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Investigation of Sedimentary Microfacies and mineralogical analyses of the Coastal Rock Cliffs (Wadi al-Zaytoun) in the Al Jaghbub, Al Faidyah, and Abraq Formations, NE Libya

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A B S T R A C T

This study analyzes the bulk mineralogy and microfacies of the Al Jaghbub, Al Faidyah, and Abraq Formations, NE Libyaalong the Eastern Libya coastline using X-ray diffraction (XRD) on five samples from different geomorphological units. The results show a dominance of terrigenous minerals—mainly quartz, albite, and kaolinite—alongside carbonate minerals (calcite and dolomite) and evaporite minerals, particularly halite. Quantitative analysis reveals significant mineral proportion variations Al Abraq Formation contains high levels of dolomite (87.9%) and albite (7.9%), while Al Faidiyah Formation is predominantly calcite (98.9%). Halite appears in All Formations, indicating evaporative processes, and kaolinite in Sample 3 suggests fluvial influence or older sediment reworking. Microfacies analysis, conducted on thin sections from Wadi al-Zaytoun, identified five types: (1) dolomite wackestone, (2) foraminiferal bioclast packstone, (3) dolomitic wackestone, (4) foraminiferal bioclastic packstone, and (5) echinoidal, foraminiferal, algal packstone.

These microfacies display features indicating deposition in various environments, ranging from arid tidal flats to high-energy shallow marine settings. Diagenetic processes such as the replacement of micritic matrices with sparry calcite and the formation of coarse dolomite crystals highlight the roles of fluid migration and redox fluctuations.

1 Introduction

One of the valleys closest to Tobruk, Wadi Al-Zaytoun, is considered a significant site for geological research due to the presence of exposed rock cliffs that offer valuable insights into the region's stratigraphy and depositional history. Previous geological investigations have focused on various wadis and coastal areas in northeastern Libya, revealing important information about the composition, mineralogy, and depositional environments of these formations. El Ebaidi et al. (2017) conducted a comprehensive geochemical analysis of the geological formations at Wadi Al-Hash, Wadi Al-Shaikh, and Wadi Al-Rahib, all located in the northeastern region of Libya. Their analysis focused on the major and trace element compositions of these formations, which span geological periods from the Late Cretaceous to the Late Miocene. The study concluded

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that the limestone formations in these wadis range from impure to highly pure limestone, containing both carbonate and non-carbonate minerals. The predominant carbonate minerals include calcite and dolomite, while non-carbonate minerals such as quartz, clay, halite, hematite, and glauconite are also present. Masoud et al. (2020) expanded on this research by investigating the mineralogical composition of geomorphological units along the Tobruk coastline. Their study covered a variety of landforms, including rock cliffs, beach sands, sand dunes, and beach rocks, focusing on the area from Wadi Ras Buiad in the east to Wadi Al-Sahal in the west. The analysis revealed that calcite is the dominant carbonate mineral in the rock cliff terraces. However, in beach rocks, the presence of dolomite and aragonite, along with high-Mg calcite, indicates that these beach rocks were formed relatively recently from beach sands, suggesting an active interaction between marine and terrestrial processes. Masoud et al. (2021) continued this line of inquiry by analyzing coastal formations from Wadi Al-Sahal to Wadi Halmy along the Tobruk coastline. Their study identified a diverse range of microfacies, reflecting distinct depositional environments. The microfacies identified include ooid rudstone (grapestone), echinoderm wackestone, algae-echinoderm packstone, sandy peloid packstone, echinoderm-bivalve grainstone, mixed grainstone, echinoderm-bivalve floatstone, and echinoderm-algae rudstone. These microfacies provide critical information on the paleoenvironments and sedimentary processes that influenced the coastal region's evolution. Masoud and Khameiss (2024) conducted an in-depth analysis of the coastal region of Wadi Al-Suwani in the Al-Bardia area, east of Tobruk City. Their research focused on the bulk mineralogy and composition of sabkha deposits, rock cliffs, and beach sands. They identified that the cliffs are primarily composed of carbonate rocks associated with the Al Abraq, Al Faidiyah, and Al Jaghbub Formations. Calcite is the dominant mineral in the rock cliffs, but traces of quartz and halite were also observed. The study's findings highlight the significance of coastal processes in shaping the mineralogical composition of these features. *Echinopora gemmacea,* a scleractinian coral species from the Early-Middle Miocene (Langhian-Serravallian), was discovered and described by Khameiss et al. (2024) in the Tobruk area of northeastern Libya, specifically within the Al Jaghbub Formation. This coral is notable for its extensive temporal and spatial distribution, with records spanning from the Miocene to the Holocene in the Red Sea, North Africa, and Southeast Asia. Such a broad geographic range highlights the species' remarkable adaptability to diverse environmental conditions. The presence of *Echinopora gemmacea* in the Miocene formations of Libya offers critical insights into coral taxonomy, reef ecology, and the paleogeographic evolution of the Mediterranean-Tethys region. This coral thrived in shallow, warm, subtropical reef ecosystems, typically within the upper photic zone. These environments were characterized by stable marine salinity, clear waters, and firm, consolidated substrates—conditions essential for the growth and development of reef-building corals. The discovery of this coral species in Libya underscores the significance of the region as a key biogeographic link in understanding the broader evolutionary and ecological history of Miocene coral reefs in the Mediterranean and adjacent regions. El-Ekhfifi et al. (2017) analyzed the foraminiferal and mineralogical components of beach sands from the Tobruk coastline. Their results revealed a high abundance of benthic foraminifera, with sediment grain sizes ranging from fine to coarse. The carbonate content of the beach sands varied between 60% and 95%, while the detrital quartz and feldspar content ranged from 5% to 40%, reflecting the influence of erosional processes. The study linked these characteristics to the action of ocean waves, which transport sediments that are subsequently reworked by wind, forming calcarenite exposures in the surrounding areas. Muftah et al. (2017) investigated the geological characteristics of Wadi Al-Rahib in the Al-Bardia area, as well as Wadi Al-Hash and Wadi Al-Shaikh in the Tobruk area. Their study identified a significant transgressive event at the base of the Oligocene-Miocene Al Faidiyah Formation. This event is marked by a disconformity surface separating the Al Faidiyah Formation from the underlying Middle Eocene Darnah Formation. Additionally, the researchers documented a disconformity surface between the Al Jaghbub Formation and the Al Faidiyah Formation, indicating a brief hiatus in sedimentation between these two units. These findings provide crucial insights into the stratigraphic framework and paleoenvironmental evolution of northeastern Libya. Collectively, these studies underscore the geological significance of the Tobruk region and its surrounding wadis. The diverse range of microfacies, mineralogical compositions, and stratigraphic relationships provide a comprehensive understanding of the depositional history and diagenetic processes in this part of Libya. Such research contributes to broader geological knowledge, with implications for resource exploration, sedimentological analysis, and coastal geomorphology.

