover, the world's largest oil and gas fields (Ghawar and North Field/South Pars straddling the Qatar/Iran border) both are reservoir in carbonate rocks. However, the carbonate rocks are extremely heterogeneous in nature due to diagenetic alterations, which is influencing the petrophysical properties significantly (Lucia, 1999; Moore, 2002; Ahr, 2011; Deng et al., 2025).

Diagenetic processes include all the physical, chemical and biological changes which sediments have undergone since their deposition to the present (Tucker and Wright, 2009; Tavakoli et al., 2011; Rahim et al., 2020; Shahzeb et al., 2024). Diagenetic changes occur in many situations that can be grouped into three stages: eogenetic, mesogenetic, and telogenetic. The stage of formation depends on the environment in which the rock has undergone. The eogenetic stage occurs shortly after the deposition of sediments. This phase involves bioturbation, micritization, dissolution, and early marine phreatic cementation (Chafetz, 1972; Deng et al., 2025). Early diagenesis can lead to the dissolution and creation of secondary porosity (Jafarian et al., 2017). The mesogenetic stage occurs at burial depth due to

increasing temperature and pressure. During mesogenesis, the rocks undergo compaction, pressure dissolution, stylolitization, and dolomitization (Rahim et al., 2020, 2025). These processes can increase or reduce porosity, depending on the interplay between fluid chemistry and mineral stability (Tavakoli et al., 2011; Jafarian et al., 2017). Telogenetic stages occur when the carbonate rocks are uplifted due to tectonic processes. This causes freshwater to flow in and causes the rock to break down, form karsts, and make highly permeable zones through vertical fractures and dissolution (Chafetz, 1972). So, knowing about diagenetic stages can help us to understand what has happened to the rocks of Lower Cretaceous succession of the Arabian Peninsula with particular focus on the Yamama Formation. Diagenesis has significant influence in modifying the petrophysical properties of any carbonate reservoir (Ahr, 2011; Sadooni, 1993; Tavakoli et al., 2011; Jafarian et al., 2017).

The Lower Cretaceous Yamama Formation is an important reservoir rock of Arabian Peninsula. This formation is widely exposed in the central Saudi Arabia (Altala and Mahdi, 2011; Khalil et al., 2024). However, the outcrop exposures are limited at few places and ongoing construction activities are diminishing these exposures. Previously, Khalil et al. (2024) have described the sedimentary facies of the formation by using outcrops and petrographic studies. The study was comprehensive in nature in respect of sedimentary facies of the formation but it has not

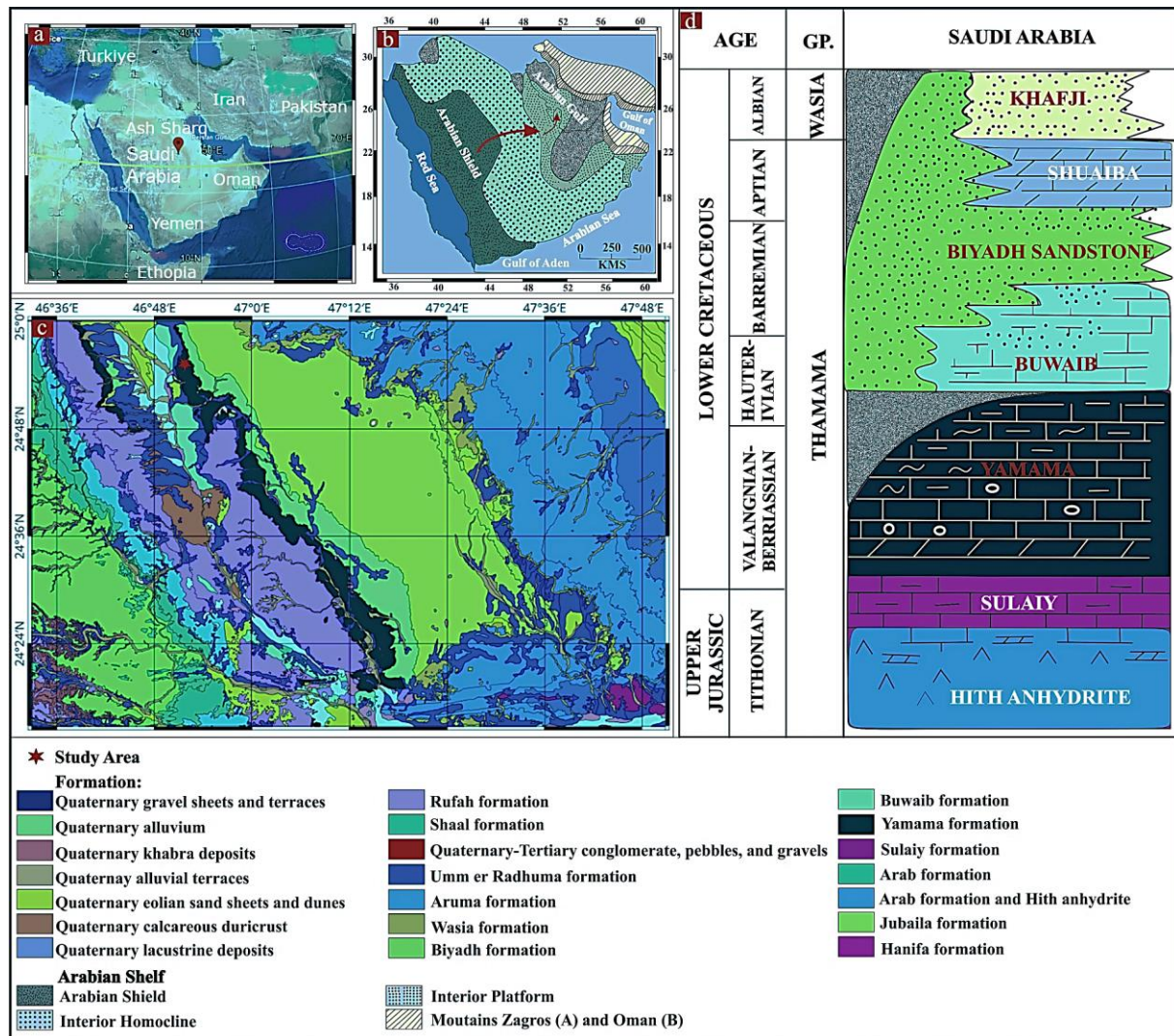


Fig. 1 Geology of Arabian Peninsula (a). Google Earth image showing the location of Arabian Peninsula with marked studied location (b). Structure and stratigraphic features of Arabian Peninsula. (c). Geological map of The AR Riyadh Quadrangle (modified after <https://ngd.sgs.gov.sa>). (d). Jurassic and Cretaceous stratigraphy with notable formations represented in the stratigraphic column.

highlighted the diagenetic character of the formation which is important to comprehensively describe the formation. In addition, this study also utilized advance techniques of carbonate sedimentology which were not previously used.

2. GEOLOGICAL SETTINGS

The study area is part of central Saudi Arabia which is the part of Arabian Peninsula (Fig. 1), which has distinct geological features. There are two main NE-SW trending structural elements. i.e., Ruba Al Khali Basin and the Arabian Arch (Nagm et al., 2018). These structural elements are resulted from three main geotectonic features; (i) Arabian Shield: it comprised of Precambrian igneous and metamorphic rocks found in central and western part of Peninsula. (ii) Arabian shelf is comprised of Phanerozoic rocks of marine and continental origin. (iii) The Zagros mountains is present in the northeastern side of Arabian shelf (Powers et al., 1966; Alshathan and Nairin, 1986).

The lower Cretaceous sedimentary rocks of Arabian Peninsula are part of stable platform belonging to the Paleozoic and Mesozoic age rocks. They rest unconformably on the Precambrian shield rocks (Alsharhan and Nairn, 1986). Stratigraphically, the Yamama Formation is an important unit of the Thamama Group (Sadooni, 1993; Altala and Medhi, 2018; Nagm et al., 2018). The Lower Cretaceous Yamama Formation is composed of platform carbonates with lithofacies of limestone, shale and marl. The microfacies are mainly of mudstone, wackestone, packstone and grainstone representing lateral and vertical changes from supratidal to deep marine environments (Altala and Mahdi, 2018; Khalil et al., 2024).

