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Impact of Diagenetic Processes and Dolomitization on the Dammam Formation in Central Iraq

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ABSTRACT

This study examines the diagenetic processes that affect the Dammam Formation, with a focus on the dolomitization mechanism of limestone rocks within Al-Najaf Governorate, Central Iraq. The Dammam Formation is composed of dolostone, limestone, and dolomitic limestone. The results of XRD analysis show the presence of primarily non-clay minerals (calcite, dolomite, quartz, and feldspar) and clay minerals (palygorskite, montmorillonite, and kaolinite) as secondary minerals. In addition to the dolostone facies, six types of limestone microfacies are identified. Most of them indicate sparse to intense dolomitization. Three facies' associations are distinguished in the Dammam Formation. Each represents a distinct depositional environment, including shallow restricted, shallow open marine, and shoal environments. Several diagenesis processes have affected the Dammam Formation, with dolomitization being the predominant one. Five major textural patterns of dolomite are distinguished: microcrystalline, planar-euhedral, planar-subhedral to euhedral, planar-porphyrotopic, and planar void-filling. Petrographic investigations, geochemical data, and isotope analysis indicate that the dolomitization of the Dammam Formation has formed in a mixing zone. The paleo-temperature of dolomite in Dammam Formation, measured based on $\delta^{18}O$, ranges from (42.2-67.1°C). Accordingly, its deposition by mixing meteoric-sea water associated with low temperature and shallow burial conditions becomes more probable. The recorded depletion in $\delta^{13}C$ value of (-7.97‰). At depth 34 m in BH3, there is a sea-level fall, and exposure of the Dammam Formation was in the late Eocene. The diagenetic history of the limestones can be subdivided into early, middle, and late stages.

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تأثير العمليات التحويرية والدلمتة على تكوين دمام في وسط العراق

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الملخص

تناقش هذه الدراسة العمليات التحويرية التي أثرت على تكوين دمام، وتركز على آلية دلمتة الصخور الكاربوناتية ضمن محافظة النجف في وسط العراق. يتكون تكوين دمام من الحجر الجيري المتدلمت والحجر الجيري والدولومايت. أظهرت نتائج تحليل الاشعة السينية وجود المعادن غير الطينية وهي الكالسايت والدولومايت والكوارتز والفلسبار، بينما تعتبر المعادن الطينية معادن ثانوية وتشمل (الباليجورسكيت والمونتموريلونيت والكاولينيت). إلى جانب سحنات الدولستون المدروسة، تم التعرف على ستة سحنات دقيقة من الحجر الجيري. قدمت معظم هذه السحنات الدقيقة أدلة على وجود الدلمتة المتناثرة والمنتشرة. تم تحديد ثلاث مجاميع ترسيبية لتكوين دمام. يمثل كل منها بيئة ترسيبية متميزة، بما في ذلك البيئات البحرية الضحلة المحصورة والبيئة البحرية الضحلة المفتوحة والحاجز المتضحل. أثرت العديد من عمليات التحوير على تكوين دمام، لكن عملية الدلمتة هي السائدة. تم التعرف على خمسة انواع من الانسجة الرئيسة من الدولومايت: الدقيق التبلور، والمستوي أحادي السطوح، وشبه المستوي إلى المستوي، المسطح البورفيروتوبي، والمستوي الذي يملأ الفراغ. أشارت الدراسة الصخرية والبيانات الجيوكيميائية وتحليل النظائر إلى أن عملية الدلمتة في تكوين دمام ربما حدثت في منطقة الخلط. درجة الحرارة القديمة للدولومايت في تكوين دمام والتي تم قياسها على أساس $\delta^{18}O$ تتراوح مابين (42.2–67.1) درجة سليزية. وعليه فإن احتمالية تكوين الدولومايت عن طريق خلط مياه البحر النيزكية تحت ظروف درجات الحرارة المنخفضة وعلى عمق دفن ضحل يصبح أكثر احتمالا. يشير الاستنزاف المسجل في قيم $\delta^{13}C$ (‰–7.97) على عمق 34 مترًا في BH3 إلى انخفاض مستوى سطح البحر وانكشاف تكوين دمام في أواخر العصر الأيوسيني. يمكن تقسيم التاريخ التحويري للحجر الجيري إلى ثلاث مراحل (مبكرة ومتوسطة ومتأخرة).

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Introduction

The Eocene Epoch in Iraq belongs to the Middle Paleocene-Eocene of the tectono-stratigraphic megasequence (AP l0), which is an important stratigraphic unit in the stratigraphic column of Iraq. The Eocene-Miocene formations in the study area, in ascending order, are Rus, Dammam, and Euphrates Formations. The Dammam Formation covers large areas in the southern desert of Iraq and occurs at different depths. Bramkamp (1941; in Bellen et al., 1959) was the first to describe the Dammam Formation from the Dammam dome in East Saudi Arabia, where it consists of limestone (chalky, organodetrital, or dolomitic), dolomites, marls, and shales. In Iraq, an accessory type section was suggested by Owen and Nasr (1958) in the well Zubair-3 in southern Iraq, where the formation consists mainly of dolomitized and locally chalky limestone, with a shale layer often occurring near the base of the formation. Al-Hashimi and Amer (1985) assumed a typical dominated lagoonal environment for the deposition of the Dammam Formation, which is distinguished by dolomitic limestone and the dominant occurrence of Miliolids and Peneroplis. According to Mahdi and Youkhanna (1996), the middle member of the Dammam Formation was deposited in a tropical-subtropical shallow marine with a depth of nearly 100 m or less. Jassim and Goff (2006) found that the Dammam Formation is composed of shoal limestone, often recrystallized and/or dolomitized. The limestone is characterized by the common occurrence of nummulites in the lower part and miliolids in the upper part. Maziqa et al. (2024) found that the Dammam Formation was deposited in a variety of settings, including peritidal inner ramp, lagoon, shoal, restricted-marine platform, and open interior platform.

Geological Setting and Stratigraphy

The sedimentary succession in the study boreholes consists of Rus, Dammam, and Euphrates formations, ranging in age from Early Eocene to Middle Miocene. The Dammam Formation is composed of limestone, fossiliferous limestone, dolomitic limestone, marl, crystalline limestone, and crystalline dolostone facies that were deposited in shallow restricted, shallow open marine, and shoal environments. It consists of three members: lower, middle, and upper, according to lithological variations and assemblage fauna. The absence of the upper member in most boreholes and the variation in its thickness in others indicate the difference in the intensity of erosion from place to another. In general, the upper member thickness is inversely proportional to the intensity of weathering and erosion. In the present work, the boundary between the Rus and Dammam formations is taken at the first appearance of massive gypsum. The upper boundary between the Upper Member of Dammam Formation and Euphrates Formation is unconformable and marked by pseudobrecciated limestone at the bottom of Euphrates Formation. The study of the upper boundary of the Dammam Formation reveals that there is karstification and a late stage of dolomitization below the unconformity. The paleokarst zone of the Dammam Formation developed as a result of exposure during Oligocene–Early Miocene time.

This study interprets the origin of the dolomitization process for the Dammam Formation based on its stratigraphic distribution, petrographic characteristics, XRD, chemistry analysis, and oxygen and carbon isotope analysis, to propose a model for dolomitization in the Al-Najaf area. In addition, the diagenetic history related to the Dammam-Euphrates unconformable boundary is studied in the same area.

The study location lies in the southern desert of Iraq, within Al-Najaf Governorate (Fig. 1). Four boreholes are selected with the geographic coordinates shown in Table 1. Structurally, the study area lies within the Arabian inner platform, Southern Desert (Fouad, 2015).

Table 1: Location coordinates of the studied wells and depth intervals of the Dammam Formation.

BH. No.	Eastern	Northern	Depth (m).	Thickness m.	Number of samples
BH2	450311	3480676	10-125	115	41
BH3	443606	3488661	35-115	80	43
BH16	391077	3538969	10- 140	130	26
BH21	423789	3506144	10-183	173	60

Materials and methods

Detailed petrographic study of core samples collected from four boreholes within Al-Najaf Governorate, which were drilled by the Iraq Geological Survey (GEOSURV). Petrographic study includes the microscopic examination of 170 thin sections of selected samples under a polarizing microscope to provide details of the petrographic components and diagenetic processes that affect the rocks. All thin sections are stained with Alizarine Red S following the procedure of Friedman (1959) to differentiate between calcite and dolomite in the thin section. The classification of (Dunham, 1962) is used to describe and classify the carbonate rocks of the formation, whereas dolostone textures are defined according to crystal size following (Chatalov, 2013). The mineralogy of six samples was identified by using chemical analysis and X-ray diffraction (XRD). Five samples were studied with a Scanning Electron Microscope (SEM) in Al-Khora Company (Baghdad) to identify the microporosity. Carbon and oxygen isotope (δ ^{18}O and δ ^{13}C) analyses were performed for eight samples in the laboratories of the Institute of Geology, Mineralogy and Geophysics at the Ruhr-University Bochum to provide information about paleoenvironmental such as temperature and salinity variations of the seawater.