1.1 Location of the study area:

The study area is located approximately 25 kilometers east of Tobruk city, along the Mediterranean Sea coast in eastern Libya. It is situated between latitude 32º 01′ 01″ N and longitude 24º 04′ 47″ E. The region is traversed by several wadis that drain into the Tobruk coastal plain, which extends several kilometers inland. These wadis, often referred to as "drowned valleys," are geomorphological features formed during Late Quaternary geologic events, specifically during periods of falling sea levels. They play a significant role in shaping the coastal zone and contributing to its sediment load. The coastal landscape is marked by highly eroded sea cliffs that enclose pockets of sandy beaches, creating a dynamic and varied shoreline. From a geological perspective, the area is composed of three distinct formations: Al Abraq Formation, Al Faidiyah Formation, and Al Jaghbub Formation (Fig. 1). These formations reflect the complex geological history of the region and provide valuable insights into the stratigraphy, sedimentology, and paleoenvironmental evolution of the eastern Libyan coast.

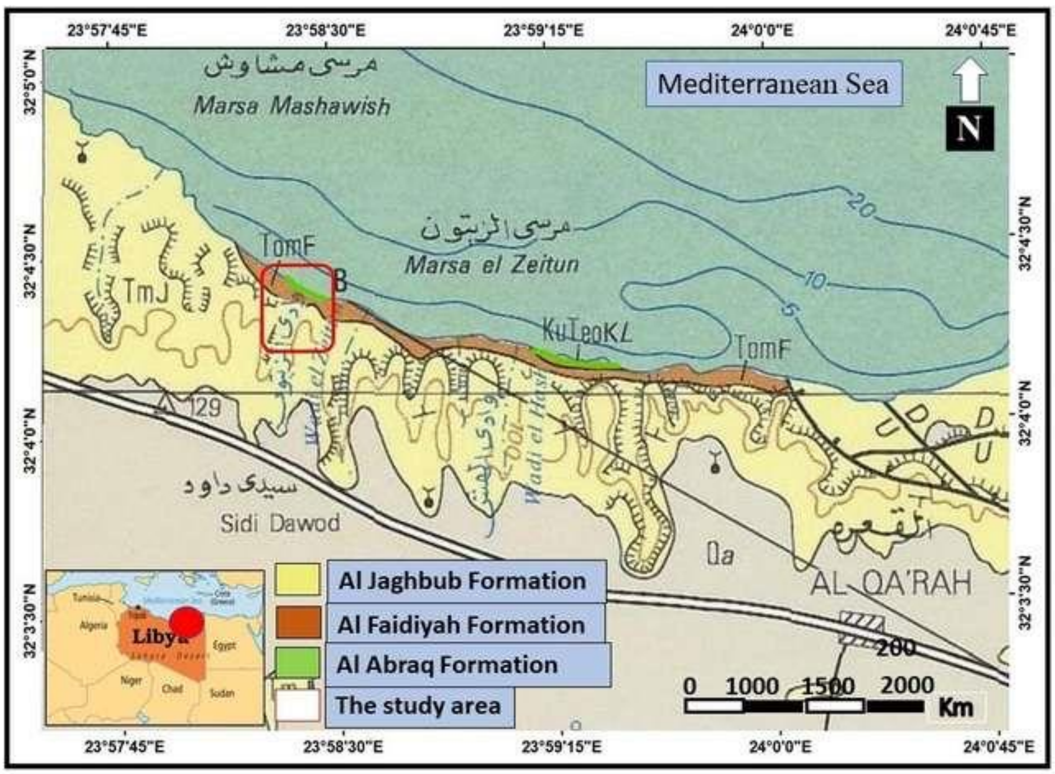


Fig. 1. Skitch map of northeastern Libya showing the location of the study area. (Modified from In Research Canter, 1977.

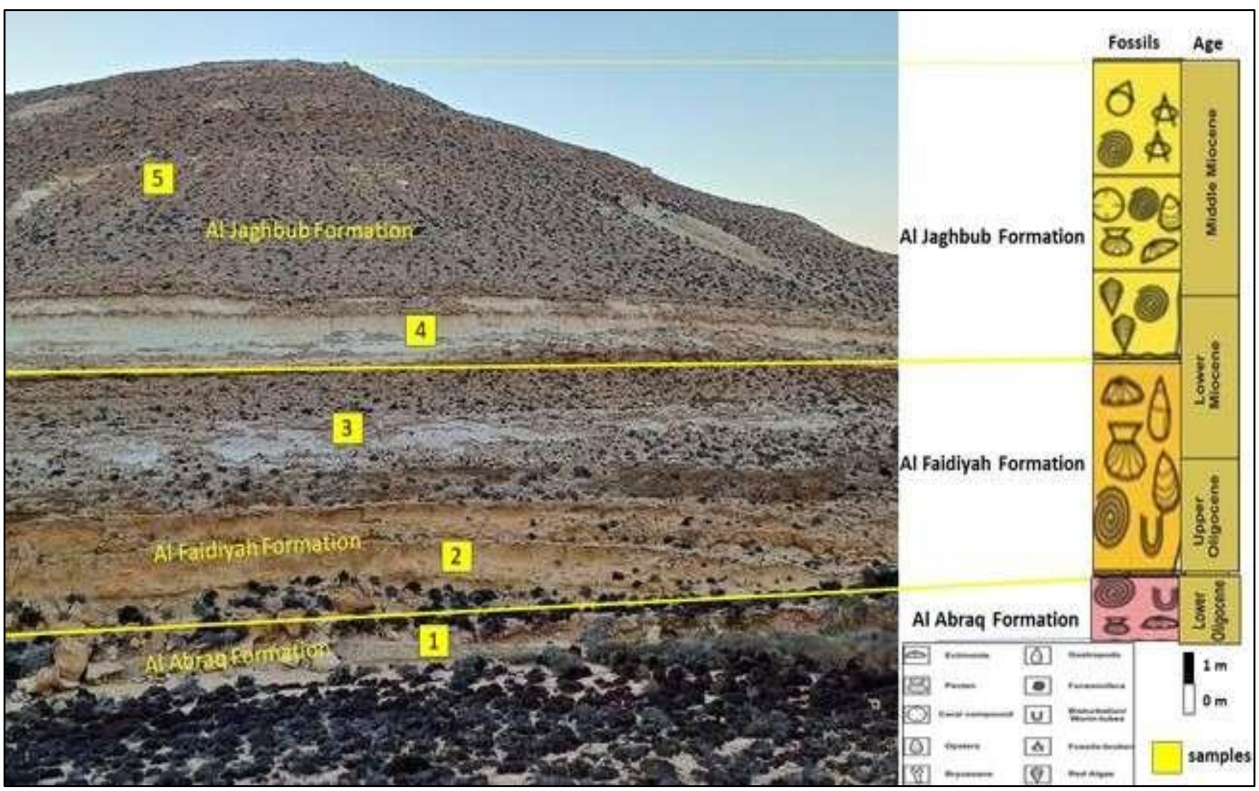
1.2. Geological Formations of the Tobruk Area

The Al Abraq Formation (Lower Oligocene) is a prominent lithostratigraphic unit in the Tobruk area, measuring approximately 36 meters in thickness. Its type of section is located 4 km north of Al Abraq town in Cyrenaica (Banerjee, 1980). The formation is composed of interbedded dolomitic limestone, dolomite, marl, and calcarenitic limestone, with the presence of significant slump structures and contorted bedding observed west of Wadi al Kuf, indicating lithological variability due to Oligocene-Miocene sea-level fluctuations (Banerjee, 1980). In Cyrenaica, the base of the Al Abraq Formation contains nummulitic limestone intercalated with algal limestone, marly deposits, and glauconitic clayey siltstone (Abdulsamad et al., 2009). Additionally, rocks once classified as the Al Khowaymat Formation are now recognized as part of the Al Abraq and Darnah Formations in the Tobruk area, while in Al Burdi, these rocks correlate with the Cretaceous Chalk and Al Abraq Formation (Megerisi & Mamgain, 1980).

