

**INTEGRATED RESERVOIR CHARACTERIZATION  
OF THE VALANGINIAN CARBONATES IN  
CENTRAL SAUDI ARABIA**

BY

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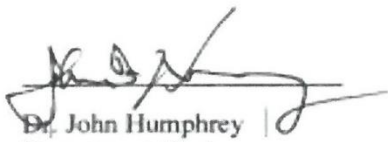
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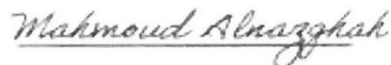


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*Dedication*

*Mom, I am going to make you proud* |

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## LIST OF ABBREVIATIONS

|              |   |                              |
|--------------|---|------------------------------|
| <b>XRF</b>   | : | XRF: X-Ray Fluorescence      |
| <b>XRD</b>   | : | X-Ray Diffraction            |
| <b>SEM</b>   | : | Scanning Electron Microscope |
| <b>mD</b>    | : | millidarcy                   |
| <b>VPDB</b>  | : | Vienna Pee Dee Belemnite     |
| <b>VSMOW</b> | : | Standard Mean Ocean Water    |

## ABSTRACT

Full Name : Sherif Shaban Ibrahim Hassan Allam  
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The lower Cretaceous (Valanginian) carbonates are proven to be prolific reservoirs globally and specifically across the Arabian Plate. Despite the economic importance of early Cretaceous carbonate reservoirs, there is little knowledge on how the interplay between depositional and diagenetic processes impacts the petrophysical properties in Saudi Arabia. Therefore, this study aims to fill the gap by investigating the excellent exposures of the Valanginian carbonates in central Saudi Arabia by integrating sedimentological and geochemical analysis, including stable isotopes. Based on field observation and petrographic thin sections, five microfacies were identified, representing a carbonate ramp depositional setting, from the inner ramp to outer ramp. The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopic compositions showed differences of 2.94 and 0.64‰, and mean values of -3.58‰ and 0.45‰ respectively. The comparison of the isotopic values of the studied samples to the isotopic values of early cretaceous rocks indicates that the  $\delta^{18}\text{O}$  studied samples shifted towards more negative values, which reflects early-stage burial diagenesis. The elemental analysis of trace elements shows low concentrations of iron and manganese, which indicates that the study area was not exposed to meteoric diagenesis. The petrophysical measurements reflect that the sandy peloidal grainstone facies has the highest reservoir quality properties with mean porosity and permeability values of 13.3% and 1.01

mD, respectively, and it is mainly affected by diagenetic processes such as micritization, cementation, and dissolution. The lowest reservoir quality facies is the calcareous mudstone, with mean porosity and permeability values of 2.2% and 0.11 mD, respectively, which is mainly controlled by the depositional settings. |

## ملخص الرسالة

الاسم الكامل: شريف شعبان ابراهيم حسن عالم

عنوان الرسالة: توصيف متكامل لخزانات الحجر الجيري الفالانجينية في وسط السعودية

التخصص: جيولوجيا

تاريخ الدرجة العلمية: ديسمبر 2023

الكربونات في الكريتاسي الأدنى (الفالانجيني) أثبتت أنها خزانات مثمرة عالميًا وبشكل خاص عبر الصفيحة العربية. على الرغم من الأهمية الاقتصادية لخزانات الكربونات في الكريتاسي الأول، إلا أن هناك قليل من المعرفة حول كيفية تأثير التفاعل بين العمليات الترسيبية والتجوية على الخصائص البتروفيزيائية في المملكة العربية السعودية. لذلك، تهدف هذه الدراسة إلى سدها من خلال التحقيق في التعرض الممتاز للكربونات في الفالانجيني في وسط المملكة العربية السعودية من خلال دمج التحليلات الرسوبية والجيوكيميائية، بما في ذلك النظائر المستقرة. بناءً على الملاحظات الميدانية والتصوير الرقيق للصخور البتروغرافية، تم التعرف على خمسة أنماط ميكروفايسيس، تمثل إعدادًا رسوبيًا للكربونات، من الرامب الداخلي إلى الرامب الخارجي. أظهرت التركيبات النظائرية  $\delta^{18}O$  و  $\delta^{13}C$  اختلافات قدرها 2.94 و 0.64‰، وقيم متوسطة قدرها -3.58‰ و 0.45‰ على التوالي. مقارنة قيم النظائر للعينات المدروسة بقيم النظائر للصخور الكريتاسية الأوائل تشير إلى أن قيم  $\delta^{18}O$  للعينات المدروسة تحولت نحو قيم أكثر سلبية، مما يعكس التحجر المبكر في مراحله الأولى. أظهر تحليل العناصر لعناصر الأثر تراكيز منخفضة للحديد والمنغنيز، مما يشير إلى أن منطقة الدراسة لم تتعرض للتحجر الجوي. تعكس قياسات البتروفيزياء أن الوجهات الصخرية الرملية البيلوئية تحتوي على أعلى خصائص للخران مع قيم متوسطة للمسامية والنفاذية تبلغ 13.3% و 1.01 مللي دارسي، على التوالي، وهي تتأثر بشكل رئيسي بالعمليات التجوية مثل تحجر الطين والتماسك والذوبان. أما أقل خصائص للخران فهي الصخور الطينية الجيرية، بقيم متوسطة للمسامية والنفاذية تبلغ 2.2% و 0.11 مللي دارسي على التوالي، والتي يتحكم فيها بشكل رئيسي الإعدادات الرسوبية.



# CHAPTER 1

## INTRODUCTION

### 1.1 Cretaceous carbonate reservoirs

Carbonate reservoirs hold significant importance as highly productive sources of hydrocarbons on a global scale, playing a pivotal role in the world's energy landscape. These reservoirs account for approximately 60% of the world's oil reserves, and they also possess substantial potential for additional gas reserves, particularly in the Middle East (Akbar et al., 2000). Across the stratigraphic records, the Cretaceous period is known for its abundant carbonate formations, which are notable not only for their large volumes and widespread occurrence but also for their diverse types, environments of deposition, and diagenetic processes (Scott et al., 1998). The Cretaceous era witnessed the development of different carbonate environments, such as expansive platforms and reef systems. These formations emerged due to various factors, including changes in continental arrangements, the evolution of marine organisms, and shifts in climate (Alsharhan & Nairn, 1986; Martin, 2001; Mazzullo et al., 1996). The Lower Cretaceous period underwent notable geological and climatic changes known as the Weissert oceanic anoxic event (OAE), creating a unique environment for the formation and alteration of carbonate rocks that influenced all living organisms, both marine and terrestrial, and impacted the processes of carbonate deposition and diagenesis (de Periere et al., 2023). During OAEs, there was an expansion in the extent

and size of shallow epicontinental and marginal seas. This expansion coincided with a remarkable increase in the production of organic carbon. The enhanced organic carbon production during OAEs has the potential to create substantial hydrocarbon reservoirs (Hattori et al., 2019; Schlanger & Jenkyns, 1976).

Carbonate reservoir characterization presents greater challenges compared to siliciclastic reservoirs, primarily due to their pronounced heterogeneity and complex characteristics (Ehrenberg & Nadeau, 2005). The significant petrophysical heterogeneity observed in carbonate reservoirs is evident through the diverse range of porosity-permeability relationships represented in core-analysis data (Lucia et al., 2003). This high degree of heterogeneity in carbonate reservoirs is linked to their different depositional settings, rock texture, pore systems, and diagenetic processes. This high degree of heterogeneity in carbonate reservoirs is linked to their different depositional settings, rock texture, pore systems, and diagenetic processes (Lucia et al., 2003). To achieve accurate reservoir characterization and gain a comprehensive understanding of carbonate reservoirs, integrated approaches are essential. This involves examining the geochemistry of the rocks, studying the depositional environment, unraveling the diagenetic history, and conducting thorough petrophysical measurements. By combining these various aspects, a more comprehensive understanding of carbonate reservoirs can be obtained. Despite extensive research efforts focused on the Lower Cretaceous formations of the Arabian Platform, there is a remarkable scarcity of published studies investigating the intricate sedimentology, stratigraphy, and petrophysics of the Valanginian section in the Middle East. Therefore, the reservoir characteristics of the early Cretaceous carbonates in Saudi Arabia are still enigmatic.

## **1.2 Previous studies**

The early cretaceous Carbonates in Saudi Arabia has been described few times. According to Sharland's study, the Lower Cretaceous Arabian Plate strata are likewise excellent sources and reservoir rocks with significant economic value. The study focused on the Middle Jurassic to Early Cretaceous period, during which much of the eastern Arabian Plate's sinking caused sea levels to rise and a widespread distribution of marine sedimentation (Simmons et al., 2007).

In 2009, a structural analysis of the Yamama Formation in the Jinadriyah area was carried out. For the very first time in the Kingdom of Saudi Arabia, the features of two south- and north-trending anticlines representing Lower Cretaceous rocks in Central Saudi Arabia are detailed in this work. The Jinadriyah anticlines are named after their locations (North and South). These anticlines could be utilized as models for the hydrocarbon fields in the subsurface anticlines of the eastern part of Saudi Arabia. (Al-Mahmoud et al., 2009).

Another study was done in 2015. The study concentrated on the low-resolution, unclear chrono and sequence stratigraphy of the Lower Cretaceous successions of the Arabian Peninsula as a result of the scarcity of biostratigraphic evidence. Additionally, the eastern part of Saudi Arabia was submerged during the Early Cretaceous transgression, establishing a proximal section in comparison to the far positions of the UAE and Oman (Wolpert et al., 2015).

A recent study in 2018 sought to introduce an improved stratigraphic background for the eastern region of Saudi Arabia's lower Cretaceous succession. It provides a thorough examination of the facies, constructs a relative sea-level curve in connection to the

development of the facies, and facilitates regional and worldwide relationships. This will help us comprehend the Cretaceous strata in this special sedimentary basin better (Nagm et al., 2018).

The most recent study, published in 2023, aims to identify the presence of the oceanic anoxic event in the Valanginian age known as the Weissert Event. This comprehensive stratigraphic framework facilitates finding the Weissert Event in the research area and recognizing its effects on the formation of the carbonate platform and climate shift in the Tethys Ocean easier. (de Periere et al., 2023).

### **1.3 Geological background**

During the Early Cretaceous period, the Arabian Platform exhibited a vast epeiric platform spanning hundreds of kilometers on the western margin of the Tethys Ocean. The sedimentary deposits in this region were predominantly composed of shallow marine carbonates, which gradually transitioned into deeper marine environments along the Tethys margin, as observed in modern-day Oman (Ziegler, 2001). During the Valanginian stage, the carbonate succession in the study area was formed and deposited along the Western margin of the Tethys Ocean, approximately at a latitude of 20 degrees south of the paleo-equator line (Stampfli & Borel, 2002). The period from the Berriasian to Valanginian is marked by a moderately high sea level that gradually decreases over time (Haq et al., 1988). During the Valanginian stage, the climate in the northern Tethys region is believed to have been warm and potentially moderately humid to arid. This climatic condition was likely influenced by significant igneous and tectonic events associated with the Paranà-Etendeka igneous province (Bottini et al., 2018). According to (Al-Mahmoud et al., 2009), the study

area experienced a compressive tectonic setting from the Late Cretaceous to the present (92 to 0 million years ago), during which the plate occupied its current position. This phase was characterized by significant tectonic events, including the closure of the Neo-Tethys Sea and the uplift of the Oman and Zagros mountains, known as the first Alpine orogeny, during the Late Cretaceous. Additionally, in the mid to late Tertiary, there was the rifting and spreading of the Gulf of Aden and Red Sea, along with a northeastward regional tilting of the Arabian Plate, known as the second Alpine orogeny.

#### **1.4 Problem statement**

Eastern Arabia's Lower Cretaceous sedimentary rocks are part of an enormous accumulation of Paleozoic to Cenozoic layers that form the Arabian Platform's stable shelf. They appear as a broad belt of hemispherical shape that encircles the Precambrian strata of the Arabian Shield in the east. These Lower Cretaceous successions exhibit a diverse range of lithologies, including siliciclastics, evaporites, and carbonates. (Powers et al., 1966). The Arabian Plate's Lower Cretaceous sequences are also excellent sources and reservoir rocks with significant economic value. The majority of research on the Lower Cretaceous of Arabia was conducted at the regional level (Hughes, 2000; Simmons et al., 2007). The distant, thicker, and tectonically influenced successions in the east, bearing oil and gas reservoirs like those of Oman and the UAE, were the main focus of the comprehensive stratigraphic research. In Saudi Arabia, closer to the West, researchers paid less attention to studying the Lower Cretaceous rocks in depth (Memesh et al., 2012; Wolpert et al., 2015).

The period from the Berriasian to the Valanginian was extensively studied in many countries in Arabia, such as Oman, Iraq, and the United Emirates, under the names of

different formations. The same period is understudied in Saudi Arabia; only three studies addressed it (Al-Mahmoud et al., 2009; de Periere et al., 2023; Nagm et al., 2018). Since the petrophysical properties of the Valanginian rocks have never been studied before, we see a chance to do so by utilizing improvements in the various analysis techniques.

