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Mineralogical Implications of the Middle to Upper Jurassic Succession at Sargelu Village in Sulaymaniyah City, Northeastern Iraq

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ABSTRACT

The present study focuses on mineralogy of the middle to upper Jurassic Sargelu, Naokelekan and Barsarin formations form northeastern Iraq to elucidate the implications of mineralogical variation for interpretation of provenance and climatic condition. The results from X-ray diffraction supported by scanning electron microscopy have revealed the presence of calcite and dolomite as dominating minerals, followed by quartz and feldspars in addition to pyrite, anatase and natrolite. The dominated clay minerals are illite-mica, kaolinite and mixed layers of illite/smectite (I/S). Illite and kaolinite are of detrital origin, while I/S is of diagenetic origin. Variation in mineralogical constituents reflects the effect of source area composition, depositional environment and diagenesis and the prevailing climatic conditions. Calcite is commonly formed in restricted evaporative conditions. Felsic igneous rocks from Zagros ophiolites and related igneous rocks, and/or Arabian Shield are suggested for the presence of detrital quartz and feldspars in addition to weathering from older clastic sedimentary rocks. Illite-mica and kaolinite as common clay minerals reflect also the contribution from felsic igneous rocks and the prevailing hot dry and humid climatic conditions which coincides with a global paleoclimatic conditions. Pyrite is formed under reducing environmental conditions. The presence of illite/smectite, natrolite and pyrite suggest the effect of diagenetic events on the studied rocks.

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المؤشرات المعدنية لتتابعات الجوراسي الاوسط الى الاعلى في قرية سركلو بمدينة السليمانية، شمال شرقي العراق

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الملخص

تركزت الدراسة الحالية على معدنية تكاوين الجوراسي الاوسط – الاعلى، وهي ساركلو، ناوكليكان وبارسرين من منطقة ساركلو في شمال شرقي العراق لتوضيح الاختلاف المعدني في تفسير مصدرية وحالة المناخ القديم. النتائج من تحاليل جهاز حيود الاشعة السينية معززة بجهاز الماسح الالكتروني اثبتت بان الكالسايت والدولومايت هما الاكثر شيوعا يعقبهما الكوارتز والفلدسبار فضلا عن وجود البايرايت والاناتيس والناترولايت. المعادن الطينية ممثلة بالالايت – مايكا، الكاؤولينايت، والصفائح المزدوجة من الالايت/ سمكتايت وهي من اصل فتاتي بينما ا الالايت/ سمكتايت من اصل تحويري. الاختلاف في تلك المكونات المعدنية يعكس اصل صخور المصدر وتأثير البيئة الترسيبية والعمليات التحويرية فضلا عن الظروف المناخية القديمة. شيوع الكالسايت دليل على البيئة الترسيبية المعزولة والتبخرية. الصخور النارية الحامضية أوفيوليت زاغروس والصخور النارية ذات الصلة او صخور الدرع العربي هي الاكثر احتمالا لاصل تلك الصخور النارية لوجود الكوارتز والفلدسبار اضافة الى عمليات التجوية من الصخور الفتاتية الاقدم. ان وجود الالايت–مايكا والكاؤولينايت يعكس تغايرا في الظروف المناخية القديمة مابين الحار الجاف الى الرطب ومتوافقا مع التغاير العالمي في المناخ القديم. البايرايت يعكس الوجود في ظروف بيئية مختزلة، بينما يعكس وجود الالايت/ سمكتايت والناترولايت تاثير العمليات التحويرية على الصخور قيد الدراسة.

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Introduction

The location of the study area in Sargelu village-near Dokan town, northeastern Sulaymaniyah City at the coordinates (35° 86' 75'' N- 45 ° 16' 37''E) is shown in figure (1). Tectonically, it is located in the Iraqi part of the Western Zagros Fold–Thrust Belt, at the boundary between the High and Low Folded Zones in the Unstable Shelf of Iraq (Buday, 1980; Jassim and Goff, 2006; Ali et al., 2013) in the Unstable Shelf of Iraq, as illustrated in figure (2).

The Jurassic formations are significant in Iraq because their rocks serve as sources, oil reservoirs, and regional seals. The Jurassic succession in northern Iraq appears to constitute a distinct and significant petroleum system, and recent research has shown that the Sargelu (Middle Jurassic), Naokelekan, Barsarin (Late Jurassic), Chia Gara Formations (Late Jurassic-Early Cretaceous) are the primary sources of oil identified in Iraq's Kurdistan Region (Beydoun et al., 1992; Sadooni, 1997;

Alshididi et al., 1995, Pitman et al., 2004; Al Ahmed, 2006; English et al., 2015; Hakimi et al., 2018; Al-Malaa and Al-Hmeedi, 2020; Omar et al., 2021; Al- Shamary et al., 2023). Compared to Cretaceous and Tertiary rocks, few studies are there on the Jurassic succession. Consequently, the geological information such as geochemistry, mineralogy of Jurassic succession formations has many unknown aspects. This study deals with the mineralogy and geochemistry of the middle-late Jurassic (Sargelu, Naokelekan and Barsarin) formations in Sargelu village, northeastern Iraq. Knowledge of clay minerals and their types and proportions are important in distinguishing depositional, paleo-environmental and paleo-climatic conditions (Chamley, 1989).

This study aims also to investigate the main clay and non-clay minerals and their variation along the studied middle-upper Jurassic succession, and to elucidate the composition of the source area and paleo-climatic conditions affecting the composition of their mineral constituents.

Geological Setting

The middle-late Jurassic formations in Iraq were deposited during the isolation of the main intra-shelf basin of Mesopotamia from the Neo-Tethyan Ocean time possibly due to renewed rifting along the NE margin of the Arabian Plate (Jassim and Goff, 2006; Ali et al., 2016; Ali et al., 2019). The opening of the Neo-Tethys was started during the Permian and Triassic periods and reached its maximum width of 4000 km during the Late Triassic to Middle Jurassic periods (Sadooni and Alsharhan, 2004; Ali et al, 2019; Jones et al., 2020). The basin was bounded to the west by the north-south Rutba uplift. During Middle Jurassic, the deposition occurred in a restricted and deep-water environment, and the basin became evaporitic during the Late Kimmeridgian-Early Tithonian period (Jassim and Goff, 2006; Tobia, 2019)

In the High-Folded, Imbricated, and Thrust Zones of Northern Iraq, the Jurassic rocks commonly appear in isolated patches at certain eroded cores and limbs of anticlines (Numan, 2000; Sissakian and Fouad, 2012) The depositional settings of the studied Jurassic formations in shallow marine restricted intertidal to subtidal and lagoonal environments may relate to the tectonic activity of the region relative to Cimmerian uplift (Buday, 1980) resulting in the formation of small sub-basins (Omar et al., 2020, 2021) within the broader Zagros Basin/Zagros Fold Belt.

