



Petrography and diagenesis of the Middle to Upper Jurassic succession from Sargelu section, northeastern Iraq

[Rebwar H. Rasool](#)^{1*}, [Sarmad A. Ali](#)^{1,2}, [Ali I. Al-Juboury](#)³

¹Department of Applied Geology, College of Science, Kirkuk University, Iraq

²GeoQuEST Research Centre, School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, Australia

³Petroleum Engineering Department, College of Engineering, Al-Kitab University, Kirkuk, Iraq

*Corresponding Author: rebwar.hussain19@gmail.com

Citation: Rasool RH, Ali SA, Al-Juboury AI. Petrography and diagenesis of the Middle to Upper Jurassic succession from Sargelu section, northeastern Iraq. Al-Kitab J. Pure Sci. [Internet]. 2023 Nov. 30 [cited 2023 Nov. 30];7(2):153-172. Available from: <https://doi.org/10.32441/kjps.07.02.p12>.

Keywords: Jurassic succession, Northeastern Iraq, Sargelu area, Petrographic components, Diagenesis, Dolomitization.

Article History

Received 12 Oct. 2023

Accepted 27 Nov. 2023

Available online 30 Nov. 2023

© 2023. THIS IS AN OPEN-ACCESS ARTICLE UNDER THE CC BY LICENSE
<http://creativecommons.org/licenses/by/4.0/>



Abstract:

Petrographic and diagenetic analysis of the Middle-Upper Jurassic successions (Sargelu, Naokelekan, and Barsarin) formations and boundaries between them in the Sargelu area, Kurdistan region, N.E. Iraq was conducted based on the lithologic description, thin section analysis, and scanning electron microscopy. The study aims to define the petrographic components and diagenetic processes that affect the carbonate rocks of Jurassic succession in the studied section. Thirty-eight thin sections have been prepared, with five samples selected using the S.E.M. technique to reveal the petrographic components and diagenetic processes. The Jurassic succession is composed mainly of carbonates (limestone and dolostone) interbedded with shale units. Petrographically, the Sargelu, Naokelekan, and Barsarin formations are composed of skeletal grains (pelagic pelecypods, radiolaria, calcispheres, planktonic and benthonic foraminifera such as miliolid, ostracods, bioclasts, and stromatolites) which are the most common, in addition, non-skeletal grains such as poloids, micritic groundmass, and recrystallized micro spars, Many diagenetic processes affected the studied carbonate rocks such as micritization, dolomitization compaction and stylolite formation, authigenic minerals (pyrite), cementation, neomorphism, dissolution and porosity formation as represented by moldic, vuggy, channel and fracture porosity.

Keywords: Jurassic succession, Northeastern Iraq, Sargelu area, Petrographic components, Diagenesis, Dolomitization.

الصخرية و العمليات التحويرية لتتابعات الجوراسي الأوسط - الأعلى في مقطع سركلو شمال شرقي العراق

ربيوار حسين رسول^١، سمرّد عاصي علي^٢، علي إسماعيل الجبوري^٣

^١ قسم علوم الأرض التطبيقية، كلية العلوم، جامعة كركوك، كركوك، العراق

^٢ مركز أبحاث جيوكويست، كلية علوم الأرض والغلاف الجوي والحياة، جامعة ولونجونج، ولونجونج، أستراليا

^٣ قسم هندسة النفط، كلية الهندسة، جامعة كركوك، التون كويري، العراق

rebwar.hussain19@gmail.com, sarmad@uokirkuk.edu.iq, alialjubory@yahoo.com.

الخلاصة:

تم إجراء دراسة للبترولوجرافية والعمليات التحويرية لتتابعات الجوراسي المتوسط – الأعلى لتكوين (ساركلو، ناوكيلكان وبارسرين) ومناطق التماس بينهم في منطقة ساركلو، إقليم كردستان، شمال شرقي العراق اعتماداً على الوصف الصخري والشرائح الرقيقة وكذلك التحليل بالمجهر الماسح الإلكتروني. تهدف الدراسة إلى التعرف على المكونات الصخرية والعمليات التحويرية المؤثرة على صخور الكربونات ضمن التعاقب الجوراسي للتكوين المدروسة. تم تحضير ودراسة ٣٨ شريحة رقيقة مع ٥ عينات تم اختيارها وتحليلها باستخدام تقنية المجهر الماسح الإلكتروني لوصف المكونات الصخرية وكذلك العمليات التحويرية، تتكون تتابعات الجوراسي بشكل رئيسي من الكربونات (الحجر الجيري والدولستون) المتداخلة مع التسجيل. من الناحية البترولوجرافية، تتكون تكوين ساركلو وناوكيلكان وبارسرين من المكونات الهيكلية (الرخويات البحرية، فاسية القدم، الشعاعيات، الكريات الكلسية، الفورامنيفرا الطافية و القاعية (ميليوليد)، الاوستراكودا، الفتات الأحيائي والستروماتوليت) وهي الأكثر شيوعاً، بالإضافة إلى الحبيبات الغير الهيكلية مثل الدمالق، والأرضية المكراتية وكذلك السبار الدقيق معاد أتبلور، أثرت العديد من عمليات التحويرية هذه التتابعات الصخرية مثل المكترية، الدلمته، المعادن موضعية النشاء مثل (البيراييت)، الانضغاط، و تكوين الستايولايت، التشكل الجديد، والإذابة وتكوين المسامية مثل المسامية القالبية، المسامية بين الحبيبات، القنوات والشقوق المجهرية.

الكلمات المفتاحية: تتابعات الجوراسي، منطقة ساركلو، المكونات الصخرية، الراديولاريا، العمليات التحويرية، الدلمته.

1. Introduction:

The Jurassic successions of Iraq have great importance in terms of their petroleum system characteristics [1-3]. Most of the petroleum exposed in Iraq was sourced from Jurassic rocks and trapped in the Cretaceous- and Tertiary-age reservoirs of the Mesopotamian Basin and the Zagros Basin/Zagros Fold Belt [4]. Other Jurassic rocks have been considered essential reservoirs, especially in the central and northern parts of Iraq [5]. These successions lack detailed studies on their mineralogical and petrographic characteristics that are widely affected by the reservoir properties of the Jurassic rocks. The petrographic study is one of the essential means for determining the depositional environments of carbonate rocks based on microfacies analysis. It is also used to investigate diagenesis and other factors affecting sedimentation, such

as climate, tectonic setting, and the nature of the source rocks (provenance), particularly for the clastic rocks [6].

The lithological composition of the Middle to Upper Jurassic successions, including Sargelu, Naokelekan, and Barsarin formations from northeastern Iraq, consists of thin to medium bedded, black, bituminous limestone, dolomitic limestone, and black papery shale, with narrow beds of black chert in the upper part of the successions. The current study examines the petrographic description using a traditional polarizing microscope supported by the SEM-EDS (Scanner Electron Microscope, energy-dispersive X-ray spectroscopy) techniques for the carbonate units in the studied succession to determine their petrographic components and the main diagenetic events affecting on them.