3. METHODOLOGY

Reconnaissance field work was conducted in the vicinity of Riyadh area to check the rock exposures of the Yamama Formation. The rock units are exposed in

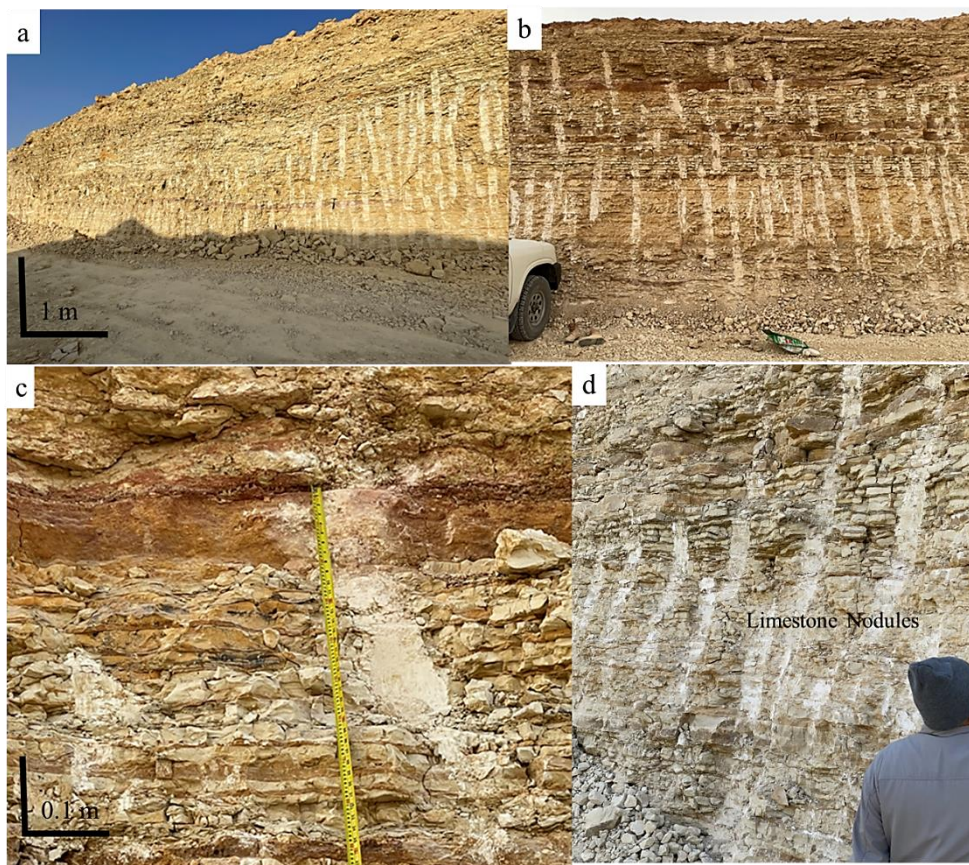


Fig. 2 Field photographs of the Yamama Formation depicting its exposures and different lithological characters. (a) Panoramic image of the Yamama Formation showing the vertical cut of the formation. All bedding characters of the formation are easily accessible. (b) Detail photograph of the Yamama Formation showing beds of limestone with few thin beds of shale. (c) Detail view of the brown color shale and thick to massive bedding in the Yamama Formation. (d). Detail view of limestone showing nodular features.

the Ash Sharaq area which is approximately 40 km away from the Riyadh City. Three different stratigraphic successions are measured by noting such important sedimentological information: Observations of bedding characteristic, textural variations and allochems type, if visible. Representative sampling is taken for further investigations. Detailed investigations of various analysis were done at the laboratories of the Faculty of Earth Sciences, King Abdul Aziz University, Saudi Arabia.

Twenty-four samples have been collected from base to top of the formation focusing on the lithological variations. Thin-sections were studied under polarizing microscope (Olympus-BX-51) with camera attachment (Nikon, DP-21) to identify different depositional and diagenetic features. The carbonate rocks are classified according to the scheme of Dunham (1962) classification.

In order to distinguish different phases of calcite cements, the cathodoluminescence petrography was done on the representative thin-sections. Representative thin sections were prepared from the collected samples. The thin-sections were placed on cathodoluminescence stage mounted on the polarizing microscope and vacuum were created in the chamber. The electron beam of 15-18 Kv was

bombarded on the polished thin section. The luminescence of excited electron was studied and photographed for the representative thin-sections by using the methodology of Boggs and Krinsley (2006).

Stable isotopic study was carried out on all representative samples belonging to different diagenetic phases. Carbonate powder of all diagenetic phases is reacted with ultrapure phosphoric acid at 70 °C and the liberated gas were analyzed at the Thermo Fisher mass spectrometer. The obtained values are reported in per mil relative to V-PDB. The analytical precision was more than 99.9 %.

Sixteen samples were selected for the porosity and permeability analyses through coring and core analysis of plugs. The analysis was done at THMS-300 instrument. In addition, during thin section preparation, blue dyed epoxy was applied for the impregnation of pores.

4. RESULTS

4.1. FIELD OBSERVATIONS

The formation is exposed as a result of road cut providing good accessibility to study sedimentary characters of the formation (Fig. 2a). Field observation show that the formation is thin to thick bedded limestone with small amount of shale and marl units

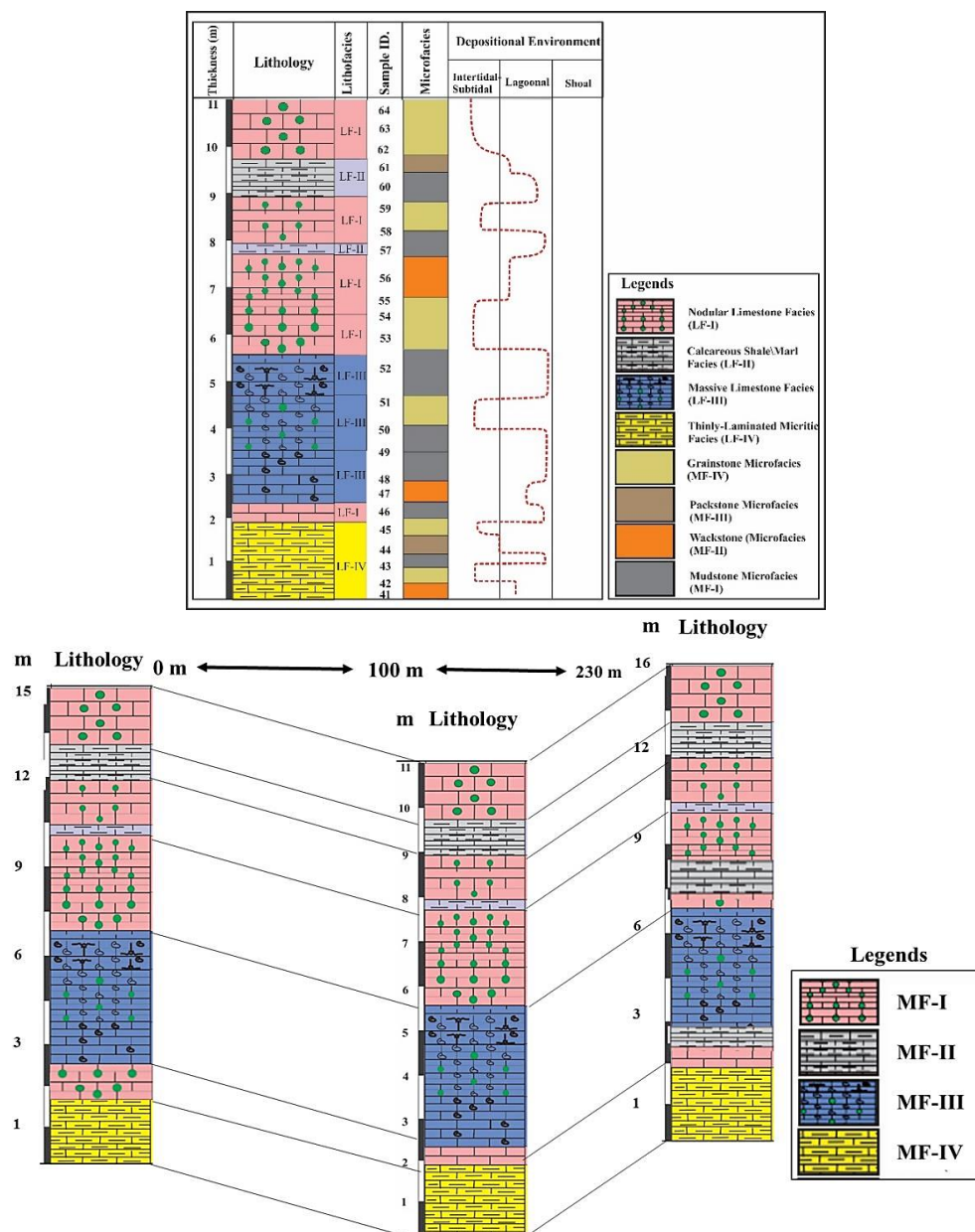


Fig. 3 (a) Lithological log of the Yamama Formation showing the observed lithofacies, microfacies and its associated depositional settings modified from Khalil et al. (2024). (b) The vertical and lateral distribution of different facies is clearly demonstrated in the fence diagram.