## **1.5 Objectives**

This study has the following objectives:

- Understanding the spatial-temporal distribution of lithofacies and depositional environment in the early Cretaceous carbonates.
- To unravel the role of depositional and diagenetic processes in the reservoir quality.
- To perform 2D-3D reservoir modeling for the Early Cretaceous carbonates. |

## **CHAPTER 2**

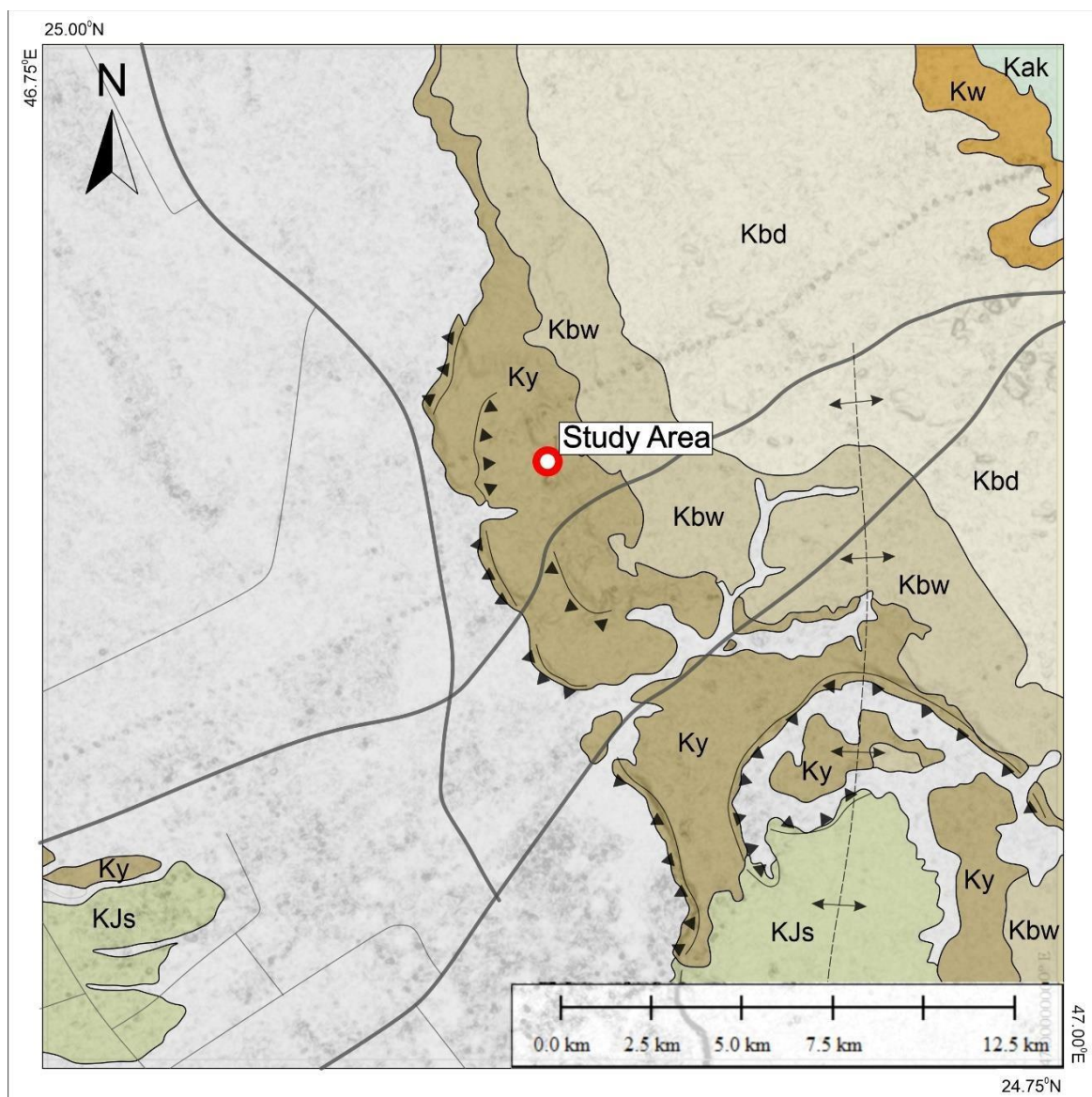
### **METHODOLOGY**

#### **2.1 Sites and Samples**

The study area is located in the area of Jinadriyah, 15 km north-east of Riyadh, central Saudi Arabia, where the early Cretaceous rocks are well exposed and cropped out (Figure 1). The study outcrops fall in the Riyadh quadrangle, where seven sedimentary sections were precisely measured and sampled (Figure 2). The study area is approximately located at 24°53'30.8"N and 46°52'46.2"E, and the sedimentary sections have an average thickness of around 14 m. For the measured sections, thorough sedimentological and stratigraphic investigations have been conducted, including recording the fossil contents, identifying grain size and color, analyzing composition using a hand lens, describing sedimentary structures, tracing fossil occurrences, and tracking sequence stratigraphic key surfaces like major unconformities and changes in depositional cycles (Figure 3A).

In all, a total of 139 samples were collected from the study area. The samples were split into several groups to perform different methods of analysis. For identifying the microfacies, the depositional model, and diagenetic processes, 26 samples were prepared as thin sections based on the field observations. 103 samples were powdered and used for the X-ray fluorescence analysis (XRF) and X-ray diffraction analysis (XRD), and 25 powdered samples were chosen to perform the stable carbon and oxygen isotopic analysis. For further investigation of some elements and minerals, we performed XRF elemental

mapping on two samples and used the scanning electron microscope (SEM) on five samples. 36 samples were used to measure the petrophysical parameters such as porosity and permeability.



**Figure 1.** Geological map of the study area.



**Figure 2.** Location map of the studied outcrops (Satellite image from Google Earth).

## **2.2 Laboratory Work**

All laboratory analyses were conducted at the King Fahd University of Petroleum and Minerals, Saudi Arabia.

### **2.2.1 Petrographic thin sections**

The prepared thin sections were used to identify the microfacies and the facies associations following the classification of (Dunham, 1962; Embry & Klovan, 1971). For petrographic acquisition and analysis, a Zeiss Axioscan Z1 automated slide scanning system with a variety of lenses and an advanced focusing technique was used.

### **2.2.2 Scanning Electron Microscope (SEM)**

High-resolution images were collected utilizing the JEOL JCM-7000 (Desktop SEM) for a better understanding of the microscale mineral crystallization that is essential to diagenesis and reservoir quality. For analysis, the representative rock chips were put on pin-type stubs following the procedures of (Amao et al., 2016).

### **2.2.3 Mineral and elemental analysis**

Powders from a chosen rock sample were prepared to analyze the mineral content within their stratigraphic layers using a PanAnalytical XRD system. The XRD patterns were obtained using a diffractometer equipped with CuK $\alpha$  radiation (operating at 45 kV and 40 mA), starting at a 2 $\theta$  angle of 4.0066 and ending at 70.0076. Additionally, elemental and oxide compositions were determined using X-ray fluorescence (XRF) analysis with the Bruker M4 TORNADO system.

#### 2.2.4 Stable carbon and oxygen isotopes

The carbonate specimens were subjected to stable carbon and oxygen isotope analyses to ascertain their geochemical conditions, diagenetic phases, and precipitation temperatures. To generate CO<sup>2</sup> gas for the automated purification process, 80–100 g of these powders were treated with 102–105% phosphoric acid at 70°C for 480 seconds in the case of calcite. Cryogenic traps were employed to eliminate impurities such as water vapor and other non-condensable gases produced during the acid digestion of the carbonates, thereby purifying the resultant CO<sup>2</sup>. This purification was efficiently executed using the Kiel IV carbonate device. The emitted CO<sup>2</sup> was then measured and analyzed using a Thermo Finnigan MAT-253 plus mass spectrometer, achieving a precision of 0.04 for <sup>13</sup>C and 0.08 for <sup>18</sup>O. Carbon and oxygen isotope data were expressed relative to the Vienna Pee Dee Belemnite (VPDB) standard, with conversion to SMOW (Standard Mean Ocean Water) based on (Anderson & Arthur, 1983):  $\delta_{\text{SMOW}} = 1.03086 \delta_{\text{VPDB}} + 30.86$ . To account for potential drift in the mass spectrometer's measurements due to factors like ion source performance or impurities, as noted by (D'Autry et al., 2010), raw <sup>18</sup>O and <sup>13</sup>C data were calibrated against internal carbonate standards (KIS; KFUPM Iceland Sparite) with established isotopic values of -6.23 for <sup>18</sup>O and 2.25 for <sup>13</sup>C. The precipitation temperature was determined from the oxygen isotope fractionation between calcite and water, applying the formula (Erez & Luz, 1983; Stewart et al., 2004; Zachos et al., 1994):  $T = 16.998 - 4.52 (\delta^{18}\text{O}_{\text{cal}} - \delta^{18}\text{O}_{\text{SW}}) + 0.03 (\delta^{18}\text{O}_{\text{cal}} - \delta^{18}\text{O}_{\text{SW}})^2$ , where T denotes the water temperature at the time of calcite precipitation (in °C),  $\delta^{18}\text{O}_{\text{cal}}$  represents the  $\delta^{18}\text{O}$  values for calcite (SMOW), and  $\delta^{18}\text{O}_{\text{SW}}$  signifies the  $\delta^{18}\text{O}$  values of the water (SMOW). For these analyses, a  $\delta^{18}\text{O}_{\text{SW}}$  value of -1‰ SMOW was assumed, reflecting the ice-free conditions of the Cretaceous era as suggested by (Shackleton, 1975).

### **2.2.5 Petrophysical parameters**

Porosity measurements were conducted on core plugs, each with a diameter of 1.5 inches, utilizing the Core Test System INC AP-608 Porosimeter. Permeability, on the other hand, was determined using a helium permeameter in conjunction with a multi-probe core scanner, specifically the NER Autoscan device.

### **2.2.6 Geological modelling**

Petrel software was employed to effectively correlate and interpolate data across various outcrops, facilitating the creation of accurate 3D models of porosity and permeability. Petrel's advanced capabilities allowed for the integration and analysis of diverse geological and petrophysical data, enabling a comprehensive understanding of the petrophysical properties for accurate reservoir modeling and analysis.

## CHAPTER 3

### RESULTS

#### 3.1 Facies

##### 1. Calcareous mudstone (MF-1)

Outcrop characteristics: 40-cm layer of finely grained calcareous mudstone was observed. Microscopic examination revealed a minimal presence of bioclasts within the mudstone, which primarily comprised calcite. Burrowing activity was detected within this layer (Figure 3B), although it was relatively limited in extent, as well as secondary gypsum veins (Figure 3C).

Microscopic description: This facies is found within intervals that are no more than one meter thick and is typically observed at the beginning of the depositional sequence. It consists of black argillaceous micrite, along with calcite cemented fractures. This microfacies acts as a permeability barrier layer, effectively separating the more porous and permeable outcrop layers because it has no pore spaces (Figure 4A). There are no obvious diagenetic processes affecting this facies.

Interpretation: The characteristics of this facies, including its depositional texture and lack of faunal content, suggest that it formed under low-energy conditions in mid-to-outer ramp environment (Figure 5) (Flügel & Munnecke, 2010; Wilson, 2012).

##### 2. Sandy peloidal grainstone (MF-2)

Outcrop characteristics: 1-m thick coarse grainstone with a distinct reddish-brown color, characterized by a notable abundance of quartz grains. Various sedimentary structures, including mud rip clasts (Figure 3D) and incise fill (Figure 3E), were identified. The lower portion of these layers exhibited a well-defined erosional surface, forming a sharp contact with the underlying calcareous mudstone layer.

Microscopic description: This facies exhibits a texture dominated by grains and is primarily composed of peloids and quartz grains, along with other skeletal grains that have undergone micritization. Various rounded skeletal grains such as echinoderms, and foraminifers are also present. In terms of porosity, the primary type observed is intraparticle porosity, where pores are contained within individual particles. The main diagenetic processes influencing this facies are micritization, which involves the transformation of skeletal grains into micrite, followed by blocky calcite cementation, which fills the interparticle pore spaces. The least common diagenetic process is dissolution (Figure 4B).

Interpretation: This facies, marked by peloidal grainstone with a substantial amount of quartz grains, shows an energetic depositional. The peloidal grainstone, commonly tied to high-energy, oxidizing environments, reflects the energetic nature of the depositional environment (Al-Saad & Sadooni, 2007). The abundant quartz grains highlight a high-energy depositional event, likely modeled by wave action (Kalińska-Nartiša et al., 2018). The roundness of quartz grains could signify their extended exposure to high-energy conditions, indicating the facies was deposited at the inner ramp close to sediment supply (Figure 5) (Martini et al., 2007).

### 3. Peloidal bioclastic wackestone (MF-3)

Outcrop characteristics: 30-cm-thick pale brown wackestone layer characterized by obvious and various types of bioclasts, including large benthic foraminifera and bivalves, as well as other types of bioclasts. This layer has no sedimentary structures and no evidence of burrowing activity.

Microscopic description: This facies exhibits a wackestone texture, encompassing diverse bioclastic grains including benthic foraminifera, bivalves, gastropods, and infrequent sand-sized quartz grains. The facies display a range of grain sizes, poorly sorted bioclasts, and a relatively high clay content. A noticeable increase in intraclasts is observed relative to the occurrence of peloids within this facies. The pores in this facies are very limited and related to one pore type, which is moldic. The main diagenetic processes that influenced this facies are micritization followed by cementation, and the least common process is dissolution, which created moldic porosity. (Figure 4C).

Interpretation: The described facies have a wackestone texture and a variety of bioclastic grains like benthic foraminifera, bivalves, gastropods, and rare sand-sized quartz grains. The mix of grain sizes, poor sorting, and noticeable micrite highlights the chaotic and sporadic nature of high-energy depositional settings in the inner ramp. (Figure 5) (Wang et al., 2021).

#### 4. Bioclastic wackestone (MF-4)

Outcrop characteristics: 30-cm-thick white floatstone layer characterized by the scarcity of bioclasts, where different kinds of bioclasts such as bivalve and benthic foraminifera are floating in the matrix. This layer lacked sedimentary structures and burrowing activity.

Microscopic description: This facies primarily consists of a micritic matrix with a minor presence of incorporated skeletal grains, including bivalves, benthic foraminifera, and gastropods. The most common diagenetic process is micritization, followed by cementation. The examined thin sections show very few pore spaces of moldic type (Figure 4D).

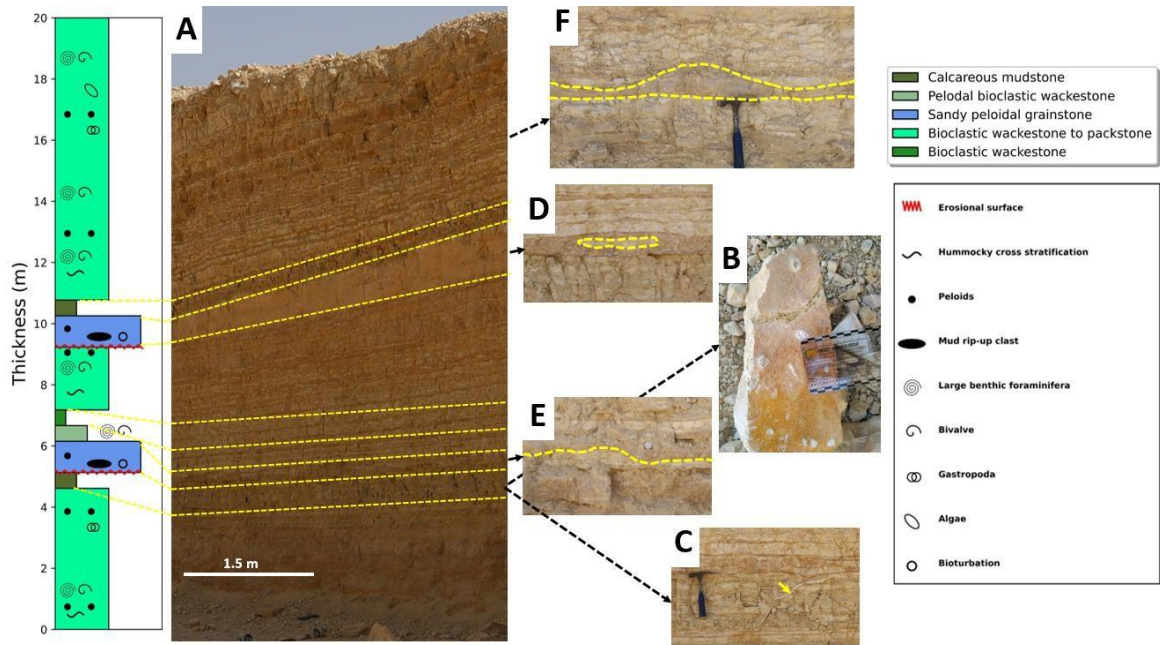
Interpretation: The bioclastic wackestone facies, with scattered skeletal grains such as bivalves, foraminifera, and echinoids in a mud matrix, represents a shallow, calm water area in the inner ramp settings especially lagoon. The skeletal fragments indicate a marine-life rich area, likely flourishing during calm weather periods when the water is gentle, allowing both skeletal pieces and mud to settle and stay preserved. (Figure 5) (Mircescu et al., 2022).