2. Geological Setting

The study area is in Sargelu village near Dokan town, northeastern of Sulaymaniyah city in the High Folded Zone of the Unstable Shelf of Iraq at the coordinates (35° 86' 75" N- 45 ° 16' 37" E) (Figures 1, 2). The Jurassic rocks existed in isolated patches at eroded cores and limbs of anticlines [7, 8]. The studied middle-late Jurassic formations in Iraq were deposited during the isolation of the central intra-shelf basin of Mesopotamia from the Neo-Tethyan Ocean time, possibly due to renewed rifting along the N.E. margin of the Arabian Plate [8,9]. The Neo-Tethys reached its maximum width of 4000 km during the Late Triassic to Middle Jurassic periods [10]. Thinly and thick-bedded, bituminous black limestones, dolomitic black limestones, stromatolitic limestones, and black papery shale beds with thin streaks of black chert in the top part is primary lithology of the middle Jurassic Sargelu Formation in the studied area and the Formation thicknesses about 103m as shown in Figure 3, Where The late Jurassic Naokelekan Formation is about 16m composed in the lower unit of laminated argillaceous bituminous limestone alternating with bituminous shale and fine-grained limestone, middle unit is consisting of thin-bedded fossiliferous dolomitic limestone referred to as the (mottled beds) and an upper unit is consists of thin-bedded, highly bituminous dolomite and limestone with beds of black shale (coal horizons). The lower and upper contacts of the Naokelekan Formation are conformable and gradational with the underlying Sargelu Formation and the overlying Barsarin Formation [12]. Stromatolitic limestone and dolomitic limestone alternating shales, contorted and brecciated beds, and some secondary gypsum and anhydrite form the main component of about 18m thickness in the Barsarin Formation of the studied section. The studied formations were deposited in tidal flats (supratidal), restricted lagoons, and shallow marine to bathyal depositional environments [13,8].

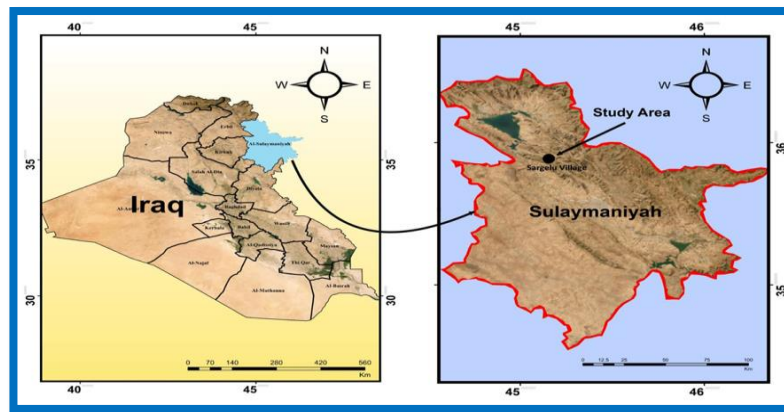


Figure 1. Location map of the study area (Sargelu village)

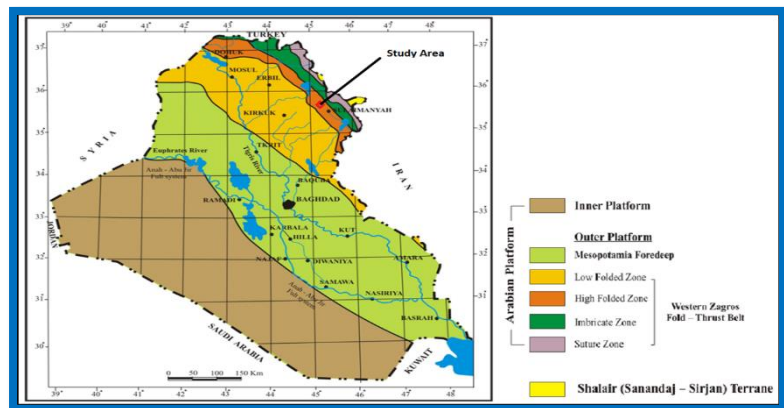


Figure 2. Tectonic map of Iraq showing the study area [after, 14]

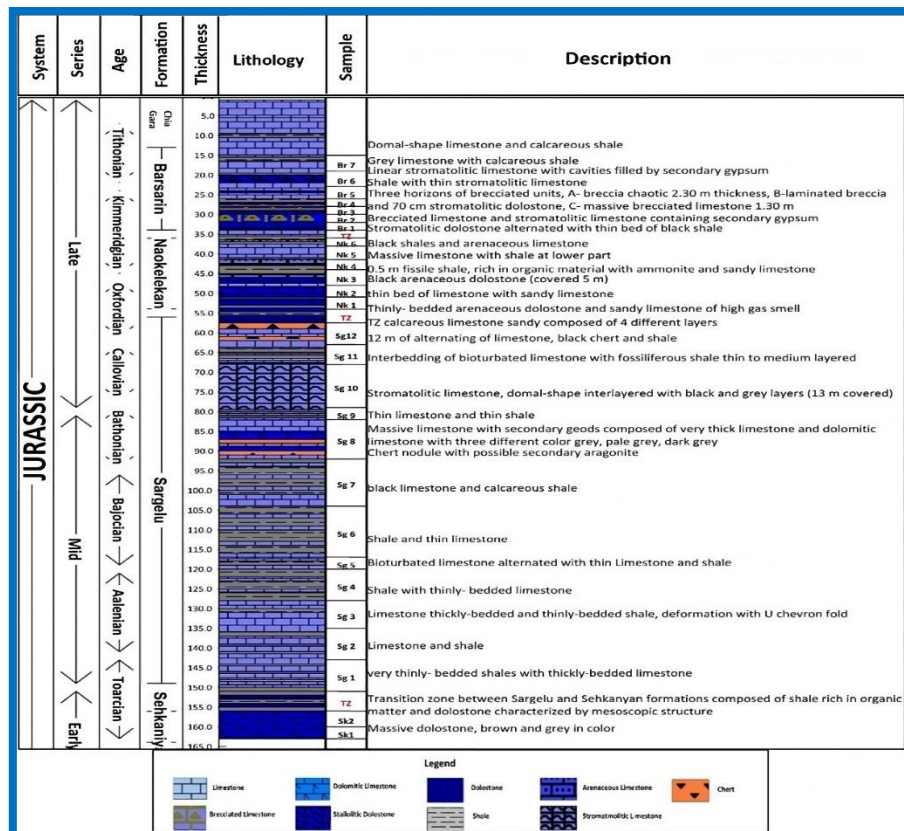


Figure 3. Lithologic section with description and sample numbers of the studied formations

3. Materials and Methods

The samples prepared for the thin section were selected from the carbonate units in the studied Jurassic formations, which are comprised mainly of limestone, dolomitic limestone, and dolomite. The petrographic study is carried out on 38 thin sections prepared from all the studied formations, including 13 slides from the Sargelu Formation, ten slides from the Naokelekan Formation, nine slides from the Barsarin Formation, four slides from the formation's contacts of the buildings and two drops from Sehkanyian Formation. The petrographic description was done at the Department of Geology and Petroleum, College of Science, Salahaddin University, Erbil, Iraq.

At the same time, imaging was achieved at the Department of Applied Geology, College of Science, Kirkuk University, Iraq.

The Scanning electron microscopic study (S.E.M.) was performed on five selected samples at Premier Corex Laboratories in Houston, U.S.A., using an F.E.I. Quanta FEG 650 FE-SEM instrument equipped with two Bruker E.D.S. XFlash 5030 energy dispersive X-ray spectroscopy (E.D.S.) detectors and an FEI R580 Everhart-Thornley (ETD) electron detector.

4. Results

4.1 Petrographic Description

Carbonate rocks consist mainly of grains and groundmass, which are essential for finding depositional environments and texture types. The grains have been divided into skeletal grains, which include fossils and their clasts, and no-skeletal grains, which include lithoclasts, grain aggregates, and peloids [6].

4.2 Petrographic component

The ratio of the skeletal grains is varied between the studied formations. They dominate the Sargelu Formation while are less abundant in the Naokelekan Formation and almost disappeared from the Barsarin Formation.