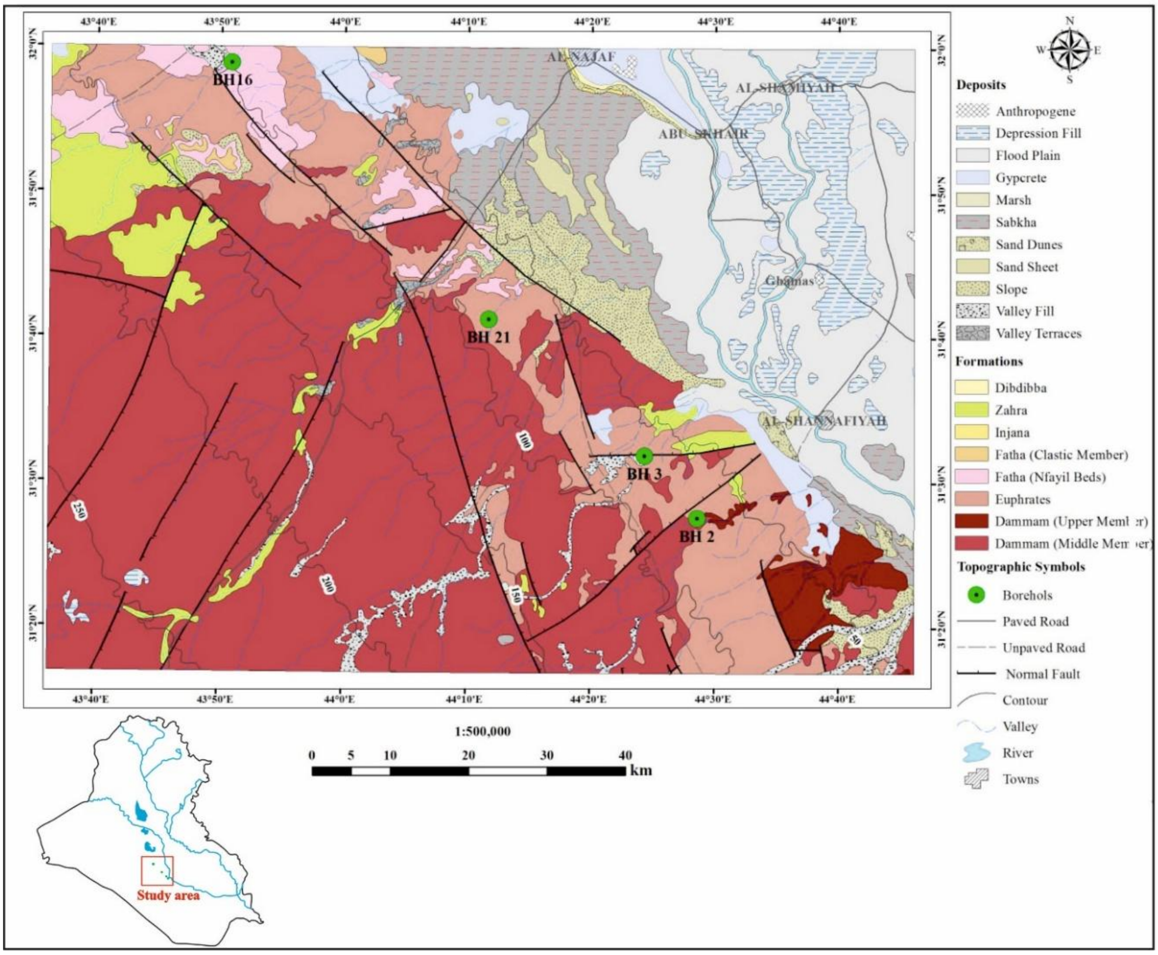


Fig. 1. Geological and location map of the studied boreholes (after Hassan *et al.*, 1995).

Results

Mineralogy and geochemistry

The main rocks of the Dammam Formation are limestone, dolostone, and dolomitic limestone. The result of XRD analysis show the presence of non-clay minerals is calcite, dolomite, quartz and feldspar, whereas clay minerals as secondary minerals including (palygorskite, montmorillonite and kaolinite) (Fig. 2). The clay minerals of Dammam Formation are various including terrigenous (detrital) like kaolinite that may formed during regressive period from the continent, and authigenic such as palygorskite (Table 2). Since kaolinite does not form in a marine environment, it has a detrital origin (Swadi et al., 2023).

Table 2: Samples and results of the XRD Test.

Ser. No.	Sample name	Depth (m)	Formation	Clay minerals	Non-clay minerals
1	BH3/A10	22	Euphrates	---	Calcite
2	BH3/A11	26	Euphrates	Palygorskite and montmorillonite	Calcite and dolomite
3	BH3/A12	35	contact	Palygorskite and montmorillonite	Calcite, quartz and feldspar
4	BH3/A15	44	Dammam	---	Calcite and dolomite
5	BH3/A19	54	Dammam	Montmorillonite and Kaolinite	Calcite and quartz
6	BH3/A26	74	Dammam	---	Calcite and dolomite

7	BH3/A30	84	Dammam	Palygorskite and Montmorillonite	Dolomite, quartz and feldspar
8	BH3/A34	94	Dammam	Montmorillonite and Palygorskite	Calcite, quartz and dolomite
9	BH3/A40	110	Dammam	---	Dolomite and quartz
10	BH3/A41	115	Dammam	---	Dolomite
11	BH3/A42	120	Rus	---	Dolomite and gypsum

The analysis of major oxides shows that the average of SiO_2 is 5.14% and it ranges from 0.02 % to 18.3%. Aluminum oxide average is 0.69%, with a range between 0.04% and 2.18 %. Silica (SiO_2) and alumina (Al_2O_3) originate from clay minerals and detrital quartz (Table 3).

The highest values of silica and aluminum in some samples were pointed out in the sandy limestone layer found above the contact within the Euphrates Formation. The average of Fe_2O_3 is 0.30% and it ranges from 0.02% to 0.88%. Sulfate oxide (SO_3) reflects values from 0.03% to 0.09%, with an average of 0.06%. Sulfate is hard to find in carbonate rocks, while the values of SO_3 are found in strata that contain gypsum cement. On the contrary, CaO, MgO, and LOI reveal high values compared with other major oxides. The average of CaO is 36.55%, and its range is between 31.03% and 44.97 %. The average of MgO is 13.74%, and it ranges from 0.77% to 20.79% (Fig. 3). The average of LOI is 43.58% and its range is between 35.15% and 47.5%. The high percentage of CaO is due to the high content of carbonate rock in the Dammam Formation, which is mainly composed of calcite. Meanwhile, the high percentage of MgO is related to dolomitization, which affects limestone poetically in the upper part of the middle member of the Dammam Formation.

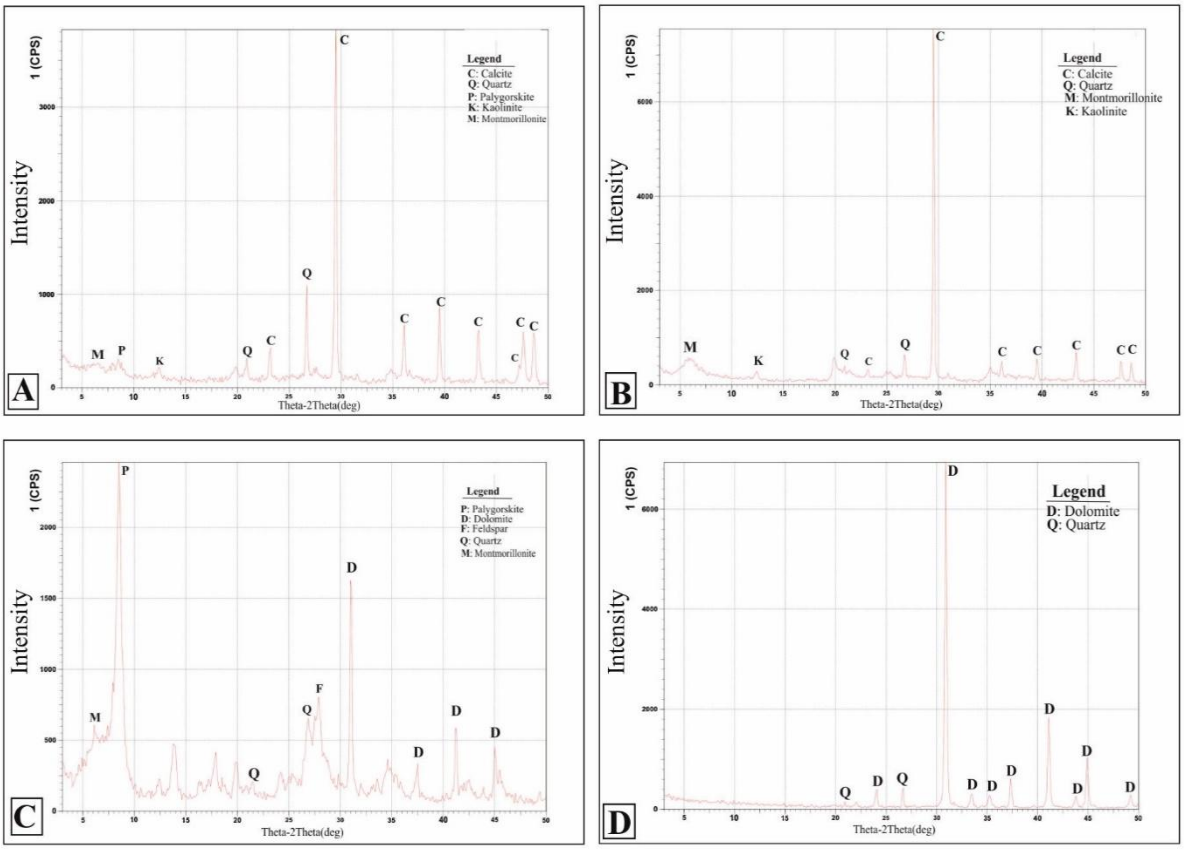


Fig. 2. X-ray diffractograms show the peak reflections of the minerals; (A) BH3/A12, 35m depth; (B) BH3/A19, 54m depth; (C) BH3/A30, 84m depth; (D) BH3/A41, 115m depth.

Table 3: Percentage of chemical analysis for Dammam Formation rocks, BH2.

Ser. No.	Sample name	Depth m.	SiO_2%	Fe_2O_3 %	Al_2O_3%	CaO%	MgO %	SO_3%	LOI%	Total
1	BH2/A1	5	18.30	0.30	2.18	42.89	0.77	0.03	35.15	99.62
2	BH2/A5	10	13.88	0.36	1.79	44.97	1.38	0.04	37.22	99.64
3	BH2/A9	20	0.81	0.10	0.55	32.9	18.58	0.06	46.99	99.99
4	BH2/A14	30	0.10	0.04	0.08	37.46	15.75	0.06	46.50	99.99

5	BH2/A20	41	0.74	0.10	0.22	31.03	20.79	0.06	47.5	100.44
6	BH2/A25	52	0.06	0.02	0.05	34.04	18.65	0.09	47.07	99.98
7	BH2/A29	60	0.04	0.25	0.06	33.08	19.54	0.08	46.07	99.12
8	BH2/A33	70	0.02	0.49	0.05	34.10	20.01	0.09	44.81	99.57
9	BH2/A42	81	0.90	0.88	0.20	32.0	18.58	0.06	47.10	99.72
10	BH2/A47	90	0.36	0.02	0.04	37.19	15.87	0.09	46.41	99.98
Min			0.02	0.02	0.04	31.03	0.77	0.03	35.15	99.12
Max			18.3	0.88	2.18	44.97	20.79	0.09	47.5	100.4
Average			5.14	0.30	0.69	36.55	13.74	0.06	43.58	99.83