##### 5. Bioclastic wackestone to packstone (MF-5)

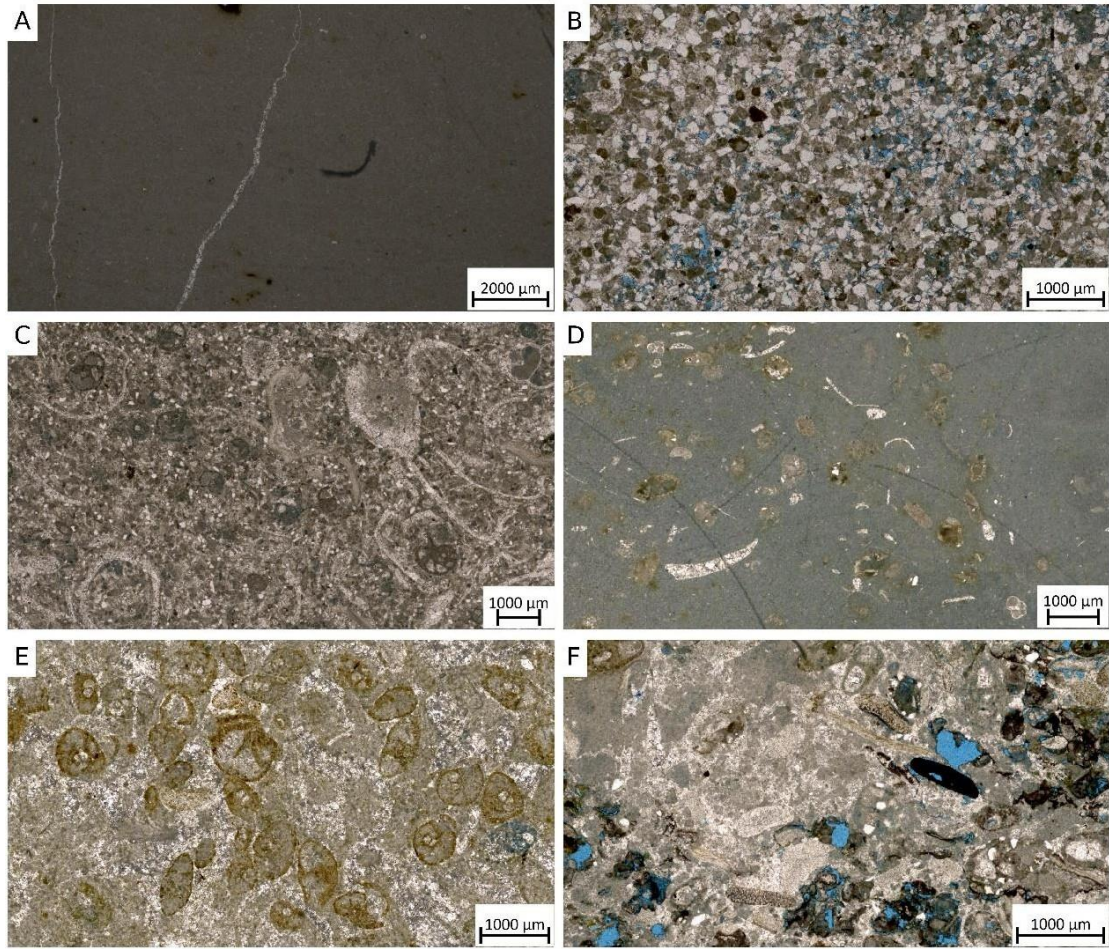
Outcrop description: 1.5-meter-thick unit of alternating intercalations of nodular wackestone to packstone, hosting a diverse array of bioclast assemblages mainly composed of large benthic foraminifera, bivalves, algae, and fragmented skeletal remains. Bioturbation activity was evident within this layer, with hummocky cross-stratification representing the prevailing sedimentary structure (Figure 3F).

Microscopic description: This facies exhibits a wackestone-to-packstone texture and is characterized by a significant abundance of large benthic foraminifera, bivalve, algae, and other bioclastic particles. The most diagenetic process is the micritization of skeletal grain, causing a micrite envelope, followed by cementation, and lastly, the presence of stylolites. In terms of porosity, the sole pore type observed is dissolution porosity. (Figure 4E & F).

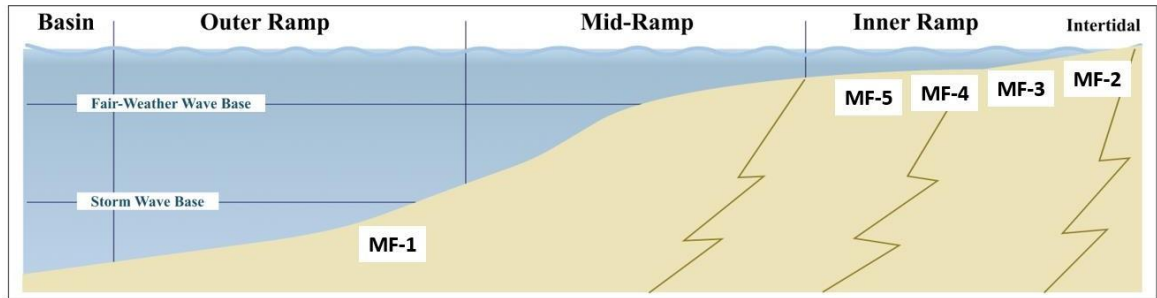
Interpretation: The mud-dominated texture of this facies indicates that the sediments were deposited in a calm environment with low energy. The diverse range of marine organisms within this facies also indicates that it was formed in a shallow-water, open marine environment in ramp crest settings (Figure 5) (Asl & Aleali, 2016; Sadooni, 1993; Sadooni & Alsharhan, 2004).



**Figure 3.** (A) Outcrop image of the study area. (B) Bioturbation (burrowing) activity. (C) Secondary gypsum vein indicated by the red arrow. (D) Mud rip-up clast in the sandy peloidal grainstone bed. (E) Incise and fill structure. (F) Hummocky cross stratification (HCS).



**Figure 4.** Microfacies types of the studied sections. (A) Calcareous mudstone (MF-1). (B) Sandy peloidal grainstone (MF-2). (C) Peloidal bioclastic wackestone (MF-3). (D) Bioclastic floatstone (MF-4). (E & F) Bioclastic bivalve wackestone to packstone (MF-5).



**Figure 5.** Schematic, not to scale, depositional model of studied successions.

## **3.2 Geochemistry**

All the results of the geochemical analyses are in Table 1.

### **3.2.1 Elemental analysis**

To further understand the elemental chemistry of the studied outcrops, the XRF data was analyzed (Figure 6). The elemental concentrations show that calcium (Ca), which ranges from 28.74 to 88.96 wt.% (mostly > 63.30 wt.%), is the most prevalent element. Silicon (Si) varies between 3.47 and 33.35 wt.%, and the mean value is 16.42 wt.%. Magnesium (Mg) values range from 10.51 to 37.24 wt.%, and the mean value equals 19.99 wt.%. Iron (Fe) concentration ranges from 0.11 to 1.80 wt.%, with a mean of 0.71 wt.%. Manganese (Mn) concentration is measured in PPM; the minimum value is 54.01 PPM, the maximum value is 540.15 PPM, and the mean value is 195.68 PPM.

### **3.2.2 Mineralogy**

All samples are mainly dominated by calcite by a percentage up to 99.8%, with a mean value of 96.1% and the lowest value being 78.6%. Moreover, all the samples have quartz percentages ranging from 0.2 to 17.4% and a mean value of 2.6%. The lowest content in the studied samples is dolomite, which is absent in many samples. The dolomite percentage ranges from 0 to 7.4%, with a mean value of 1.3%.

### 3.2.3 Stable isotopes

The composition of the oxygen isotopes in the samples ( $\delta^{18}\text{O}_{\text{VPDB}}$ ) ranges from -5.41 to -2.47‰, with a difference of 2.94‰ and mean value of -3.58‰. The samples' carbon isotopic ratio ( $\delta^{13}\text{C}_{\text{VPDB}}$ ) shows a narrow range from 0.13 to 0.76‰ and a difference of 0.64‰ and mean value of 0.45‰. The palaeotemperature inferred from the oxygen isotope ratios of samples ranges from 23.7 to 37.49 °C, with a mean of 28.88 °C. The isotope analysis results for the samples are presented (Figure 8).

### 3.3 Porosity types

The porosity of the studied samples was examined in the laboratory through microscopic analysis using thin sections and SEM. During the microscopic investigation, multiple types of porosity were identified in the studied samples. The prevailing pore type observed was moldic porosity (Figure 9A & B), categorized as secondary porosity resulting from complete dissolution of particles. Interparticle porosity (Figure 9C), classified as primary porosity, was the second most abundant pore type. Intraparticle porosity (Figure 9D) and dissolution porosity (Figure 9E), both characterized by partial dissolution of particles, were found to be less common. Under SEM, micropores were discovered in the interstitial spaces between calcite grains (Figure 9F).

### 3.4 Diagenetic processes

The diagenetic process that affected the studied outcrops is studied on many different scales. Diagenetic processes were observed in the petrographic thin sections and SEM, such as micritization (Figure 10A), cementation (Figure 10B), Dolomitization (Figure 10C

& D), dissolution (Figure 10E), stylolites (Figure 10F), and fracturing (Figure 10G). On the outcrop scale, fractures were observed on the centimeter scale (Figure 10H) and the meter scale (Figure 10I).

### **3.5 Petrophysical analysis**

A total of 36 core plugs were subjected to helium porosity and permeability measurements (Table 2). In the calcareous mudstone facies, the porosity values range from 1.5% to 4.2%, with a mean of 2.2% (Figure 11). The permeability values range from 0.08 mD to 0.16 mD, with a mean of 0.11 mD (Figure 12). For the bioclastic floatstone facies, the porosity values range from 1.9% to 4.8%, with a mean of 3.4% (Figure 11). The permeability values range from 0.08 mD to 0.17 mD, with a mean of 0.11 mD (Figure 12). In the peloidal bioclastic wackestone facies, the porosity values range from 5.5% to 8.7%, with a mean of 6.9% (Figure 11). The permeability values range from 0.08 mD to 0.32 mD, with a mean of 0.17 mD (Figure 12). The bioclastic wackestone to packstone facies exhibits porosity values ranging from 7.9% to 15.2%, with a mean of 10.3% (Figure 11). The permeability values range from 0.09 mD to 0.31 mD, with a mean of 0.19 mD (Figure 12). Finally, in the sandy peloidal grainstone facies, the porosity values range from 11.5% to 15.2%, with a mean of 13.3% (Figure 11). The permeability values range from 1.61 mD to 3.87 mD, with a mean of 1.01 mD (Figure 12).

### **3.6 Geological models**

Petrel Software has introduced multiple procedures that employ a range of data to construct geological models. These processes commence with the creation of pseudo wells and culminate in the distribution of petrophysical parameters, ultimately leading to the final step of interpretation (Cannon, 2018). Step 1 involves the creation of pseudo wells using stratigraphic logged sections derived from field observations. This process is crucial for zonal attribution within the model and should be kept straightforward, aligning with the conceptual model, and providing an explanation for the observed variations in zone thickness between outcrops (Figure 13). In step 2, the focus is on generating top and lower surfaces for the designated study area. This entails determining the elevations and depressions within the study area (Figure 14). In step 3, these pseudo-wells are then correlated using microfacies data, assigning sedimentological attributes to each zone. This correlation helps identify lateral continuity and variations in sedimentological properties, enhancing the understanding of the geological model (Figure 15). In step 4 The construction of the geological model involved utilizing data acquisition and well logs. Petrophysical properties such as porosity (Figure 16) and permeability (Figure 17) were distributed to each cell of the 3D grid in the model using geo-statistical methods facilitated by Petrel software. The primary objective of the reservoir model was to provide a comprehensive set of continuous reservoir parameters for every cell within the 3D grid. Numerous techniques were employed to process and visualize these reservoir parameters, ensuring their effective representation and analysis (Bellorini et al., 2003).