The Jurassic carbonate rocks were highly affected by diagenetic processes such as dolomitization, dissolution, and compaction [15-17]. The identified skeletal grains include mainly fossils and fossil shells; below is a brief description of each of these components:

4.3 Pelagic pelecypods

These skeletal grains predominate in the middle and upper parts of the Sargelu Formation in the study area. They commonly exist in shallow or deep marine environments [18] and are the most abundant in the basinal facies from the Late Triassic-Middle Jurassic ages [19,20]. Two types of pelecypods have been diagnosed: single valve (*Halobia* sp. (Figure 4a) and class

Bivalvia (Posidonia Sp, Bositra Sp.) (**Figure 4a, b**), which is widely spread in the Sargelu Formation.

4.4 Radiolaria

It is a single-celled marine organism with rigid structures, spherical shapes, and serrated, spiny perforated walls containing lateral protrusion [21]. It generally presents in a small proportion and is affected by diagenetic processes. It exists typically in less than 1 mm and frequently between 0.1 and 0.2 mm in size. Radiolaria are recorded in the upper part of the Sargelu Formation (**Figure 4c**) and in the lower and middle parts of the formation, where calcispheres accompany them. It is also presented in the central part of the Naokelekan Formation (**Figure 4d**). Radiolaria was found in pelagic limestones, and they are planktonic organisms living in open marine environments [22,20].

4.5 Calcispheres

The calcareous balls or spheres belong to the group of *Pithonella* and are formed of minute calcareous spherical shells devoid of openings; they belong to the Upper Jurassic-Cretaceous in age [23]. The sizes of calcispheres range from 100-200 microns [24]. The walls consist of a single layer of lamellar form consisting of homogeneous calcareous crystals [23,25]. Calcispheres are common in open marine environments; they are indicators for the environment of marine settings from the edge of the continental shelf to the slope [21,26]. In the present work, calcispheres have been found in the Sargelu and Naokelekan formations, which are absent in the Barsarin Formation (**Figure 4d, e**). It was observed in the Naokelekan Formation as coccolithophores, which is in shape that has been pointed out in the S.E.M. image.

4.6 Foraminifera

They are dominantly marine protozoa, mainly of microscopic size [6]. They are the most significant type of microfossils because they are common in rocks. Therefore, they are useful for dating and reconstructing sedimentary environments [27]. Petrographic study has revealed different types of planktonic foraminifera in the Sargelu and Naokelekan formations, while miliolid is common in the Barsarin Formation (**Figure 4f**), most of them are difficult to distinguish due to the effect of diagenesis (**Figure 4g**). In the Sargelu limestones, planktonic foraminifera are often tiny, consolidated spherical chambers that are filled with calcite or pyrite. Most of them are affected by the recrystallization process and leaching, like the previous study by [28].

4.7 Ostracods

They have been found in almost all sorts of aquatic environments and have been known since the Late Cambrian [26]. Ostracods are useful for stratigraphic investigations because they can

be found in a wide variety of depths and depositional settings, including marine, transitional, and fresh waters [24,29]. Ostracods are recognized in the Sargelu Formation, especially in the upper parts. They are commonly affected by diagenetic processes such as cementation and compaction, resulting in filling chambers with spay calcite cement and elongation and distortion of the shells (Figure 4h).

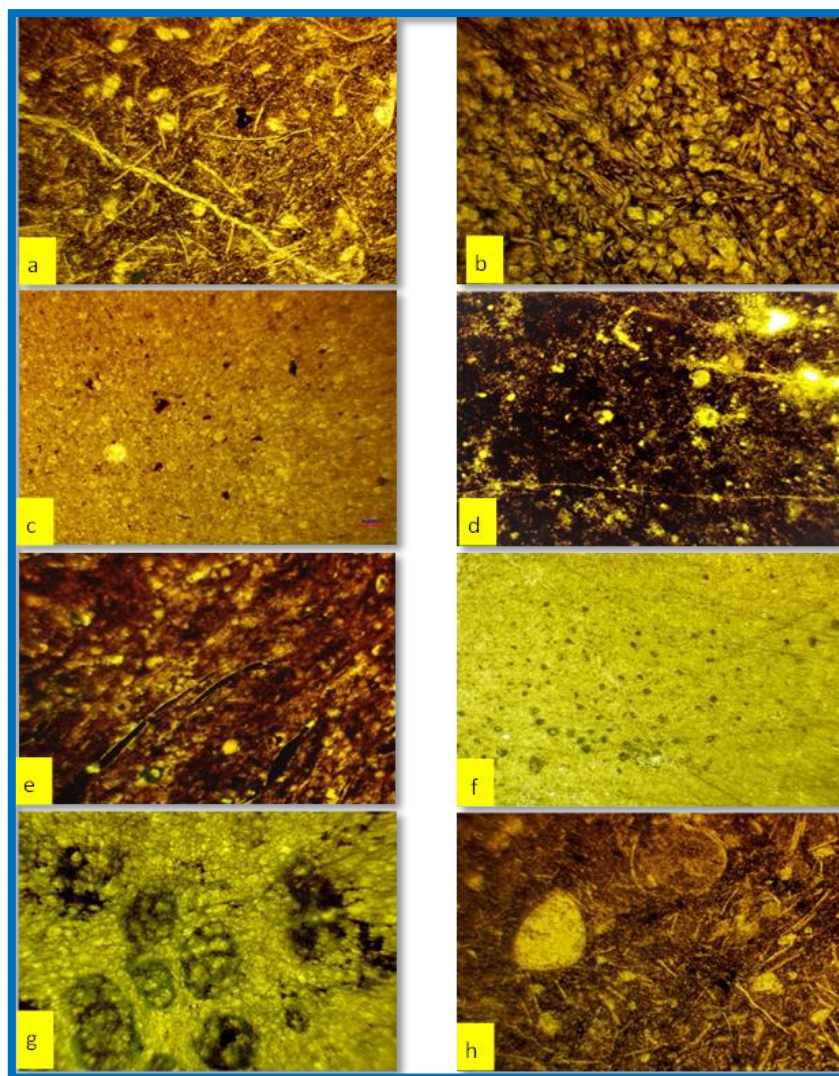


Figure 4. Photomicrograph illustrating

Figure 4 (a) Pelecypod's single valve long curved Halobia (red arrow) in the upper part of the Sargelu Formation in sample (Sg-9B) Magnification, 4X, N.L. **(b)** Thin shelly class bivalve pelagic pelecypod *Bositra* (blue arrow) in metamorphosed and dolomitized limestone in middle part of the Sargelu Formation in sample (Sg-8B), Mag. 4X, N.L. **(c)** Calcitized radiolaria (white arrow) affected by dissolution and filled with sparry calcite cement within a micritic matrix in the lower part of the Sargelu Formation IN Sample (Sg-3B), Mag. 4X, N.L. **(d)** Radiolarian (white arrow) affected by dissolution and filled with sparry calcite cement preserved as moldic

porosity associated with calcispheres (red arrows) and authigenic pyrite in the middle part of the Naokelekan Formation in Sample (Nk-4B), Mag. 4X, N.L. **(e)** walled and un-walled calcispheres filled by granular cement (red arrow) with chert (white arrows) embedded in micrite groundmass, the upper part of the Sargelu Formation in a sample (Sg-12B), Mag. 4X, N.L. **(f)** Different types of foraminifera (planktonic, benthonic) (red arrows) highly affected by diagenesis in the lower part of the Barsarin Formation in a sample (Br-1B) Mag., 4X, N.L. **(g)** Miliolid shell highly affected by dissolution in the middle part of the Barsarin Formation in a sample (Br-4B), Mag., 10X, N.L. **(h)** Spindle ostracoda (red arrow) filled with sparry calcite cement and pelagic pelecypod with authentic pyrite in shape of black spots (white arrow), in micrite ground mass in upper part of the Sargelu Formation in sample.