The Al Faidiyah Formation (Upper Oligocene–Lower Miocene) represents the oldest exposed Miocene rock unit in the Tobruk region. Its lithology is marked by fossiliferous clay beds, marly limestone, and thick to thin limestone beds. This unit contains a diverse assemblage of fossils, including serpulid worm tubes, echinoids, oysters, Operculina complanata, and Lepidocyclina species, reflecting a shallow marine depositional environment (El Deftar & Issawi, 1977). El Hawat and Shelmani (1993) later revised the earlier identification of Nummulites fichtelli within the formation. The term “Al Faidiyah Formation” was introduced by Pietersz (1968) to describe the calcareous rocks and shale overlying the Shahat Formation, emphasizing its stratigraphic significance in tracing the transition from Oligocene to Miocene marine environments.

The Al Jaghbub Formation (Early-Middle Miocene) is the most widely distributed formation in the Tobruk area, with a maximum recorded thickness of 34.5 meters (Adam, 2018). It is composed of yellowish-white to reddish firm limestone and is well-exposed in various localities, especially in abdominal regions (Fig. 2). The widespread nature of this unit reflects shallow marine depositional conditions associated with reef-building environments during the Early to Middle Miocene. The Al Jaghbub Formation plays a crucial role in understanding the paleoecology of Miocene coral reefs and the evolution of Mediterranean-Tethys paleogeography Khameiss etal.,2024. Its extensive exposure and lithological characteristics make it a key reference point for geological mapping and stratigraphic correlation in the eastern Libyan coast.

Fig. 2. Overview Of Exposure Through the Study Area Shown Schematic Section and Stratigraphic Succession of the Al



Abraq, Al Faidiyah and Al Jaghbub Formations (Wadi Al-Zaytoun.)

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2. Methodology

2.1 Sample Collection

During a field trip to Wadi al-Zaytoun, a total of five rock samples were collected from various geological formations. The sampling process considered variations in lithology, color, texture, and sedimentary structures. Each sample was carefully extracted using a geological hammer and stored in labelled special bags. The precise geographic coordinates of the collection sites were recorded using a GPS device to ensure accurate spatial reference (Fig. 3). Notably, several fossils were recovered from the Al Jaghbub and Al Faidiyah Formations, highlighting the paleontological significance of these units (Fig. 4).

2.2 Laboratory Methodology

2.2.1 Bulk Mineralogy

Following field collection, the rock samples were air-dried to eliminate moisture. A small portion of each sample was then crushed using an electric mortar to produce a fine powder. This powdered material was placed into a sample holder for X-ray diffraction (XRD) analysis, a technique used to determine the mineral composition of the sediments. Mineral identification followed the guidelines of Chao (1969) and Chen (1977), using reference tables of characteristic X-ray diffraction patterns. The relative proportions of each mineral were quantified by measuring the principal peak heights of the XRD spectra, following the procedures outlined by Tucker (1988), Milliman (1974), and Carver (1971). The sedimentation process was analyzed in accordance with the methodologies described by Folk (1968) and Brown (1972), allowing for a comprehensive assessment of the mineralogical composition and depositional history of the collected samples.(need to mention the place where the XRD available

2.2.2 Microfacies analysis

Five thin sections were prepared from rock samples, collected from the sea cliffs in front of the studied wadi mouths. The Olympus BX51 polarizing microscope was used for thin section petrographic investigation, and digital photomicrographs were taken. After identifying the depositional conditions and ensuing diagenetic changes, the microfacies relationships of limestones were categorized using Dunham's (1962) classification method and the revisions made by Embry and Klovan (1971).

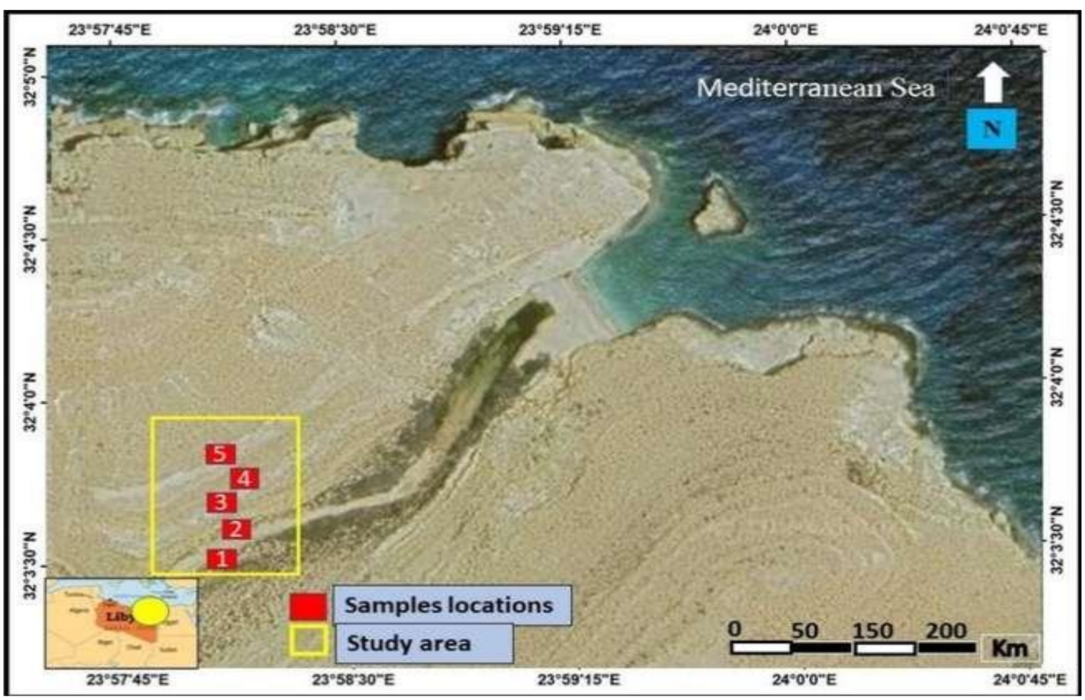

Fig .3. Satellite image showing the location of the studied area (goggle map)