| Sample no. | Ca (wt. %) | Si (wt. %) | Mg (wt. %) | Fe (wt. %) | Mn (PPM) | Calcite % | Quartz % | Dolomite % | δ13C  | δ18O   | Temperature °C |
|------------|------------|------------|------------|------------|----------|-----------|----------|------------|-------|--------|----------------|
| 1          | 77.57      | 13.34      | 1.74       | 0.54       | 247.10   | 99.00     | 0.9      | 0.095      |       |        |                |
| 2          | 65.16      | 11.29      | 5.32       | 0.51       | 185.94   | 99.19     | 0.7      | 0.109      | 0.199 | -3.314 | 27.62          |
| 3          | 78.18      | 7.58       | 5.18       | 0.71       | 345.38   | 98.49     | 1.5      | 0.014      |       |        |                |
| 4          | 77.54      | 6.15       | 3.73       | 1.01       | 516.03   | 98.89     | 1.1      | 0.014      |       |        |                |
| 5          | 68.96      | 16.54      | 3.47       | 0.62       | 214.77   | 98.62     | 1.3      | 0.081      |       |        |                |
| 6          | 82.10      | 8.35       | 2.71       | 0.70       | 339.19   | 99.00     | 1        | 0.000      | 0.289 | -3.165 | 26.92          |
| 7          | 85.28      | 3.47       | 4.81       | 0.65       | 388.30   | 99.14     | 0.6      | 0.258      |       |        |                |
| 8          | 56.34      | 24.86      | 3.55       | 0.59       | 159.37   | 92.13     | 5.3      | 2.567      | 0.125 | -2.507 | 23.88          |
| 9          | 78.97      | 11.56      | 2.38       | 0.85       | 356.67   | 97.21     | 1.8      | 0.991      |       |        |                |
| 10         | 56.23      | 13.45      | 12.93      | 0.43       | 74.61    | 96.27     | 1.9      | 1.833      |       |        |                |
| 11         | 72.90      | 13.28      | 3.36       | 0.78       | 278.29   | 92.58     | 6.8      | 0.625      |       |        |                |
| 12         | 44.65      | 24.58      | 7.74       | 0.75       | 108.70   | 78.58     | 17.4     | 4.020      |       |        |                |
| 13         | 81.07      | 10.14      | 1.49       | 1.14       | 355.59   | 96.27     | 1.9      | 1.833      |       |        |                |
| 14         | 64.53      | 19.60      | 2.96       | 1.29       | 261.93   | 90.47     | 9.3      | 0.231      | 0.239 | -3.773 | 29.76          |
| 15         | 57.86      | 21.06      | 3.46       | 0.99       | 206.97   | 83.17     | 15.8     | 1.032      |       |        |                |
| 16         | 71.79      | 12.50      | 4.22       | 0.94       | 347.10   | 91.16     | 8.3      | 0.543      | 0.314 | -4.205 | 31.79          |
| 17         | 63.74      | 17.25      | 3.53       | 1.53       | 276.48   | 91.03     | 6.4      | 2.567      |       |        |                |

|           |       |       |       |      |        |       |     |       |       |        |       |
|-----------|-------|-------|-------|------|--------|-------|-----|-------|-------|--------|-------|
| <b>18</b> | 56.34 | 27.02 | 4.50  | 0.78 | 256.08 | 97.82 | 2   | 0.177 | 0.238 | -4.52  | 33.28 |
| <b>19</b> | 72.56 | 10.09 | 6.50  | 1.24 | 297.86 | 96.27 | 1.9 | 1.833 |       |        |       |
| <b>20</b> | 55.40 | 23.05 | 5.19  | 0.73 | 147.73 | 94.75 | 1.9 | 3.354 |       |        |       |
| <b>21</b> | 74.16 | 8.31  | 6.64  | 1.05 | 297.59 | 95.90 | 2.2 | 1.901 |       |        |       |
| <b>22</b> | 41.29 | 19.68 | 15.07 | 0.62 | 126.27 | 91.29 | 1.3 | 7.415 |       |        |       |
| <b>23</b> | 68.91 | 8.26  | 9.67  | 0.77 | 296.14 | 94.63 | 3.2 | 2.173 |       |        |       |
| <b>24</b> | 70.30 | 10.10 | 7.87  | 0.75 | 258.31 | 97.42 | 1.6 | 0.978 | 0.385 | -4.139 | 31.48 |
| <b>25</b> | 57.89 | 16.54 | 6.99  | 0.95 | 179.09 | 97.50 | 1.3 | 1.195 |       |        |       |
| <b>26</b> | 48.67 | 16.68 | 13.79 | 1.06 | 120.55 | 87.65 | 7.2 | 5.147 |       |        |       |
| <b>27</b> | 52.55 | 21.28 | 7.44  | 0.91 | 135.40 | 92.91 | 2   | 5.093 |       |        |       |
| <b>28</b> | 79.94 | 6.54  | 5.12  | 1.00 | 283.37 | 97.51 | 1.1 | 1.385 | 0.402 | -3.837 | 30.06 |
| <b>29</b> | 40.44 | 33.35 | 5.22  | 0.82 | 64.79  | 90.90 | 3.7 | 5.405 |       |        |       |
| <b>30</b> | 60.14 | 19.87 | 5.25  | 0.78 | 170.72 | 96.47 | 2.2 | 1.331 | 0.56  | -2.842 | 25.43 |
| <b>31</b> | 55.28 | 23.34 | 5.05  | 0.70 | 131.07 | 95.30 | 2.8 | 1.901 |       |        |       |
| <b>32</b> | 67.18 | 14.37 | 5.26  | 1.29 | 244.90 | 96.78 | 0.9 | 2.322 |       |        |       |
| <b>33</b> | 54.43 | 16.95 | 10.94 | 1.35 | 171.43 | 95.06 | 1   | 3.938 |       |        |       |
| <b>34</b> | 69.61 | 13.49 | 5.10  | 0.65 | 206.33 | 96.27 | 1.9 | 1.833 |       |        |       |
| <b>35</b> | 78.00 | 7.51  | 4.68  | 1.55 | 267.81 | 99.08 | 0.7 | 0.217 | 0.517 | -3.839 | 30.07 |

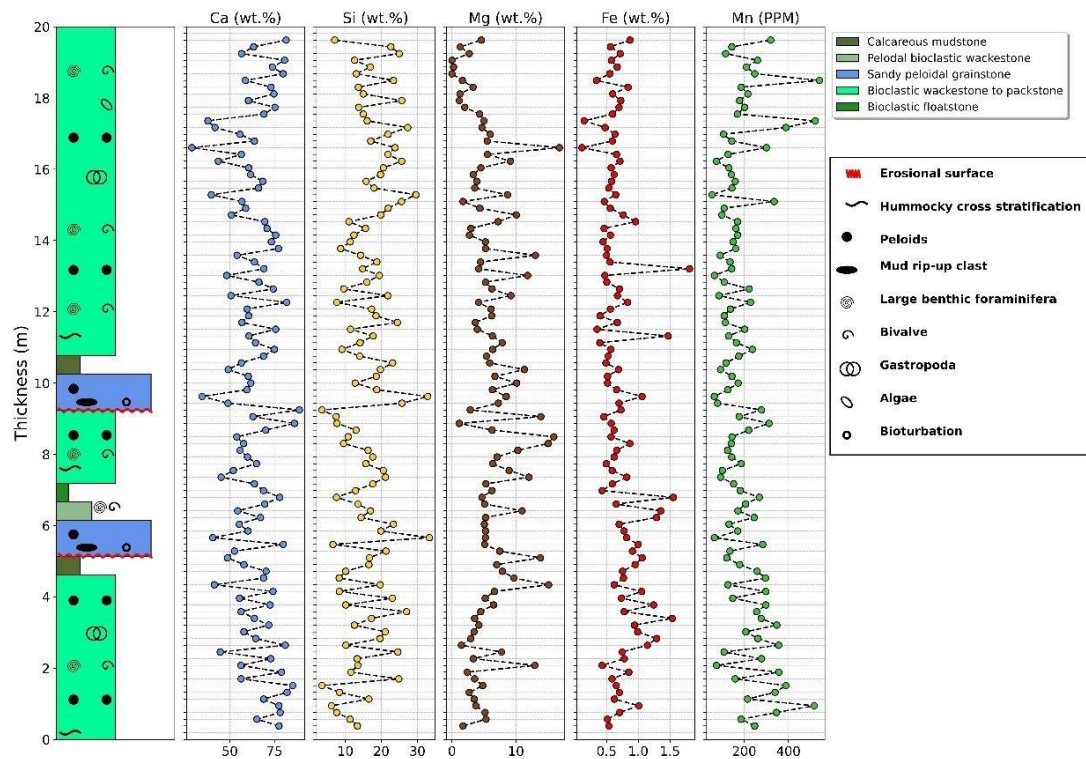
|    |       |       |       |      |        |       |     |       |       |        |       |
|----|-------|-------|-------|------|--------|-------|-----|-------|-------|--------|-------|
| 36 | 68.82 | 12.82 | 6.27  | 0.43 | 182.61 | 98.84 | 1   | 0.163 |       |        |       |
| 37 | 63.76 | 17.60 | 5.31  | 0.59 | 151.67 | 98.47 | 1.1 | 0.430 |       |        |       |
| 38 | 45.12 | 21.15 | 12.01 | 0.82 | 92.94  | 97.05 | 1.5 | 1.454 |       |        |       |
| 39 | 51.93 | 20.56 | 8.92  | 0.59 | 101.06 | 93.05 | 2.2 | 4.747 |       |        |       |
| 40 | 64.94 | 15.67 | 6.37  | 0.49 | 186.81 | 95.83 | 2.4 | 1.765 |       |        |       |
| 41 | 59.90 | 17.59 | 7.03  | 0.62 | 143.47 | 97.73 | 1.2 | 1.068 | 0.544 | -2.991 | 26.12 |
| 42 | 55.73 | 16.31 | 10.28 | 0.66 | 124.69 | 96.57 | 1.8 | 1.632 |       |        |       |
| 43 | 57.72 | 9.48  | 15.00 | 0.87 | 141.36 | 94.44 | 1.5 | 4.065 |       |        |       |
| 44 | 53.89 | 10.75 | 15.89 | 0.57 | 144.20 | 97.62 | 0.9 | 1.484 | 0.365 | -4.74  | 34.32 |
| 45 | 70.07 | 12.95 | 6.27  | 0.62 | 220.03 | 94.83 | 0.9 | 4.273 |       |        |       |
| 46 | 86.24 | 7.65  | 1.17  | 0.57 | 311.92 | 93.80 | 5.8 | 0.401 |       |        |       |
| 47 | 62.94 | 7.44  | 13.86 | 0.46 | 177.19 | 99.49 | 0.5 | 0.015 | 0.262 | -5.119 | 36.12 |
| 48 | 88.97 | 3.49  | 2.86  | 0.73 | 277.78 | 96.57 | 2.7 | 0.727 |       |        |       |
| 49 | 48.99 | 25.73 | 7.23  | 0.70 | 79.20  | 99.80 | 0.2 | 0.000 | 0.195 | -5.405 | 37.49 |
| 50 | 34.46 | 32.89 | 8.47  | 1.06 | 64.30  | 95.74 | 3   | 1.261 |       |        |       |
| 51 | 59.60 | 18.72 | 6.31  | 0.66 | 125.87 | 82.57 | 14  | 3.427 |       |        |       |
| 52 | 61.79 | 12.71 | 10.09 | 0.52 | 172.12 | 97.86 | 1.8 | 0.341 | 0.63  | -3.258 | 27.36 |
| 53 | 60.35 | 18.56 | 6.71  | 0.52 | 144.23 | 96.89 | 1.6 | 1.513 |       |        |       |

|    |       |       |       |      |        |       |     |       |       |        |       |
|----|-------|-------|-------|------|--------|-------|-----|-------|-------|--------|-------|
| 54 | 49.09 | 19.72 | 11.30 | 0.69 | 92.65  | 97.95 | 1.5 | 0.549 |       |        |       |
| 55 | 56.47 | 23.13 | 5.88  | 0.49 | 117.72 | 95.61 | 3   | 1.395 |       |        |       |
| 56 | 68.85 | 13.95 | 5.39  | 0.52 | 175.40 | 96.76 | 2.6 | 0.638 |       |        |       |
| 57 | 74.95 | 9.03  | 6.37  | 0.57 | 236.46 | 98.59 | 1.2 | 0.208 | 0.596 | -3.09  | 26.58 |
| 58 | 64.37 | 14.08 | 7.86  | 0.39 | 164.28 | 99.12 | 0.6 | 0.282 |       |        |       |
| 59 | 60.74 | 17.73 | 6.30  | 1.47 | 129.55 | 97.56 | 1.7 | 0.742 |       |        |       |
| 60 | 75.67 | 11.43 | 3.96  | 0.35 | 201.82 | 98.67 | 1.2 | 0.134 |       |        |       |
| 61 | 56.81 | 24.46 | 3.65  | 0.67 | 113.97 | 98.97 | 0.9 | 0.134 | 0.632 | -2.998 | 26.15 |
| 62 | 60.55 | 18.49 | 6.21  | 0.40 | 109.94 | 96.28 | 3.3 | 0.415 |       |        |       |
| 63 | 59.73 | 17.27 | 6.11  | 0.56 | 137.56 | 97.92 | 1.9 | 0.178 |       |        |       |
| 64 | 81.91 | 7.60  | 4.15  | 0.83 | 228.64 | 97.48 | 2   | 0.519 |       |        |       |
| 65 | 50.64 | 21.77 | 9.19  | 0.67 | 85.76  | 96.20 | 3.8 | 0.000 | 0.252 | -4.961 | 35.37 |
| 66 | 74.35 | 9.53  | 6.26  | 0.70 | 221.77 | 94.92 | 2.9 | 2.181 |       |        |       |
| 67 | 66.27 | 15.96 | 5.25  | 0.50 | 109.80 | 98.85 | 0.6 | 0.549 |       |        |       |
| 68 | 48.23 | 19.46 | 11.79 | 0.47 | 65.11  | 96.10 | 1.9 | 2.003 |       |        |       |
| 69 | 69.10 | 14.78 | 4.20  | 1.80 | 143.11 | 98.00 | 1.6 | 0.401 | 0.522 | -3.444 | 28.22 |
| 70 | 63.77 | 18.74 | 4.48  | 0.55 | 135.85 | 96.19 | 2.3 | 1.513 |       |        |       |
| 71 | 54.05 | 14.21 | 13.01 | 0.50 | 90.94  | 98.02 | 1.8 | 0.178 | 0.566 | -3.497 | 28.47 |