(Fig. 2b). The limestone is of yellowish-brown color which is hard and brittle in nature. The limestone is showing few bioclasts on the rough and fresh surfaces. The shale and marl are mostly splintery in nature which easily breaks (Fig. S1(b)). The contact between different bedding units is usually sharp which is evident due to sharp color contrast (Fig. S1(c)). From the field and petrographic studies, the sedimentary facies of the formation are recognized (Fig. 2).

4.2. DIAGENETIC FEATURES

4.2.1. BURROWING

Burrowing is one of the initial phenomena that sediments encounter after their deposition and before consolidation. The study of trace fossils significantly improves sedimentological interpretation by providing

information that cannot be inferred solely from studying the physical sedimentary features (Pedley, 1992; Pemberton et al., 1992).

In the Yamama Formation, bioturbation is only observed in the muddy matrix particularly in the mudstone facies (Fig. 3a). the muddy matrix of the formation is turned into the homogenized groundmass (Fig. 4a).

4.2.2. MICRITIZATION

Micritization is the process of alteration of bioclasts by algae, fungi and bacteria (Tucker and Wright, 2009). The skeletal grains are altered and replaced by the micro to crypto crystalline carbonate matrix. The process start with the development of micrite envelopes around the grains in the photic zone.

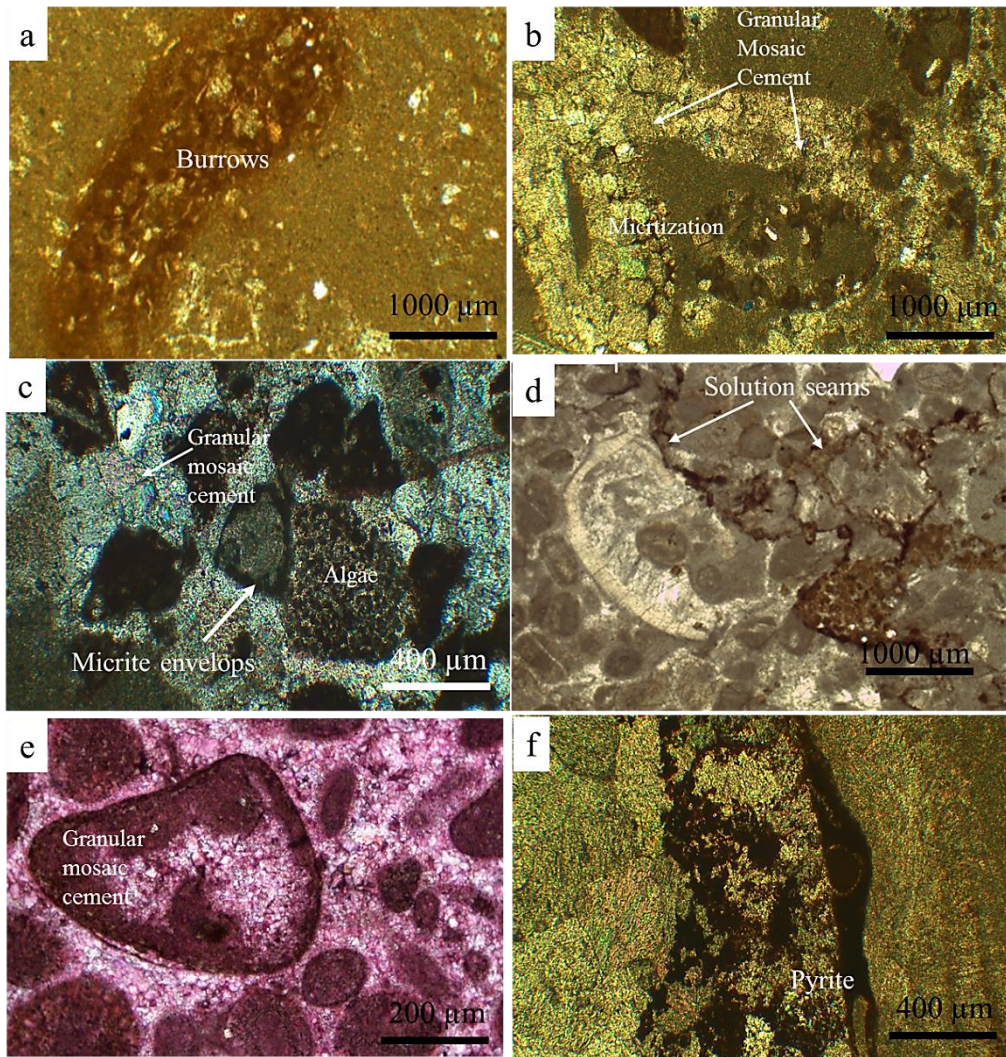


Fig. 4 Petrographic studies of the Yamama Formation showing various diagenetic features. (a) PPL photomicrograph showing the vertical burrow filled with brownish carbonaceous material. (b) XPL photomicrograph showing the micritization of bioclastic grains and the drusy mosaic cements. Note that cementation is postdating the micritization. (c) Detail view of granular mosaic cement with cement crystals of equal size and it is acting as a binding material for the grains. (d) mudstone microfacies with prominent solution seams clearly visible in the stained thin section. The seams are filled with brown color dolomite (RD-1). (e) XPL photomicrograph showing the detail view of granular mosaic cement observed in stained thin section. Note that the cement is postdating the micritization formed as a result of aragonite dissolution and later filling with calcite cement. (f) PPL photomicrograph showing the pyrite framboids in the blocky calcite cement.

This phenomenon is quite common in skeletal and non-skeletal grains of the Yamama Formation as observed during the detail petrography (Fig. 4b).

4.2.3. NEOMORPHISM

Neomorphism is the transformation of mineral by its polymorph. This is not simple pore filling as the older crystals are gradually consumed and replaced simultaneously by its polymorph (Bathurst, 1972). During this process dissolution and re-precipitation took place at the same time

In the Yamama Formation the observed equant cement is displaying the characteristics of aggrading neomorphism resulting from the replacement of aragonite to spar (Fig. 5g).

4.2.4. CEMENTATION

In the Yamama Formation, cementation is the most observed phenomena that has changed the entire character of the formation. The major cementation types observed are as follows:

Isopachous rim cement: This cement is observed as finely crystalline isopachous fibers making the rims along the allochems. These thin fringes are very common in the Yamama Formation as observed in the petrographic studies (Fig. 5c). This type of cement is represented as first generation of cement and usually formed in marine diagenetic conditions (Longman, 1980).