In the study section, the Sargelu Formation (middle Jurassic) thickness is about 103 m and made up of bedded bituminous black limestones, dolomitic black limestones, Stomatolitic limestones, and black papery shales with thin layers or streaks of black chert at the top as shown in figure (3). The Sargelu Formation was deposited in a basinal euxinic marine environment (Jassim and Goff, 2006; Abdula et al., 2015; Omar et al., 2023). The late Jurassic Naokelekan Formation is about 16 m thick and composed at its lower unit of laminated argillaceous bituminous limestone alternating with bituminous shale and fine-grained limestone, whereas its middle unit consists of thin-bedded fossiliferous dolomitic limestone referred to as the "Mottled Beds". The upper unit, which is mostly obscured in the type section, consists of thin-bedded, highly bituminous dolomite and limestone with beds of black shale "coal horizons" at the bottom. The lower and upper contacts of the Naokelekan Formation are conformable and gradational with the underlying Sargelu Formation and the overlying Barsarin Formation (Abdula, 2016; Sharezwri et al., 2019). The formation was deposited in two different environments, shallow marine subtidal environment at the lower and upper parts respectively, and the middle part of an outer shelf in a euxinic environment (Al-Malaa and Al-Hmeedi. 2020; Dohan et al., 2022). The thickness of the Late Jurassic Barsarin Formation is about 18 m composing of stromatolitic limestones, dolomitic limestone, argillaceous, alternating shales with contorted and brecciated beds and some of secondary gypsum and anhydrite (Bellen et al., 1959; Jassim and Buday, 2006).

The upper part of the Barsarin Formation is indicated by a confined lagoon, which was deposited in an intertidal environment, whereas its lower part was deposited in a shallow subtidal environment (Daoud and Karim, 2010; Al-Badrani and Al-Humaidi, 2020).

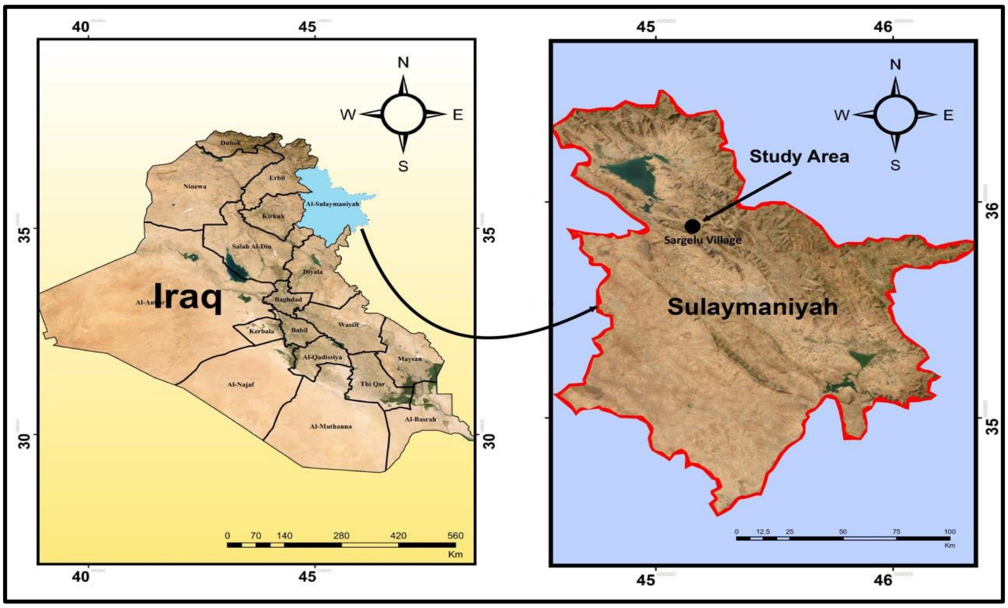

Fig. 1. Location of Studied section.

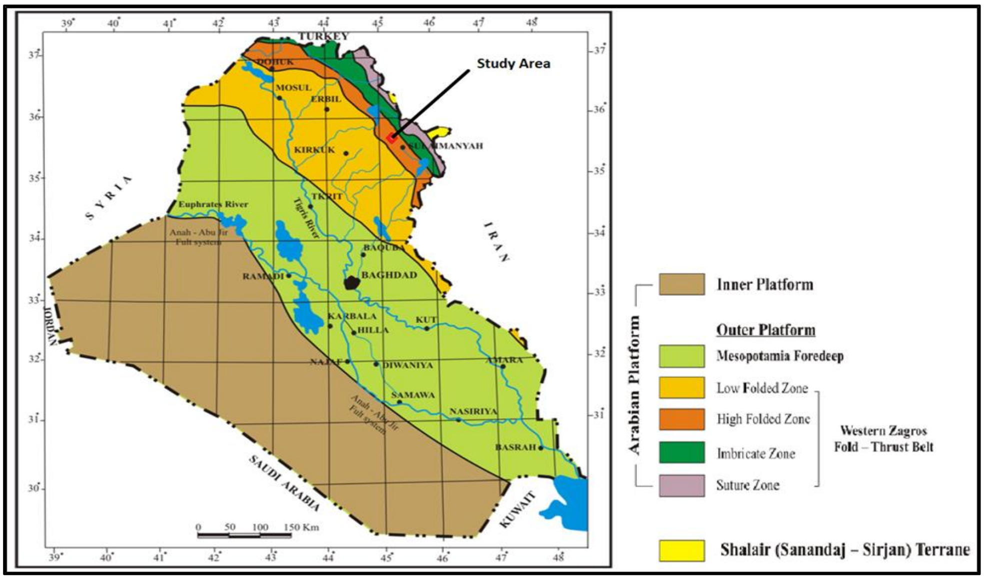

Fig. 2. Tectonic map of Iraq showing the study area (after Fouad, 2015).