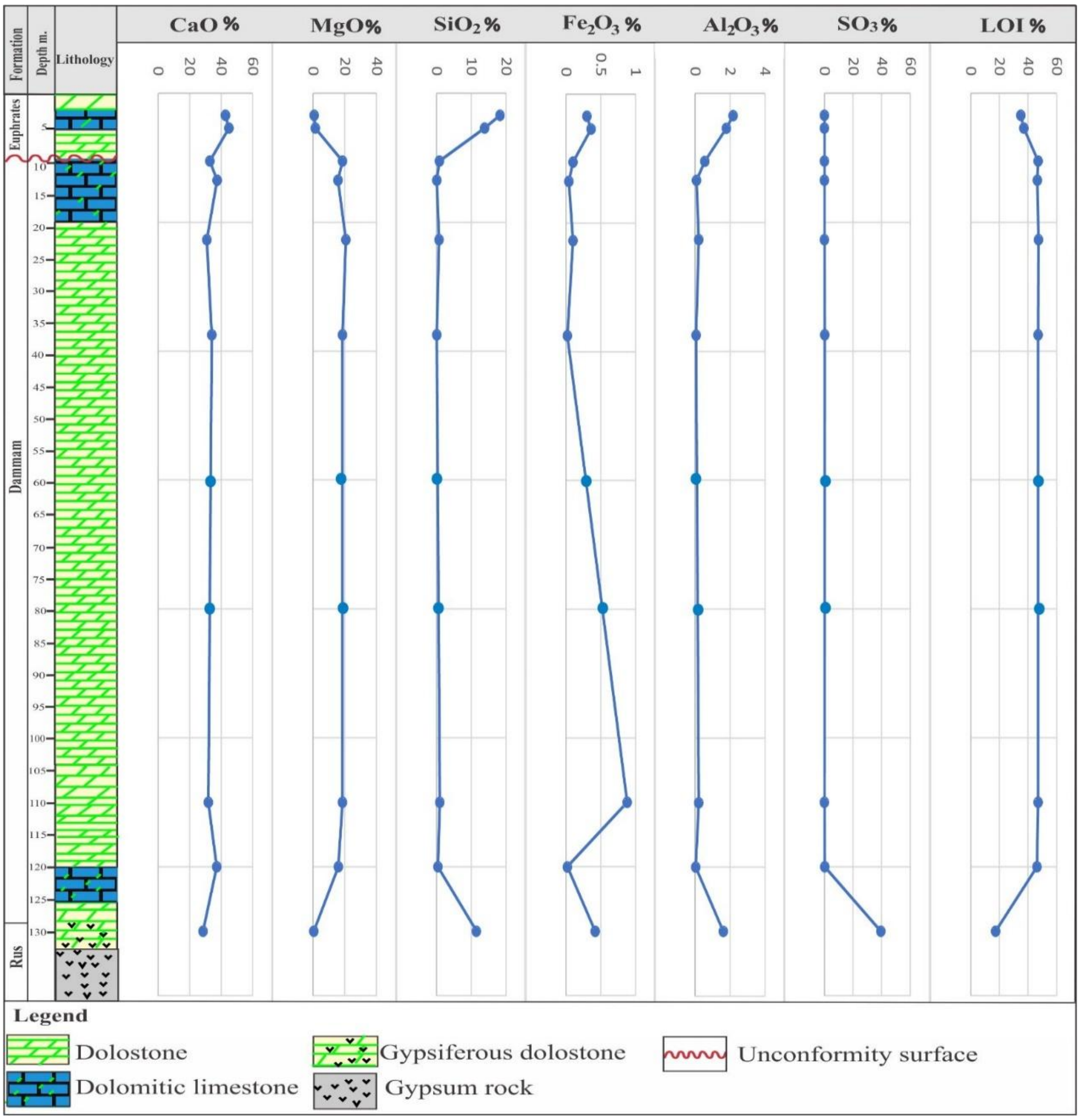


Fig. 3. Chemostratigraphy of major oxides of Dammam formation in BH2.

Oxygen and carbon isotopes

The stable oxygen isotope composition ($\delta^{18}O$) of a precipitated carbonate depends mainly on the isotope composition, salinity, and temperature of the host fluid, whereas the stable carbon isotope composition ($\delta^{13}C$) reflects the source of CO_2 for precipitation, such as meteoric or seawater, shell dissolution, or various biochemical origins, including microbial oxidation of organic matter and methane. Consequently, plots of $\delta^{18}O$ versus $\delta^{13}C$ for carbonate materials can help identify their depositional and/or diagenetic environments (Nelson and Smith, 1996).

Eight samples of limestone and dolomitic limestone are analysed for oxygen and carbon isotopes. The values of $\delta^{18}O$ and $\delta^{13}C$ for Dammam Formation vary from -9.09‰ to -5.13‰ and -7.97‰ to -5.28‰ respectively, while the values of $\delta^{18}O$ and $\delta^{13}C$ for Euphrates

Formation vary from -10.48 ‰ to -0.59‰ and -7.40‰ to 0.20‰ respectively (Fig. 4). The calcite paleotemperature equation is used to calculate the "isotope temperature" of the formation. Epstein et al. (1953; in Taha and Abdullah, 2019) used the $\delta^{18}O$ value of the water responsible for calcite precipitation, known as:

$$T=16.5 - 4.3\,\delta + 0.14\,\delta^2$$

Where: *T* is the temperature in °C.

The paleotemperature of the Dammam carbonates ranges from (42.2- 67.1 °C) in the studied borehole (BH3) (Table 4).

Table 4: The analytical results of $\delta^{18}O$ and $\delta^{13}C$ show the temperature of calcite precipitation, T and Z values.

Sample Name	Depth (m)	Formation	Lithology	$\delta^{13}C^{PDB}$ [‰]	$\delta^{18}O^{PDB}$ [‰]	T (°C)	Z	Salinity
BH3/A1	2.3	Euphrates	Calcite	-0.65	-10.48	76.9	120.7	marine
BH3/A6	15	Euphrates	Calcite+ dolomite	0.20	-0.59	19.1	127.4	marine
BH3/A11	24	Euphrates	Calcite	-7.40	-5.44	44.1	109.4	Meteoric-marine
Min				-7.40	-10.48			
Max				0.20	-0.59			
Average				-3.01	-5.51			
BH3/A12	35	Contact	Calcite	-7.97	-8.70	64.5	106.6	Meteoric-marine
BH3/A14	42	Dammam	Calcite	-6.66	-8.17	60.9	109.5	Meteoric-marine
BH3/A26	74	Dammam	Calcite	-5.42	-9.09	67.1	111.6	Meteoric-marine
BH3/A35	94	Dammam	Calcite+ dolomite	-5.28	-5.13	42.2	113.9	Meteoric-marine
Min				-7.97	-9.09			
Max				-5.28	-5.13			
Average				-6.43	-7.55			
BH3/A41	118	Rus	Dolomite	-1.96	0.89	12.7	123.7	marine

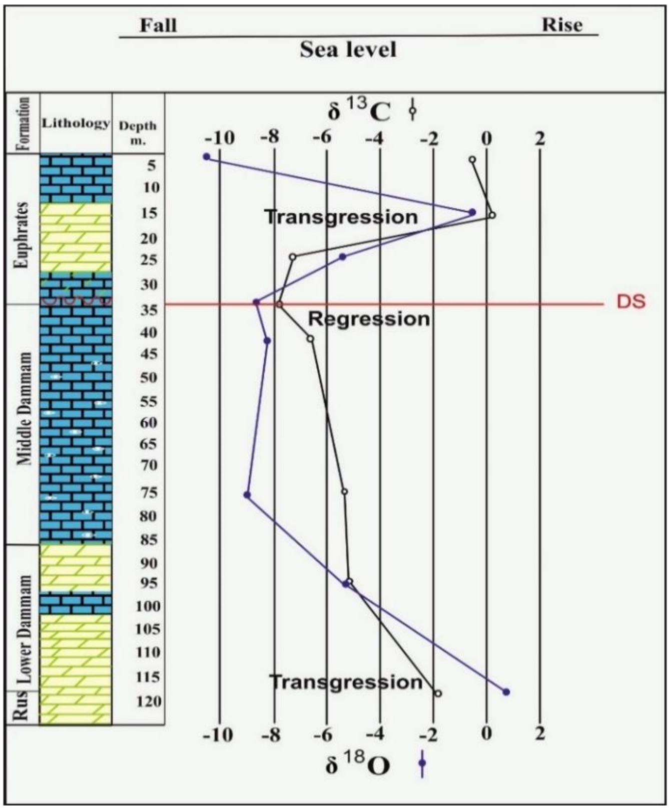


Fig. 4. The variations of $\delta^{13}C$ and $\delta^{18}O$ values for limestone and dolostone lithologies versus depth in wells BH3.

To differentiate between marine and freshwater limestone, the following equation is used (Keith and Weber, 1964):

The paleo-salinity (Z values) = $2.048(\delta^{13}C + 50) + 0.498(\delta^{18}O + 50)$

Where both $\delta^{13}C$ and $\delta^{18}O$ are measured as ‰ PBD. The Z values above 120 for carbonate rocks would be classified as marine, while the values below 120 as freshwater. The Z values for the Dammam carbonate samples range from 106.6 to 113.9 in the studied area. The Z value less than 120 indicates that regional regression caused the exposure of the study area. The exposed sediments were subjected to fresh water diagenesis, with aragonite dissolution, cementation by calcite spar, and sediment stabilization to low-Mg calcite, taking place in vadose and phreatic zones.

Discussion

Facies associations of Dammam Formation

Three facies' associations are distinguished in the Dammam Formation. Each represents a distinct depositional environment, including restricted, shallow open marine, and shoal environments (Table 5). In addition, diagenetic carbonate facies are identified.

Table 5. Facies associations in the Dammam Formation.

Facies association	Microfacies	Skeletal and non-skeletal	Diagenesis
Restricted	Bioclastic mudstone and dolomitic bioclastic mudstone	fossils <10% with carbonate mud matrix. Benthonic foraminifera	Early dolomitization, dissolution, and porosity developments such as intercrystalline.
	Dolomitic intraclastic mudstone	Intraclasts consist of microcrystalline dolomite and range in size from fine to medium sand (0.2–0.4 mm)	Early dolomitization
	Dolomitic foraminiferal bioclastic wackestone	Fossils (15-20 %) with carbonate mud matrix. The bioclasts include *Coskinolina* sp., miliolids,	Dolomitization, micritization, dissolution and porosity development such as intraparticle, vugs, biomolds, and

		Peneroplis sp., *Elphidum* sp., *Textularia* sp.	intercrystalline and selective silicification of some fossils
Open marine	Bioclastic nummulitic wackestone- packstone	Fossils (15-20 %) with carbonate mud matrix. The bioclasts include *Nummulites bayhariensis*, *Nummulites gizehensis*, *Nummulites perforatus*, *Nummulites* sp., *Coskinolina* sp. echinoderm plates, and echinoid spines. Other bioclasts are relatively rare, including ostracods, a few gastropods and broken shell fragments	Partial dolomitization, micritization, neomorphism (recrystallization and inversion), dissolution and porosity development (vugs, intercrystalline, and intraparticle), cementation by granular calcite, and selective silicification of shell fragments
Shoal	Nummulitic packstone	Fossils (40-50) % with carbonate mud matrix. The recorded bioclasts (30–50%) consist of *Nummulites gizehensis*, *Nummulites perforates*, *Nummulites planulatus*, and *Nummulites* sp.	Neomorphism (recrystallization and inversion affecting fossils), physical compaction, dissolution, and porosity development (intraparticle and intercrystalline).
	Bioclastic nummulitic grainstone	Fossils (50-60) % with sparry calcite cement. The recorded bioclasts consist of *Nummulites gizehensis*, *Nummulites bayhariensis*, *Nummulites millecaput*, *Nummulites* sp. and bryozoa.	Dissolution and porosity development (intraparticle, intercrystalline, and vugs), cementation of some pores by secondary calcite such as granular, syntaxial rim, and isopachous rim cement, and neomorphism (inversion affecting fossils).