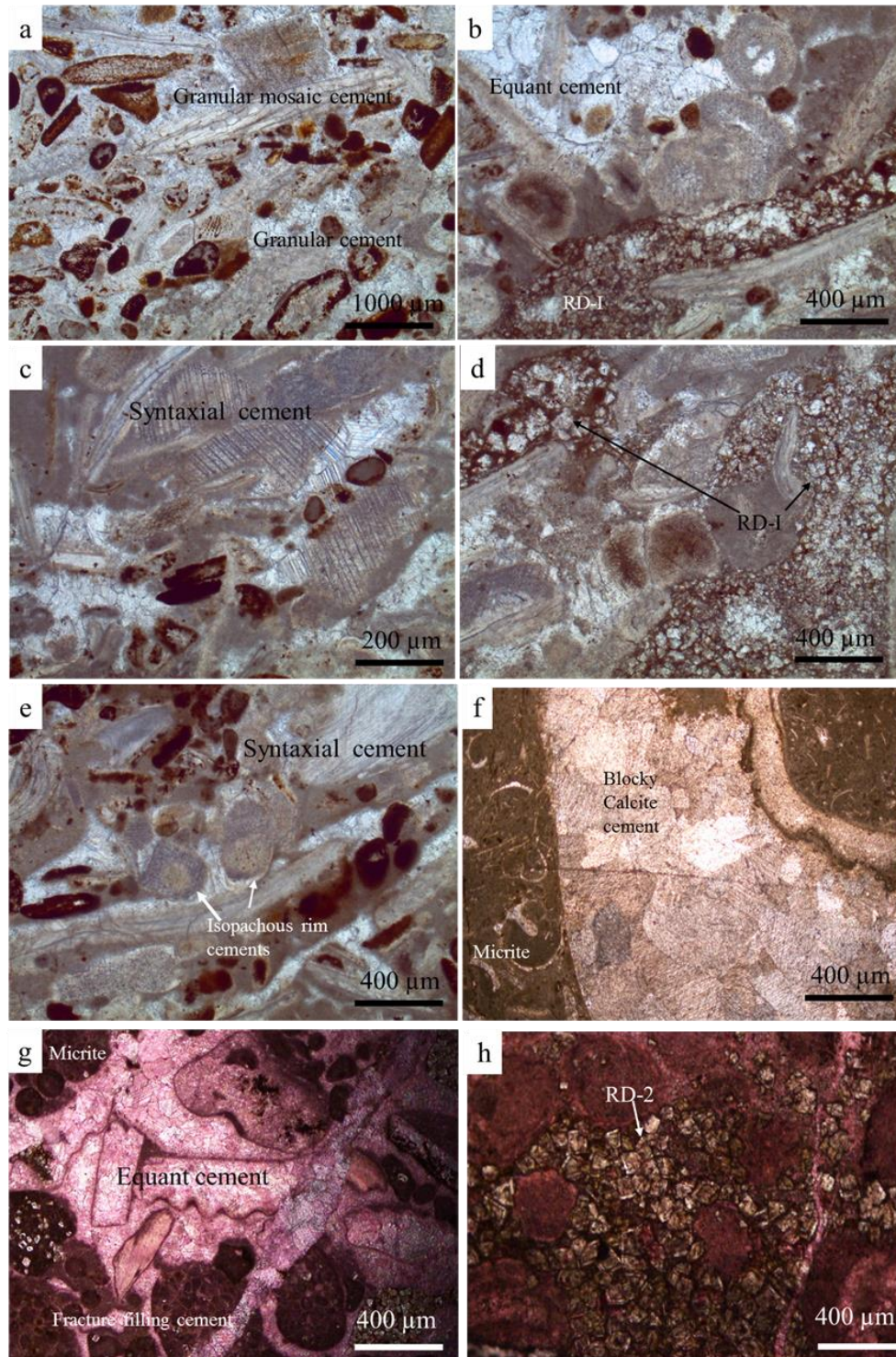


Fig. 5 Petrographic studies of the Yamama Formation showing various types cements observed. (a) XPL photomicrograph showing the granular mosaic cements. Note that the allochemical particles are gradually replaced by the emplacement of these cements (b) XPL photomicrograph showing the remaining pore spaces are filled with equant calcite cement and replacive dolomite cement (RD-1). (c) Detail view of syntaxial cements with prominent cleavage planes. (d) Detail view of replacive dolomite RD-1 acting as a cement and filling the pore spaces. (e) XPL photomicrograph showing the isopachous rim cement and Syntaxial cement. (f) Detail view of blocky calcite cement (g) XPL photomicrograph showing equant calcite cement. Note that the micrite lining of shell fragments is preserved, the replacement of aragonite material with spar as a result of aggrading neomorphism. (h) The RD-2 dolomite with euhedral to subhedral crystal morphology is filling the pore spaces. RD-2 is filling the pore spaces of host limestone.

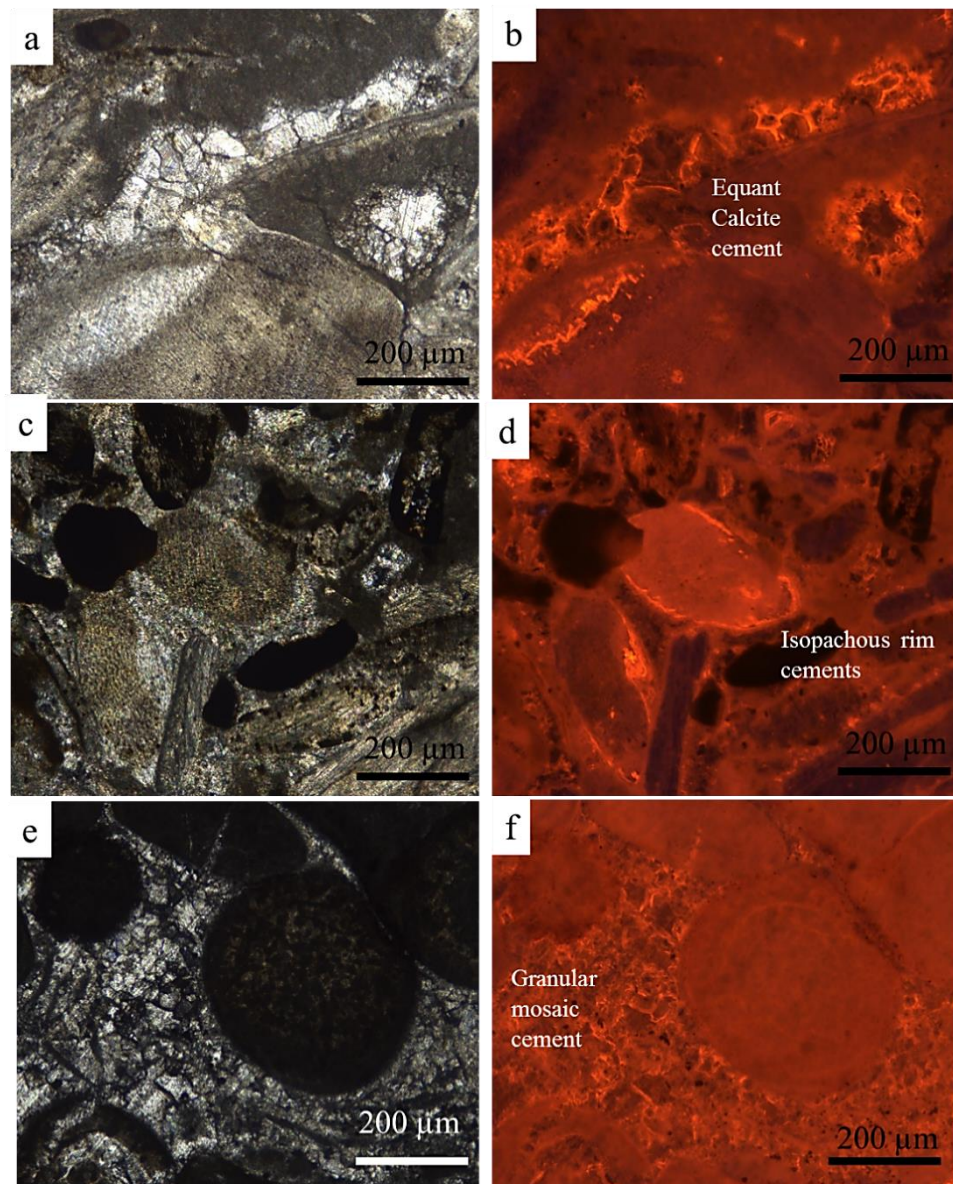


Fig. 6 Combined polarizing and cathodoluminescence petrography showing different types of calcite cements observed (a, b) Paired XPL and CL photomicrographs showing blocky calcite cement. Note that overgrowth along the nucleus is very prominent indicated by sharp luminescence contrast (c, d). Paired XPL and CL photomicrographs showing isopachous rim cement lining the intraclast. The remaining pore space is filled with drusy mosaic cement (e, f). Paired XPL and CL photomicrographs showing the granular mosaic cement. Note that the cement is covering the allochems and impeding further compaction and cementation.