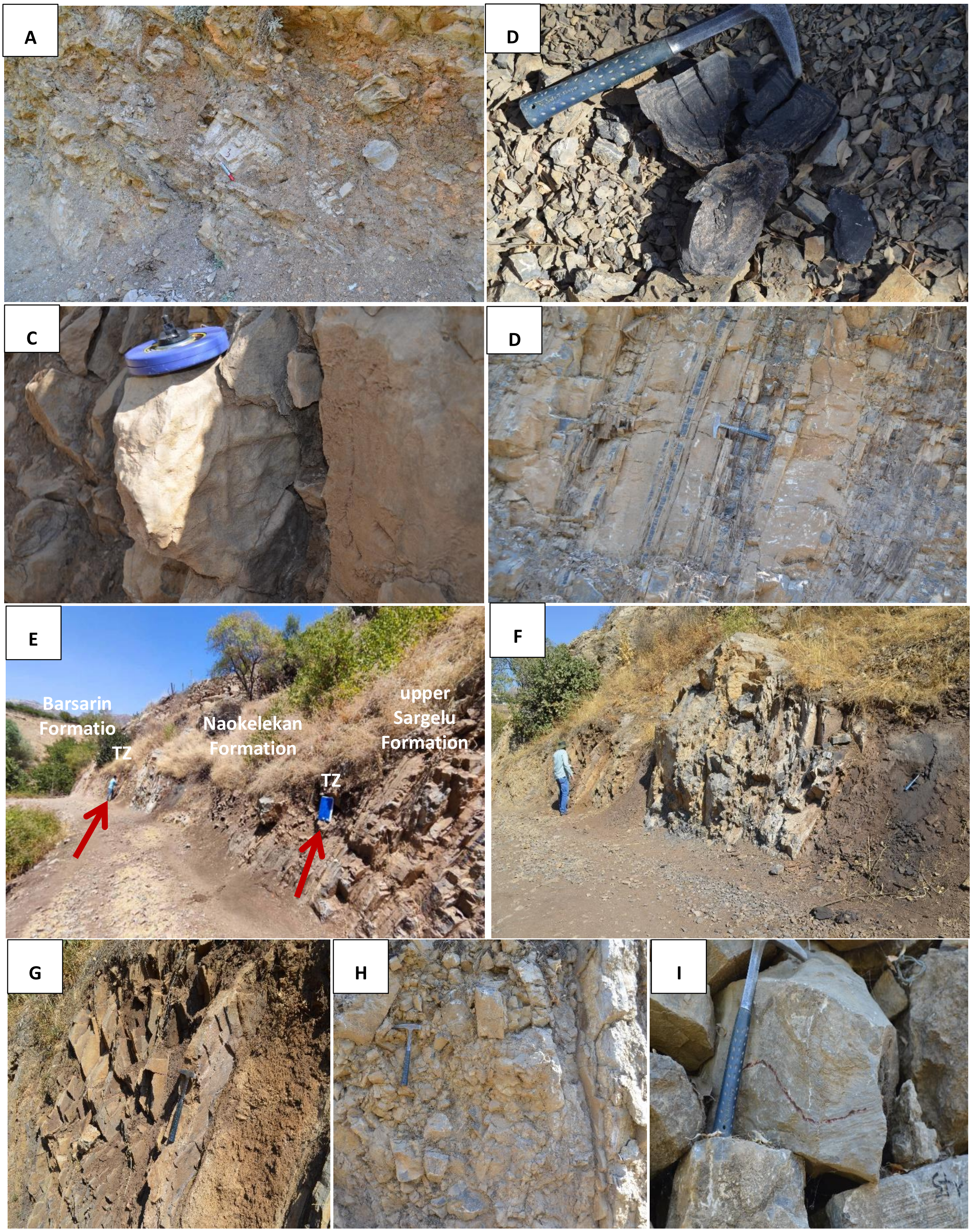

Fig. 3. Field images illustrating A- grey to brown dolostone with rich organic shale TZ between Sehkaniyan and Sargelu formations. B- Domal-shaped stromatolites in Sargelu Formation interlayered with black and grey bituminous limestone. C- Bioturbated limestone in middle part of the Sargelu Formation. D- thin streaks of black chert in the upper part of the Sargelu Formation. E- Sequence of the three studied formations. F- thick layers of bituminous reddish-brown shale rich in organic material and massive bed of grey limestone and argillaceous bituminous limestone alternating with bituminous shale in the lower part of Naokelekan Formation. G- Stromatolitic dolostone in the lower part of the Barsarin Formation (sample Br1). H- Brecciated limestone in the middle part of the Barsarin Formation. I- wavy and parallel grey dolostone in the Barsarin Formation.

Materials and methods

A field trip has been performed to Sargelu village near Dokan, Sulaymaniyah City. Seventy fresh samples have been taken from the Jurassic formations (Sargelu, Naokelekan and Barsarin) and from contact between them, in addition to one sample from the contact between the Sargelu and underlying Sehkaniyan Formation as shown in figure (4). The samples are then prepared for analyses. Mineralogical studies utilizing X-ray diffraction (XRD) and scanning electron microscopy (SEM-EDS) are often used to differentiate mineral components (carbonate and non-carbonate) minerals and different types of clay mineral.

The X-Ray diffraction (XRD) analysis is performed on selected bulk, whole rock samples at Premier Corex Laboratories in Houston, U.S.A. using a Bruker D8 Advance XRD instrument equipped with a theta-theta goniometer with a 250 cm radius and a Lynxeye XE-T detector. All measurements are performed using CuK radiation, and the applied voltage and current were 40 kV and 30 mA respectively. Quantification of mineral phases in the bulk diffraction pattern is accomplished using the TOPAS software package. Scanning electron microscopy (SEM) analyses are completed on selected samples at Premier Corex Laboratories in Houston, U.S.A., using an FEI Quanta FEG 650 FE-SEM instruments equipped with two Bruker EDS XFlash 5030 energy dispersive X-ray spectroscopy (EDS) detectors and an FEI R580 Everhart-Thornley (ETD) electron detector.