4.8 Bioclasts

They are remains of fossils that are created by the action of waves and currents in the depositional basin, and they may provide information about the water energy, where the rounded bioclasts denote a high energy level and flattened ones a low energy level [30,26]. The varying ratios of their presence may be caused by the fluctuation of the current energy created by changes in sea level [26]. In the current study, reworked bivalve skeletons and other unidentified mollusks, some of which are phosphatized, are represented in the Sargelu Formation (Figure 5a). They are also found in different intervals in the Naokelekan and Barsarin formations.

4.9 Stromatolite

It is sedimentary carbonate structures of inorganic origin that developed because of biological and chemical sedimentary processes associated with the growth and development of benthic assemblies such as blue-green algae and anaerobic bacteria through the deposition of calcium carbonate inside the ground or algal mats [31]. In the current study, stromatolites are observed in the limestones of the lower and upper parts of the Sargelu Formation with braze eye shapes (Figure 5b). It's more common in Barsarin Formation as parallel stromatolites (laminated limestone) in the upper part of the formation and planer and crinkled (wavy) stromatolitic limestone in the middle and lower parts of the formation (Figure 5b-c). Microscopically, they are observed in the Barsarin Formation, which is filled by calcite cement and organic maters (Figure 5d).

4.10 Non-skeletal grains

Peloids are inorganic grains of different shapes and sizes; they are characterized by their fine carbonate grains of size (0.1-0.5) mm, spherical, cylindrical, or angular, without internal structures and dark color [26]. They are frequently considered to be by-products of ooids or

microscopic processes involving bioclast fragments [32,33]. In the current study, peloids were found in the Naokelekan and Barsarin formations (**Figure 5d**).

4.11 Micrite

According to [34], micrite is a microcrystalline calcite crystal with grains typically smaller than four m. Micrite is characterized by its brown to dark color, according to its content of impurities, organic materials, clay minerals, and iron oxides, in addition to other factors such as the nature of the transformational processes, sedimentation rate, and oxidation and reduction factors [35,26]. The micritic groundmass is common in the Sargelu and Naokelekan formations **Figure (5e, f)** Spray calcite cement of various sorts, such as drusy, granular, and blocky calcite cement, have also been identified in the samples of the current study.

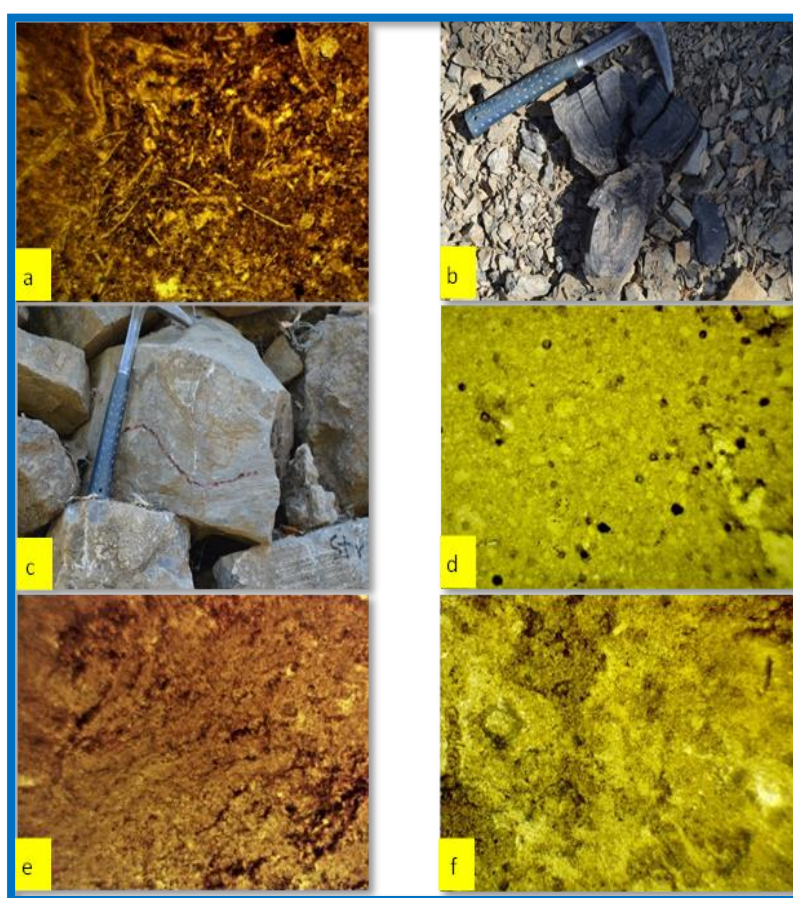


Figure 5. photomicrograph illustrating

Figure 5 (a) Bioclastic fragments (blue arrows) in the Sargelu Formation in a sample (Sg-4B), 4X, N.L. **(b)** field photo of stromatolitic limestone with braze eyes observed in the upper and lower parts of the Sargelu Formation. **(c)** Field photo of the wavy (red arrow) and parallel (blue arrow) stromatolitic limestone in the upper part of the Barsarin Formation in sample Br-6. **(d)** Peloids (red arrows) highly affected by diagenesis chemical compaction (pressure

solution) in the upper part of Naokelekan Formation in sample (Nk-5B), 4X, N.L. **(e)** Micrite groundmass with organic material filled microfracture and pores in the Lower part of Sargelu Formation in sample Sg-2B. 4X, N.L. **(f)** Micrite groundmass with bioclasts in the lower part of Barsarin Formation sample (Br-2B). 4X, N.L.

5. Diagenesis

Diagenetic processes are defined as all biological, chemical, and physical changes affecting sediments after deposition and before reaching the metamorphism stage [36]. There were some important factors that affect the diagenesis processes on carbonate rocks, such as changes in sea level levels associated with tectonic events and climate changes [37]. Carbonate minerals are metastable minerals, and therefore, they are more highly affected by diagenesis than clastic rocks [38]. Therefore, they rapidly respond to diagenetic processes such as cementation, dissolution, porosity, and neomorphism that lead to the destruction of the sedimentary textures, skeletal grains, and groundmass [35]. In the current study, the limestone, dolomite, and dolomitic limestone of the studied Sargelu, Naokelekan, and Barsarin formations have suffered from various types of diagenetic processes in different degrees, but it seems that severe effects have occurred on the carbonates of the Naokelekan Formation. The main diagenetic processes that affected the formations under study include.

5.1 Micritization

Micritization is an early diagenetic process that affects skeletal grains [39], Where the micrite envelopes the skeletal grains or bioclasts. In marine diagenesis, micritization is a basic process that takes place at the sediment-water interface [40] and under low-energy conditions. Micritization is observed in all formations of the study area (Figure 6a, b).

5.2 Dissolution and porosity formation

Dissolution is considered one of the types of histochemically destructive diagenetic processes. Dissolution is controlled by the stability of a particular mineral, the degree of fluid saturation with the targeted mineral, fluid pressure, and temperature [24]. Melodic pores are formed when grains dissolve completely to leave pores with shapes like the dissolved grains, while vuggy pores are those that have irregular shapes and are formed by a dissolution process that affects the components of the texture, as shown in (Figures 4g, h and 6b). Pore systems in sedimentary carbonates are often complicated in terms of shape and origin [41]. Porosity decreases by cementation and compaction, whereas it is acquired through solution, dolomitization, and tectonic cracks. Porosity is controlled by a group of factors, the most important of which are climate, fluctuation in sea level, the rate of gravity of sedimentary accumulation, sedimentation, and compression. and cementation [42,43]. Primary and

secondary porosity were noted in the carbonates of Jurassic succession in the study area. The primary porosity includes only interparticle porosity, whereas secondary porosity is revealed by moldic, vuggy, channels, and fracture porosity [26], as shown in (Figure 6b, c, d) and (Figure 7A, B, C).