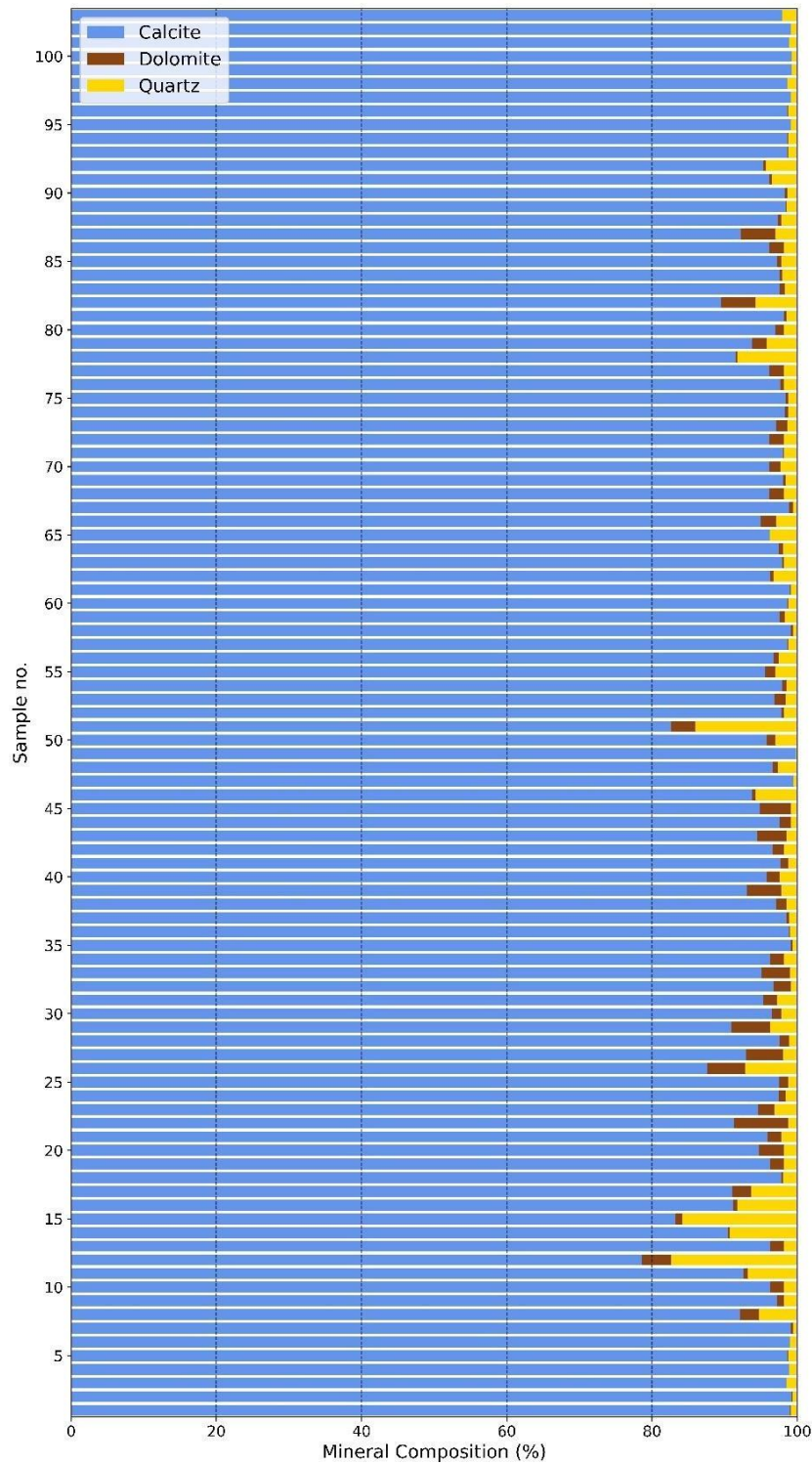
|           |       |       |       |      |        |       |     |       |       |        |       |
|-----------|-------|-------|-------|------|--------|-------|-----|-------|-------|--------|-------|
| <b>72</b> | 77.26 | 8.68  | 5.25  | 0.51 | 161.96 | 96.10 | 1.9 | 2.003 |       |        |       |
| <b>73</b> | 73.22 | 11.35 | 5.22  | 0.44 | 149.58 | 97.07 | 1.4 | 1.528 |       |        |       |
| <b>74</b> | 75.68 | 12.37 | 2.73  | 0.56 | 170.22 | 98.33 | 1.3 | 0.371 |       |        |       |
| <b>75</b> | 70.83 | 15.58 | 2.97  | 0.46 | 162.39 | 98.37 | 1.2 | 0.430 |       |        |       |
| <b>76</b> | 69.60 | 10.97 | 7.20  | 0.96 | 169.99 | 97.63 | 1.9 | 0.475 |       |        |       |
| <b>77</b> | 50.88 | 19.81 | 10.04 | 0.76 | 99.17  | 96.10 | 1.9 | 2.003 |       |        |       |
| <b>78</b> | 58.88 | 21.90 | 4.36  | 0.56 | 108.56 | 91.55 | 8.3 | 0.148 |       |        |       |
| <b>79</b> | 56.83 | 25.61 | 1.73  | 0.46 | 334.99 | 93.77 | 4.2 | 2.032 |       |        |       |
| <b>80</b> | 39.63 | 29.58 | 8.68  | 0.64 | 54.01  | 96.97 | 1.9 | 1.127 |       |        |       |
| <b>81</b> | 66.06 | 17.97 | 3.56  | 0.54 | 144.36 | 98.16 | 1.5 | 0.341 | 0.76  | -2.617 | 24.39 |
| <b>82</b> | 68.44 | 15.78 | 3.88  | 0.58 | 159.28 | 89.48 | 5.8 | 4.718 |       |        |       |
| <b>83</b> | 61.69 | 19.76 | 3.32  | 0.62 | 142.12 | 97.59 | 1.7 | 0.712 | 0.709 | -2.724 | 24.88 |
| <b>84</b> | 60.55 | 20.55 | 4.52  | 0.57 | 130.63 | 97.54 | 2.1 | 0.356 |       |        |       |
| <b>85</b> | 43.50 | 25.65 | 9.12  | 0.71 | 74.23  | 97.24 | 2.2 | 0.564 |       |        |       |
| <b>86</b> | 56.46 | 21.83 | 5.53  | 0.66 | 126.87 | 96.10 | 1.9 | 2.003 |       |        |       |
| <b>87</b> | 28.74 | 23.79 | 16.76 | 0.11 | 300.12 | 92.18 | 3   | 4.821 |       |        |       |
| <b>88</b> | 63.75 | 17.03 | 5.51  | 0.59 | 143.62 | 97.34 | 2.2 | 0.460 |       |        |       |
| <b>89</b> | 55.71 | 21.86 | 5.98  | 0.63 | 106.54 | 98.37 | 1.5 | 0.134 | 0.682 | -2.47  | 23.71 |

|            |       |       |      |      |        |       |     |       |       |        |       |
|------------|-------|-------|------|------|--------|-------|-----|-------|-------|--------|-------|
| <b>90</b>  | 41.68 | 27.32 | 4.68 | 0.48 | 388.69 | 98.32 | 1.4 | 0.282 |       |        |       |
| <b>91</b>  | 37.73 | 16.06 | 5.01 | 0.15 | 521.02 | 96.14 | 3.5 | 0.356 |       |        |       |
| <b>92</b>  | 69.08 | 14.99 | 4.33 | 0.59 | 168.85 | 95.34 | 4.3 | 0.356 |       |        |       |
| <b>93</b>  | 75.26 | 13.68 | 2.01 | 0.70 | 201.54 | 98.66 | 1.3 | 0.045 | 0.557 | -2.995 | 26.13 |
| <b>94</b>  | 60.42 | 25.69 | 1.16 | 0.72 | 178.89 | 98.64 | 1.3 | 0.059 |       |        |       |
| <b>95</b>  | 74.66 | 15.01 | 1.25 | 0.60 | 216.28 | 99.09 | 0.9 | 0.015 |       |        |       |
| <b>96</b>  | 73.08 | 13.62 | 3.29 | 0.84 | 186.06 | 98.69 | 1.3 | 0.015 |       |        |       |
| <b>97</b>  | 58.72 | 23.36 | 1.65 | 0.34 | 540.15 | 99.10 | 0.9 | 0.000 |       |        |       |
| <b>98</b>  | 79.86 | 13.03 | 0.01 | 0.55 | 247.39 | 98.59 | 1.4 | 0.015 |       |        |       |
| <b>99</b>  | 73.86 | 16.93 | 0.27 | 0.67 | 209.40 | 99.20 | 0.8 | 0.000 | 0.713 | -3.071 | 26.49 |
| <b>100</b> | 80.68 | 12.55 | 0.01 | 0.58 | 259.87 | 99.20 | 0.8 | 0.000 |       |        |       |
| <b>101</b> | 56.55 | 24.94 | 2.72 | 0.72 | 115.56 | 98.90 | 1.1 | 0.000 |       |        |       |
| <b>102</b> | 63.30 | 22.63 | 1.29 | 0.56 | 143.57 | 99.10 | 0.9 | 0.000 |       |        |       |
| <b>103</b> | 81.56 | 7.02  | 4.60 | 0.87 | 319.42 | 97.90 | 2.1 | 0.000 |       |        |       |

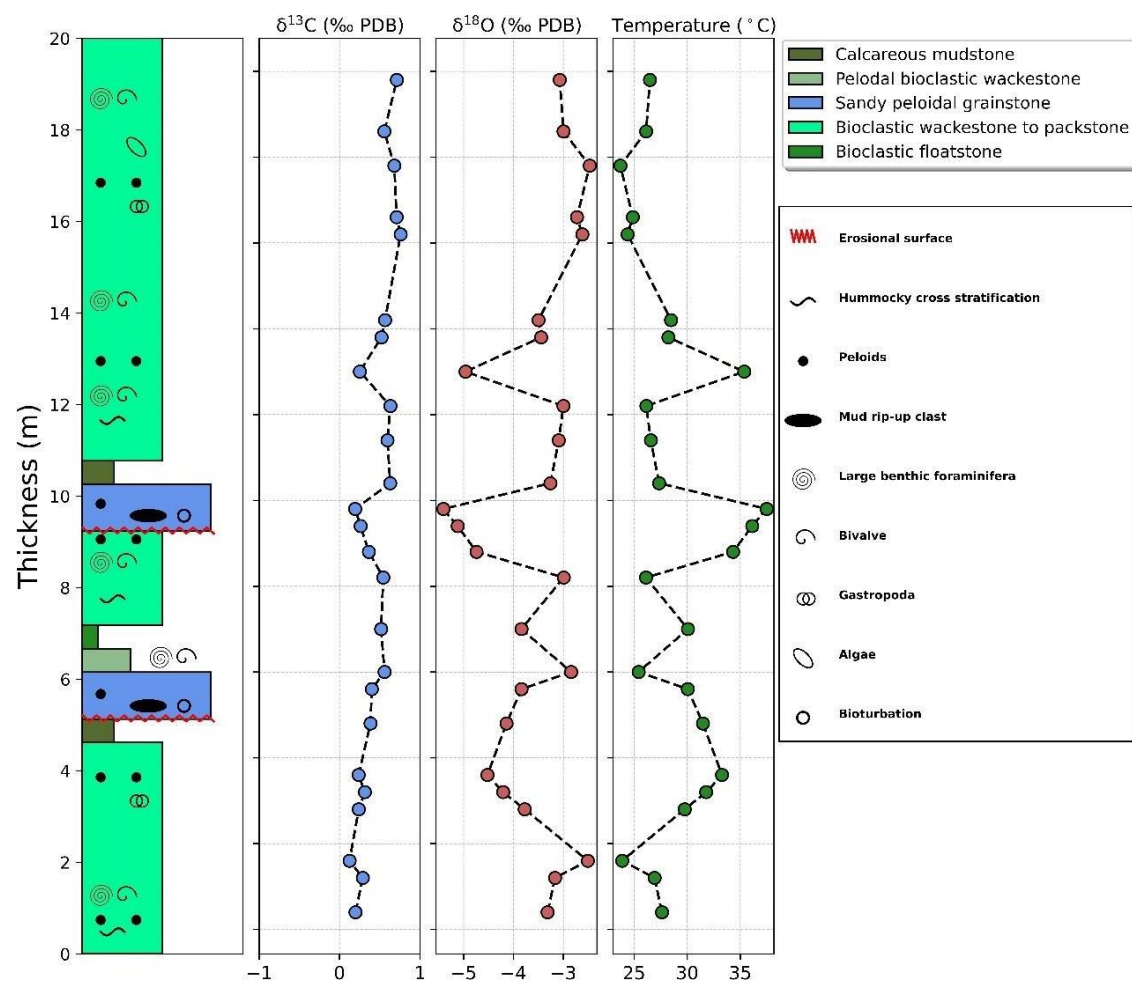
**Table 1.** Results of geochemical analyses of the studied samples.



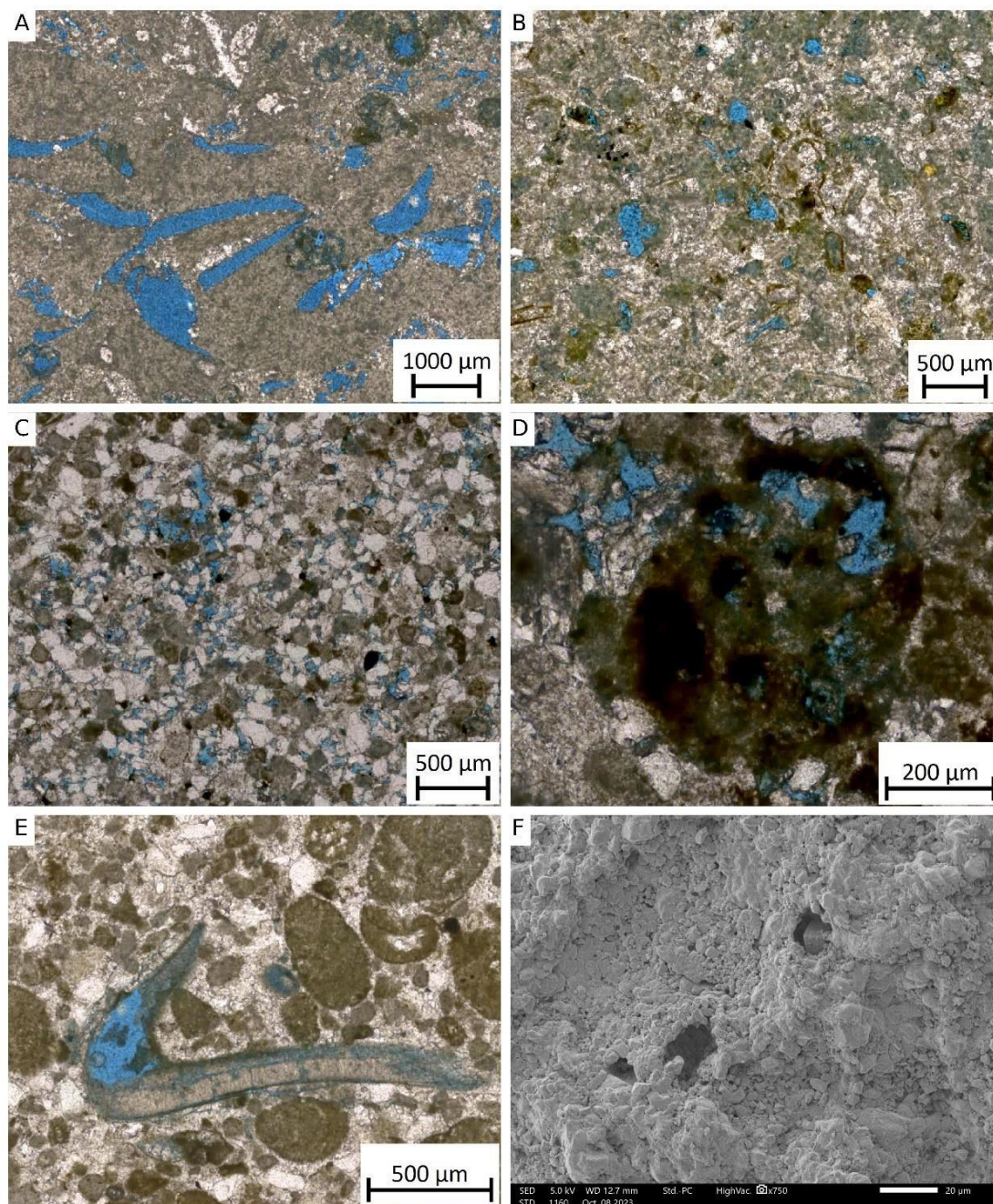
**Figure 6.** The elemental composition of the studied samples corresponds to the sedimentary log.