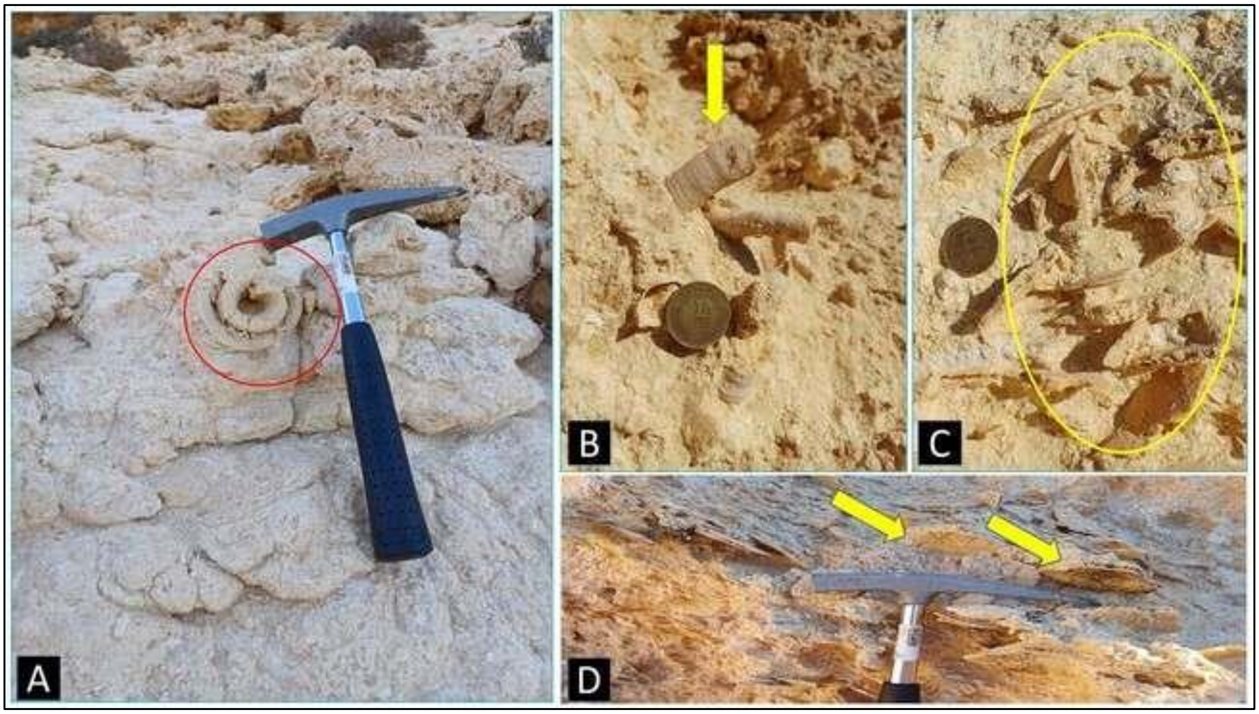

Fig 4. Close View of The Al Jaghbub Formations Showing Mold of Fossiliferous Limestone , A) Gastropods (Strombus *SP*.,) B) Worm Tubes Al Faidiyah Formation C) & D) Chinoids (Eroded And Fragments of (Clypeaster *SP*.,).

3. Result

3.1. Bulk mineralogy of the exposed rock:

Table.1. Data of bulk mineralogy determined in five samples.

S. No.	Geomorphologic units	Carbonate minerals		Evaporite minerals	Detrital minerals		
		Calcite (%)	Dolomite (%)	Halite (%)	Quartz (%)	Albite (%)	Kaolinite (%)
1	Rock Cliffs	0.9	87.9	2.7	0.6	7.9	0
2	Rock Cliffs	98.9	0	1.1	0	0	0
3	Rock Cliffs	0	57.0	36.2	3.4	0	3.4
4	Rock Cliffs	95.6	0	3.1	1.2	0	0
5	Rock Cliffs	91.8	8.2	0	0	0	0

The mineralogical composition of the three formations is predominantly characterized by the presence of terrigenous minerals, including quartz, albite, and kaolinite. Carbonate minerals are represented by calcite and dolomite, while evaporite minerals are limited to halite. This mineralogical assemblage reflects the depositional environment and diagenetic processes affecting the formations.

In Sample 1, dolomite is the most abundant carbonate mineral, accounting for 87.9% of the total mineral composition (Fig. 5). Albite is the second most dominant terrigenous mineral, with a maximum concentration of 7.9%. Unlike the other samples, kaolinite is notably absent in Sample 1, though trace amounts of calcite, halite, and quartz are present. This unique mineral distribution highlights the variability in depositional conditions across the formations. A summary of the bulk mineral percentages for all samples is provided in Table 1, while X-ray diffraction (XRD) patterns are illustrated in Figs. 6. The data are further represented graphically in Fig. 15, providing a comprehensive visual comparison of the mineralogical composition across the formations.

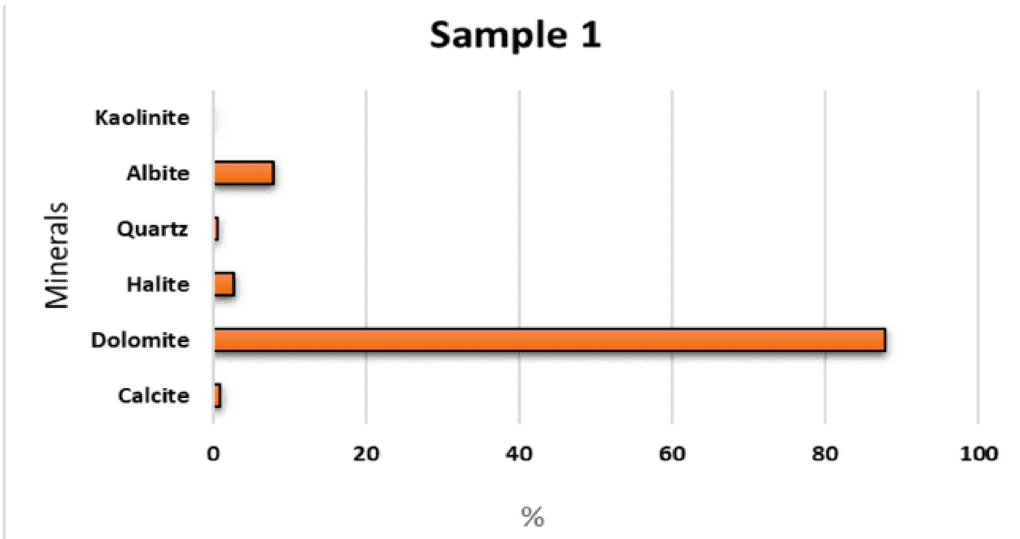

Fig.5 A Bar graph showing the relative percentages of the bulk mineralogy in the Al Abraq Formation