5.3 Chemical compaction and stylolite formation

Compaction is one of the destructive processes that commonly occurs in carbonate rocks. The process reflects the compaction caused by the severe lithostatic load, leading to a reduction in the porosity. According to [21], compaction is divided into two types: physical compaction and chemical compaction. Dissolution surfaces and stylolites are formed because of the pressure solution [24]. Stylolites result from increasing overburden sedimentation or tectonic pressure, which affects the grains within the carbonate rock, promotes dissolution, and propagates seams [44]. This process is noted in the Sargelu, Naokelekan, and Barsarin formations in the form of low and high-amplitude peaks stylolite (Figure 6c, d) and (Figure 7E).

5.4 Cementation

Cementation is the diagenetic process by which voids and pores are filled by calcite cement. The cementation process is one of the chemically similar structural processes. According to [38,45], there are many factors that control the cementation process, which include temperature, mechanical stress, pH, carbon dioxide pressure, type of dissolved elements, and their concentration in the solution. In the current study, several types of cement were distinguished based on the classification of [26], including granular, drusy, and blocky cement. This type of cement dominantly fills the fossil's mold, pores, and fractures (Figure 6c, d).

5.5 Neomorphism

Neomorphism includes both recrystallization and inversion processes. The recrystallization process is defined as a change in the size and shape of the crystal, which results in an increase or decrease in the crystalline size without any change in the chemical composition [36]. It has been recorded in the form of transformation of the fine micritic groundmass with a size of (4) microns to a microsite with a size greater than (4) microns (Figure 6g) and (Figure 7F, G). The occurrence of dissimilar parts of recrystallized dolomite crystals is evidence of neomorphism (Figure 6h). Inversion is the transformation of an unstable mineral, such as aragonite, into a stable mineral (calcite) without any change in the chemical composition. The inversion process was observed in the three studied formations, as shown in (Figure 8a). Neomorphism was also noted within the dolomites of the Sargelu and Naokelekan formations in the form of the creation of dolomite crystals (i.e., aggrading neomorphism) (Figure 8b, c).

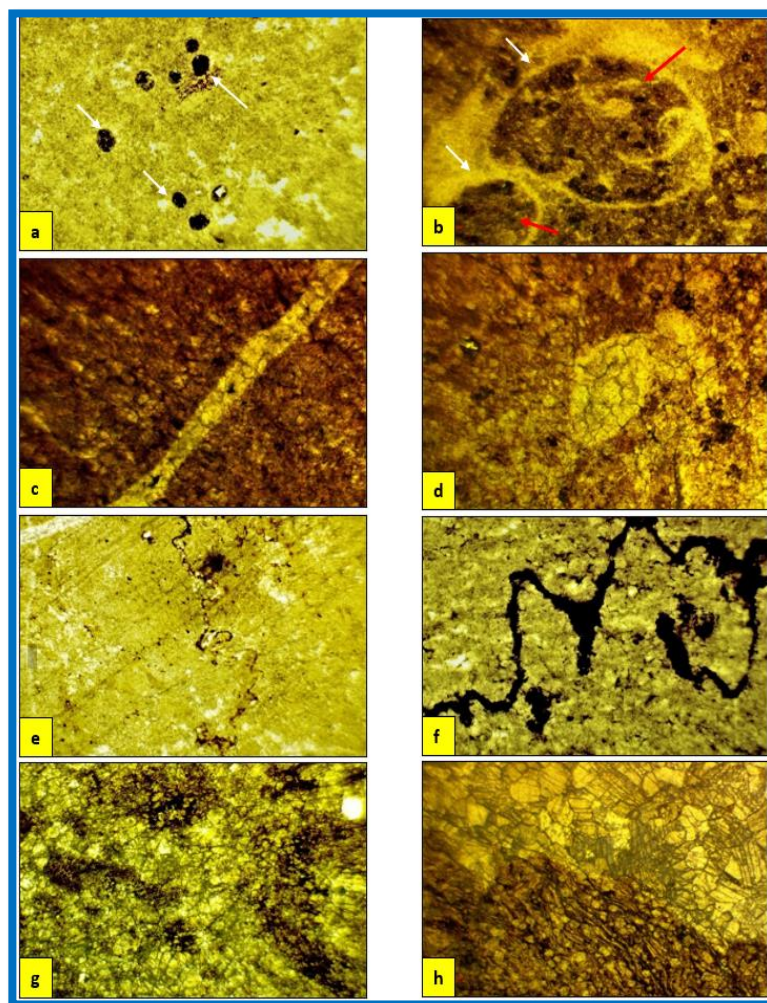


Figure 6. Photomicrograph illustrating

Figure 6 (a) Micritization of skeletal grains (white arrows) in the lower part of the Naokelekan Formation sample (Nk-2B), 4X, N.L. **(b)** Micrite envelop (rim) (white arrow) surrounding Ostracoda in the middle part of the Sargelu Formation in the sample (Sg-7B), note high effect by dissolution process leaving melodic porosity (red arrow). Authigenic pyrite in the shape of black spots also exists, 4X, N.L. **(c)** Chemical compaction led to stylolite formation in low and high amplitude types and filled by organic material in the middle and upper parts of the Barsarin Formation in sample (Br-3B), 4X, N.L. **(d)** Chemical compaction and stylolite formation of high amplitude type filled by organic material in the upper part of the Naokelekan Formation in the sample (Nk-5B), 4X, N.L. **(e)** Fracture filled by drusy calcite cement in the lower part of the Naokelekan Formation within micrite groundmass in the sample (Nk-2B), 4X, N.L. **(f)** Sparry calcite cement (blocky cement) (red arrow) filled an ostracoda within micrite groundmass in the upper part of the Sargelu Formation in sample (Sg-12B), 4X, N.L. **(g)** Neomorphism (recrystallization) of micrite groundmass and transformation to microsite in the middle part of the Barsarin Formation in the sample (Br-3B), 4X, N.L. **(h)** Neomorphism

(recrystallization) of micrite groundmass and transformation to separate in the middle part of the Sargelu Formation with dolomitization and compaction processes in the sample (Sg-8B), 4X, NL.

5.6 Dolomitization

Dolomitization is one of the important diagenetic processes in Jurassic formations in the studied area, with extensive and pervasive dolomitization with a variety of crystal sizes, especially in the Naokelekan Formation, leading to the disappearance of the main skeletal and non-skeletal grains. Different kinds of dolomites were observed in the examined samples, such as scattered fine-grained dolomite rhombs, floating rhomb fabric, and sutured mosaic fabric dolomite (**Figure 7H**) and (**Figure 8b, c, d, e, f**).