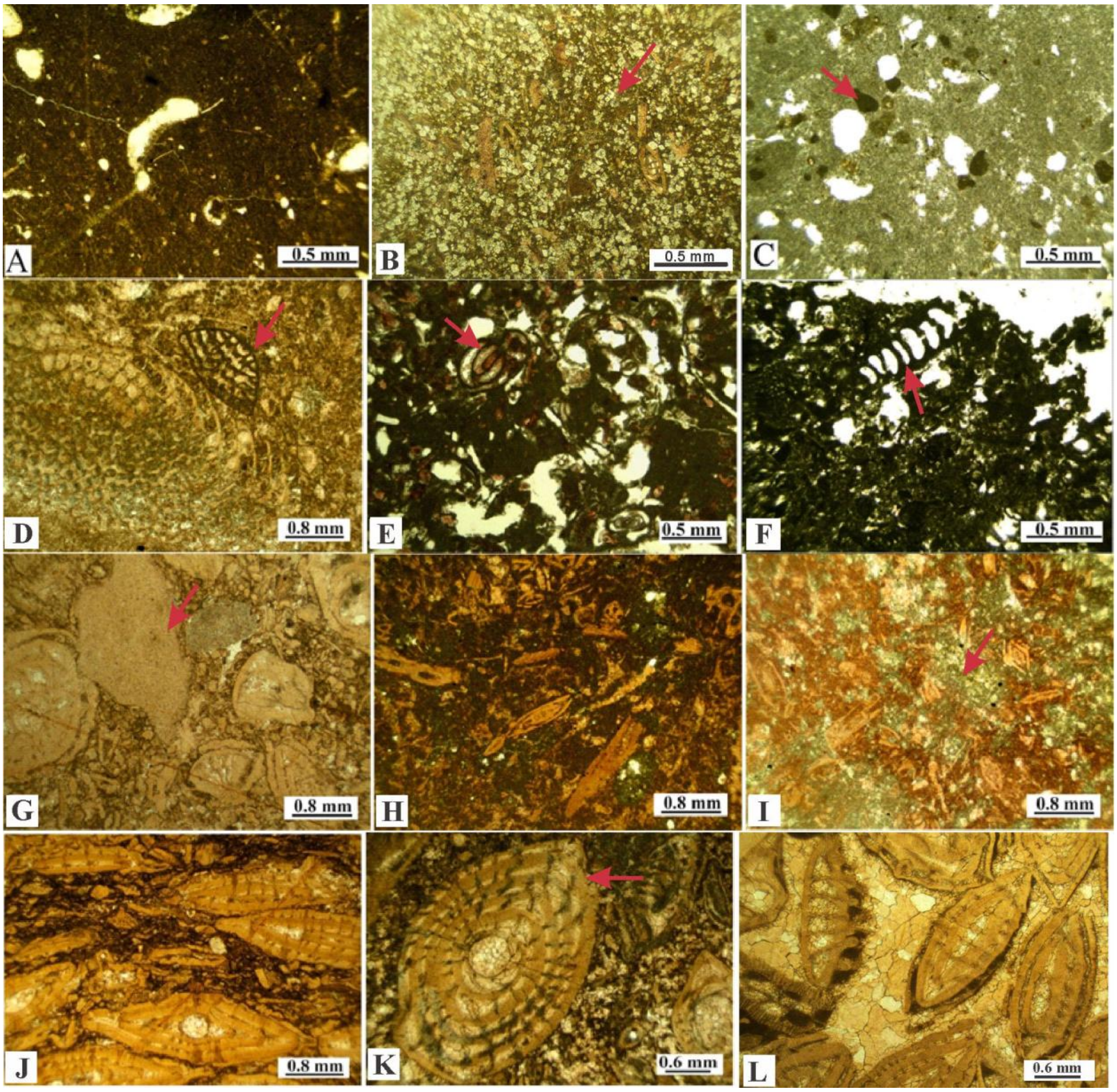


Fig. 5. Microfacies of the Dammam Formation; (A) Bioclastic mudstone, BH21, 106 m depth, PPL.; (B) Dolomitic bioclastic mudstone BH21, 81m depth, PPL; (C) Dolomitic intraclastic mudstone, BH21, 177 m depth, PPL.; (D) *Coskinolina* sp., BH3, 53 m depth, PPL.; (E) Dolomitic foraminiferal bioclastic wackestone showing miliolids, BH3, 96m depth; F) *Peneroplis* sp., BH16, 120m depth, PPL.; (G) Bioclastic nummulitic wackestone-packstone showing Echinoderm plate, BH3, 43 m depth; H) Fragments of *Nummulites* sp., BH3, 80 m depth, PPL.; (I) Dolomitization selectively affects groundmass, BH3, 60m depth PPL.; (J) Nummulitic packstone showing packed nummulites which affected by physical compaction, BH3, 61 m depth, PPL.; (K) *Nummulites perforatus*, BH3, 70 m depth, PPL.; (L) Bioclastic nummulitic grainstone, BH3, 50m depth, PPL.

Diagenetic carbonate facies

In addition to the above-mentioned microfacies, three diagenetic facies within the Dammam Formation are recognized. These facies are not included in the facies associations as they were affected by diagenetic changes that severely affected the original textures and structures of the rocks, as well as the fauna. The diagenetic facies include crystalline dolostone, biomoldic fine to medium crystalline dolostone, and crystalline limestone.

1. Fine to medium crystalline dolostone

The rocks assigned to these facies are varicolored (beige, grey, yellowish white, and greyish white), mostly tough and very tough. Petrographic investigation reveals that dolomite is considered the main component (98.5–100 %). It is present as fine to medium (0.04-0.14) mm, subhedral to euhedral and rhombohedral tightly interlocking crystals, most of which show zoning. The zoning indicates the changes in fluid geochemistry of the formation during the growth of dolomite crystals. These facies are severely affected by diagenetic processes, such as late dolomitization, dissolution, and porosity development (intercrystalline, vugs, and intracrystalline), cementation by different types of cement including secondary calcite such as granular, blocky and poikilotopic enclosing fine to medium rhombic dolomite (Fig.12 G and H), and then selective silicification of shell fragments by chalcedony (Fig. 13 G).

2. Biomoldic fine to medium crystalline dolostone

The rocks that belong to these facies are white, grayish white, chalky, tough to very tough, and enclose a large number of biomolds. These facies are identified by the occurrence of abundant biomolds (10–35%) with fine to medium (0.04 and 0.12) mm, euhedral to rhombohedral intergrown dolomite crystals. Most of the fossils are dissolved and remain as biomolds. These molds represent the spaces resulting from dissolved fossils (mostly nummulites and pelecypod-shaped molds) (Fig. 7F).

3. Crystalline limestone

In these facies, calcite forms the main constituent occurring as anhedral interlocking crystals and forming a sort of mosaic texture with variable sizes ranging from fine to coarse. The sparry calcite of this facies is probably produced by recrystallization of the micritic matrix. Most of the original depositional textures and constituents are obliterated. This facies is observed in the uppermost part of the Dammam Formation, and it indicates the exposure of the formation in the late Eocene. Recrystallization from micrite to coarse sparry calcite depends on changes in temperature, pressure, water chemistry, and rates of flow in fresh water vadose and/or phreatic environments (Longman, 1980). This facies is formed in supratidal and intertidal flats under subaerial exposure and during fluctuations in sea level (sea-level regression) (Flügel, 2004).

Diagenetic Processes

The diagenetic processes and products are identified by petrographic study and chemical analysis. Several diagenetic processes affect the rocks of the Dammam Formation, including dolomitization, which appears widespread, micritization, leaching, cementation, neomorphism, silicification, physical compaction, and dedolomitization. These observations (Figs. 14 and 15) are discussed below:

Dolomitization

The Dolomites can be subdivided into primary and secondary based on mode of formation (Pichler and Humphrey, 2001). Usually at or close to room temperature (20–35°C), primary dolomite precipitates straight from aqueous solution without $CaCO_3$ dissolution required (Wells, 1962). But dolomite can also be formed as a subsequent phase that replaces the precursor mineral calcite. These diagenetic processes highly affect the middle members of the Dammam Formation in the study boreholes (Figs. 14 and 15).

Dolomite-rock textures

Five dolomite-rock textures are distinguished and classified according to crystal-boundary shape (planar or non-planar) and crystal-size, using the dolomite-rock classification scheme of Sibley and Gregg (1987) and Chatalov (1971).

1. Microcrystalline dolomite: This type consists of very fine-grained, unimodal, and euhedral crystals of dolomite (Fig. 6A).

2. Planar-euhedral dolomite: this type consists mostly of limpid and euhedral to rhombohedral crystals of dolomite ranging in size from fine to coarse (0.2-0.6) mm (Fig. 6 B and C). In some samples, dolomite has zoning with a cloudy center and clear rim (CCCR) (Fig. 6E). The center of dolomite crystals is cloudy because of high calcite inclusion. The presence of

subhedral to euhedral and zoned crystals of dolomite suggests a major, probably long-lasting dolomitization event during a marine-meteoric mixing zone environment under low temperature and pressure (Chafetz, 1972). The zoning indicates changes in the geochemistry of formation fluids during the growth of dolomite crystals. This process is formed under a hypersaline environment.

3. Planar-subhedral to euhedral dolomite: These crystals are subhedral with straight and scarcely curved boundaries ranging in size from fine to medium (0.15-0.4) mm with low inter-crystalline porosity (Fig. 6D).

4. Planar void-filling dolomite: The dolomite crystals are euhedral, lining pores or vugs (Fig. 6F). At the late stage, dissolution is followed by reprecipitation of dolomite occurs as pore-filling dolomite, which is known as dolomite cement.

5. Planar- porphyrotopic dolomite: It occurs as euhedral crystals floating within micritic matrix (Fig. 7A).

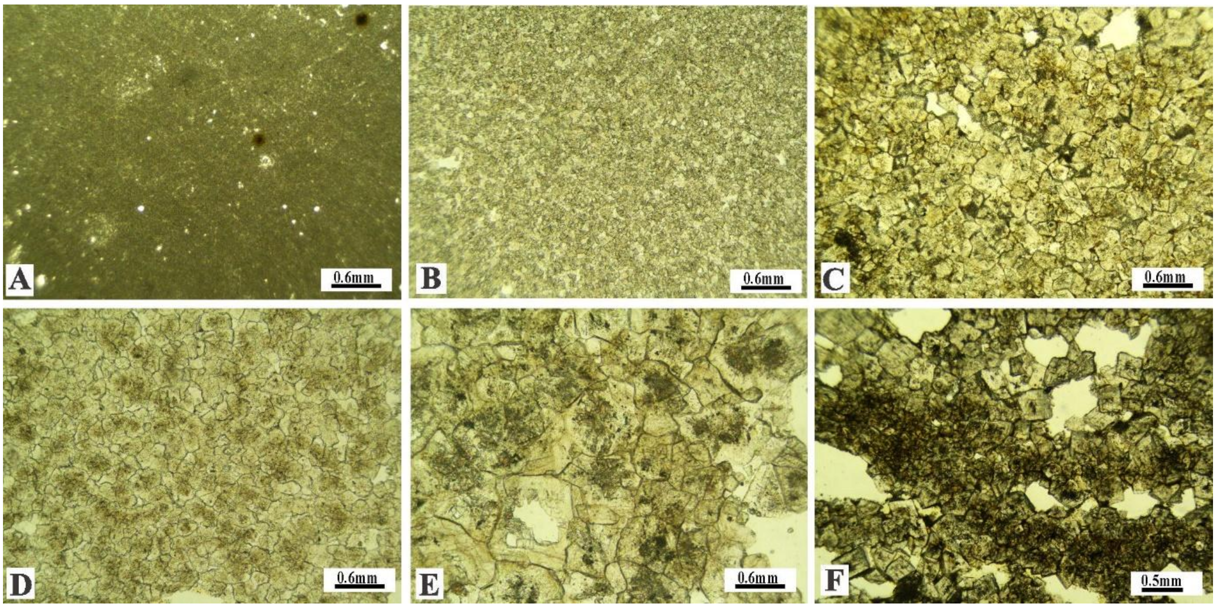


Fig. 6. (A) Non planar- microcrystalline dolomite, BH3, 87m. depth, PPL; (B) Fine crystalline planar-subhedral dolostone, BH21, 36m. depth, PPL; (C) Medium crystalline planar-subhedral-euhedral dolostone, BH16, 65m. depth, PPL; (D) Medium crystalline planar subhedral dolostone, BH21, 56m. depth, PPL; (E) Coarse crystalline planar- euhedral dolostone, BH16, 55m. depth, PPL; (F) Planar void-filling dolomite with cloudy center and clear ream (CCCR), BH16, 50m. depth, PPL.