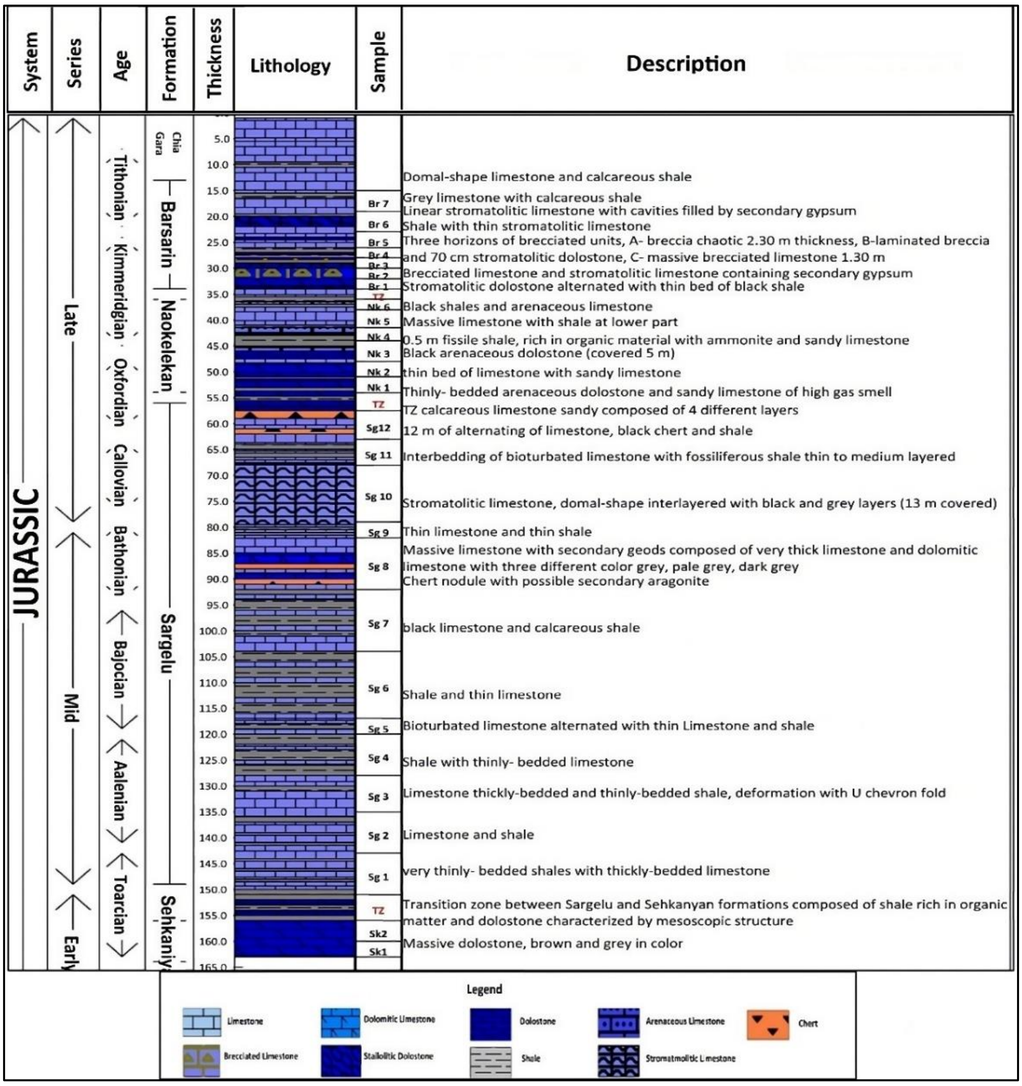

Fig. 4. Lithologic section with description and sample numbers of the studied formations

Results

Mineralogy

The mineralogical study of the middle to late Jurassic formations and the contacts between them has been conducted on 15 sample from shale, limestone and dolostone units. The minerals and their ratios are illustrated in Table (1); these include quartz, plagioclase, K-feldspar, calcite, dolomite, Fe-dolomite (ankerite), anatase, pyrite and natrolite. The clay minerals are represented by mixed-layers illite/smectite, illite (mica) and kaolinite (Table 1). Representative XRD diffractograms are illustrated in figure (3).

Calcite is the most abundant mineral in all the studied formations followed by quartz as depicted in Table (1), while dolomite is recorded mainly from the Naokelekan Formation. This is supported by the petrographic study that shows common dolomitization process affecting on the rocks of the Naokelekan Formation (Rasool et al., 2023). Below is a description of the minerals recorded in the currents study.

Non-Clay Minerals

1. Carbonate minerals (calcite, dolomite, Fe-dolomite ‘ankerite’)

XRD analysis reveals that calcite is the dominant non-clay (carbonate) mineral in all the studied formations (Fig. 5). Calcite forms 40% in the shale sample of the transition zone between lower and middle Jurassic (Sehkaniyan and Sargelu) formations with absence of both dolomite and Fe-dolomite, while calcite ranges between 55-64% with an average 58.3% accompanied with traces of dolomite and Fe-dolomite, which are recorded in 0-2%, 0-3% respectively in the four samples analyzed from the Sargelu Formation. In the Transition zone between Sargelu and Naokelekan formations, sample (TZ-2A), the carbonate minerals significantly change with high content (28%) of dolomite, 7.3% Fe-dolomite and 37% calcite as shown in Table (1) and figure (5 C).

The high average of dolomite and Fe-dolomite continues to the middle part of the Naokelekan Formation, where the average ratio in both samples Nk-1 and Nk-3 is 51.5% and 8.6% respectively, while the calcite average is 14.8% in these two samples.

In contrast, the upper part of the Naokelekan Formation shows fluctuation in the carbonate minerals content as recorded from sample Nk-4 to Nk-6, where the calcite is the dominate mineral with an average of 85.9% with no significant value for dolomite as shown in Table (1). The average of calcite in the upper Jurassic Barsarin Formation is 77.4% ranging between 47-94% with traces of dolomite as depicted in figure (5 A).

In SEM images (Figs. 6 and 7), calcite is observed in several forms, scattered calcite fragments (Fig. 6 a,b), euhedral hexagonal, star-shaped Mg-calcite microcrystals (Fig. 4 c), columnar and euhedral (rhombohedral) calcite (Fig. 6 d, e), while dolomite exists in rhomb shape (Fig. 7 b) and coccolith nannofossil shells filling with blocky calcite (Fig.7 c).

2. Framework Silicates

Quartz

Quartz is 7.3% recorded in the transition zone between the Sehkanyan and Sargelu formations (Table 1), while the average content of quartz is 13.6 % (range 6.4 –29%) in the Sargelu Formation as shown in Table (1). In the transition zone between the Sargelu and Naokelekan formations, quartz content is 12.8%, whereas, the average content of quartz decreased in the Naokelekan Formation to average of 3.5% with a range 0.9-7.7% (Table 1). However, in the Barsarin Formation, the average content of quartz is 6% with range between 1.3-13.9%. In SEM images, quartz is present in irregular shape of sub-hederal to sub angular crystal with conchoidal fracture and etch pits (Fig. 7 e, f).

Feldspars (Alkali K-feldspar and plagioclase)

Feldspars in the form of both alkali K-feldspar and plagioclase feldspars are recorded in the studied Jurassic formations with variable content. The average of 1.6% feldspars (0.6% plagioclase and 1% K-feldspar) of the whole bulk sample in TZ1A which represents the contact between the Sargelu and Sehkaniyan formations. The same average (0.6%) is recorded for both K-feldspar and plagioclase content in the Sargelu Formation as shown in Table (1). An abrupt change in the feldspar content occurred in the contact between the Sargelu and Naokelekan formation, where it increases to 4% in sample TZ-2A as depicted in Table (1). This increase in feldspar content continues in the lower part samples of the Naokelekan Formation, where it is recorded 4.6% and 4.2% in samples NK1 and NK3 respectively, and also in sample NK6 (3.6%) from the upper part of the Naokelekan Formation, while it is recorded 0.3-0.5% in the samples from the middle part of the formation. Both feldspar minerals decrease in the Barsarin Formation to trace-1.2% content as shown in Table (1).

Other minerals (Anatase, Pyrite and Natrolite).

These minerals are depicted by XRD in figure (5) and Table (1).

Anatase

Anatase is present in all the studied formation but with low percent rarely exceeds 0.5% depicted by XRD analysis as shown in figure (5 A, E) and Table (1).

Pyrite

Pyrite is frequently present in the Sargelu Formation as compared to Naokelekan and Barsarin formation, supported by results from petrographic study (Rasool et al., 2023). It ranges between 0.2-0.4% with an average 0.3% in the four analyzed samples from the Sargelu Formation (Table 1). Pyrite is also recorded from the upper part of the Naoklekan Formation, sample Nk6 with 0.2%. While traces-0.3% of pyrite is recorded in the Barsarin Formation as shown in figure (5 B, D) and Table (1).