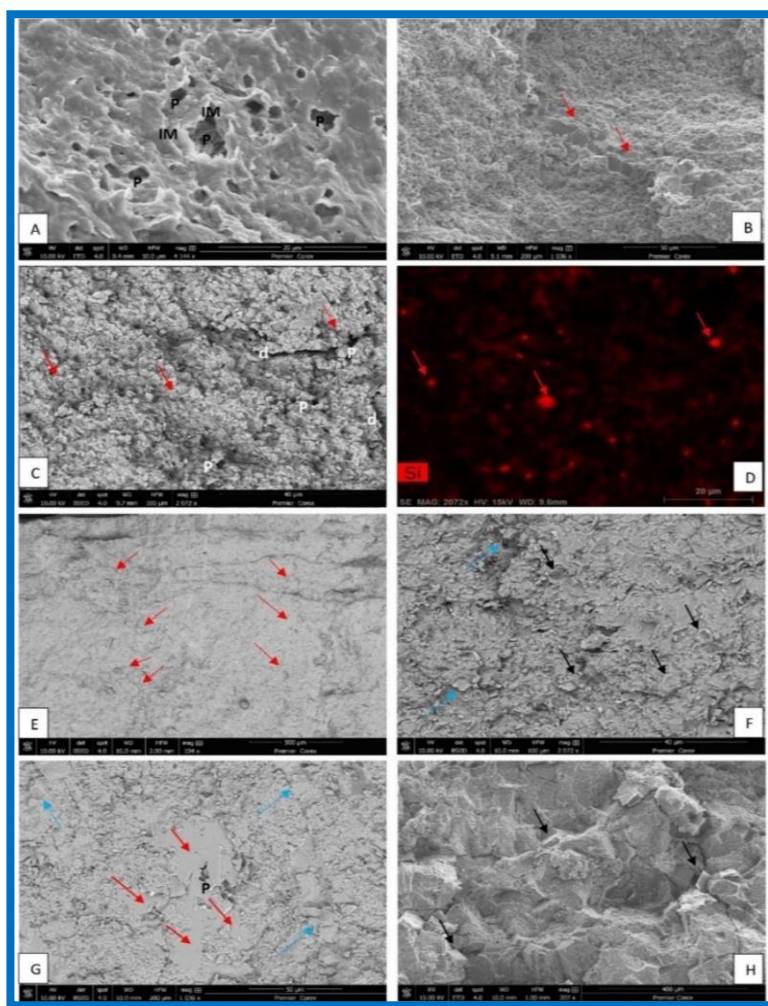


Figure 7. Scanning electron micro images (S.E.M.) illustrating

(A) Common pores (P) referring to the dissolution process and illite-mica (I.M.) with common carbonate (c) in sample TZ-1A. (B) Micro vein (red arrows) filled by a cluster of calcite crystals, euhedral hexagonal and columnar crystals relating to the cementation process and embedded in the micritic groundmass, sample Sg4A. (C and D) S.E.M. and E.D.X.

microimages for sample Sg4A show common radiolarian shells in different sizes with fine fractures (f) and pores (p). In D, the same locations of red arrows refer to silica content (Si), the main composition of the radiolarian shell. **(E)** Chemical compaction and stylolite formation (red arrow) in sample Br-5A. **(F)** Cementation in nannofossil shell (coccolith shell) and other different types with recrystallization of fine calcite grain in sample Nk-4A **(G)** cementation of fossil shell (red arrows) with recrystallization of fine calcite grain, dissolution and porosity formation of fossils (p) and in sample Br-5A. **(H)** Dolomitization in very fine dolomite rhombs (black arrows), with fracturing in sample Nk-1

5.7 Anthogenesis

Authigenic minerals are created in many of the studied rocks. These minerals are formed diagenetically by local chemical reactions [26,27]. Pyrite is the common authigenic mineral in the studied rocks; this mineral is formed when dissolved sulfide from microbial sulfate reaction reacts with detrital iron-bearing minerals in anoxic marine sediments [46]. Pyrite is common in the Sargelu and Barsarin formations as patches and framboidal pyrite (**Figure 8g, h**), which are composed of tightly packed spherical or sub-spherical clusters of pyrite crystals [47].

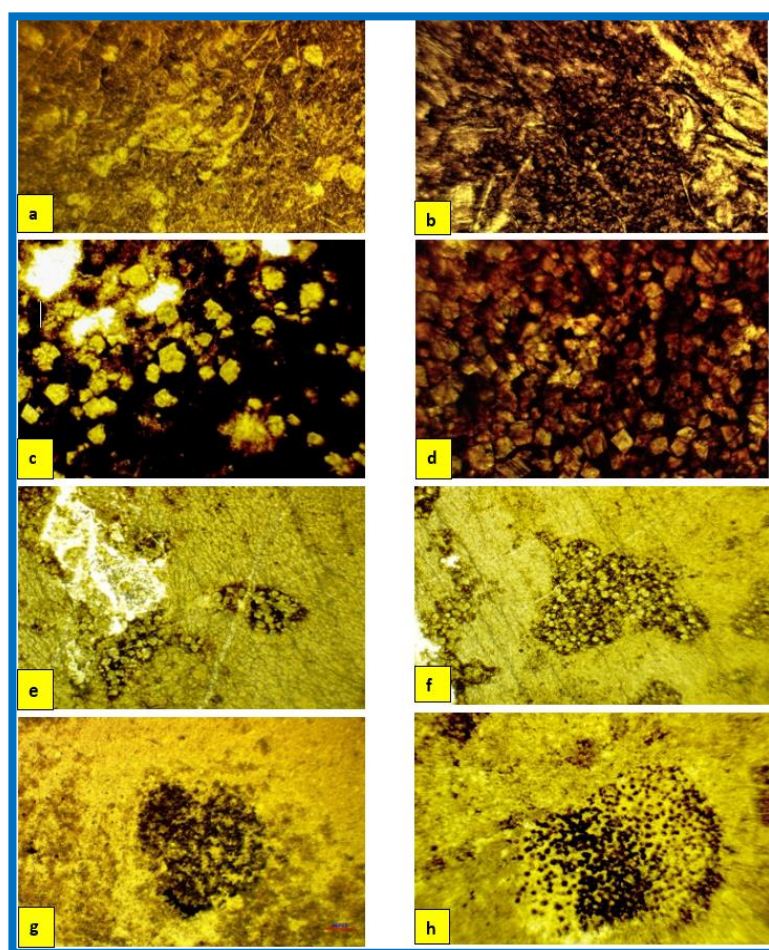


Figure 8. Photomicrograph illustrating

Figure 8 (a) Neomorphism, authigenic pyrite, and dolomitization in the upper part of the Sargelu Formation in the sample (Sg-9B), 4X, N.L. **(b)** Selective dolomitization, scattered fine-grained dolomite rhombs dolomitization neomorphism process affected the micrite matrix in the upper part of the Sargelu Formation in the sample (Sg-10B), 4X, N.L. **(c)** Floating rhomb dolomite fabric in the lower part of the Naokelekan Formation, neomorphism embedded in micritic groundmass in the sample (Nk-1B) 4X, N.L. **(d)** Subhedral-euhedral dolomite rhomb in the middle part of the Naokelekan Formation in sample (Nk-3B), 4X, N.L. **(e)** Dolomitization in the middle part of the Barsarin Formation affecting skeletal grains filled with organic material in sample (Br-4B), 10 X, NL. **(f)** Dolomitization in the middle part of the Barsarin Formation affects skeletal grains filled with organic material in the sample (Br-4B), 10 X, NL. **(g)** Pyritized radiolarian shell in the middle part of the Sargelu Formation in the sample (Sg-6B), 10 X, NL. **(h)** Packed spherical or sub-spherical clusters of pyrite crystals in the lower part of the Barsarin Formation in the sample (Br-2B), 10 X, NL.