Syntaxial overgrowth cements: Syntaxial overgrowth cements are characterized by the growth of new calcite crystals over the or in alignment with the existing calcite crystal (Longman, 1980). The resulting texture of mineral overgrowth provide important clues about the sedimentary environment under which it is formed. In the Yamama Formation, syntaxial overgrowth cement is very common with multiple cleavage planes formed due to effect of overburden stresses (Figs. 4c, 4e).

Drusy mosaic cement: Drusy mosaic cement is characterized by the mosaic of small interlocking crystals which interlock in a mosaic pattern. This type

of cement form from the precipitation of calcite crystals from the supersaturated solution. They mostly fill the void spaces resulting in interlocking of grains and occultation of porosity (Arosi and Wilson, 2015). In the Yamama Formation, this type of cement is observed with crystals of sparkling appearance (Figs. 5b, 5c).

Granular mosaic cements: This type of cement is characterized by uniform crystals which also interlock in a mosaic pattern. The difference between drusy and granular mosaic is the equidimensional grains are more common in granular mosaic cement (Longman, 1980). This is one of the most common cement type

observed in the Yamama Formation that gradually binds the allochemical particles of the formation (Figs. 4e, 5a).

Equant calcite cement: This type of cement is composed of crystals of uniform size (200-500 μm) with sharp crystal edges. This type of cement is mostly found in meteoric environment (Figs. 5g, 5h). In the Yamama Formation, this type of cement is common in the grainstone facies due to the fact that larger allochemical grains have larger pore space which is mostly filled with cement of medium to coarse grain size (Figs. 4g, 4h). As the setting time of crystals is high which results in the formation of uniform size crystals (Figs. 4g, 4h; 5a, 4b).

Blocky calcite cement: It is a type of calcite cement which is characterized by medium to coarse grain crystals (500-1000 μm) with no exact orientation. The crystals are ferroan in nature as observed in the petrographic studies of stained thin sections (Fig. 5f). In the Yamama Formation, this type of cement is mostly found along the fracture filled vein or dissolution pore space (Fig. 5f). This type of cement is commonly found in meteoric phreatic, meteoric vadose and burial settings and is infrequent in marine and reef environments (Flügel and Munnecke, 2010; Arosi and Wilson, 2015; Rahim et al., 2020).

Dolomite cements: Dolomite cements are also found in the Yamama Formation extensively filling the pore spaces. Dolomites are mostly fabric retentive in nature and the original rock fabric is visible (Figs. 5b, 5d, 5h). Two types of dolomites based on texture and morphology:

(i) Fine crystalline subhedral dolomite (RD1): the dolomite is composed of subhedral crystals with size ranging from 40-60 μm . this kind of variety is mostly pore filling cement and occluding the pore spaces (Figs. 4b, 4d).

(ii) Medium crystalline subhedral to euhedral dolomite (RD-2): this type of dolomite is composed on subhedral to euhedral crystals (100-200 μm) which are usually free from inclusions. They are also filling the pore spaces created due to the dissolution of carbonates (Fig. 4h).

Pressure Dissolution features: Pressure dissolution is the phenomena whereby grains undergo dissolution at their contact as a result of localized strain. If the strain is localized it may result in pressure dissolution seams and if the phenomena is at larger scale, it is called stylolite. Stylolites mostly act as a permeability barrier due to precipitation of clay minerals along the interface.

In the Yamama Formation, chemical compaction features are not very common, however, they are observed at the outcrop scale (Khalil et al., 2024). The solution seams and wispy seams are observed in the petrographic studies and in some cases they are filled with fine grained dolomite cements (Fig. 3d).

Fractures: The imprints of stresses (overburden, gravitational and tectonic) after burial and compaction of sediments resulted in the formation of fracture, veins and broken allochems (Figs. 2c, 4d). The fractures are very common in the Yamama Formation with intensity of fractures is more prevalent in the upper part of studied formation.

4.3. CATHODOLUMINESCENCE ANALYSIS:

Cathodoluminescence (CL) analysis is a valuable tool for distinguishing relative percentage of carbonate phases i.e., original grains, replacement phases and cements (Hiatt and Pufahl, 2014; Rahim et al., 2024a). Cathodoluminescence (CL) analysis is widely used in studying the diagenetic alteration in carbonate rocks. Based on the intensity and pattern of luminescence, it is easier to identify the relative timing of different diagenetic events (Boggs and Krinsley, 2006).

In the Yamama Formation, CL analysis was done to detect different events of cementation based on the intensity of luminescence (Fig. 6). Different types of cements and their nucleation sites are identified which helped us to identify the genesis of different types of cements in the studied formation. Different types of cements such as equant, granular mosaic and isopachous rim cements are easily identified based on this technique (Fig. 6).

4.4. STABLE ISOTOPES

The stable isotopic analysis is conducted on the unaltered limestone and all diagenetic phases. Their values from are depicted in the Table 1. Samples of different diagenetic phases showing a wide variation of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from the Cretaceous sea water which is the indicative of diagenetic alteration in different environments (Table 1; Fig. 7). The isotopic values are compared with Sea water signatures compiled by Mansour et al. (2021).

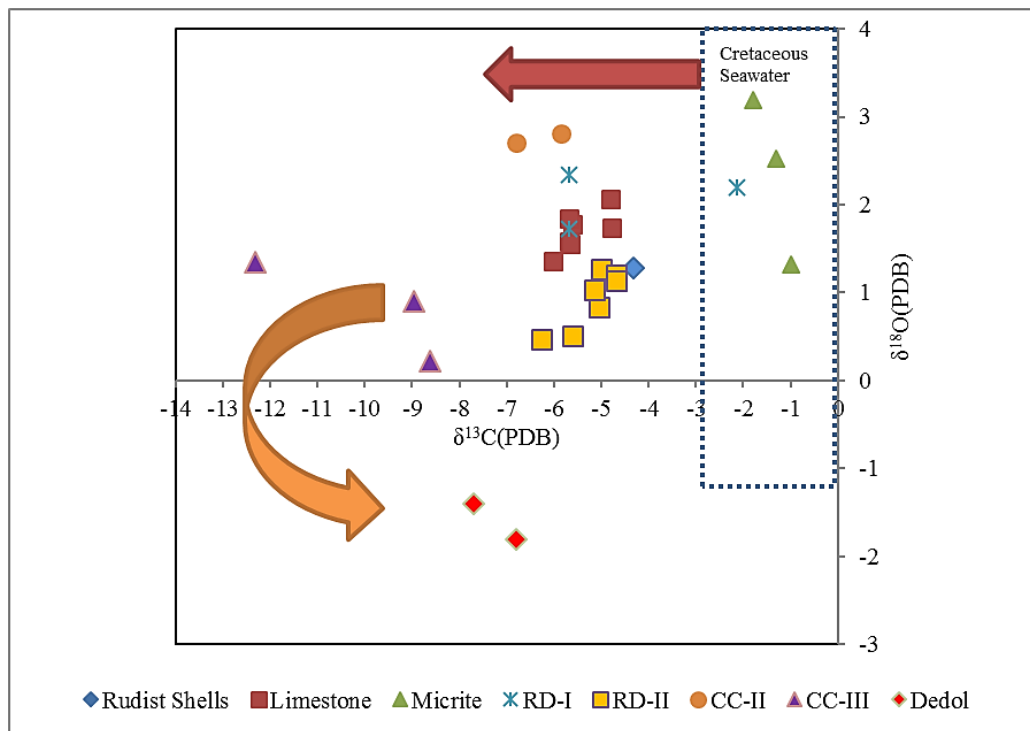
The $\delta^{13}\text{C}$ value of micrite matrix ranges from 3.19 ‰ to 1.32 ‰ V-PDB and $\delta^{18}\text{O}$ value ranges from -1.8 ‰ to 1.00 ‰ V-PDB which is in line with known Cretaceous seawater signatures (Fig. 7). The $\delta^{13}\text{C}$ values of limestone ranges from 2.07 ‰ to 1.58 ‰ V-PDB and $\delta^{18}\text{O}$ values ranges from -6.01 ‰ to -0.34 ‰ V-PDB showing depletion from the marine isotopic signatures (Fig. 7). The $\delta^{13}\text{C}$ values of replacive dolomites (RD-1 and RD-2) ranges from 2.19 ‰ to +1.58 ‰ and $\delta^{18}\text{O}$ values ranges from -6.27 ‰ to -4.37 ‰ showing depletion in oxygen isotopic signatures (Fig. 6).