Natrolite

Natrolite appears in the last sample of the Sargelu Formation, transition zone between the Sargelu and Naokelekan formations and in the first sample of the Naokelekan Formation with content of 3.0, 2.0 and 1.6 % respectively as shown in figure (5 B, C) and Table (1), while no any significant content of the mineral is recorded in other analyzed samples.

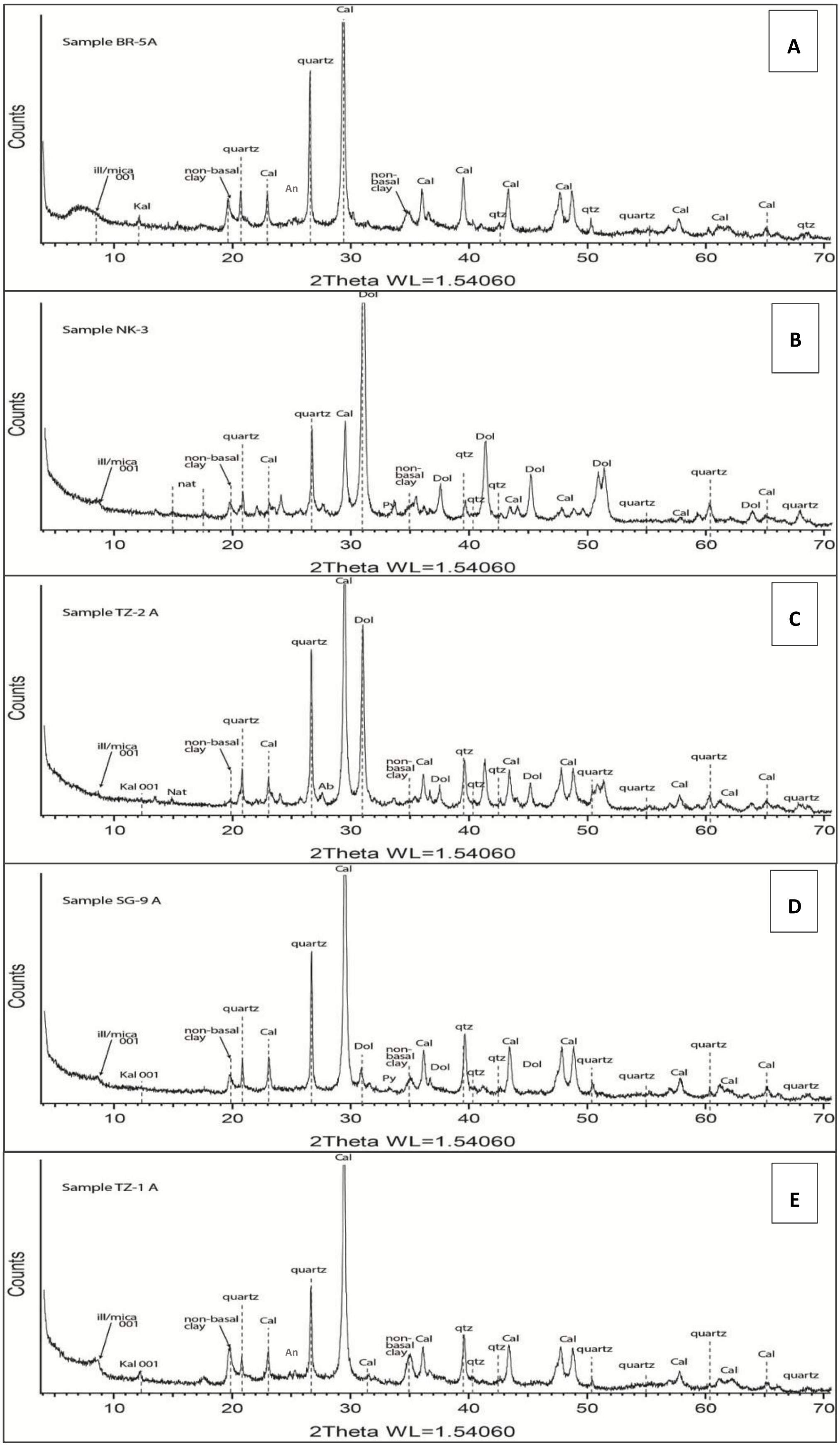

Fig. 5. X-ray diffraction for selected bulk whole rock samples. Kao= Kaolinite, Nat=Natrolite, Cal=Calcite, Dol= Dolomite, Py= Pyrite, An= Anatase

Table 1. XRD results of representative bulk samples showing the mineralogical components.

Sample	Formation	Framework Silicates			Carbonate			Others			Total	Clay Mineral			Total %
		Quartz %	Plagioclase %	K-feldspar %	Calcite %	Dolomite %	Ferroan dolomite (ankerite) %	Anatase %	Pyrite %	Natrolite %		Mixed Layers Illite/Smectite %	Illite+Mica %	Kaolinite %	
Br-7 B	Barsarin	1.3	0.4	0	94	0	0	0	0	0	95.7	2.3	0.8	1.2	4.3
Br-7 A	Barsarin	3.3	Trace	Trace	91.2	0.4	0	Trace	Trace	0	94.9	3.5	Trace	1.6	5.1
Br-5 A	Barsarin	13.5	1.2	0	47	0	0	0.5	0.3	0	62.9	21.7	10	4.4	36.1
Nk-6 A	Naokelekan	3.9	0	3.6	66.8	0	0	0.3	0.2	0	74.8	25.2	Trace	0	25.2
Nk-5 B	Naokelekan	0.9	0.3	0	94	0	0	0	0	0	95.2	0.7	3.7	0.4	4.8
Nk-5 A	Naokelekan	1.1	0.3	0	92	0	0	0	0	0	93.4	0.8	5.8	0	6.6
Nk-4 A	Naokelekan	2.3	0.5	0	90.6	0	0	0	0	0	93.4	1.4	5.2	0	6.6
Nk-3	Naokelekan	7.7	1	3.2	13	52	5.5	0.2	0	1.6	84.2	1	14.8	0	15.8
Nk-1	Naokelekan	5	1.2	3.4	16.5	51	11.7	0.2	0	2	91	0.4	8.1	0.5	9
TZ-2 A	Transition Zone	12.8	1	3	37	28	7.3	0	0	3	92.1	0	6.7	1.2	7.9
Sg-12 A	Sargelu	29	0.6	0.9	57	0	0	0.2	Trace	0	87.7	3	9.3	0	12.3
Sg-9 A	Sargelu	12	1	0.4	55	2	3	0.2	0.4	0	74	4	21	1	26
Sg-4 A	Sargelu	6.4	0.3	0.5	64	0	0	0.4	0.2	0	71.8	3.5	17.3	7.4	28.2
Sg-2 A	Sargelu	7	0.3	0.5	57	0.3	0	0.3	0.2	0	65.6	4	22.2	8.2	34.4
TZ-1 A	Transition Zone	7.3	0.6	1	40	0	0	0.2	0.2	0	49.3	0	46.3	4.4	50.7

Clay minerals

The main types of clay minerals, which are distinguished by the XRD in the current study are kaolinite, mixed-layers illite/smectite, illite + mica as shown in Table (1) and figure (5)

Kaolinite

Kaolinite is found in the transition zone between the Sehkaniyan and Sargelu formations with 4.4%. In the Sargelu Formation, the average of 4.2% and range (0-8.2%) is recorded as illustrated in Table (1) and figure (5 A, C, D, E). Kaolinite is defined in SEM analysis in plates as degraded kaolinite (Figure 6 c, d and 7e).