6. Discussion

The Sargelu Formation lithological is made up of thin-bedded, bituminous black limestones, dolomitic black limestones, and black papery shales with thin black chert streaks in the top part. The depositional environment was primarily anoxic marine [8]; this is supported by the recognized petrographic components, including pelagic pelecypods, radiolarian, and calciphores organisms. Naokelekan Formation consists of argillaceous bituminous limestone and dolostone alternating with bituminous shale and fine-grained limestone, while Barsarin Formation is composed of stromatolitic limestones and evaporite layers [11]; according to [48], the Naokelekan Formation was deposited in restricted tidal flats and lagoons, marshes, and euxinic saline swamps. This suggestion can be supported in this study by the presence of peloids, which are commonly present in protected environments such as lagoons, tidal flats, and other quiet environments [24]. On the other hand, the overall characteristics of the Naokelekan microfacies indicate that formation was deposited in two different environments: the shallow marine subtidal environment in the lower and upper parts and the outer shelf in an euxinic environment in the middle part [16, 49]. The upper part of the Barsarin Formation was deposited in an intertidal environment, whereas the lower part of the formation was deposited in the shallow subtidal environment [50].

Mineralogically, variation in the composition of the middle to upper Jurassic Sargelu, Naokelekan, and Barsarin formations from northeastern Iraq demonstrates the influence of the source area, the depositional environment, and the paleoclimatic conditions [51], the presence

of calcite and dolomite reflect the deposition in such restricted and evaporative conditions [52,53]. The predominance of illite-mica and kaolinite clay minerals with other components such as quartz and feldspars reflect the contribution of felsic igneous rocks and the prevalent environment, which can be recognized by variation between hot, arid, and humid climates, where the development in quartz and feldspars in the area which are both related to felsic igneous rocks, may be associated to a provenance where felsic rocks from the Rutba Uplift and/or Arabian Shield predominate [51,54].

The petrographic study revealed the variation in the petrographic components reflects the range of the diagenetic processes that affected the studied formations, leading to difficulty in identifying them due to the destruction of most of the skeletal grains as in Naokelekan Formation, which is highly affected by diagenesis.

The detected skeletal grains in the studied formations primarily consist of fossils and fossil shells, including radiolaria, calcispheres of different sizes, benthonic foraminifera such as (Miliolidae) and different types of unrecognized planktonic due to diagenetic effect, ostracods, bioclasts, pelagic pelecypods (Bositra and Halobia) and two types of stromatolites parallel and wavy stromatolites all these components are embedded in a groundmass of micrite and microsparite. Where the non-skeletal grains only recognized peloids.

The diagenetic processes that affected these components occasionally had a very strong impact on these components, making it harder to recognize the grain or such as micritization, dissolution and porosity formation, cementation, compaction (pressure solution), neomorphism, dolomitization, and authigenic minerals.

7. Conclusions

The Jurassic succession in the Sargelu section comprises petrographic constituents represented by skeletal grains, which are very common, especially in the Sargelu Formation; these include pelecypod, radiolaria, planktonic foraminifera, benthonic foraminifera, bioclasts, and calcispheres and stromatolites as well as non-skeletal grains, such as peloids. All these components are in two recognized types: micrite and microsite groundmass. Dissolution and porosity formation, cementation, neomorphism, dolomitization, compaction and stylolite formation, and authigenic minerals such as (pyrite) are mainly the kinds of diagenetic processes that had a significant effect on the carbonates of these formations.

8. References

- [1] Al-Ameri TK, Zumberge J. Middle and Upper Jurassic hydrocarbon potential of the Zagross Fold Belt, North Iraq. Mar Pet Geol [Internet]. 2012;36(1):13–34. Available from: <http://dx.doi.org/10.1016/j.marpetgeo.2012.04.004>

- [2] Al-Juboury AI, McCann T. Petrological and geochemical interpretation of Triassic-Jurassic boundary sections from northern Iraq: TRIASSIC-JURASSIC BOUNDARY OF NORTHERN IRAQ. Geol J [Internet]. 2015;50(2):157–72. Available from: <http://dx.doi.org/10.1002/gj.2537>
- [3] Abdula RA, Soran University. Source rock assessment of naokelekan formation in Iraqi Kurdistan. J Zankoy Sulaimani - A [Internet]. 2016;19(1):103–24. Available from: <http://dx.doi.org/10.17656/jzs.10589>
- [4] Pitman JK, Steinshouer D, Lewan MD. Petroleum generation and migration in the Mesopotamian Basin and Zagros Fold Belt of Iraq, results from abasin-modeling study, GeoArabia, Gulf PetroLink. Vol. 9. Bahrain; 2004.
- [5] Al-Naqib SQ, Al-Juboury AI. A new look on the Jurassic formations of the western part of Iraq. Arab J Geosci [Internet]. 2014;7(2):559–88. Available from: <http://dx.doi.org/10.1007/s12517-012-0820-2>
- [6] Tucker ME. Sedimentary petrology, an introduction, Blackwell Scientific publications. Blackwell Scientific publications. 1981;
- [7] Numan NMS. Cretaceous tectonic events in Iraq. Rafidain Jour Sci. 2000;11(3):32–54.
- [8] Jassim, S.Z. and Goff, C. Geology of Iraq. Dolin, Prague and Moravian Museum, 2006. Brno.
- [9] Ali SA, Buckman S, Aswad KJ, Jones BG, Ismail SA, Nutman AP. The tectonic evolution of a Neo-Tethyan (Eocene-Oligocene) island-arc (Walash and Naopurdan groups) in the Kurdistan region of the Northeast Iraqi Zagros Suture Zone. The Island Arc. 2013;22:104-e125.
- [10] Ali SA, Nutman AP, Aswad KJ, Jones BG. Overview of the tectonic evolution of the Iraqi Zagros thrust zone: Sixty million years of Neotethyan ocean subduction. J Geodyn [Internet]. 2019;129:162–77. Available from: <http://dx.doi.org/10.1016/j.jog.2019.03.007>.
- [11] Bellen VRG, Dunnington HV, Wetzel R, Morton DM. Lexique Stratigraphic International, V.3, Asie Fascicule Ioa-Iraq. Vol. 333. Paris; 1959.
- [12] Sharezwri AO, Nourmohammadi MS, Abdula R.A. Facies Analysis and Depositional Environment of the Upper Jurassic Naokelekan Formation in Two Selected Outcrop Sections from Kurdistan Region, Ne Iraq. Iraqi Bulletin of Geology and Mining. 2019;16:1–14.
- [13] Omar N, McCann T, Al-Juboury AI, Franz SO, Zanoni G, Rowe H. A comparative study of the paleoclimate, paleosalinity and paleoredox conditions of Lower Jurassic-Lower Cretaceous sediments in northeastern Iraq. Mar Pet Geol [Internet]. 2023;156(106430):106430. Available from: <http://dx.doi.org/10.1016/j.marpetgeo.2023.106430>.
- [14] Fouad S.F. Tectonic Map of Iraq. Iraqi Bulletin of Geology and Mining. 2015;1:1–8.
- [15] Balaky SM. Sequence stratigraphic analyses of Naokelekan Formation (Late Jurassic), Barsarin area, Kurdistan region—Northeast Iraq. Arab J Geosci [Internet]. 2015;8(8):5869–78. Available from: <http://dx.doi.org/10.1007/s12517-014-1638-x>.