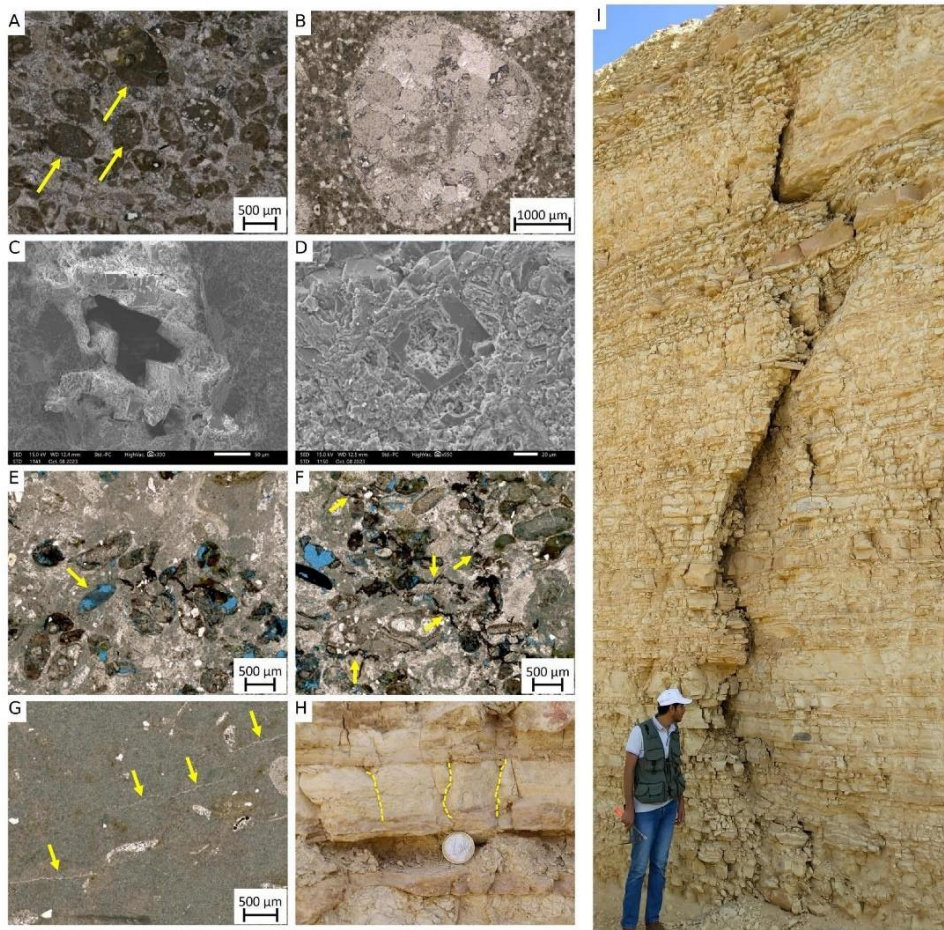
**Figure 7.** The mineral composition of the studied samples, where each horizontal bar represents one study sample.



**Figure 8.** The stable carbon and oxygen isotope analyses and the calculated paleotemperature of the studied samples correspond to the sedimentary log.



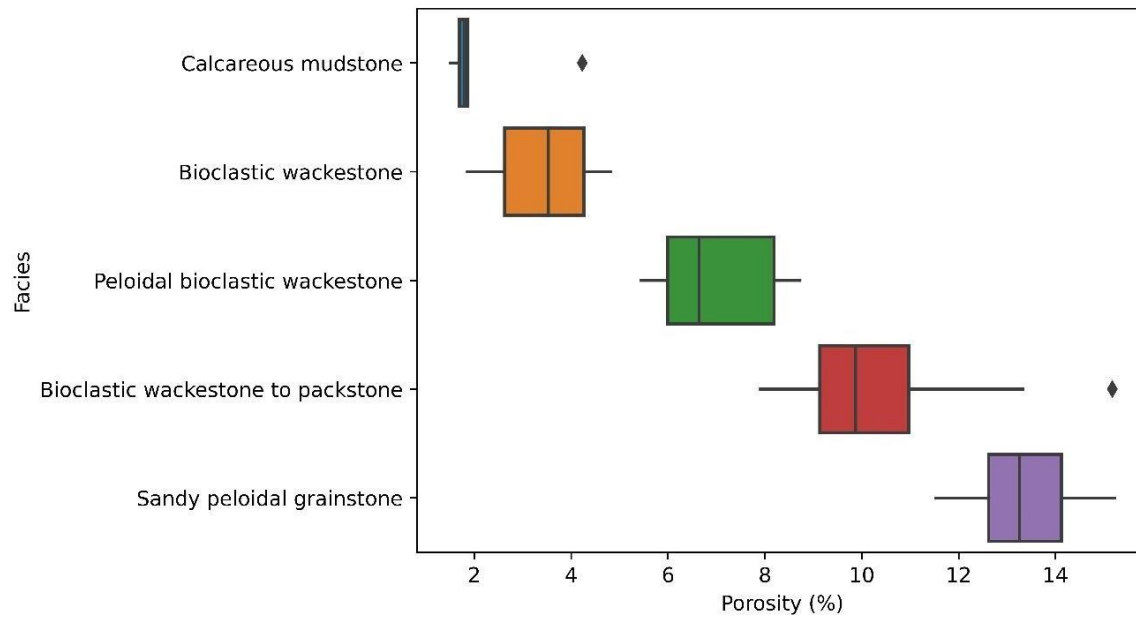
**Figure 9.** Petrographic images of selected samples impregnated with blue resin in plane polarized light and SEM. (A) & (B) Moldic porosity. (C) Interparticle porosity. (D) Intraparticle porosity. (E) Dissolution porosity. (F) Microscopic porosity.



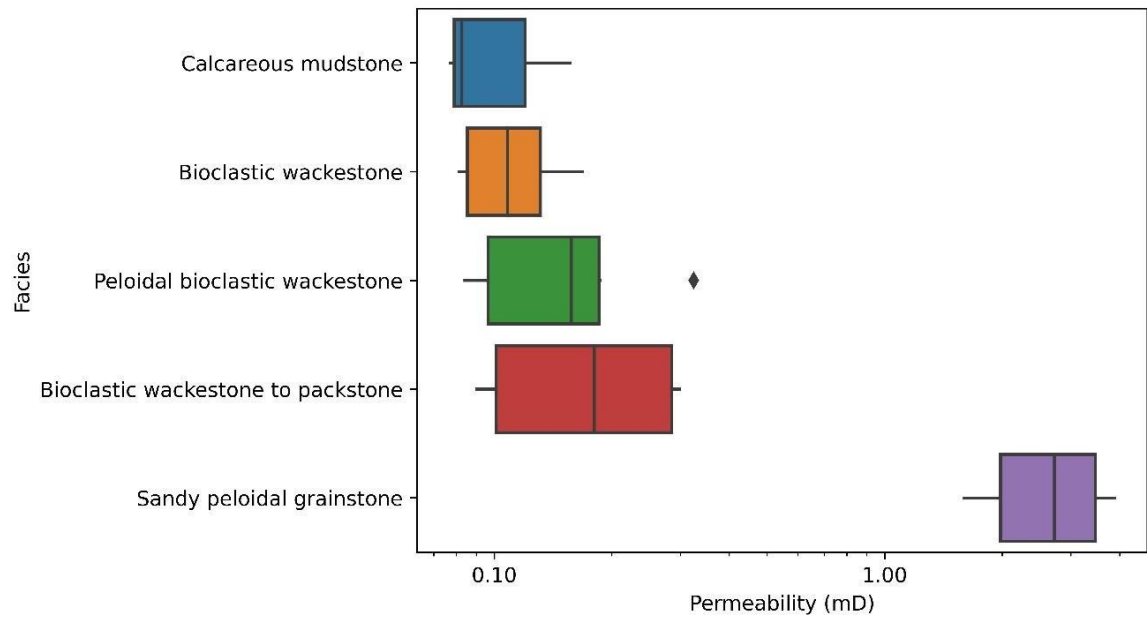
**Figure 10.** Photomicrographs of diagenetic processes. (A) Micritized bioclasts annotated by yellow arrows. (B) Blocky calcite cement. (C) Rhombohedral dolomite crystal surrounding micropore space. (D) Uncomplete rhombohedral dolomite crystal. (E) Partially dissolved bioclasts. (F) Compaction dissolution stylolites represented by yellow arrows. (G) Microscale cemented fractures annotated by yellow arrows. (H) Centimeter-scale fractures. (I) Outcrop scale fracture.

**Table 2.** The porosity and permeability values for the measured core plugs.

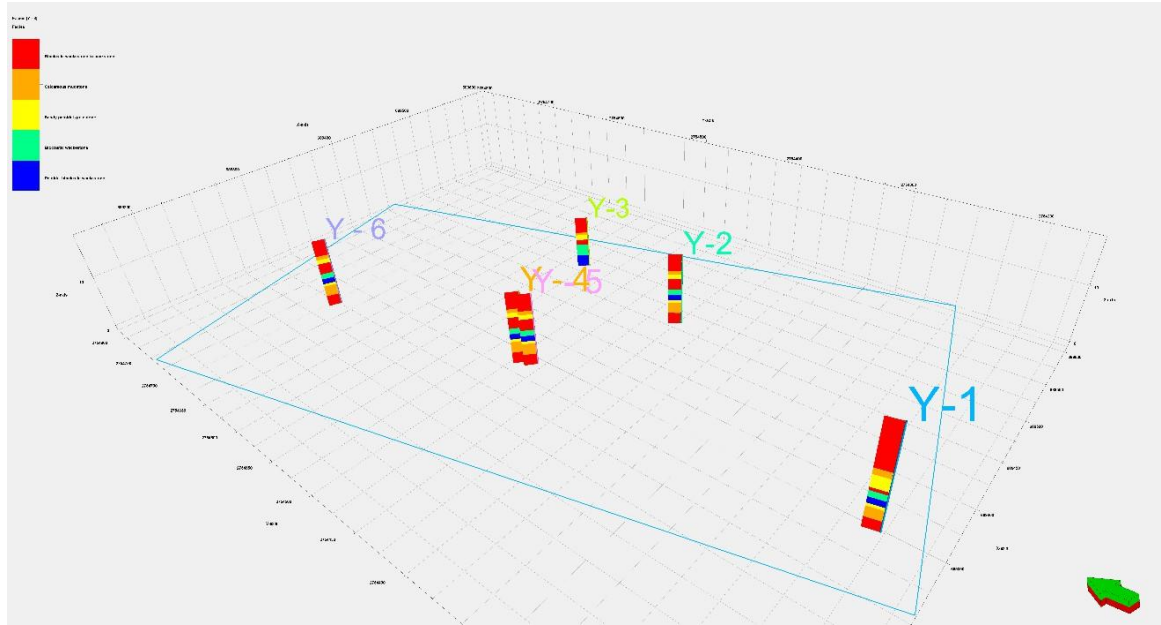
| <b>Facies</b>                      | <b>Porosity</b> | <b>Permeability</b> |
|------------------------------------|-----------------|---------------------|
| Bioclastic floatstone              | 4.23            | 0.08                |
| Bioclastic floatstone              | 3.53            | 0.12                |
| Bioclastic floatstone              | 2.89            | 0.09                |
| Bioclastic floatstone              | 4.81            | 0.08                |
| Bioclastic floatstone              | 4.30            | 0.17                |
| Bioclastic floatstone              | 2.36            | 0.15                |
| Bioclastic floatstone              | 1.86            | 0.11                |
| Bioclastic wackestone to packstone | 7.91            | 0.30                |
| Bioclastic wackestone to packstone | 15.17           | 0.28                |
| Bioclastic wackestone to packstone | 7.91            | 0.11                |
| Bioclastic wackestone to packstone | 11.27           | 0.27                |
| Bioclastic wackestone to packstone | 9.68            | 0.10                |
| Bioclastic wackestone to packstone | 10.17           | 0.13                |
| Bioclastic wackestone to packstone | 13.32           | 0.29                |
| Bioclastic wackestone to packstone | 9.54            | 0.10                |
| Bioclastic wackestone to packstone | 10.87           | 0.23                |
| Bioclastic wackestone to packstone | 9.60            | 0.10                |
| Bioclastic wackestone to packstone | 7.91            | 0.30                |
| Bioclastic wackestone to packstone | 10.06           | 0.09                |
| Calcareous mudstone                | 4.23            | 0.08                |
| Calcareous mudstone                | 1.51            | 0.08                |
| Calcareous mudstone                | 1.80            | 0.08                |
| Calcareous mudstone                | 1.87            | 0.12                |
| Calcareous mudstone                | 1.69            | 0.16                |
| Peloidal bioclastic wackestone     | 8.72            | 0.13                |
| Peloidal bioclastic wackestone     | 8.68            | 0.18                |
| Peloidal bioclastic wackestone     | 6.72            | 0.08                |
| Peloidal bioclastic wackestone     | 5.45            | 0.19                |
| Peloidal bioclastic wackestone     | 6.56            | 0.08                |
| Peloidal bioclastic wackestone     | 5.80            | 0.32                |
| Sandy peloidal grainstone          | 15.21           | 3.87                |
| Sandy peloidal grainstone          | 12.78           | 1.60                |
| Sandy peloidal grainstone          | 11.53           | 2.22                |
| Sandy peloidal grainstone          | 14.25           | 3.54                |
| Sandy peloidal grainstone          | 12.56           | 1.90                |
| Sandy peloidal grainstone          | 13.73           | 3.22                |



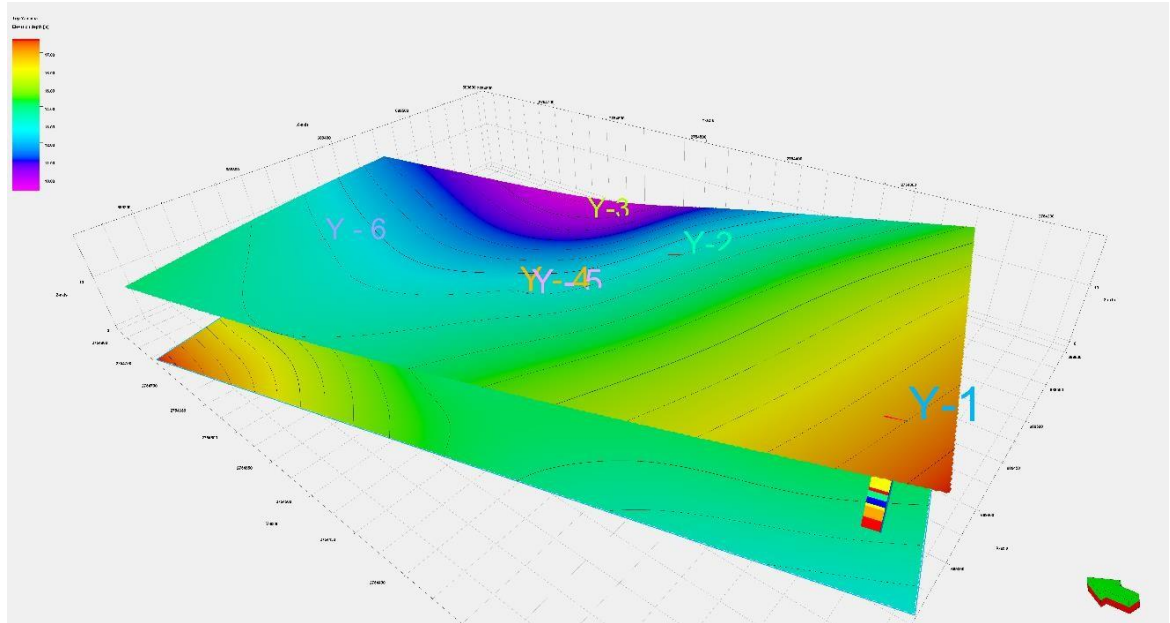
**Figure 11.** Statistical distribution of the porosity values for each facies in the study area.