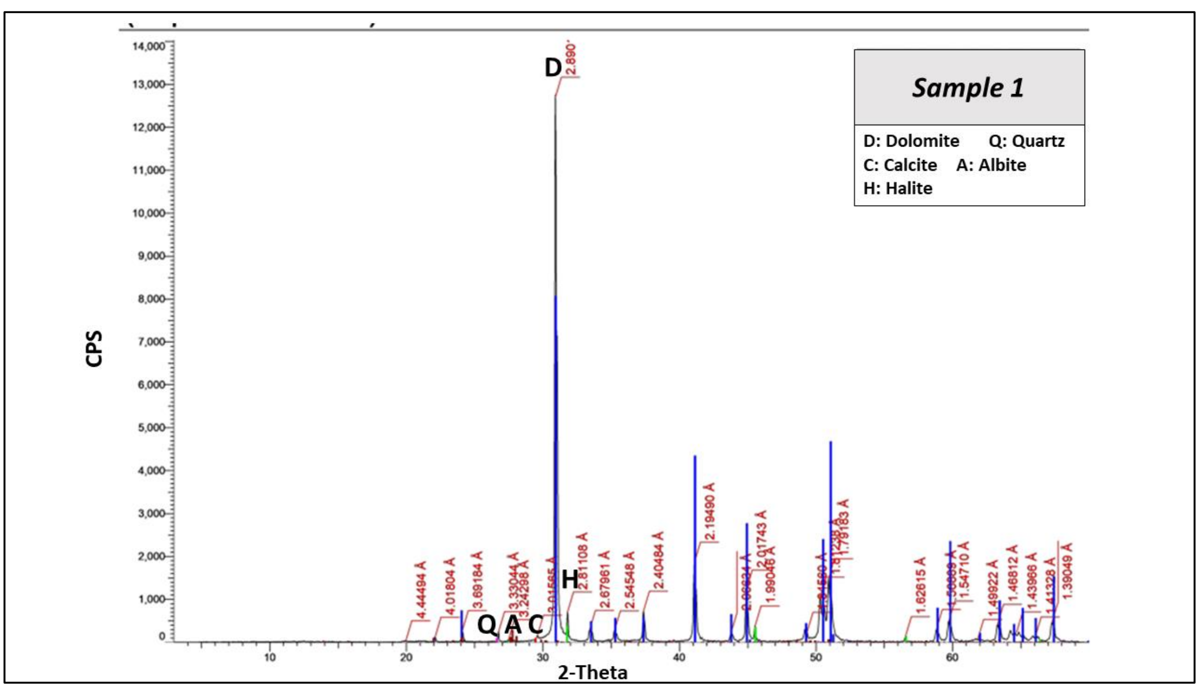

Fig. 6 X-ray diffraction patterns showing the bulk mineral components identified in rock.)

In Sample 2, calcite is the most dominant mineral, comprising a significant 98.9% of the total mineral composition. This indicates a strong presence of carbonate material in the formation. In contrast, halite is present in minor amounts, accounting for only 1.1% of the sample's bulk mineralogy (Table 1, Fig. 7). The limited presence of halite suggests minimal evaporitic influence in this specific depositional environment. The specific to the sample's origin.

X-ray diffraction (XRD) patterns for Sample 2 are displayed in Fig. 8, confirming the mineralogical composition. A bar graph (Fig. 15) provides a clear visual representation of the relative abundance of calcite and halite in this sample, highlighting the predominance of calcite. This mineral distribution reflects the depositional environment and diagenetic processes

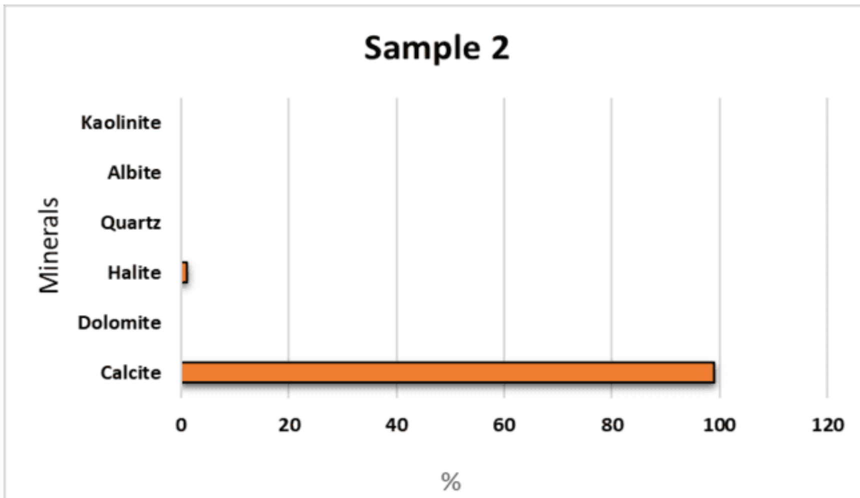

Fig. 7. Bar graph representation showing the relative percentages of the bulk minerals in the Al Faidiyah Formation.

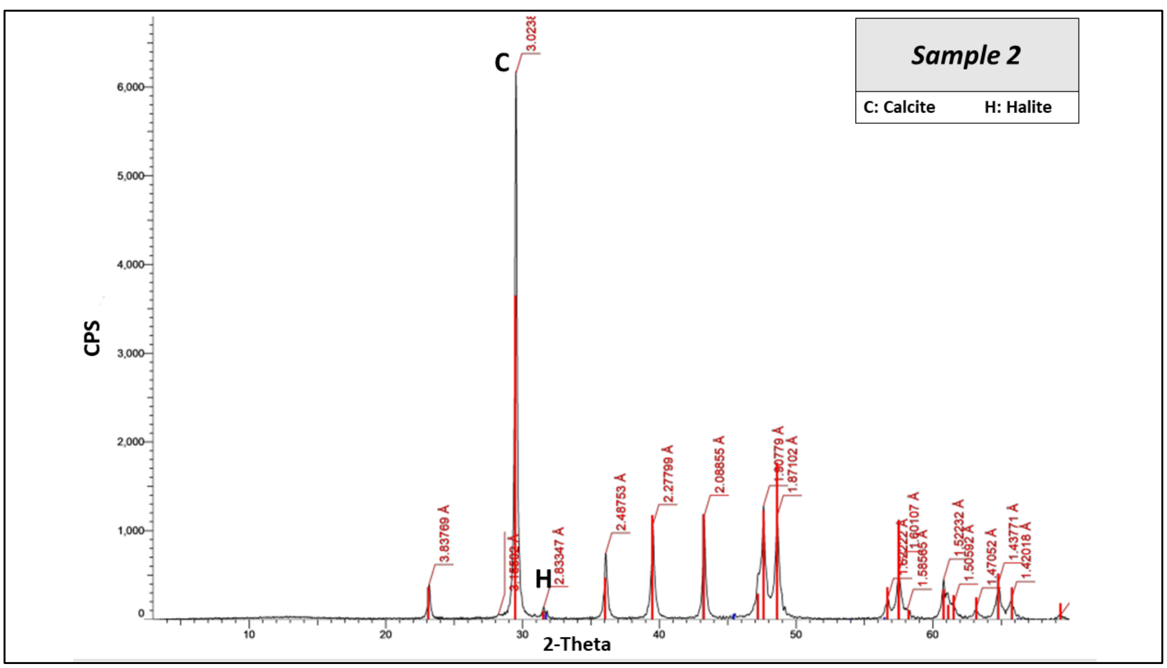

Fig. 8. Representative X-ray diffraction patterns showing the bulk mineral components identified in rock.

In Sample 3, the predominant mineral phases identified are dolomite and halite, comprising 57.0% and 36.0% of the total mineralogical composition, respectively (Fig. 9). Minor constituents include trace amounts of quartz and kaolinite, reflecting their limited presence within the sample matrix. The mineralogical composition was determined through X-ray diffraction (XRD) analysis, and the corresponding diffractogram is presented in Fig. 10. The characteristic diffraction peaks for dolomite and halite are prominently displayed, while the weaker intensity peaks associated with quartz and kaolinite indicate their subordinate abundance. This mineral assemblage suggests a depositional environment influenced by evaporitic and detrital inputs