The CC-I is drusy mosaic and granular mosaic cement. As they are closely associated with limestone therefore its sampling was not possible due to contamination factor therefore its values are not separated for the isotopic analysis.

CC-II is equant calcite cement filling the pores are described above. The $\delta^{13}\text{C}$ value of ranges from 2.81 ‰ to 2.70 ‰ V-PDB to and $\delta^{18}\text{O}$ value ranges from -6.79 ‰ to -5.85 ‰ V-PDB which is in line with known Cretaceous seawater signatures (Table 1; Fig. 7).

Table 1 Stable isotopic values of C, O isotopes of observed diagenetic phases in the Yamama Formation. the standard deviation of every value is ± 0.1 ‰.

No.	Sample Code	$\delta^{13}\text{C}$ (‰, V-PDB)	$\delta^{18}\text{O}$ (‰ V-PDB)	Diagenetic phase
1	Y-41A	-1.40	-7.70	Dedol
2	Y-41B	1.32	-1.80	Micrite
3	Y-42	1.28	-4.31	Rudist Shells
4	Y-43	1.58	-5.04	Limestone
5	Y44A	1.34	-12.32	CC-III
6	Y-44B	-1.80	-6.79	Dedol
7	Y-46	1.36	-6.01	Limestone
8	Y-48A	1.73	-2.12	RD-I
9	Y-48B	0.90	-8.97	CC-III
10	Y-48C	1.20	-5.60	RD-II
11	Y-49A	1.03	-6.27	RD-II
12	Y-49B	1.14	-5.00	RD-II
13	Y-49C	0.23	-8.61	CC-III
14	Y-50	1.58	-5.67	Limestone
15	Y-51	2.53	-1.31	Micrite
16	Y-52	1.56	-5.65	Limestone
17	Y-53A	0.83	-5.06	RD-II
18	Y-53B	1.74	-4.79	Limestone
19	Y-54	2.07	-4.80	Limestone
20	Y-55	2.34	-5.67	RD-I
21	Y-56A	2.81	-5.85	CC-II
22	Y-56B	2.19	-5.67	RD-I
23	Y-57A	2.70	-6.79	CC-II
24	Y-57B	3.19	-1.00	Micrite
25	Y-58	1.78	-5.61	Limestone
26	Y-59	1.84	-5.68	Limestone
27	Y-61	1.26	-5.15	RD-II
28	Y-62	0.47	-4.68	RD-II
29	Y-63	0.51	-4.69	RD-II

**Fig. 7** Carbon and oxygen cross plot of showing the distribution of limestone, calcite and dolomite phases. The Cretaceous marine signature is compiled after Mansour et al. (2021). Note that most of the diagenetic phases are showing the depleted oxygen isotopic signature with few showing depleted carbon isotopes. Red arrow showing the temperature affect and the orange arrow showing the influence of meteoric fluids.

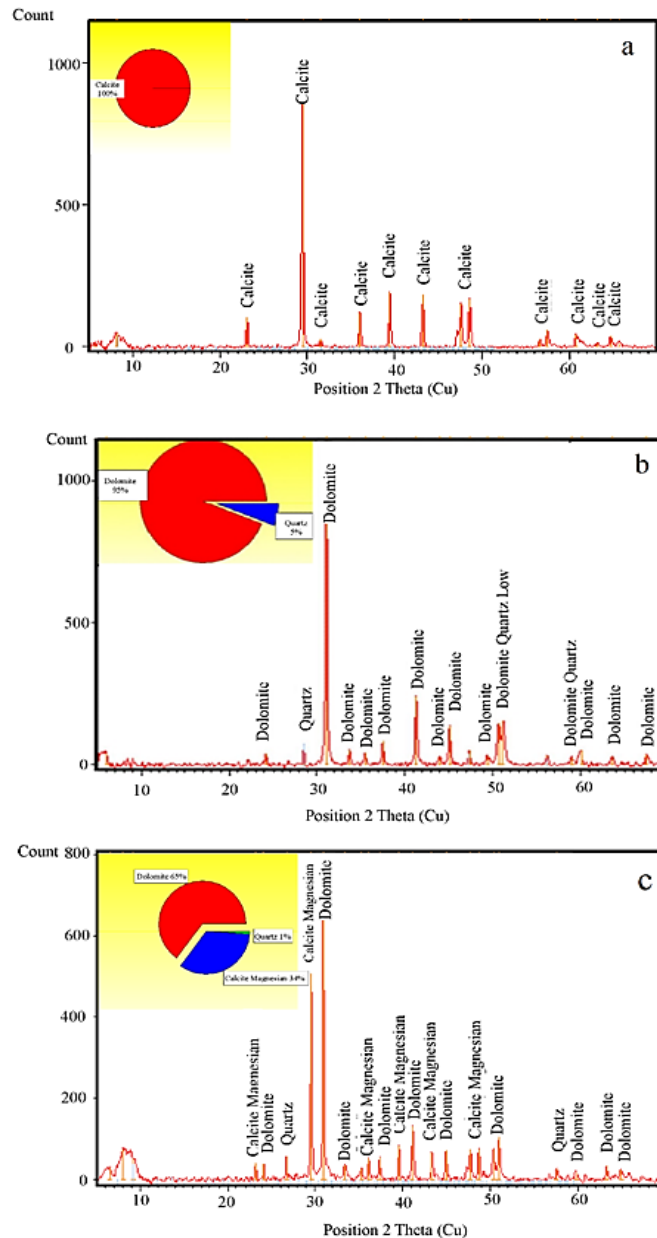


Fig. 8 XRD graphs showing the mineralogical composition of different samples. The inset pie chart explains the mineral composition of the samples (a) limestone (b) pure dolomite (c) impure dolomite.

CC-III is the blocky calcite cement which mostly fills the fracture filling veins. The $\delta^{13}\text{C}$ value of ranges from 1.34 ‰ to 1.32 ‰ V-PDB to and $\delta^{18}\text{O}$ value ranges from -1.8 ‰ to -8.61 ‰ V-PDB which are showing most depleted signatures in respect oxygen isotopes with the known Cretaceous seawater signatures (Table 1; Fig. 7).

The cross plot indicates the range of different diagenetic phases very well (Fig. 7). It shows that most of the diagenetic phases show depletion in respect of oxygen isotopes with the known range of Cretaceous marine signatures which is a very good indicator diagenetic overprinting of carbonate rocks (Fig. 7).

4.5. MINERAL COMPOSITION

The mineralogical composition present in the chosen carbonate samples was comprehensively discerned through the utilization of XRD bulk analysis. The resulting data revealed a spectrum of mineral levels, including calcite, dolomite, halite, and quartz. It is noteworthy that only a few select samples contained certain minerals, suggesting the occurrence of local diagenetic events.

Calcite, which is typically prevalent in carbonate, was confirmed in all the samples. However, the quantities showed considerable variation, ranging from 40 to 98 weight percent (wt.%). Dolomite was identified in some of the analyzed samples but was not consistently present. The abundance of dolomite ranged between 0 to 60 wt.% in instances where it was detected (Fig. 8).