In the transition between Naokelekan and Sargelu formations, kaolinite is present in 1.2%. In samples Nk1A and Nk5B, while in the Naokelekan Formation, it is present in 0.5% and 0.4% from the lower and upper parts of the Naokelekan Formation respectively. In the Barsarin Formation, kaolinite exists with range 1.2-4.4% and an average 2.4%.

Illite-Mica

Illite-Mica is the dominant mineral in the present study, it is recorded in all the analyzed samples of the studied formations with different ratios. In the transition zone between Sehkaniyan and Sargelu formations, the higher value is 46.3% of total bulk sample is recorded. While in the Sargelu Formation, an average content of 17.5% and range between 9.3-22.2% is seen. The illite-mica decreases at the contact zone with Naokelekan Formation to 6.7%, whereas in the Naokelekan Formation an average of 7.5% and range from trace-14.8% is recorded. In the Barsarin Formation, illite-mica is recorded in 5.4% as average in the samples Br5A and Br7B, with trace content in sample Br7A. In SEM images, illite-mica is observed in fibrous and flaky habits (Figs. 6 a, b, c, f and 7 a, d, e, f)

Mixed layer illite/smectite (I/S)

The mixed layer illite-smectite is distributed and recorded among all the studied formations, while it disappears in the transition zone between the formations (samples TZ-1A and TZ-2A) respectively. The average of I/S in the Sargelu Formation is 3.6 % and ranges from 3.6-4%. In the Naokelekan Formation, an average of 4.9% with ranges 0.4-25.2 % is recorded. In the Barsarin Formation, the highest ratio of 21.7% is recorded and the lowest ratio is 2.3%. Scanning electron microscopic study has revealed that I/S exists in matted crenulated plates (Figs. 6 d, f and 7 e, f).

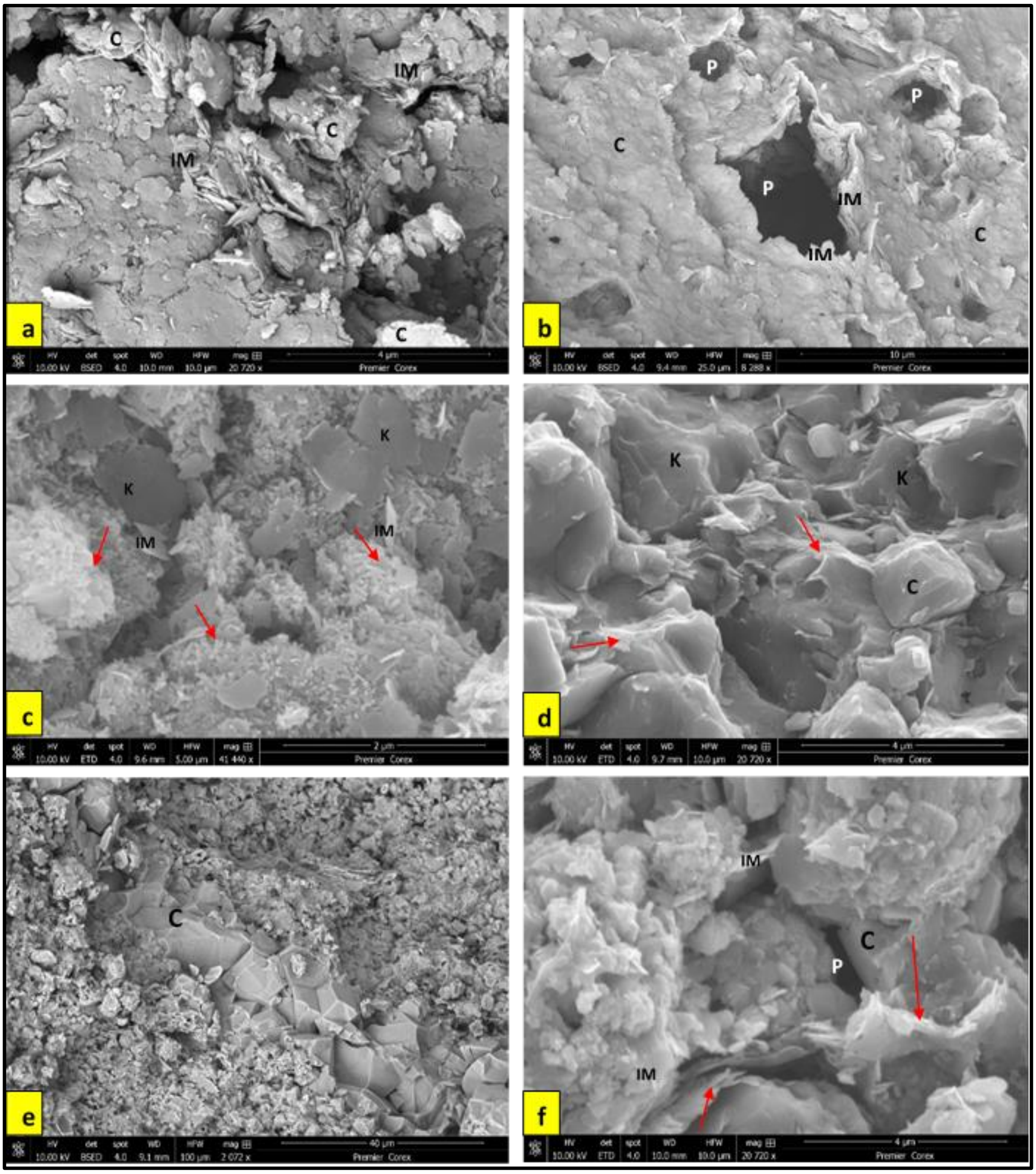

Fig. 6. Scanning electron microimages (SEM) illustrating: (a) Common clay mineral of flaky illite-mica (IM) sheets and scattered carbonate grains (C) in sample TZ−1A. (b) Common pores (P), and illite-mica (IM) with common carbonate (C) in sample TZ−1A. (c) Star-shaped Mg-calcite microcrystals (red arrows) and, flat-lying platy crystals of illite-mica sheets (IM) and degraded kaolinite (K) in sample TZ−1A. (d) Euhedral calcite crystals (C), eroded edges of degraded kaolinite (K), with matted crenulated illite-smectite mixed layers (red arrows) in sample Sg−4A. (e) Micro vein including cluster of calcite crystals, hexagonal, columnar and euhedral (rhombohedral) shapes in sample Sg−4A. (f) Fibers of illite-mica (IM) and matted illite-smectite crenulated plates (red arrows), calcite crystal (C), and dissolution signs or pores (P) in sample Sg−4A