Replacive dolomite

Many dolostones in the stratigraphic record contain fossils that suggest typical marine habitats of deposition, which is a sign of dolomitization as a result of the partial and total replacement process of mineral calcite or aragonite (Nichols, 2009; in Mahdi et al., 2023). Replacive dolomite usually occurs at the early and middle stages, where dolomite replaces limestone with enough amount of Mg^{2+} source. Replacive dolomite usually retains the original texture of precursor limestone. This process is the dominant type in the Dammam Formation and is verified by the occurrence of very finely crystalline dolomite that is wholly or partly replaced by micritic matrix and fossils (Fig. 7).

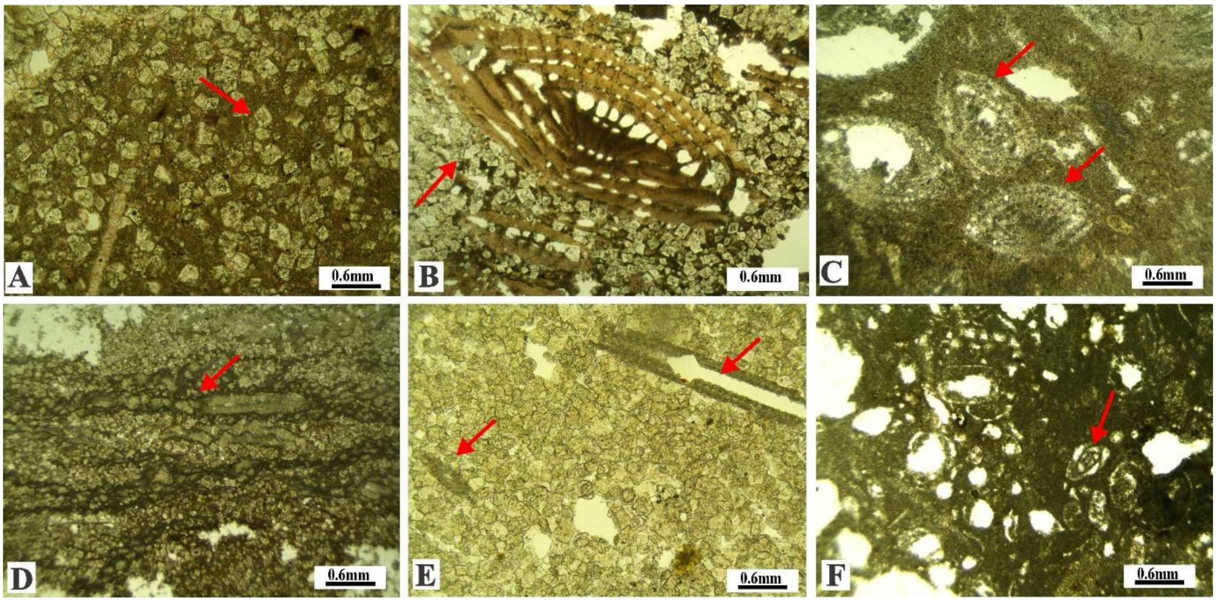


Fig. 7. Replacive dolomite (A) Scatter rhomb of planar- porphyrotopic dolomite in the matrix, BH21, 112m. depth, PPL; (B) Selective dolomitization affecting groundmass of dolomitic nummulitic wackestone, BH21, 78m. depth, PPL; (C) Pervasive dolomitization affecting fossils and groundmass, BH16, 42m. depth, PPL; (D) Dolomitization completely affects groundmass and nummulite, BH16, 45 m. depth, PPL. (E) Dolomitization affecting groundmass and echinoid spine, BH21, 115m depth, PPL; (F) Pervasive dolomitization affecting groundmass and fossils such as miliolids.

Dolomite origin

Dolomite $CaMg(CO_3)_2$ can be deposited by two different mechanisms (Machel, 2004): (1) by substitution of $CaCO_3$ by $CaMg(CO_3)_2$ (replacive dolomite) and (2) by deposition of dolomite from aqueous solution in primary or secondary pores (dolomite cement). Dolomite can form as a hydrothermal phase, a diagenetic replacement, or a primary mineral; all that is needed is sufficient magnesium and fluid movement. Tucker and Wright (1990) and Warren (2000) proposed five models to explain the dolomitization process: seepage-reflux, burial, evaporative (penecontemporaneous; in hypersaline sabkha/supratidal), seepage-zone, and seawater models. The first and second models occur on a lower scale, while the rest models occur in large-scale dolomitization (Nichols, 2009). Petrographic investigations, geochemical data, and isotope analysis show that the dolomitization of the Dammam Formation occurred in a mixing zone. These observations are shown in Figure 8, and as explained below:

1. Petrographic investigation shows the common occurrence of planar (euhedral, subhedral) dolomite texture and the lack of non-planar (anhedral) dolomite, which specifies that the dolomitization took place under low salinity and temperature conditions (Gregg and Sibley, 1984). The crucial roughening temperature for dolomites is between 50 and 60 °C, which is the range around which planar crystals form (Gregg and Sibley, 1984). These are lower than the temperatures that are expected to arise when limestones are dolomitized at hydrothermal water (100–220 °C) or deep burial temperature (70–90 °C) (Warren, 2000). The paleotemperature of dolomite in Dammam Formation, which is calculated based on $\delta^{18}O$, ranges from (42.2-67.1°C). Consequently, the likelihood of its development by the mixing of meteoric sea water in situations of low temperature and shallow burial depth increases.
2. The studied dolostones do not include evaporite minerals, according to thin-section observations, chemical analysis, and XRD analysis. This suggests that the examined dolomite is typically not compatible with the dolomitization model in environments with brine reflux or evaporitic supratidal (sabkha) (Machel, 2004). Thus, the dolomitization of the Dammam Formation probably occurred in a mixing zone at shallow burial depth. It is mainly developed during major sea-level fall periods in the carbonate platform. The sea-level fall is associated with the progradation of the meteoric-marine mixing zone.

3. Dolomite formed in equilibrium with normal seawater has $\delta^{18}O$ values of 1-3‰, while hypersaline water has $\delta^{18}O$ values greater than +3‰ (Land, 1985; Warren, 2000). Thus, the values of oxygen isotope in the dolomite samples at depths 94-118 m (-5.13 to +0.89‰) indicate that dolomitization was unlikely resulted from hypersaline or seawater. Therefore, the reduction in the oxygen values (-5.13 to +0.89‰) implies that the dolomitization was caused by a seawater-meteoric water mixture.
4. The depletion in $\delta^{13}C$ values (-7.97‰) at depth 34 m in BH3-NJ indicates sea-level fall, and exposure of the Dammam Formation in the Late Eocene (Fig. 4).
5. The Late Eocene sea-level fall that affected the carbonate platform of the Dammam Formation in the study area supports the mixing meteoric-seawater model of Tucker and Wright (1990).

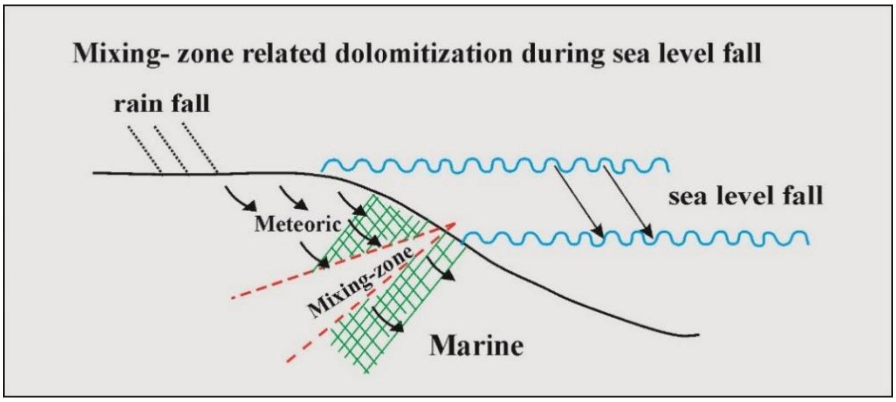


Fig. 8. Suggested dolomitization model (after Wright, 1993) for the Dammam Formation based on petrographic, mineralogical, and geochemical characteristics of Dammam dolostone.

Dissolution and porosity evolution

This process occurs when the pore-fluids are undersaturated relative to carbonate minerals, leading to dissolution of metastable carbonate grains and cement. This process affects shallow near-surface meteoric environments, and according to Choquette and Pray (1970), it resulted in the development of three types of pores. They are:

1. Fabric-selective pores:

This is related to the components of the carbonate rock. These pores are classified into different types:

A. Moldic pores

The moldic pores are caused by the solution of whole fossils. It is the most common type of porosity in the upper Dammam Formation, and appears clearly in biomoldic dolostone facies. Certain molds (nummulites and pelecypod-shaped molds) depict the spaces left by the majority of fully dissolved skeleton grains (Fig. 9A). This kind of pore is typical in meteoric-phreatic zones and is widely distributed in shallow marine carbonates.

B. Intraparticle pores

This type of pore is formed by solution within individual particles or grains, mainly within the chambers of skeletal grains (Fig.9 B). The majority of submicrofacies exhibit this phenomenon to varying degrees. Meteoric vadose and phreatic conditions influence the development of this kind of solution.

C. Intercrystalline

The intercrystalline pores result from dolomitization (Fig. 9C) that causes an increase in porosity as limestone facies are dolomitized.

2. Non-fabric selective pores

These pores occur where they are formed, independent of original textures. They are:

A. Vugs

These pores are irregular without a definite shape. They represent solution enlargement of fabric-selective pores presumably due to the interface of meteoric water with seawater in the subsurface environment.