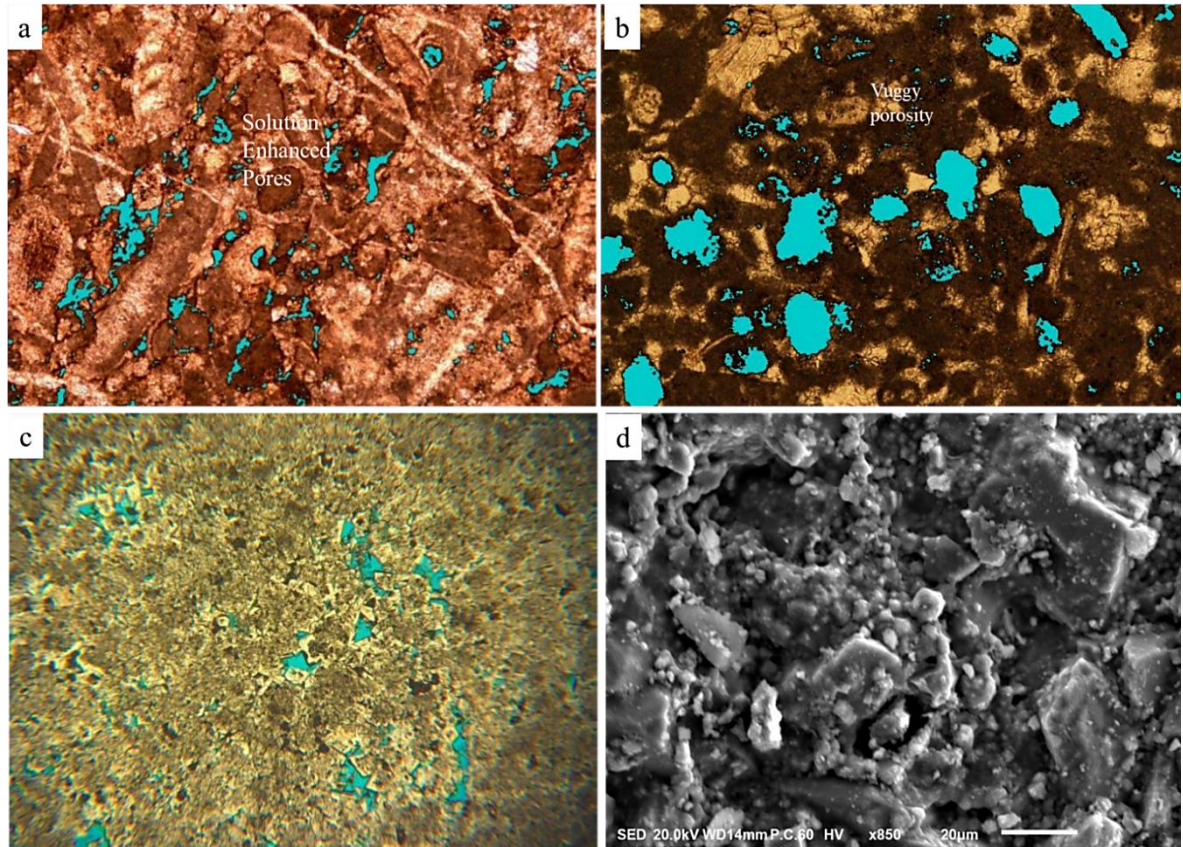


Fig. 9 Petrographic and SEM images reveal various reservoir related features that in the Lower Cretaceous carbonates (a) solution enhanced pore spaces (b) vuggy porosity (c) inter-crystalline porosity (d) SEM image showing detail view of inter-crystalline pores.

4.6. POROSITY TYPES

Through the analysis of rock samples under a microscope and SEM, two distinct porosity categories have emerged, distinguished by their relation to the rock's fabric: fabric-selective and non-fabric-selective. Fabric-selective porosity predominantly aligns with the rock's depositional or post-depositional fabric. This category encompasses various sub-types. For instance, interparticle microporosity, found between micrite particles, is one such type (Fig. 9). Bioclastic moldic porosity emerges due to the dissolution of shell fragments (Fig. 9a), while intrafossil porosity is predominantly observed in *Orbitolina* large benthic foraminifera (Fig. 9a). Intercrystal porosity can also be attributed to the existence of connected and non-connected intercrystal spaces in dolomite crystals (Figs. 9a-9c). Furthermore, intrafossil vuggy porosity, which originates within fossils like *Orbitolina* large benthic foraminifera (Fig. 9a), and porosity derived from dissolved dolomite rhombs (dolomite molds) (Fig. 8d), also fall within this category.

Contrarily, non-fabric-selective porosity is dictated by processes that supersede the rock fabric (Ahr, 2011; Tavakoli et al., 2011). Fracture porosity, stemming from open fractures or cracks within a rock, is a form of non-fabric-selective porosity (Fig. 9b). Moreover, vuggy porosity, pertaining to minute to

considerable cavities within the rock (Fig. 8c), and solution-enlarged fractures porosity, resulting from fractures that have broadened due to the dissolution of the rock by circulating fluids (Fig. 9c), are included in this category. An intriguing observation from the study is that virtually every type of porosity has been identified in samples obtained from the Yamama Formation.

5. DISCUSSION

5.1. DIAGENETIC ENVIRONMENTS

The Lower Cretaceous Yamama Formation have gone through several episodes of diagenetic alteration as reported in the field and petrographic studies. The diagenetic stages are relative in nature inferred on the basis of crosscutting relationship among different phases.

Detail petrographic studies show that the Yamama Formation has undergone three distinct diagenetic stages such as eogenetic, mesogenetic and telogenetic. The detail paragenetic sequence of all the observed phases is established in this study (Fig. 10).

5.1.1. EOGENETIC STAGE

The eogenetic stage is further divided into marine and meteoric environments as indicated by their diagnostic features (Figs. 10, 11).

Relative Timing	Early → Late				
Diagenetic Processes	Marine	Meteoric	Shallow Burial	Deep Burial	Uplift
Micritization					
Cementation					
Isopachous Rim					
Radiaxial Fibrous					
Granular Mosaic					
Equant					
Blocky					
Neomorphism					
Dolomite Cement					
RD-1					
RD-2					
Mechanical Compaction					
Chemical Compaction					
Fracturing					
Calcite Veins Filling					

Fig. 10 Detailed paragenetic sequence encompassing different diagenetic processes observed in the Yamama Formation based on detail petrographic studies.

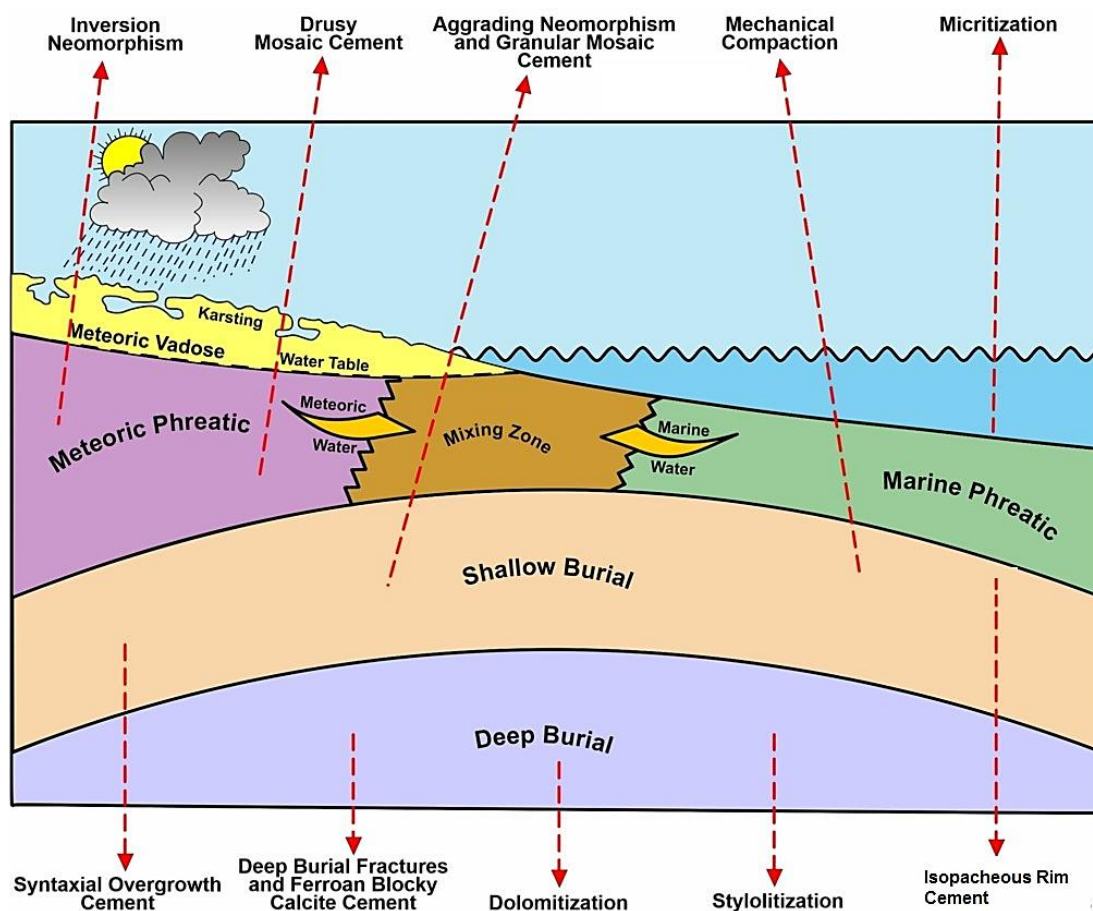


Fig. 11 Schematic model illustrating the diagenetic environments observed in the Yamama Formation.