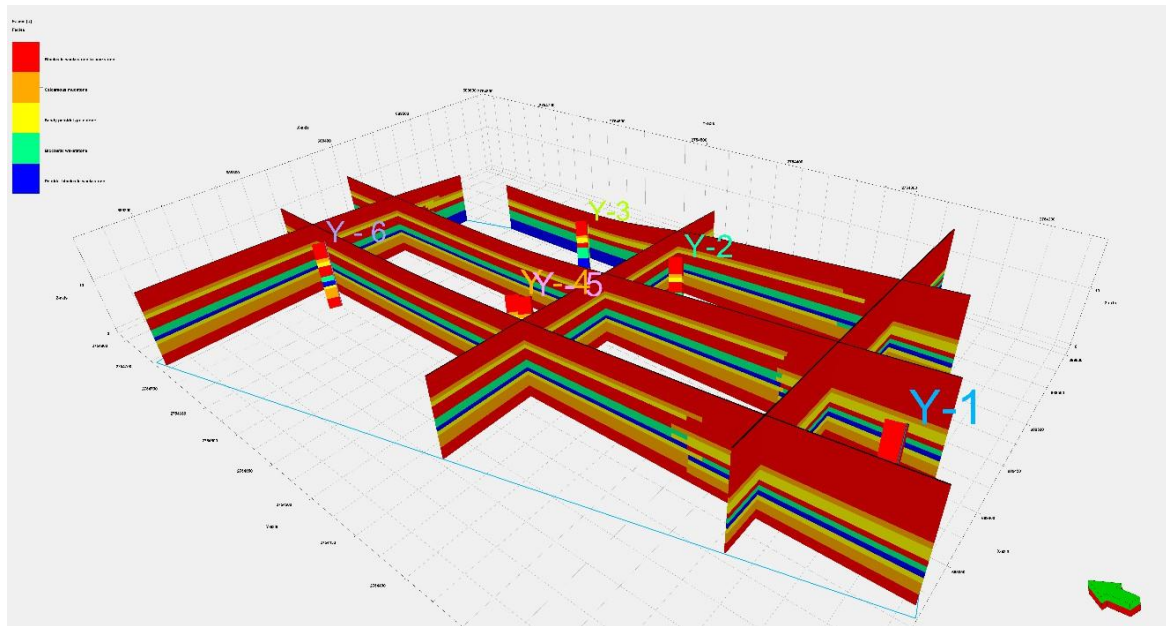
**Figure 12.** Statistical distribution of the permeability values for each facies in the study area.



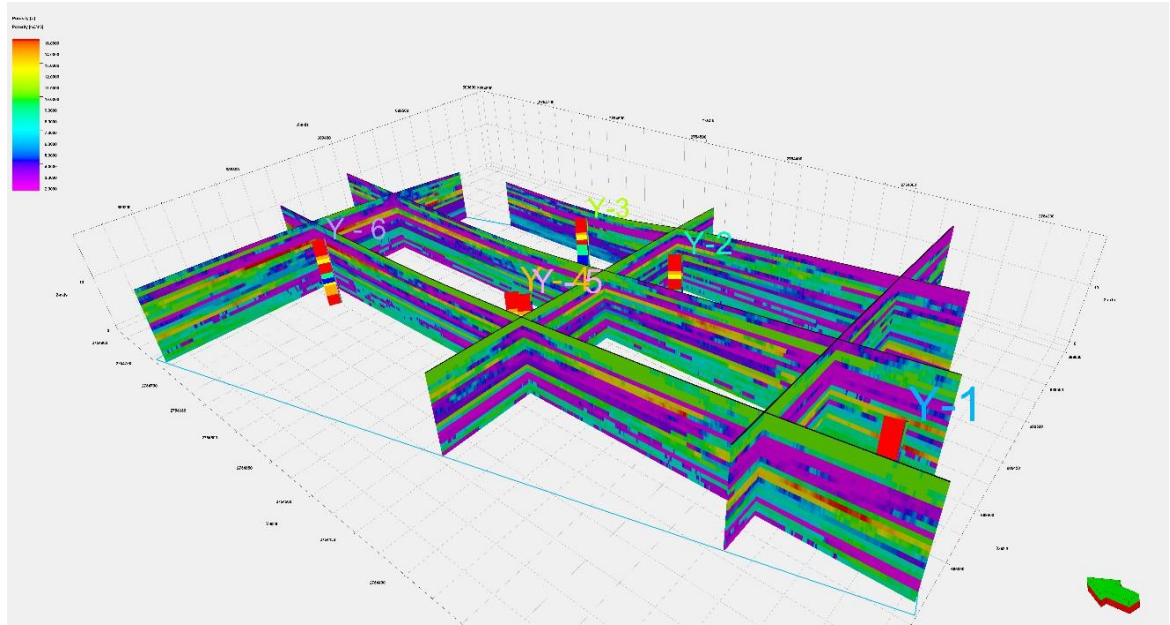
**Figure 13.** Pseudo logs represent the different outcrops in the study area, and colors reflect different microfacies.



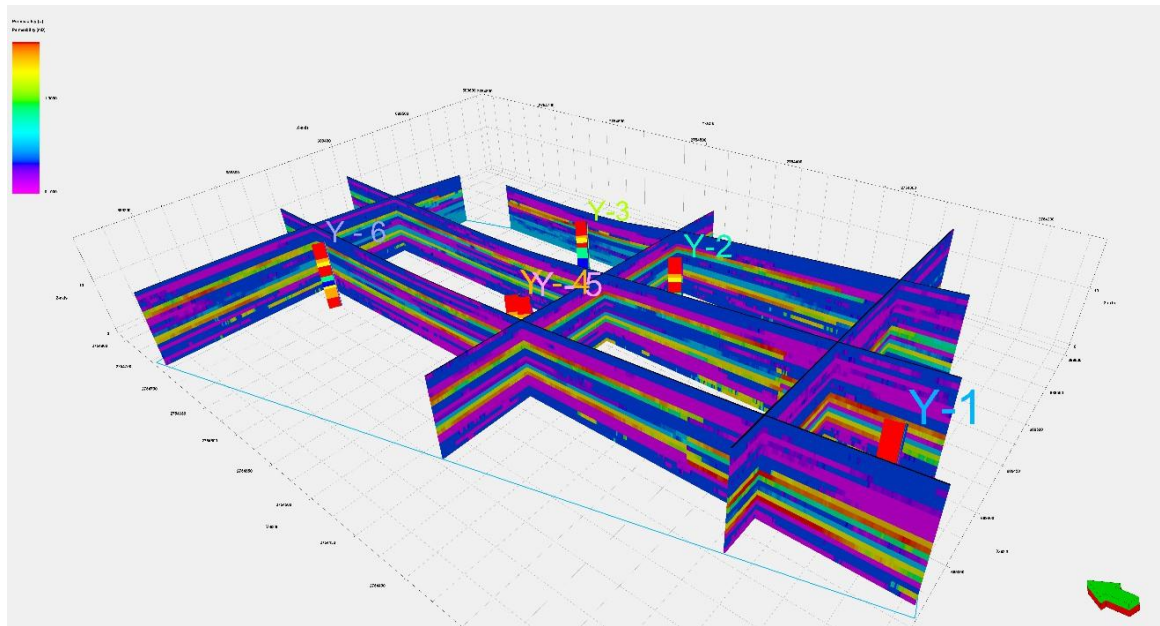
**Figure 14.** The top and bottom layers of the 3D geological model for the study area are colored to reflect elevation.



**Figure 15.** Facies distribution of the 3D geological model for the study, and colors reflect different microfacies.



**Figure 16.** Porosity distribution model in the study area. Different colors refer to various porosity values.



**Figure 17.** Permeability distribution model in the study area. Different colors refer to various porosity values.

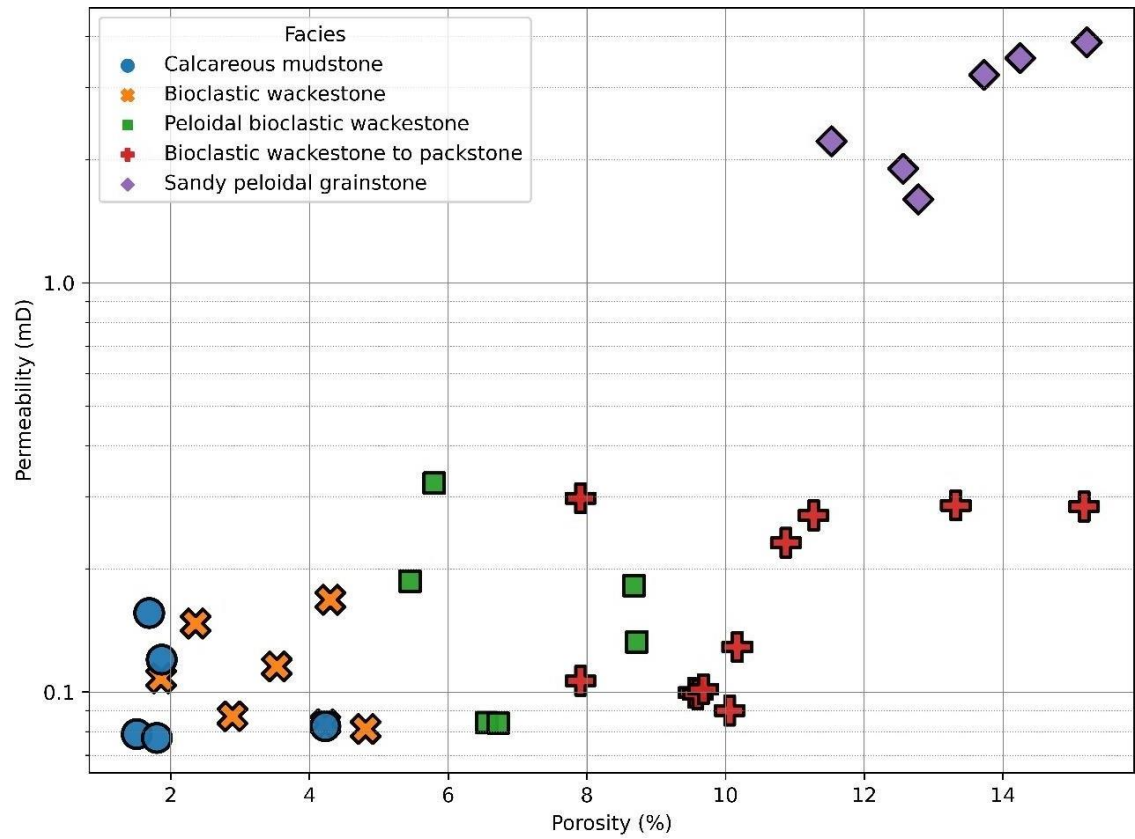
## **CHAPTER 4**

### **Discussion**

#### **4.1 The impact of depositional settings on reservoir quality**

Understanding the impact of paleoenvironmental settings on the quality of reservoirs in the studied outcrops can be determined by analyzing the relationship between the types of sedimentary facies and the properties of the reservoirs (Figure 18). Analysis of the petrophysical parameters of different facies types reveals significant differences in porosity and permeability. These variations in the petrophysical parameters were influenced by both depositional settings and other parameters such as sorting and grain size. The microfacies of calcareous mudstone and bioclastic floatstone exhibit the lowest reservoir quality, likely due to their predominant composition of micrite matrix with limited interconnectivity. Both microfacies were deposited in low-energy conditions, resulting in low reservoir quality (Makeen et al., 2021). It is worth noting that the bioclastic floatstone microfacies show slightly higher reservoir quality compared to the calcareous mudstone microfacies. This difference in porosity and permeability arises due to the presence of bioclastic grains in the bioclastic floatstone microfacies. The peloidal bioclastic wackestone microfacies exhibits a relatively higher reservoir quality compared to the preceding microfacies. However, it is still classified as having low reservoir quality, which can be attributed to an increase in micrite content. Although this facies was deposited in high-energy conditions, the poor sorting of particles significantly reduces the interconnectivity between pores, further contributing to the reduced reservoir quality of this microfacies. The microfacies of

bioclastic wackestone to packstone displays an increase in porosity measurement, but there is a minimal increase in permeability. The increase in porosity can be attributed to dissolution processes, as these facies exhibit favorable moldic porosity types when observed under a microscope. However, it is important to note that despite the increase in porosity, this facies still has low reservoir quality as it was deposited under low-energy conditions. The sandy peloidal grainstone microfacies exhibits a substantial improvement in reservoir quality. This improvement can be attributed to the deposition of this facies under high-energy conditions, leading to a minimal presence of micritic matrix and well-connected interparticle pore spaces.



**Figure 18.** Porosity–permeability relationships for the studied samples.

## **4.2 The impact of diagenetic processes on reservoir quality**

The studied carbonates of the early Cretaceous underwent various diagenetic processes, including micritization, cementation, dolomitization, dissolution, compaction, and fracturing. These diagenetic aspects interpreted in the carbonates represent early, intermediate, and late changes that took place in different diagenetic environments. Diagenetic processes have significant control over reservoir quality, and the above processes have greatly influenced the reservoir quality of early Cretaceous carbonates (Lucia et al., 2003; Moore, 2001).

### **4.2.1 Diagenetic processes**

#### **Micritization**

It refers to the alteration of initial allochems to cryptocrystalline carbonate (micrite) by endolithic algae (Bathurst, 1966; Longman, 1980). This alteration could create peloids, micrite mud, and diagenetic pellets (R. G. C. Bathurst, 1966; Flügel & Munnecke, 2010b; M'Rabet, 1987). Micritization has been observed in the skeletal fabric of the packstone and wackestone facies, as well as in the non-skeletal allochems (peloids) of the sandy peloidal grainstone facies in the studied carbonates. Micritization occurs inside these microfacies in the form of a micritic envelope surrounding the peripheries of bioclasts or fully micritized bioclastics. The process of micritization indicates an early stage of diagenesis (Bathurst, 1972), and it has a negative impact on the reservoir quality.