B. Cavern pores

The term cavern is used for larger openings of channel or vug shapes developed mainly by karstic solution processes. These pores are recorded in the karst zone, which is located below the contact between the Dammam and the Euphrates Formations (Fig. 10C).

C. Veins and fractures

They are dominant in the upper part of the Dammam Formation and filled with granular calcite cement (Fig. 12F).

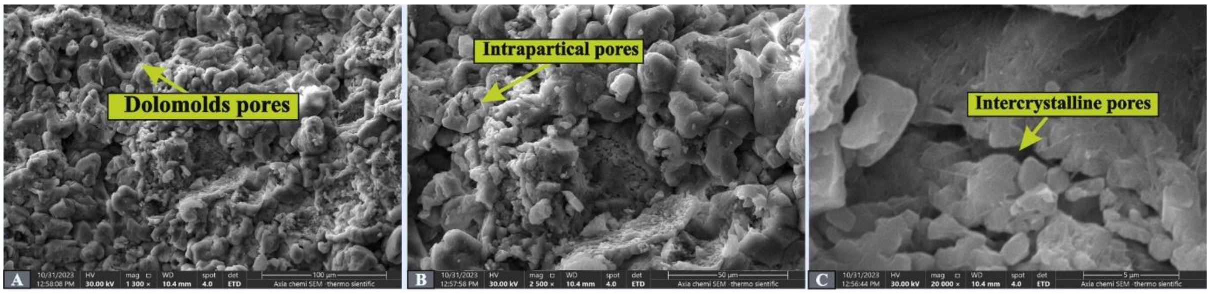


Fig. 9. SEM microphotograph showing rhomb's dolomite in crystalline dolostone; (A) Dolomolds pores; (B) Intraparticle porosity; (C) Intercrystalline porosity.

Karstification

Groundwater enriched with carbon dioxide seeps through carbonate rocks, dissolving portions of the formations and creating solution pipes, sinks, and caverns. The geomorphological features developed by the solution process are referred to as karst features. In this study, the Dammam Formation is subdivided into three members: upper, middle, and lower, with a paleokarst zone at the top. The paleokarst zone is formed when the Dammam Formation was exposed during Oligocene–Early Miocene time. This study includes a detailed investigation of the paleokarst zone, which is located below the contact between the Dammam and Euphrates formations, as noted in the Al-Najaf borehole (BH3). Petrographic evidence for subaerial exposure includes dolocrete features, mixing zone dolomites, and secondary porosity. These observations are shown in Figure 10 and are explained below:

A. The exposed upper part of the Dammam Formation consists of chalky microcrystalline dolostone. The Dammam Formation is extensively fractured. The dolomite is replaced by dolocrete in the weathered zone. A pseudobreccia occurs near the contact zone as a result of the difference in color and texture of dolomite and dolcrete (Fig. 10A). It is observed in BH3, Najaf at 20-25 m depth.

B. Solution vugs and cavities range in size from 4–8 cm and are partially or fully filled with calcite (Fig.10 B).

C. Fractures and small caves occur within the Dammam Formation below the dolomitized zone (Fig. 10C).

D. Friable sediments filling the cave and vugs (Fig. 10D).

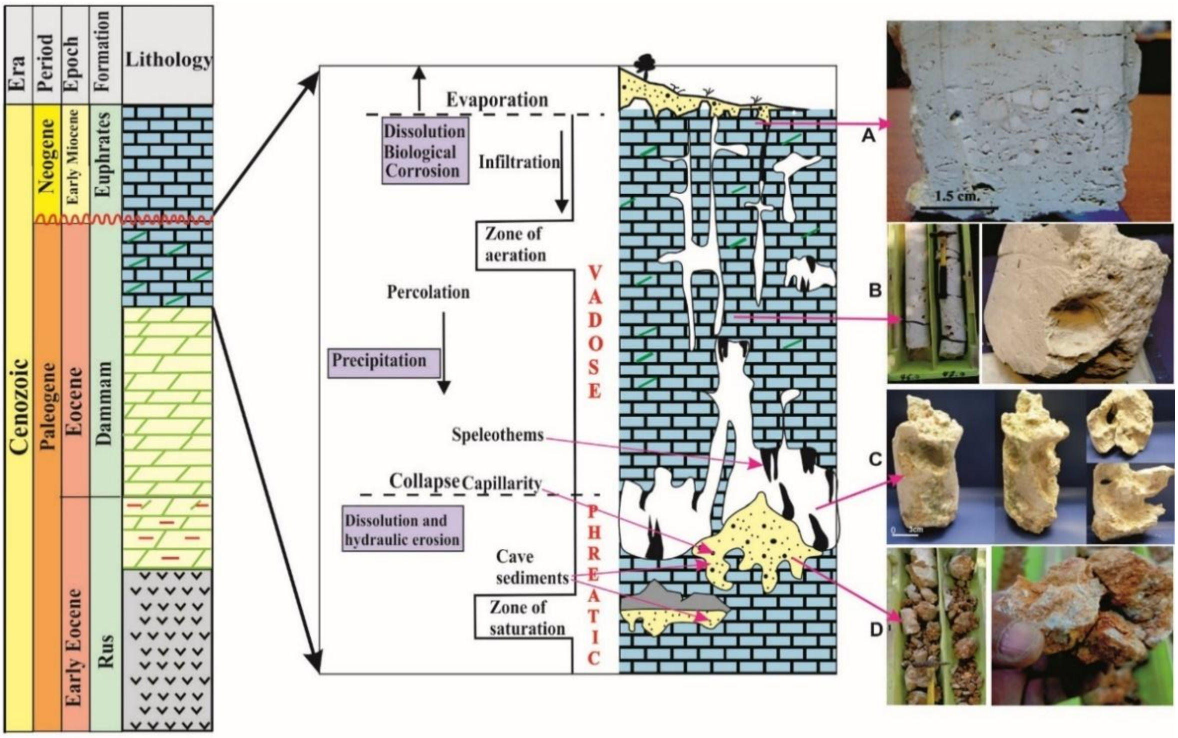


Fig. 10. Paleokarst zone, BH3, compared with Boggs (2009); (A) Pseudobreccia at the top of Dammam Formation, 25 m. depth; (B) Dissolution affects the rocks, which are represented by vugs and cavities, 31m depth; (C) Small caves are present as a result of dissolution at 34-36m depth; (D) Cave sediments filling vugs, 35m depth.

The results of XRD analysis show that the soft sediments filling vugs consist of non-clay minerals such as calcite, quartz, and feldspar, whereas clay minerals include palygorskite and montmorillonite (Fig.11). This indicates that the detrital sediment supply, such as quartz and feldspar, occurred during the exposure stage.

Cementation

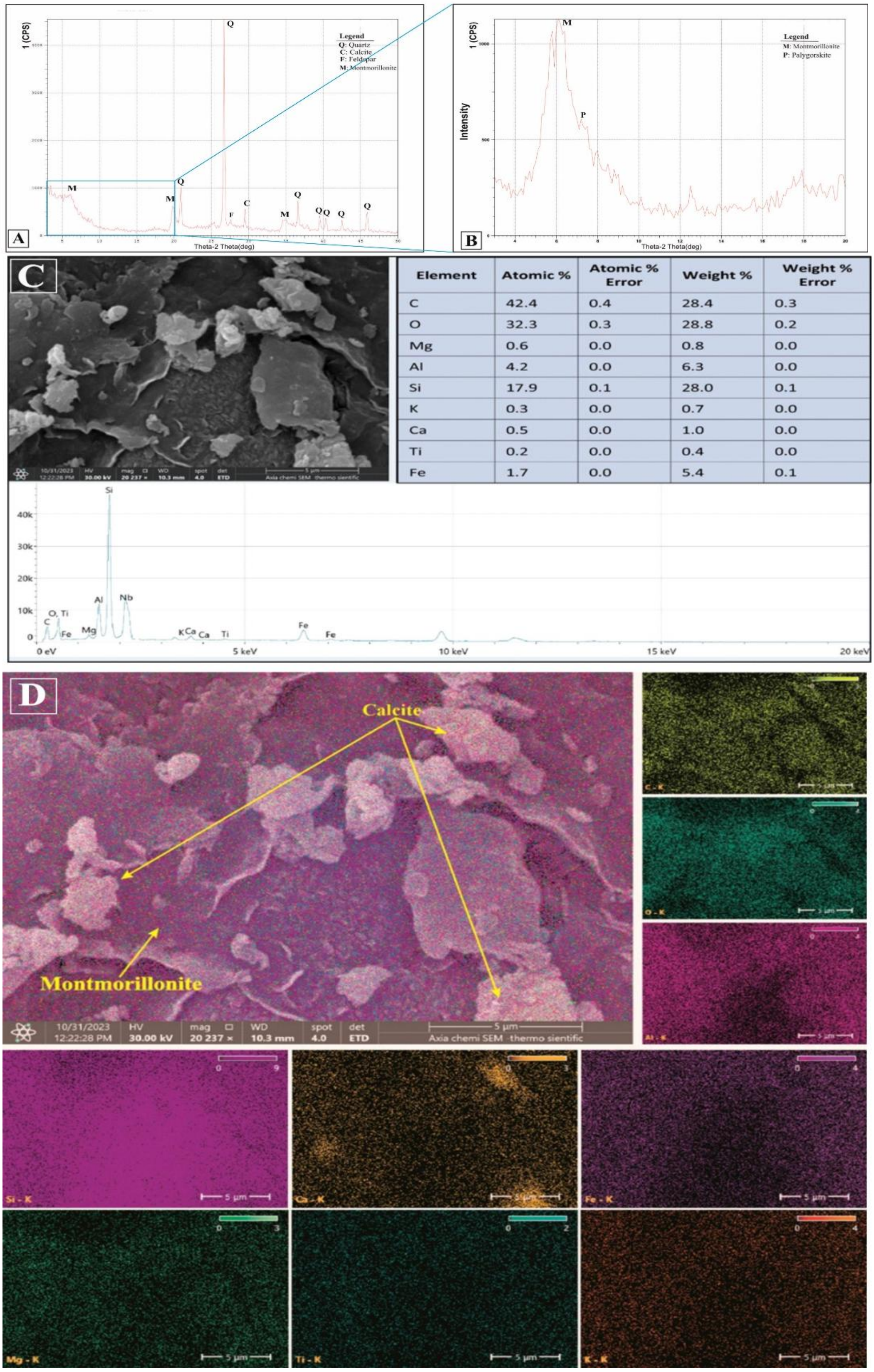
It represents the process of precipitation of minerals in primary or secondary pores. This process takes place when the pore fluids are supersaturated with respect to the minerals. In the study boreholes, calcite is the common cementing mineral in the carbonate facies, whereas silica and gypsum are less common cements. Calcite cement includes granular (Fig.12. A), blocky (Fig.12. B), poikilotopic calcite cement (Fig.12. C), and syntaxial overgrowth cement (Fig. 12.D).