- [16] Abdula R.A. Stratigraphy and lithology of Naokelekan Formation in Iraqi Kurdistan Review. The International Journal of Engineering and Sciences. 2016;5:7–17.
- [17] Omar N, Mccann T, Al-Juboury AI, Franz SO. Petrography and geochemistry of the Middle- Upper Jurassic Banik section, northernmost Iraq - Implications for palaeoredox, evaporitic and diagenetic conditions. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen. 2020(2):125–52.
- [18] Molina JM, Reolid M, Mattioli E. Thin-shelled bivalve buildup of the lower Bajocian, South Iberian paleomargin: development of opportunists after oceanic perturbations. Facies [Internet]. 2018;64(3). Available from: <http://dx.doi.org/10.1007/s10347-018-0532-5>.
- [19] P. J. B. J. L. Wilson 1975. Carbonate Facies in Geologic History. xiv + 471 pp., 183 figs, 30 pls. Springer-Verlag, Berlin, Heidelberg, New York. Price DM 90.00 ISBN 3 540 07236 5. Geol Mag [Internet]. 1976;113(6):584–5. Available from: <http://dx.doi.org/10.1017/s0016756800041406>.
- [20] Kuhry B, Declercq SWG, Dekker L. Indications of current action in Late Jurassic limestones, Radiolarian limestones, Saccocoma limestones, and associated rocks from the Subbetic of SE-SPAIN. Jour Sed Geology. 1976;15:235–58.
- [21] Flugel E. Microfacies Analysis of Limestones. Heidelberg: Springer; 1982.
- [22] Bishop BA. Petrography and origin of Cretaceous limestones, Sierra de Picachos and vicinity, Nuevoleon, Mexico. Jour Sed Pet. 1972;42(2):270–86.
- [23] Hart MB. The Late Cenomanian Calcisphere global bioevent, Ussher, Soc. J. 1991;(7):413–7.
- [24] Flugel, E., Microfacies of carbonate rocks: analysis, interpretation and application, 2 and. Edition: Springer- Verlage, Berlin, 2010.
- [25] Scholle PA, Ulmer - Scholle DS. A Color Guide to the Petrography of Carbonate Rocks: Grains, Textures, Porosity, Diagenesis, A.A.P.G. Memoir - 77. Vol. 474. Tulsa, Oklahoma, U.S.A.; 2003.
- [26] Flugel, E. Microfacies of carbonate rock, analysis, interpretation and application, Springer-Verlag, Berlin; 2004, 976.
- [27] Edgar K, Bohaty S, Gibbs S, Sexton P, Norris R, Wilson P. Symbiont "bleaching" in planktic foraminifera during the Middle Eocene Climatic Optimum. Geology. 2013;41(1):15–8.
- [28] Balaky S.M.H. Stratigraphy and sedimentology of Sargelu formation (Middle Jurassic) in selected sections in Erbil and Duhok Governorates-Iraq Kurdistan. M. 2004.
- [29] Awadeesian A.M.R., Al-Jawed S.N.A., Saleh AH, Sherwani G.H. Mishrif carbonates facies and diagenesis glossary, South Iraq microfacies investigation technique: types, classification, and related diagenetic impacts. Arab J Geosci [Internet]. 2015;8(12):10715–37. Available from: <http://dx.doi.org/10.1007/s12517-015-1954-9>.
- [30] Maikliem WR, Bebout DG. Glaister Classification of anhydrite: A practical approach. Bull Can Pet Geol. 1969;17(2):194–233.

- [31] Bosak T, Knoll AH, Petroff AP. The meaning of stromatolites. *Annu Rev Earth Planet Sci* [Internet]. 2013;41(1):21–44. Available from: <http://dx.doi.org/10.1146/annurev-earth-042711-105327>.
- [32] Zadeh, P.G., Adabi, M.H., Sadeghi, A., Microfacies, geochemistry and sequence stratigraphy of the sarvak formation (mid cretaceous) in the kuh-e siah and kuh-e mond, fars area, southern Iran. *J. Afr. Earth Sci*, 2019, 160, 103634.
- [33] Ahmad F, Quasim MA, Ahmad AHM. Microfacies and diagenetic overprints in the limestones of middle Jurassic fort member (jaisalmer formation), western Rajasthan, India: implications for the depositional environment, cyclicity, and reservoir quality. *Geol J*. 2021;56(1):130-151.
- [34] Folk, R.L., Practical petrographic classification of limestone. *A.A.P.G, Bull*. 1959;43(1):1-38.
- [35] Boggs SJ. *Principles of Sedimentology and Stratigraphy*. Pearson Prentice - Hall; 2006.
- [36] Larsen G, Chillinger GV. Diagenesis in sedimentary rocks. *Development in Sedimentology*. 1979;25:1–29.
- [37] Blatt, H. *Sedimentary Petrology*, Freeman, San Francisco, 1982, 564.
- [38] Bathurst R.G.C. Carbonate Sediment and Their Diagenesis, *Development in Sedimentology* 12. *Development in Sedimentology*. 1975;12.
- [39] Tucker ME. Black well scientific publ. An introduction. 1985;3.
- [40] Samankassou E, Tresch J, Strasser A. Origin of peloids in Early Cretaceous deposits, Dorset, South England. *Facies* [Internet]. 2005;51(1–4):264–74. Available from: <http://dx.doi.org/10.1007/s10347-005-0002-8>.
- [41] Choquette PW, Pray LC. Geologic nomenclature and classification of porosity in sedimentary carbonates. *Pettijohn, F J*. 1970;54.
- [42] Tucker ME. *Sedimentary petrology: an introduction to the origin of sedimentary rocks*. Blackwell Science, Oxford, and Northampton. 2001;262.
- [43] Machel HG. The geometry and petrogenesis of dolomite hydrocarbon reservoirs. *Brathwaite C.J.R., Rizzi G, Darke G, editors. Vol. 235. Geo. Soc. Lond. Spec*; 2004.
- [44] Sadd J, Alsharhan AUAE, Embry AF, Klovan J. A late Devonian reef tract on northeastern Banks Island. *Bulletin of Canadian Petroleum Geology*. 1971;19(4).
- [45] Lingman, M.W., Carbonate diagenetic textures from upper near surface diagenetic environment. *A.A.P.G. Bull*, 1980; 64(4):461-486.
- [46] Berner RA. *Principles of Chemical Sedimentology*. Mc Graw Hill Book Company; 1971.
- [47] Wilkin RT, Barnes HL. Formation processes of framboidal pyrite. *Geochim Cosmochim Acta* [Internet]. 1997;61(2):323–39. Available from: [http://dx.doi.org/10.1016/s0016-7037\(96\)00320-1](http://dx.doi.org/10.1016/s0016-7037(96)00320-1).

- [48] Al-Badry AM, Stratigraphy G, Of J. Selected Sections-North Iraq. Ph.D. dissertation (unpublished). Vol. 183. Baghdad, Iraq; 2012.
- [49] Dohan AH, Kadhim LS, Hassan FN. Microfacies and Diagenetic Processes of the Late Jurassic Naokelekan Formation in selected wells at Balad, Ajil and Baiji Oilfields, Central Iraq. Central Iraq Tikrit Journal of Pure Science. 2022(4):60–9.
- [50] Daoud HS, Karim KH. Types of Stromatolites in the Barsarin Formation (Late Jurassic). Iraqi Bulletin of Geology and Mining. 2010;6–7.
- [51] Rasool RH, Ali SA, Al-Juboury AI. Mineralogy of the middle to upper Jurassic succession from Sargelu section, northeastern Iraq. Iraqi National Journal of Earth Science. 2023.
- [52] Warren J. Occurrences, evolution and economically important association. Earth Science reviews. 2000;1–81.
- [53] Asaad IS, Al-Juboury AI, Bal Akkoca D, Jha P. Petrography and mineralogy of rinded ferrous-carbonate concretions in the Middle Eocene carbonate rocks: A case study from the Avanah Formation in north-east Erbil City, northern Iraq. Geol J [Internet]. 2022;57(8):3021–32. Available from: <http://dx.doi.org/10.1002/gj.4463>.
- [54] Ali SA, Ismail SA, Nutman AP, Bennett VC, Jones BG, Buckman S. The intra-oceanic Cretaceous (~108 Ma) Kata-Rash arc fragment in the Kurdistan segment of Iraqi Zagros suture zone: implications for Neotethys evolution and closure. Lithos. 2016;260:154–63.