Marine diagenesis: Early marine diagenesis is recorded throughout the formation and is represented by burrowing, lithification, compaction, micritization and Syntaxial overgrowth cementation (Figs. 10, 11).

Burrowing is one of the earliest stage of diagenesis observed owing to animal activity (Pedley, 1992). In the Yamama formation horizontal and vertical burrow are recorded mostly in the mudstone (Fig. 3a). Micrite envelops are the earliest diagenetic phase started in the marine environment (Melim et al., 2002). In the studied formation, micrite envelops along the grains is very common phenomena (Fig. 4c). these micrite envelops tend to grow along the allochems and replaces the unstable aragonite into more stable micrite (Fig. 4b). Syntaxial overgrowth cement most commonly predate mechanical compaction therefore they are designated as earlier phenomena (Fig. 5c).

Meteoric diagenesis: After marine diagenesis, the studied rock unit is subjected to the meteoric diagenesis. The main features of meteoric diagenesis are dissolution, drusy mosaic and granular mosaic cements. The metastable skeletal material transformation is the most common phenomena of meteoric diagenesis (Fig. 5; Melim et al., 2002). This transformation also leaves cavities in the carbonate units which are mostly filled with the drusy mosaic and granular mosaic cements (Figs. 4, 5). Drusy mosaic is the diagnostic of meteoric conditions (Longman et al., 1980). In the Yamama Formation, drusy mosaic mostly lying along the grain boundaries while the center of cavities is filled with the granular mosaic cement (Fig. 5a).

5.1.2. MESOGENETIC STAGES

The studied carbonate rocks have undergone burial conditions which resulted in the mechanical and chemical compaction of grains. Mechanical compaction brings the grains in closer packing with long and sutured contacts while the chemical compaction brings pressure dissolution of grains (Paganoni et al., 2016).

In the Yamama Formation, burial conditions also resulted in the squeezing of formation water fluids. These formation water are usually rich in Mg and other exotic ions. These Mg rich fluids are penetrated in the cavities, fissures and fractures and precipitated in the form of dolomite crystals (Figs. 5b-5d; Rahim et al., 2025). Two types of dolomites are based on concentration of Mg ions. Crystal morphology of dolomite is very good indicator of concentration of dolomitizing fluid as reported by various workers (Rahim et al., 2020). RD-1 fluids are the earliest phase where the fluids are not supersaturated with respect to the Mg ions so this resulted in the formation of anhedral to subhedral crystals (Figs. 5b, 5d). RD-2 designates the 2nd stage of dolomitization where the fluids are supersaturated with respect the Mg ions resulting in the formation of euhedral crystals of RD-2 (Fig. 5h).

5.1.3. TELOGENETIC STAGES

The final phase of diagenesis reported in the Yamama Formation is linked with the tectonic uplift of the study area which is evident by the presence of large scale open fractures. These fractures cause percolation of meteoric fluids which cause dissolution phenomena due to acidic nature of meteoric fluids (Khalil et al., 2024). Some of the observed fractures are filled with the meteoric blocky calcite cement (Fig. 8).

5.2. CONSTRAINTS FROM CL AND STABLE ISOTOPES

Cathodoluminescence analysis is tool which is very helpful in tracking the diagenetic history of carbonate rocks. The subtle variation in the intensity of luminescence give information about the mineral composition, crystal growth and structure, recrystallization etc. The degree of luminescence is mainly controlled by the Fe and Mn concentration in the diagenetic calcite cement. The Mn usually acts as a main activator and Fe is considered as main quencher of CL. The Fe/Mn ratio is therefore considered as a reliable proxy to control the intensity of CL (Boggs and Krinsley, 2006; Rahim et al., 2024a). In the Yamama Formation, the cement growth and morphology are studied. The study indicates the formation mechanism of equant cement is started to grow along the micritic grain (Figs. 6a, 6b). The isopachous rim cement is forming the growth rings along the grain (Figs. 6c, 6d). the granular mosaic cement is forming along the grain and filling the pore space (Figs. 6e, 6f).

The stable oxygen isotopic values of carbonate cements mostly reflect the temperature and water composition of the diagenetic fluids at the time of its precipitation (Xie et al., 2020). Therefore, the carbonates that are influenced by the diagenetic alterations usually have more variable values than the original marine signatures (Allen and Mathews, 1977; Friedman and O'Neil, 1977). In case of Yamama Formation, the obtained $\delta^{18}\text{O}$ values micrite matrix fall within the range of marine signatures however, all other diagenetic phases show depletion in terms of oxygen isotopic values, hence it is confirmed that that these carbonate units are subjected to the conditions different from their depositional settings which causes resetting of their isotopic values (Fig. 6; Friedman and O'Neil, 1977; Rahim et al., 2020, 2024). In literature it is reported that if the oxygen isotopic values show values less than -8 ‰ V-PDB, the possible source of fluids is from hydrothermal origin (Coniglio et al., 2000; Arosi and Wilson, 2015; Rahim et al., 2024). In the studied carbonate unit, the blocky calcite cement (CC-III) which is filling the fractures showing the highest depleted values which suggest its possible origin is from the hydrothermal fluids (Fig. 7).

The carbon isotope values represent the biological productivity and photosynthesis in the adjacent terrestrial and marine environments. So any change in

these parameters causes shift in the carbon isotopic values (Friedman and O'Neil, 1977; Coniglio et al., 2000). Carbon isotopic values are very good indicator of past climatic conditions. However, the carbon isotopic values in the carbonate rocks are more resistant to the diagenetic alteration (Friedman and O'Neil, 1977). Moreover, the meteoric waters can have carbon isotopic values from extremely negative to positive (Coniglio et al., 2000). In case of the Yamama Formation, most of the carbon isotopic values are in positive indicating the original marine signature, however, few dedolomite samples show negative values indicating their influence from the meteoric fluids (Fig. 7).

5.3. COMPARISON WITH AGE EQUIVALENT CARBONATE ROCK UNITS

The obtained data set is of the diagenetic studies of Yamama Formation is compared with the time equivalent rock units of the Arabian Peninsula.

In Iran, the similar time equivalent rock unit is called Fahliyan Formation which is situated in the Zagros Mountains of central Iran. In Kuwait, the similar time equivalent rock unit is called Fahliyan Formation. In United Arab Emirates, the similar time equivalent rock unit is called Ratawi Formation. In Oman, the similar time equivalent rock unit is called Habshan Formation. when the diagenetic character of these formations is studied in detail, it is noted that diagenetic evolution took place in all these time equivalent rock units, however, the intensity of events vary significantly which suggests that the local tectonic events have played its role in modifying the diagenetic properties of similar rock units. For example, in the Habshan Formation, dolomitization is prevalent character of the formation while such character is not prevalent in the other units. So, this suggests that the dolomitization is the local phenomena (Vandeginste et al., 2013).

6. CONCLUSIONS

- Different diagenetic phases observed in the petrographic investigations show that the Yamama Formation underwent diagenesis in a variety of settings.
- The carbonate rocks of the Yamama Formation have undergone substantial change since their deposition, according to the paragenetic sequence based on known diagenetic processes.
- The types and morphology of carbonate cement that have been identified are excellent indicators of the diagenetic circumstances that the rock unit is exposed to.
- According to the cathodoluminescence studies, the diagenesis primarily occurred in a closed system with little variation and interchange of major and trace elements. This is indicated by the bright to dull orange luminescence color.

- Variation in stable oxygen isotope values from the Cretaceous seawater suggests that the diagenetic processes are altering the formation. Blocky calcite's extremely low oxygen isotope values suggest that it is originated from hydrothermal fluids. The majority of stable carbon isotope values are within the range of the Cretaceous marine signature; nevertheless, the depleted carbon isotopic values show that few dolomites are being dedolomitized by the meteoric fluids.
- The reservoir quality of the carbonates is mostly determined by these diagenetic modifications. The extensive compaction and cementation have reduced the reservoir properties while fracturing and dissolution have greatly enhanced the reservoir properties.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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