Micritization

This process is common in the Dammam Formation. It is the first diagenetic alteration (early marine diagenesis) seen in the studied boreholes and occurred soon after deposition since it predates all other diagenetic features, producing a micritic envelope surrounding skeletal grains, which is composed of high Mg calcite. The occurrence of a micrite envelope is important for the grain shape. Most fossils affected by this process include *Peneroplis* sp. and Miliolids (Fig. 13A). Such a process occurred in the shallow marine environment (Tucker and Wright, 1990).

Neomorphism

This process involves inversion of aragonite to calcite and mainly calcite to recrystallized calcite (Bathurst, 1983). The neomorphic replacement of micritic matrix and fossils is by microsparite calcite (Fig.13. B). In an aqueous environment, inversion occurs when aragonite is gradually replaced by calcite via solution and in situ precipitation. Radial calcite preserves the original aragonitic fossils (Fig.13. C).



Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	42.4	0.4	28.4	0.3
O	32.3	0.3	28.8	0.2
Mg	0.6	0.0	0.8	0.0
Al	4.2	0.0	6.3	0.0
Si	17.9	0.1	28.0	0.1
K	0.3	0.0	0.7	0.0
Ca	0.5	0.0	1.0	0.0
Ti	0.2	0.0	0.4	0.0
Fe	1.7	0.0	5.4	0.1

Fig. 11. Soft sediment in unconformity contact between Dammam and Euphrates Formations, 35m depth, BH3 (A) X-ray diffractograms show the peak reflections of the minerals including quartz, calcite, feldspar and montmorillonite; (B) The same of (A) but showing the peak reflections of the clay minerals; (C) SEM image and EDS test result of soft sediment; (D) EDX colour mapping showing carbon, oxygen, aluminium, silicon, calcium, iron, magnesium, titanium and potassium.

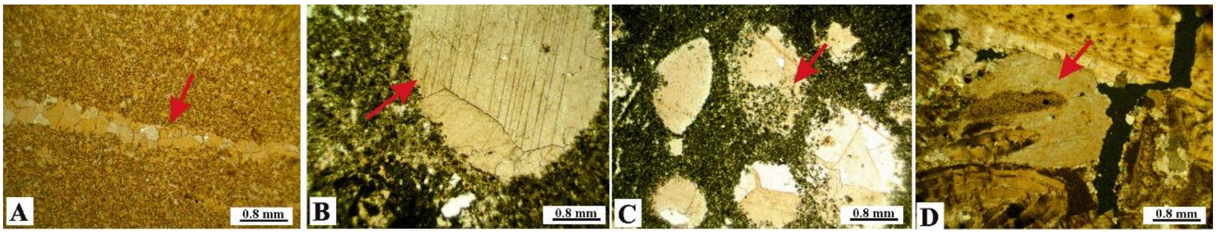


Fig. 12. (A) Fracture filled with granular calcite cement; (B) Blocky calcite cement filling biomolds, PPL.; (C) Poikilotopic calcite cement consists of coarse crystals of calcite enclosing fine and rhombic crystals of dolomite, PPL.; (D) Syntaxial overgrowth cement, BH3, 46m depth, XPL.

Silicification

In the Dammam Formation, the effect of silicification on carbonate rocks involves the partial or complete replacement of shell fragments by silica as well as the precipitation of pore-filling silica cement. The shell fragments of pelecypods are found to be among the most affected bioclasts by selective silicification and either completely or partially replaced by fibrous chalcedony with a preferred orientation parallel to the shell microstructures (Fig.13D).

Dedolomitization

Dedolomitization is the diagenetic replacement of dolomite by calcite to produce a limestone again. Dedolomitization is considered a surface or near-surface process resulting from the interaction between sulphate-rich solution and dolomite. This process is most effective in the uppermost part of the Dammam Formation, and it indicates the exposure of the formation in the late Eocene. The widespread occurrence of dedolomitization is indicated by the following identifiable textures:

- The presence of well-developed composite calcite rhombohedra as pseudomorphs of calcite after dolomite (Fig.13E).
- Remnants of dissolved dolomite are preserved inside the pseudomorphs of calcite or at their boundaries.
- The development of some rhombohedral pores is evidence for dedolomitization in limestone.

Compaction

In the present study, the carbonate rocks of Dammam are subjected to physical compaction. The criteria used to estimate the effect of physical compaction are the preferred orientation of skeletal grains parallel to the bedding, fragmentation of shell fragments, and deformation of fossils such as Nummulites sp. (Fig. 13F).

Paragenesis

The Eocene carbonates of the Dammam Formation in the Al-Najaf area were sampled to study their diagenetic history. These carbonates were cyclically deposited in a shallow water environment and are characterized by extensive dolomitization. The diagenetic history of the limestones can be subdivided into early, middle and late stages (Fig. 16). The term early diagenesis refers to the diagenesis formed immediately after deposition (Berner, 1980; in Flügel, 2010), while the late diagenesis occurs a long time after deposition, when sediments are more compacted into a rock due to burial processes acting in the subsurface over a long geological time (Flügel, 2010). These subdivisions in the Dammam Formation are characterized by porosity evolution, cement type, and recrystallization events, and are separated by periods of dissolution and secondary porosity development. The early stage of diagenesis occurred in a near-surface setting and is characterized by reduction of primary porosity (such as intragranular and intercrystalline pores), micritization, and marine cementation. The middle and late stages reflect post-depositional modification in shallow meteoric to deep burial settings. Middle stages are characterized by neomorphism, secondary porosity, silicification, and formation of equant calcite spar cements. The late stage of diagenesis occurred in a deep burial environment and is represented by blocky cement, dolomite cement, compaction, and dedolomitization.

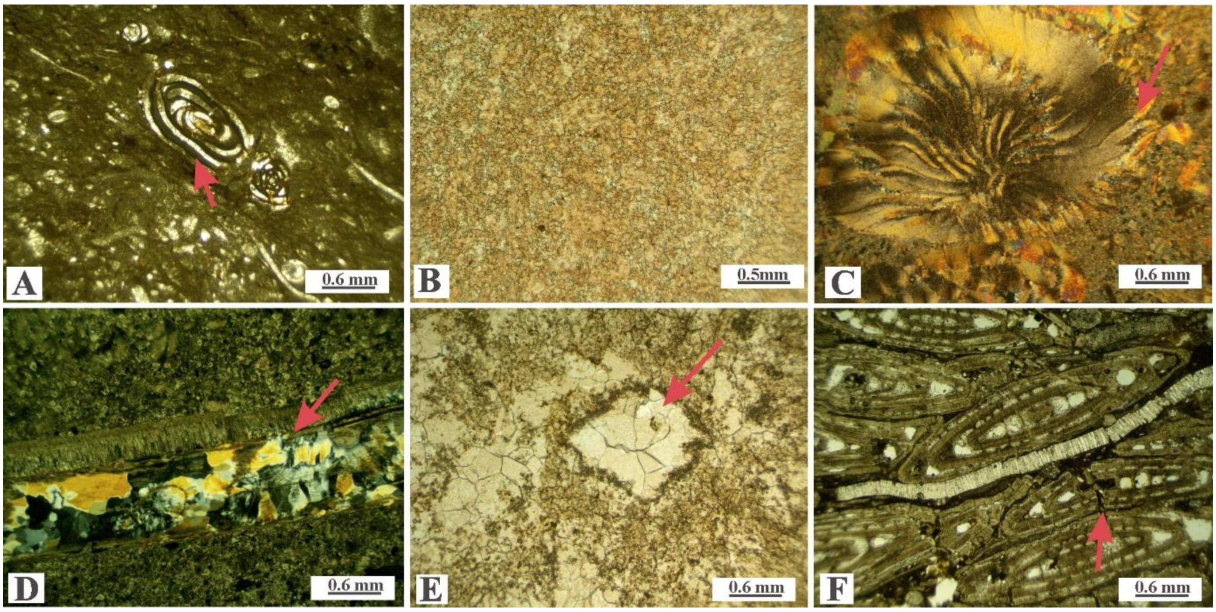


Fig. 13. (A) Micritization affects Miliolids, BH3, 17m depth, PPL.; (B) Crystalline limestone from micrite to microsparite, BH2, 12m depth, XPL.; (C) Inversion affects nummulite, XPL. (D) Complete replacement of shell fragments by silica (fibrous chalcedony); (E) Dedolomitization affects groundmass, pseudomorphs of calcite after dolomite; (F) Nummulitic bioclastic packstone showing deformed nummulite due to physical compaction, PPL.

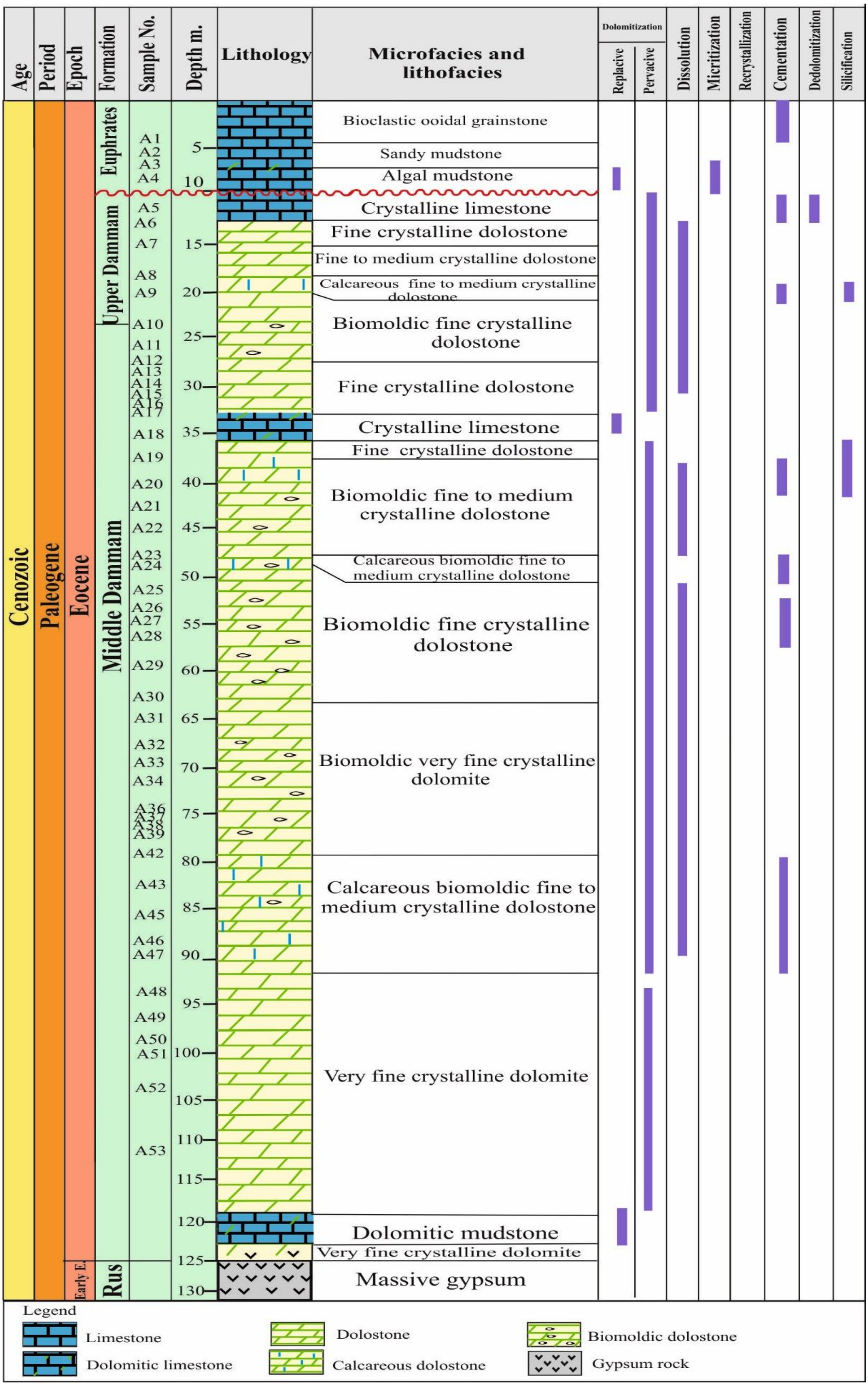


Fig. 14. Stratigraphic column of BH2 illustrating facies and diagenetic processes.