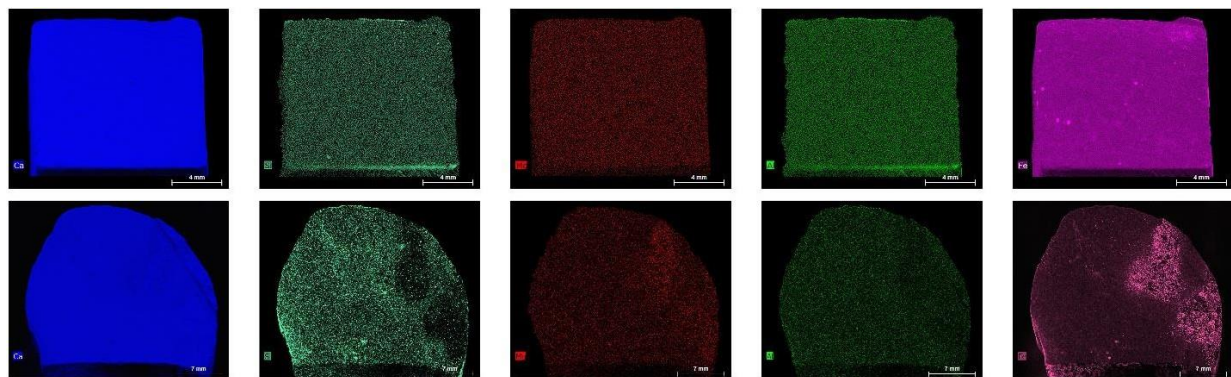
#### **Cementation (Blocky)**

Blocky cement is made up of fine- to coarse-grained crystals that formed in the studied samples. The blocky cement in the studied carbonates generally occurs as pore filling in

the intergranular spaces between bioclasts and peloids, as well as the intragranular pores of the internal cavities of the bioclasts and as fracture filling. The low  $Mg^{2+}$  concentration found in meteoric water favors the precipitation of this type of cement, which is mostly generated in meteoric phreatic diagenetic meteoric environments (Choquette & James, 1987; Flügel & Munnecke, 2010b; Tucker, 2001). In the current study, dissolution features are associated with pore blocky cement, which is interpreted to indicate middle stage burial diagenesis (Bathurst, 1976). The cementation process has a negative impact on reservoir quality as it reduces porosity and prevents permeability.

#### Dolomitization

Dolomite is formed when calcite ions are replaced by magnesium ions (Mehmood et al., 2018). The analysis of the studied samples indicates a limited impact of dolomite on diagenetic processes, as the percentage of dolomite was found to be relatively low. Microscopic examination did not reveal the presence of dolomite crystals; however, through the utilization of XRF elemental mapping to identify regions with elevated concentrations of Mg and Fe (Figure 19), followed by SEM analysis of those specific areas, we successfully detected the presence of dolomite crystals. The diagenetic process of dolomitization is an indicator of the early to middle stage of diagenesis (Machel, 2005). The process of micritization does not have a high effect on the reservoir quality.



**Figure 19.** XRF elemental mapping of two samples. The brighter the color, the higher the elemental concentration.

## Dissolution

The solubility of minerals is the most important controlling factor in the dissolution process (Moore, 2001). Dissolution takes place in undersaturated fluids with respect to calcite minerals (Tucker & Wright, 2009). The dissolution is mostly facilitated by aragonite and high magnesium calcite, both of which are unstable minerals (McIlreath & Morrow, 1990). The examined samples exhibit a notable enrichment of Mg and a relatively low proportion of dolomite mineral. This observation suggests a prevalence of high-Mg calcite minerals, which are prone to dissolution under prevailing conditions. Bioclastics such as benthic foraminifera and bivalves are the most vulnerable to dissolution, according to their mineral composition, creating moldic porosity. Dissolution is common in the middle to late stages of diagenesis (Machel, 2005). The process of dissolution affected most of the depositional facies, but it has a great impact in the bioclastic wackestone to packstone facies, where dissolution enhanced the porosity of the facies, but it did not contribute significantly to enhancing the interconnectivity between pore spaces.

## Compaction

Mechanical and chemical activities lower the bulk volume of rocks, resulting in the compaction-diagenetic process. Carbonates with very high initial porosity are prone to a considerable porosity decrease during and after mechanical compaction. Chemical compaction occurs due to pressure solution, which is induced by the application of load or tectonic stress at the grain contacts. This stress leads to an increase in the solubility of minerals. Furthermore, the presence of bioclasts within the carbonate matrix can have varying effects on carbonate solubility, depending on the specific clay types and their

composition. The initiation and progression of pressure solutions are influenced by multiple factors, including burial depth, pore water composition, mineralogy, and the presence or absence of organic matter, including oil and gas in the pore spaces (Fabricius et al., 2000). Microscopic analysis revealed the existence of stylolites, but macroscopic examination of the outcrops did not yield any evidence of stylolites. The occurrence of stylolites suggests the presence of a middle stage of diagenesis, typically associated with burial processes (Choquette et al., 1990; Ricken, 1987). The process of stylolites has a negative impact on the reservoir quality.

### Fracturing

Fractures in carbonate reservoirs enhance permeability by creating additional pathways for fluid flow, bypassing low-permeability rock. This increased connectivity improves production efficiency and allows for the extraction of hydrocarbon resources (Wennberg et al., 2016). Fracturing patterns were observed and documented on the studied outcrops across three distinct scales. On the meter scale, long vertical fractures were identified, spanning the entire outcrop, and aiding in the development of karstification processes. On the centimeter scale, fractures were found to be localized in specific areas, influenced by the mechanical and stratigraphic properties of the layers. The propagation of these fractures ceased when encountering layers that exhibited increased ductility or hardness. Lastly, on the micrometer scale, fractures were found to be cemented by calcite minerals. The occurrence of fractures suggests the presence of middle- to late- stage of diagenesis, typically associated with burial processes (Machel, 2005). Open fractures have a positive impact on the reservoir quality.

#### **4.2.2 Paragenetic sequence**

The sequence of diagenetic events within a carbonate system is influenced by several factors, including the sediment composition, grain size, texture, mineralogy, pore fluid characteristics, and climate. Based on petrographic characteristics and geochemical analysis, diagenetic processes have been identified to occur in three distinct environments (Flügel & Munnecke, 2010a; Tucker, 1993; Tucker & Wright, 2009). During the early diagenetic stage, processes occur in both marine and meteoric phreatic environments. Marine diagenetic environments are characterized by the presence of first-generation cement and micritization. In meteoric phreatic environments, dissolution processes take place, leading to the development of intraparticle and moldic porosity. In addition to the aforementioned processes, dolomitization also plays a minor role in the early diagenetic stage. During the burial diagenetic stage, the early Cretaceous carbonates in deeper and higher temperature areas experienced distinct processes compared to the marine diagenetic stage. At this stage, diagenetic processes included cementation, physical and chemical compaction (evidenced by stylolites and increased grain contacts), dissolution, and fracturing. During the late diagenetic stage, which occurred after the closure of the Neo-Tethys Sea and the uplift of the Oman and Zagros mountains in the Late Cretaceous (first Alpine orogeny) (Al-Mahmoud et al., 2009), the early Cretaceous carbonate rocks were subjected to specific processes. Among these processes, dissolution and fracturing played crucial roles in creating secondary porosity within this interval (Figure 20).

| Diagenetic Process                        | Early     |          | Middle<br>(Burial) | Late<br>(Uplift) | Reservoir Quality |
|-------------------------------------------|-----------|----------|--------------------|------------------|-------------------|
|                                           | Marine    | Meteoric |                    |                  |                   |
| Micritization                             | —         |          |                    |                  | ↓                 |
| Cementation (Blocky Cement)               | · · · · · | —        | —                  |                  | ↓                 |
| Dolomitization                            | —         |          |                    |                  | ?                 |
| Dissolution                               |           | —        | · · · · ·          | —                | ↑                 |
| Compaction (Stylolites)                   |           |          | —                  |                  | ↓                 |
| Fracturing                                |           |          | —                  | —                | ↑                 |
| ↑ Enhance Porosity      ↓ Reduce Porosity |           |          |                    |                  |                   |

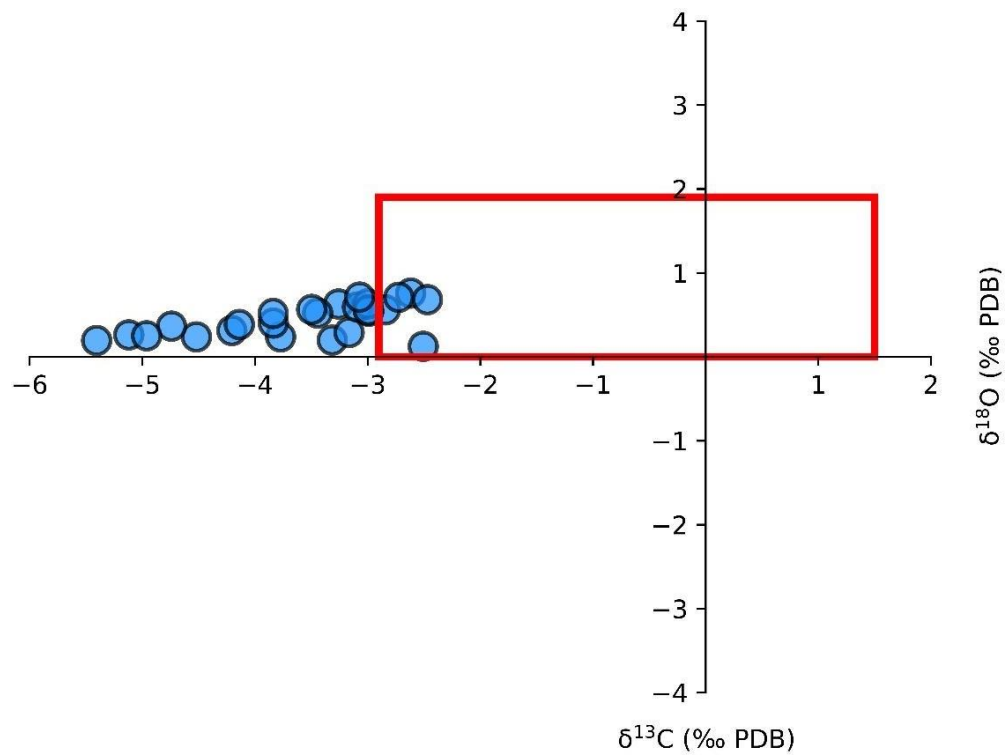
**Figure 20.** Paragenetic sequence of the study area.

### 4.3 The origin of diagenesis

The concentration of Fe and Mn in the study samples reflects the meteorological diagenetic processes (Mahboubi et al., 2002). The low concentration of Fe and Mn indicates that the outcrop was not subjected to meteoric diagenesis for a long time before burial. The relatively high Fe concentration is associated with the facies with high porosity and permeability values, where the fluids rich in Fe can move and precipitate. It is important to highlight that only the reduced forms of  $\text{Fe}^{+2}$  and  $\text{Mn}^{+2}$  are incorporated into carbonate minerals. Hence, if the concentrations of Fe and Mn rise, it indicates that the carbonates were formed in an environment with reduced conditions (Froelich et al., 1979; Oglesby, 1976).

Oxygen and carbon Stable isotope measurements have become an essential component of most current carbonate research. The Valanginian carbonates' stable isotope geochemical investigation has been done to interpret their paleotemperature and unravel the diagenetic processes. Oxygen isotopes are more sensitive to diagenesis than carbon isotopes. This is due to the temperature-dependent fractionation of oxygen isotopes. In marine carbonates, diagenesis frequently leads to greater negative  $\delta^{18}\text{O}$  values. This is a result of cementation and recrystallization that occur in fluids that are low in  $\delta^{18}\text{O}$  compared to sea water or at high temperatures (Morse & Mackenzie, 1990). The palaeotemperature inferred from oxygen isotope ratios of early Valanginian carbonates ranges from 23.7°C to 37.49°C, which indicates early-stage diagenesis of shallow burial. The data are presented in a bivariate plot of  $\delta^{18}\text{O}$  against  $\delta^{13}\text{C}$ , which was first proposed by (Hudson, 1977) and then updated by (Nelson & Smith, 1996). They identified separate isotopic fields for carbonates of diverse sources. In this bivariate plot, almost all the whole rock samples fall out of the

red box (Figure 21), which represents the original carbon and oxygen isotopic values of the early Cretaceous (Veizer & Prokoph, 2015). The carbon isotopic ratios of the samples are falling in the same range as the original ratios of the carbon isotopes of the pristine early Cretaceous carbonates. This suggests minimal diagenetic alteration of the study samples by meteoric fluids (Price & Mutterlose, 2004). Regarding the oxygen isotopic ratios studied, almost all samples fall outside the range of the original oxygen isotopic value, moving towards more negative  $\delta^{18}\text{O}$  values. The small difference between the original oxygen isotopic values and those of the studied samples suggests that these samples went through an early stage of shallow burial diagenesis (Ahm et al., 2018). According to the equation by (Keith & Weber, 1964):  $Z = 2.048 * (\delta^{13}\text{C} + 50) + 0.498 * (\delta^{18}\text{O} + 50)$ , carbonate rocks with Z values greater than 120 are considered marine, those with values less than 120 are considered freshwater, and those with Z values approaching 120 are considered intermediate. In the current study, all of the whole rock samples exhibited Z values greater than 120, indicating a marine depositional environment.



**Figure 21.** Comparison between the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of the study samples with the early Cretaceous isotopic values.

## **CHAPTER 5**

### **Conclusion**

The key findings of this study can be summarized as follows: 1) The early Cretaceous carbonates in the Jinadriyah area were deposited in shallow marine carbonate ramps, mostly deposited in inner ramp settings. 2) The carbonates in the study are mainly formed of calcite minerals, with dolomitization playing a minor role. The occurrence of quartz signifies the input of siliciclastic material and serves as a reliable indicator of high-energy events. Notably, when there is a distinct and abrupt change in the presence of quartz, it further supports the occurrence of such energetic events. 3) The elemental analysis results in low Fe and Mn concentrations suggest that the outcrop was not subjected to meteoric diagenesis for a long time before burial. 4) The stable carbon and oxygen analyses conducted on the samples indicate that they have undergone early-stage burial diagenesis. 5) The investigation of diagenetic processes in the study area revealed a range of transformations that the carbonates underwent, including micritization, cementation, compaction, dissolution, dolomitization, and fracturing. By constructing a paragenetic sequence, the order in which these diagenetic processes occurred was determined. 6) The petrophysical measurements conducted on the studied samples indicate that the early Cretaceous carbonates in Saudi Arabia exhibit characteristics of tight reservoirs. The average porosity was determined to be 7.91%, while permeability was measured at 0.296 mD. In addition, the study examined the impact of the depositional environment and

various diagenetic processes on the reservoir quality of each microfacies, providing insights into the factors influencing the tightness of these carbonate reservoirs.

## References

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## Vitae

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