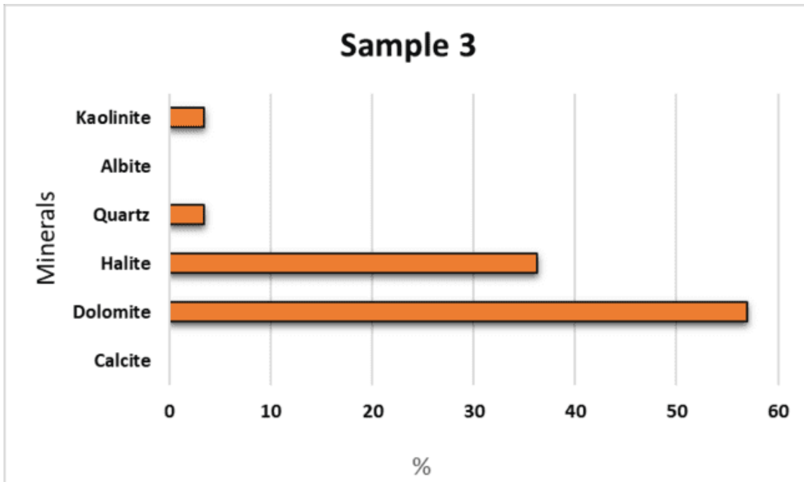

Fig. 9. Bar graph representation showing the relative abundance of the bulk minerals in the Al Faidiyah Formation

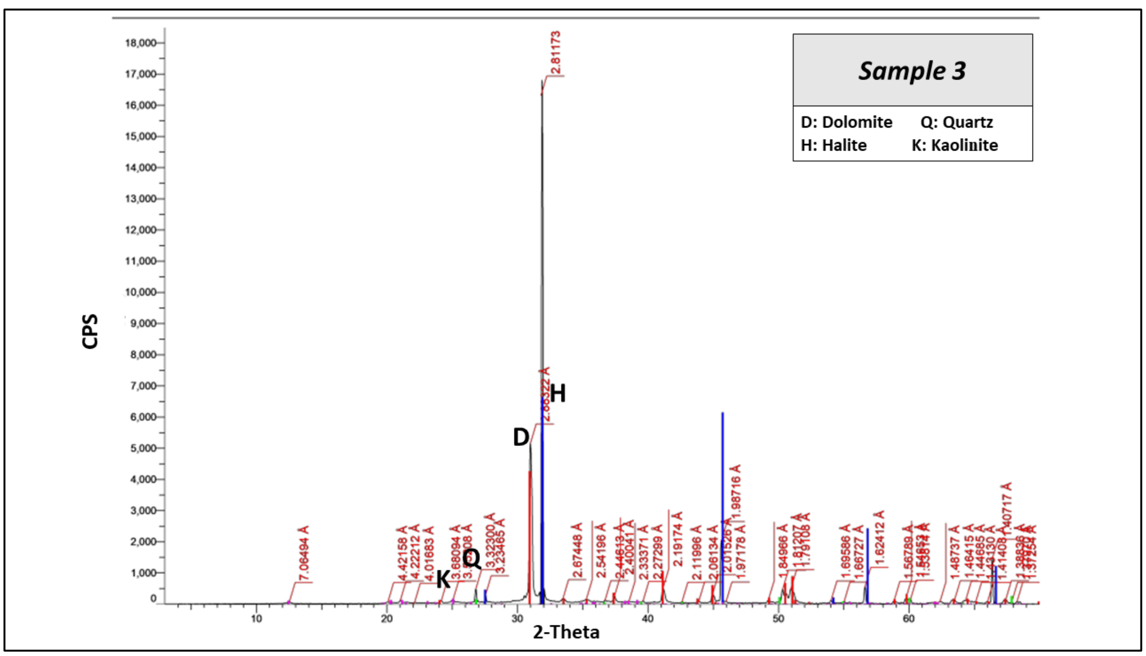

Fig. 10. Representative X-ray diffraction patterns showing the bulk mineral components identified in rock.

In Sample 4, calcite emerges as the most abundant and dominant carbonate mineral, accounting for 95.6% of the total mineral composition (Fig.11). In contrast, halite and quartz are present only in minor quantities, indicating their relatively low contribution to the overall mineral assemblage. The X-ray diffraction (XRD) analysis confirms these findings, as illustrated by the diffractogram in Fig. 12. The prominent diffraction peaks corresponding to calcite demonstrate its dominance, while the low-intensity peaks for halite and quartz reflect their limited occurrence. This mineralogical composition is indicative of a depositional environment heavily influenced by carbonate precipitation with minimal detrital or evaporitic inputs.

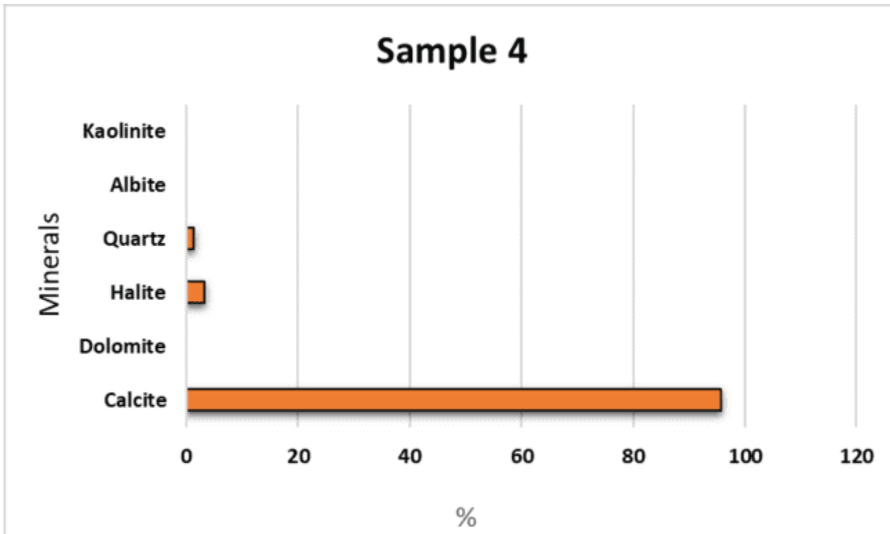

Fig. 11. Bar graph showing the relative percentages of the bulk minerals in the Al Jaghbub Formations.

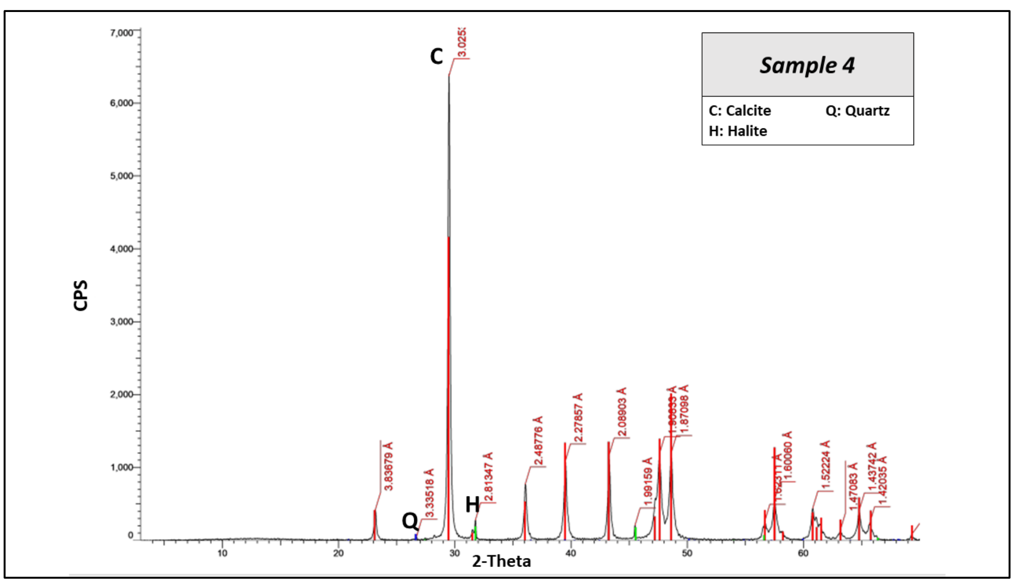

Fig. 12. Representative X-ray diffraction patterns showing the bulk mineral components identified in rock.