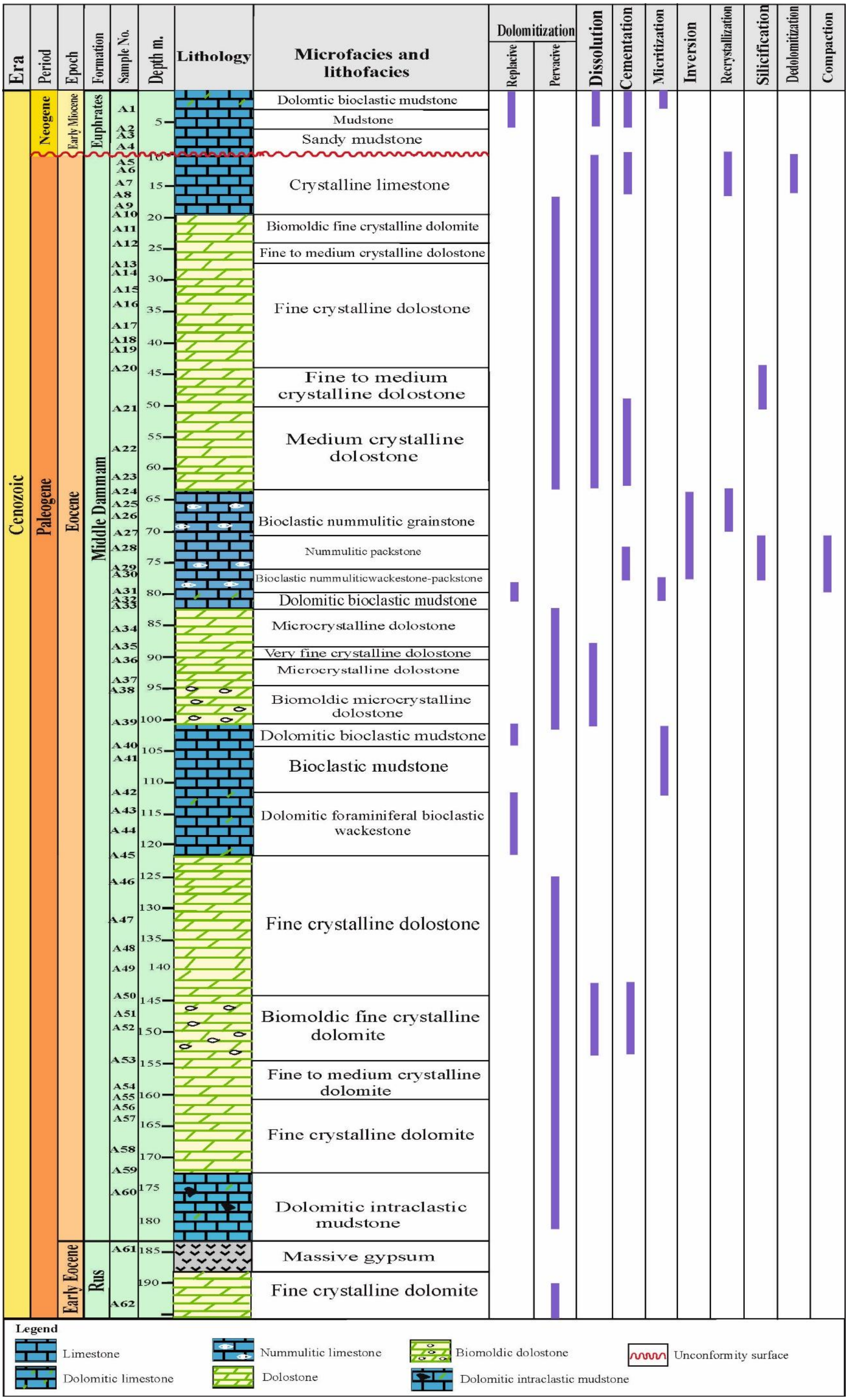


Fig. 15. Stratigraphic column of BH21 illustrating facies and diagenetic processes.

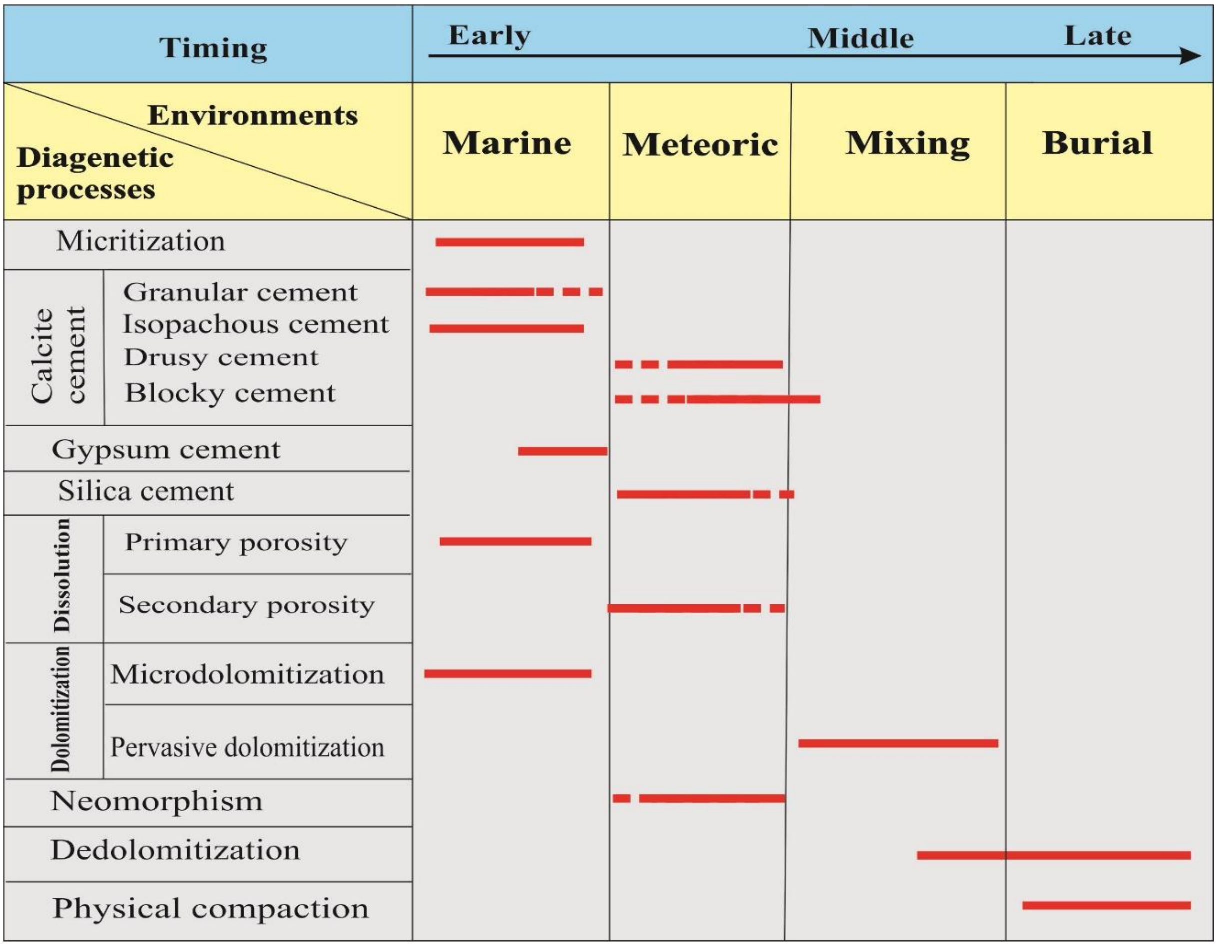


Fig. 16. The main diagenetic processes that affect the Dammam Formation in the study boreholes.

Conclusions

In this study, the Dammam Formation is subdivided into three members: upper, middle, and lower, with a paleokarst zone at the top. The paleokarst zone formed when the Dammam Formation was exposed during Oligocene–Early Miocene time. The results of XRD analysis show the presence of non-clay minerals (calcite, dolomite, quartz, and feldspar), whereas the clay minerals, as secondary minerals, include palygorskite, montmorillonite, and kaolinite.

Six microfacies are distinguished in the Dammam Formation, in addition to dolostone and crystalline limestone facies. Each represents a distinct depositional environment, including restricted, shallow open marine, and shoal environments. Most of these microfacies show indications of scarce to prevalent dolomitization. Five main textural types of dolomites are identified: microcrystalline dolomite, planar-euhedral dolomite, planar-subhedral to euhedral dolomite, planar-porphyrotopic dolomite, and planar void-filling dolomite. The dominance of planar textures and lack of non-planar textures indicates dolomitization under low temperature and salinity conditions. Petrographic investigations, geochemical data, and isotope analysis indicate that the dolomitization of the Dammam Formation was developed in a mixing zone. The decrease of $\delta^{13}C$ values (-7.97‰) at depth 34 m in BH3 indicates sea-level fall, and exposure of the Dammam formation in the late Eocene. During the Late Eocene, the sea-level fall along the carbonate platform of the Dammam Formation supports the model mixing of meteoric-seawater. The paleotemperature of dolomite in Dammam Formation, which is calculated based on $\delta^{18}O$, ranges from (42.2-67.1 °C). Therefore, dolomite deposition by mixing meteoric seawater with low temperature conditions at shallow burial depth becomes a more probable mechanism. The diagenetic history of the limestones can be subdivided into early, middle, and late stages. The early stage of diagenesis occurred in a near-surface setting and is characterized by reduction of primary porosity, micritization, and marine cementation. The middle and late stages reflect post-depositional modification in shallow meteoric to deep burial settings. The middle stage is characterized by neomorphism, secondary porosity, silicification, and formation of equant calcite spar cements. The late stage of diagenesis occurred in a deep burial environment and is represented by blocky cement, dolomite cement, compaction, and dedolomitization.

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