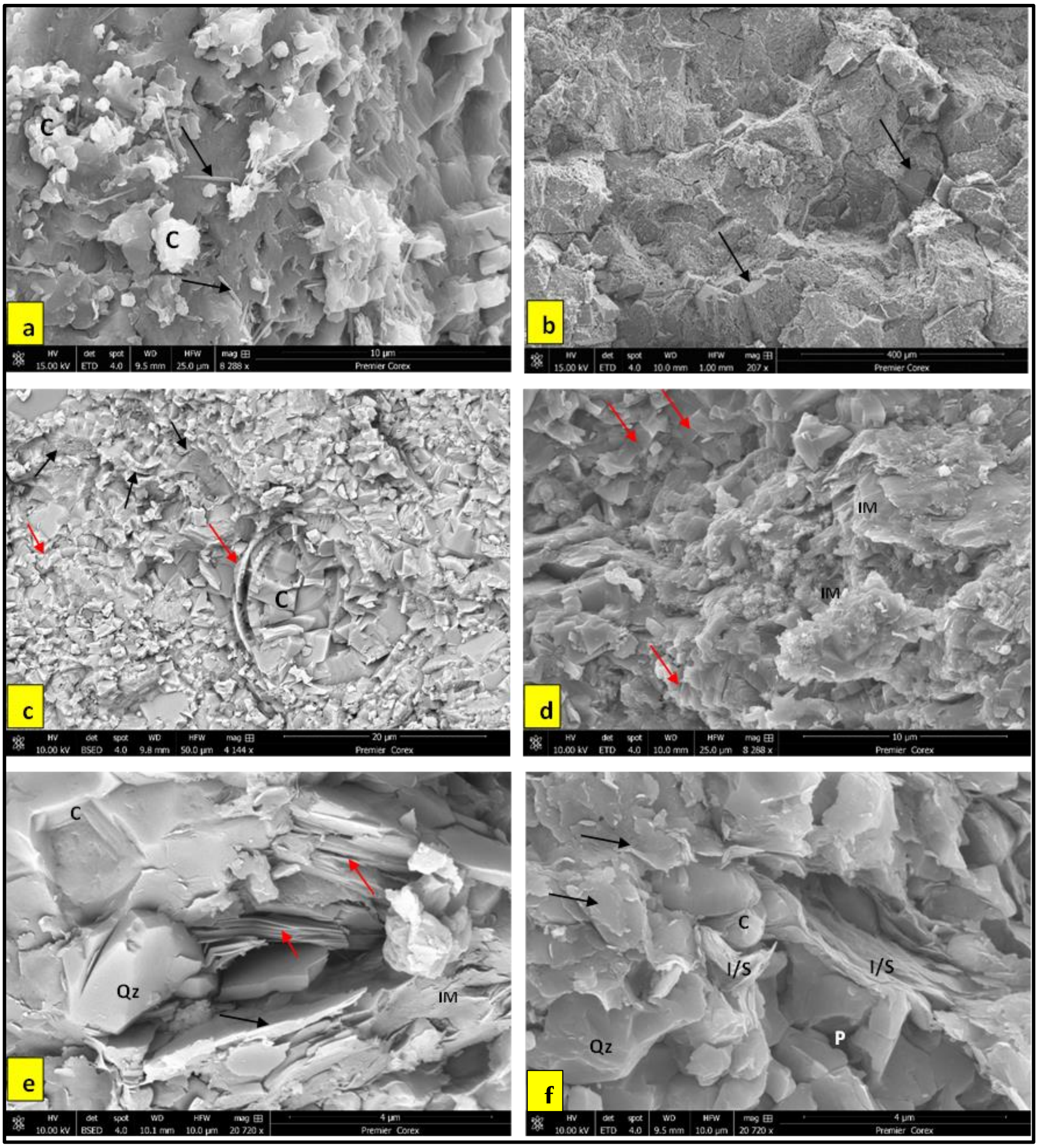

Fig. 7. SEM images illustrating: (a) Illite fibers (arrows) and scattered calcite fragments (C) in sample Nk−1A (b) dolomite rhombs (arrows) in sample Nk-1A (c) Coccolith shell (red arrow) filled with blocky calcite cement (C) with other fossil shells (black arrows) in sample Nk−4A. (d) recrystallization of very fine calcite crystals (red arrows), flakes of illite-mica (IM) in sample Nk−4A. (e) Kaolinite booklets (black arrow), illite mica (IM), illite –smectite matted long flakes (red arrows) and cluster of calcite with etch pits (C) and quartz (Qz) in sample Br−5A (f) Crenulated flakes illite-smectite (I/S), illite-mica lath (black arrow), calcite fragments (C), Quartz grains (Qz) in irregular shape and pores (P) in sample Br−5A

Discussion

The study of mineralogical composition of middle-late Jurassic succession in Sargelu area reveals variation in mineralogical components as illustrated in figure (8). The presence of calcite reflects the deposition in such evaporative conditions (Warren, 2000; Al-Haj et al., 2019). Clay mineral types inferring the prevailing climatic conditions at the time of sedimentation and the weathering conditions in the sedimentary basin (Chamley, 1989). Fractionation in clay minerals is related to climatic conditions, tectonic events, and modulatory processes related to pressure and temperature and geochemical interactions (Weaver, 1989).

In general, the relative high proportion of quartz especially in the upper part of Sargelu Formation and in the middle part of Barsarin Formation indicates that the source rocks are rich in quartz of detrital origin, which may reflect contribution by weathering from older sedimentary clastic rocks rich in quartz (Buday, 1980). Detrital origin of quartz is supported by irregular shapes of the grains and presence of dissolution etch pits surface textures on the quartz grains as revealed from SEM images (Fig. 7e, f) as a result from differential dissolution during transportation (Zhu et al., 2021). Gradual increase in quartz from the middle Jurassic Sargelu Formation to late Jurassic Naokelekan Formation is obvious in figure (8). This may relate to more detrital influx by gradual increase of weathering from older sources as confirmed in the middle to upper Jurassic formations from northern Iraq (Tobia et al., 2019; Mena and Abdula, 2023) who also concluded that the main source rocks of the Sargelu and Naokelekan formations are felsic and felsic-intermediate igneous rocks supplied from the Mid Oceanic Ridge and deposited in an active setting.

An abrupt increase of silica and/or quartz in sample (Sg12), the last sample in Sargelu Formation and the transition zone with the Naokelekan Formation in sample (TZ-2A) may relate to presence of chert layers (see Figure 4 and Table 1). The percent of feldspar in the same trend in figure (8) also refers to the influx by weathering and/or sediment supply from older sedimentary rocks. The presence of quartz and feldspars reflects the contribution from older clastic sedimentary rocks in the region, in addition to source area rich in felsic igneous rocks (granite) (Mahdi et al., 2021; Rasool et al., 2023) such as the Zagros ophiolites and related igneous rocks (Buday, 1980, Jassim and Goff, 2006).

The increase in clastic minerals (quartz, chert, feldspar) as a result of increasing in weathering and or erosion can be attributed to perturbation events operating gradually before deposition of the Naokelekan Formation (Harris et al., 2017, Dai et al., 2022).

Pyrite is frequently found in sediments that have undergone diagenesis in an alkaline reducing environment (Hanjo et al., 1965). Pyritization, which results in the formation of various crystal forms of pyrite, occurs under reducing conditions and is likely aided by the breakdown of organic materials, which is then brought on by anaerobic bacteria, or by the solution of sulfate caused by reducing bacteria (Hudson, 1982).

Anatase is one polymorph of three TiO_2 phases found in rocks, along with rutile and the rarer phase brookite, it can be found in sedimentary rocks from a variety of environments (Papineau et al., 2017).

Natrolite is a common zeolite found in cavities and veins in altered basaltic rocks, but there are also occurrences as diagenetic alteration products in sedimentary rocks. Presence of natrolite in some of the studied sample conjugated with high values dolomite, ankerite and feldspars especially K-feldspar could indicate that the carbonate rocks were exposed to strong diagenetic processes (Deer et al., 2004).

Kaolinite refers to deposition in humid tropical climate, while illite, chlorite and smectite are present and developed in areas with dry climates (Grim, 1968, Singer 1984, Weaver 1989, Chamley, 1989).

Most of the clay minerals in the studied samples are of detrital origin as revealed by presence of degraded kaolinite (Fig. 6 c) and scattered flakes and fibers of illite (Fig. 7 a), whereas, the presence of long matted illite/smectite flakes (Fig. 7 e, f) reflects the diagenetic source as indicated by many authors (e.g., Singer, 1984; Chamley, 1989).

High amount of illite-mica at the transition zone between the lower Jurassic Sehkaniyan Formation and the Sargelu Formation (TZ-1A sample) may reflect the prevailed hot dry conditions, which changed to more humid conditions in the lower part of the Sargelu Formation by increasing amount of kaolinite (Fig. 8). The variation between the dry and humid conditions continues during the upper part of the Sargelu Formation, while dry and hot condition was prevailed during the deposition of the Naokelekan Formation as suggested by the high amount of illite as compared to kaolinite content.

The dry condition in the Naokelekan Formation is promoted by relatively high amounts of dolomite and ferroan dolomite as shown in figure (8) in this formation. Dolomite is a common mineral that formed in hot and dry conditions (Warren, 2000). In the Barsarin Formation, the same trend of hot and humid conditions also prevailed as inferred from the presence of both illite and kaolinite clay minerals. Furthermore, warming and aridity during the Jurassic across the region of northern Iraq coincided with a global warming that governed the Jurassic period (Hallam, 1982; Chao et al., 2021; Omer et al., 2023).

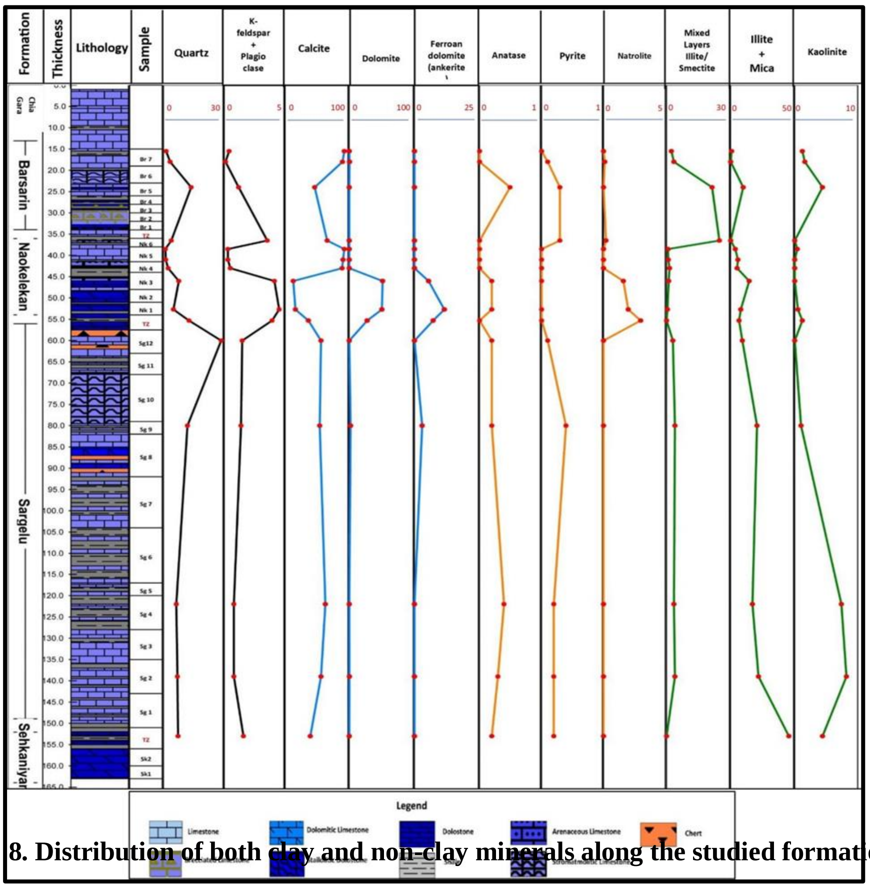

Fig. 8. Distribution of both clay and non-clay minerals along the studied formations.

Conclusions

The variation in mineralogical composition of the middle to upper Jurassic succession from northeastern Iraq reflects the effect of depositional environment, diagenesis, source area composition and the prevailing climatic conditions during the deposition of the Sargelu, Naokelekan and Barsarin formations. The common calcite reflects the restricted and evaporative environmental deposition. The presence of both quartz and feldspars with conjugated traces natrolite reflects the contribution of felsic igneous rocks and may relate to a provenance dominated by felsic rocks from the Zagros ophiolites and related igneous rocks and/or Arabian Shield in addition to weathering from older sedimentary rocks. The dominance of illite-mica and kaolinite clay minerals also reflects the contribution from felsic igneous rocks under prevailing climatic conditions characterized by variation between hot arid and hot humid climates which coincides with the global paleoclimatic conditions.

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