In Sample 5, calcite is identified as the dominant carbonate mineral, comprising 91.8% of the total mineral composition. Dolomite represents the second most abundant carbonate mineral, with a maximum concentration of 8.2% (Fig. 13). The quantitative results are tabulated in Table 1 and visually illustrated in the bar graph presented in Fig. 15. The X-ray diffraction (XRD) analysis further substantiates these findings, with the corresponding diffractograms displayed in Fig. 14. The pronounced diffraction peaks for calcite underscore its dominance, while the peaks associated with dolomite are less intense, reflecting its subordinate abundance. This mineralogical profile highlights a carbonate-dominated depositional environment with a significant contribution from calcite relative to dolomite.

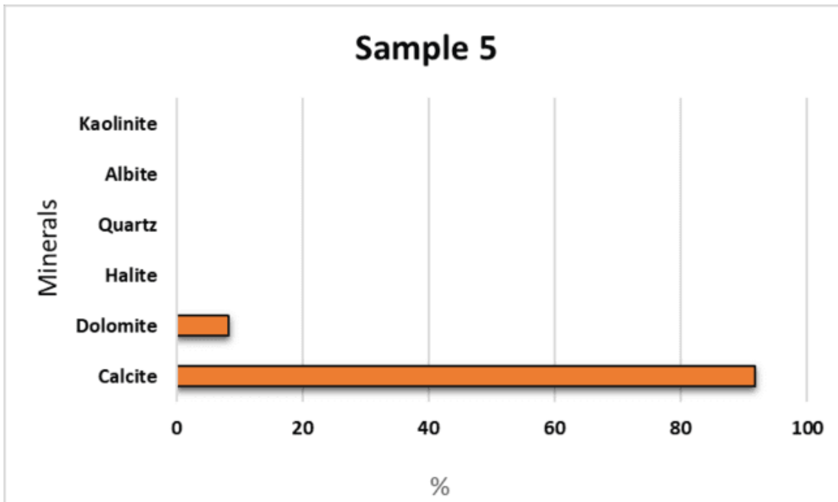

Fig. 13. Bar graph representation showing the relative percentages of the bulk minerals in the Al Jaghbub Formations

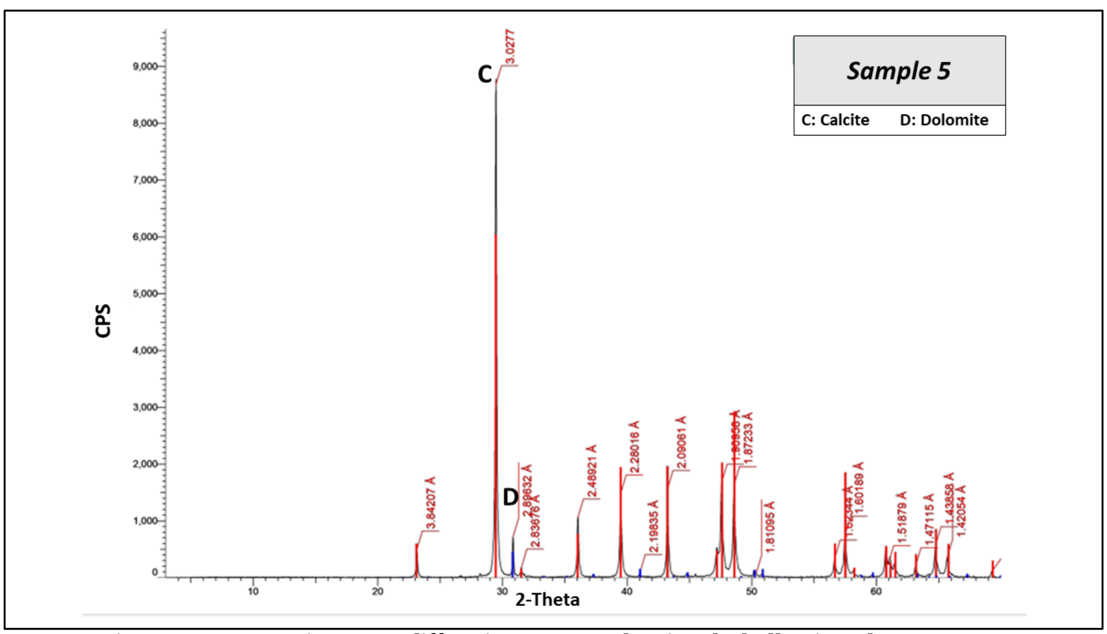

Fig. 14. Representative X-ray diffraction patterns showing the bulk mineral components identified in rock.

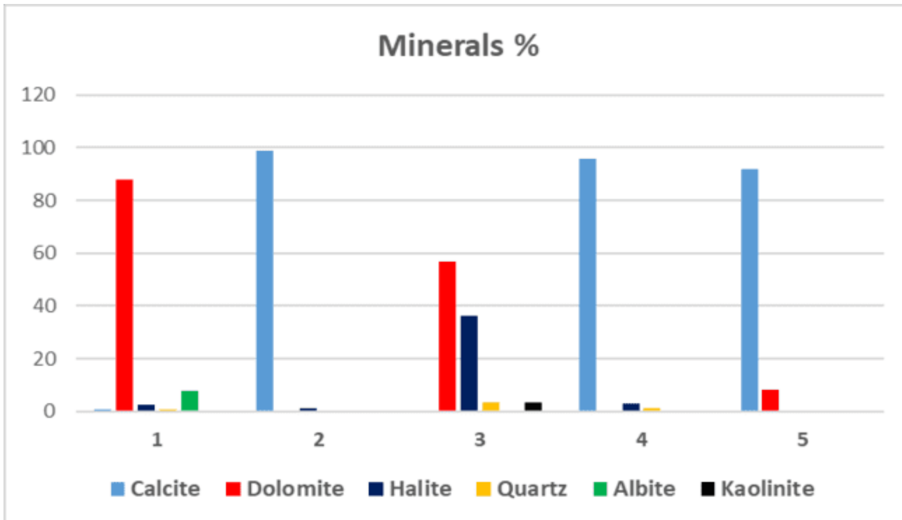

Fig. 15. Bar graph representation showing the relative percentages of the bulk minerals in the different in all samples

3.2 Microfacies description

The next sections provide a detailed description of the many microfacies that were identified in the formation under study:

Sample no. 01: Dolomite wackestone

This microfacies shows medium-grained, equigranular, euhedral dolomite crystals as a groundmass. Many dolomite crystals are stained with dark brown ferruginous matter. The abundance of uni-sized homogeneous rhomboid dolomite crystals suggests that deposition took place within arid tidal flats (Selley, 1967, and 1968; Reading, 1991). This thin section shows a highly fossiliferous carbonate rock, densely packed with small, well-preserved microfossils and a fine-grained calcite matrix. The numerous small, round to polygonal microfossils, likely composed of foraminifera, as you seen figure 16, indicate that this rock was deposited in a shallow marine setting with low-energy conditions, allowing for the accumulation and preservation of delicate calcareous organisms. The uniformity of the grain size and the micritic (very fine-grained) matrix suggest limited water agitation, characteristic of lagoonal or protected shelf environments. Such settings, typically warm and tropical to subtropical, promote the growth of carbonate-secreting organisms and facilitate the lithification of sediment into limestone or marl. The abundance and close packing of microfossils indicate a high productivity environment, where foraminifera thrived in response to stable, nutrient-rich conditions

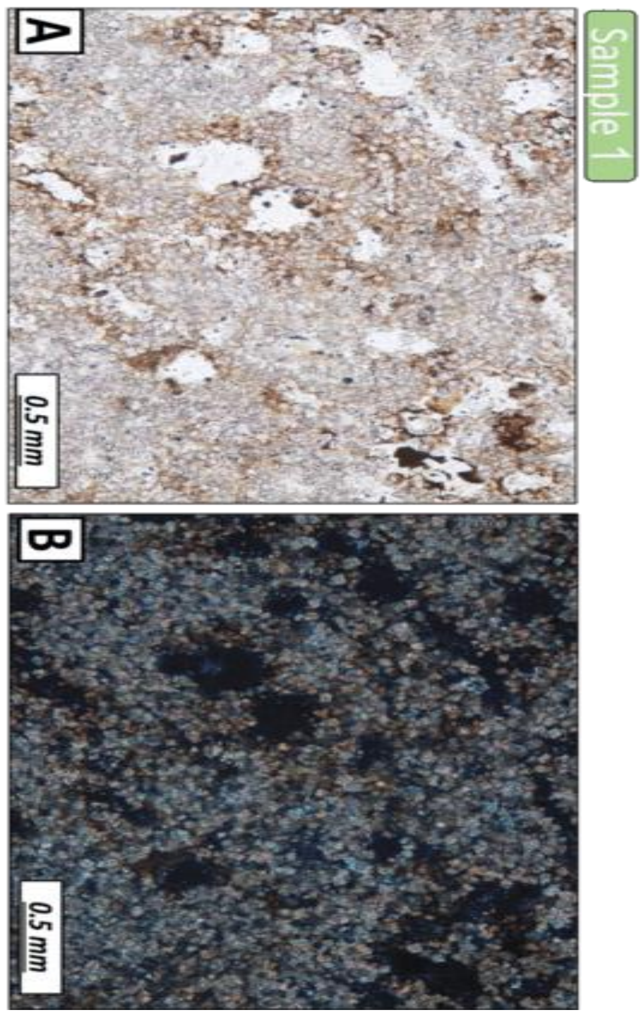

Fig. 16. Photomicrograph showing A& B Dolomite wackestone wackstone

Sample no. 02: Foraminiferal bioclasts packstone

The photomicrograph shows fine-grained cryptocrystalline micritic matrix enriched with allochems of different varieties floating in micritic matrix. These allochems are represented by echinoid spines, bryozoans, algae, foraminiferal tests (milliolids and nummulites), various debris of bivalves and gastropods and bivalve shell fragments cemented by sparry mosaic calcite. Diagenesis is caused by the dissolution of micritic matrix replaced by well-developed coarse sparry calcite, as you seen in figure 17. Deposition prevailed within an inner shelf, shallow marine conditions. This thin section represents a carbonate-rich marine sediment containing well-preserved benthic foraminiferal fossils, suggesting deposition in a shallow marine environment, likely a continental shelf or lagoonal setting. The fine-grained matrix, primarily composed of micritic calcite, and the abundance of foraminifera indicate a low-energy depositional environment, where calcareous microorganisms thrived and accumulated. The preservation of these microfossils within a stable carbonate matrix suggests that sedimentation was steady, allowing for the burial and lithification of marine biota. This environment likely had warm, clear, and shallow waters, promoting the proliferation of benthic foraminifera typical of tropical to subtropical marine conditions. The benthic foraminifera are Borelis melo melo.

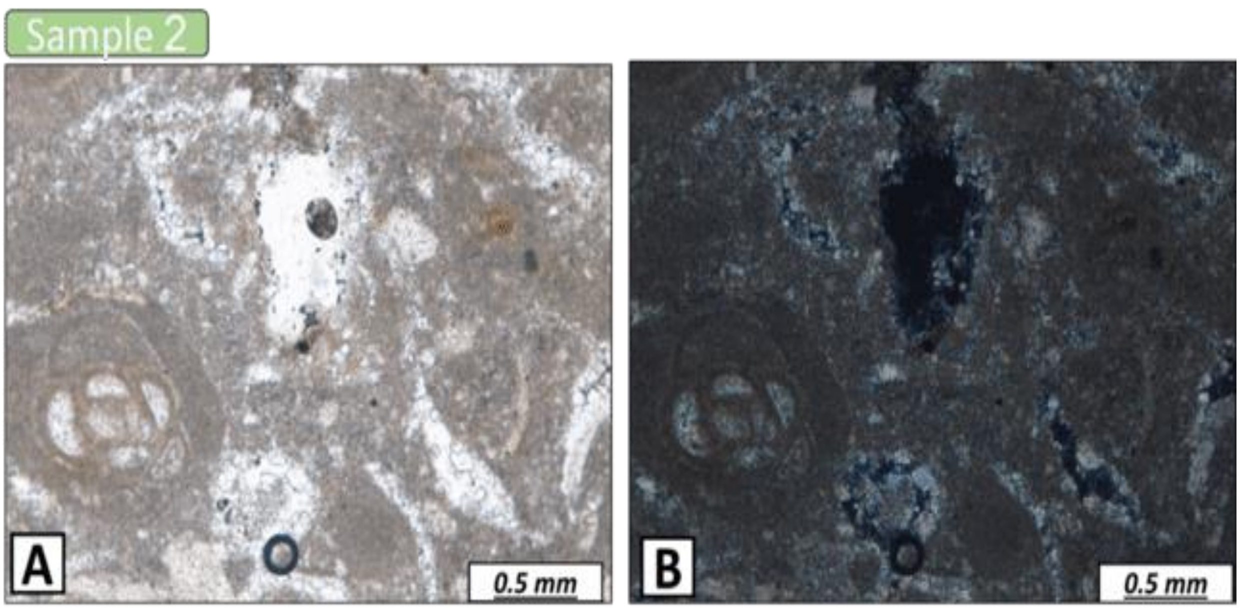

Fig.17 Photomicrograph showing A& B Foraminiferal bioclasts packstone, the benthic foraminifera are *Borelis melo melo.*.

Sample no.03 . Dolomitic wackestone

This microfacies is characterized by a fine-grained matrix predominantly composed of equigranular dolomite crystals. The dolomite crystals exhibit a range of shapes, from well-formed (euhedral) to partially formed (subhedral) structures, indicating varying degrees of crystal growth and development. These dolomite crystals serve as the main groundmass of the microfacies, providing a stable framework. As you seen in figure 18. A notable feature of this microfacies is the presence of ferruginous (iron-rich) staining, which appears as dark brown deposits coating or partially filling the dolomite crystals. This staining suggests the influence of iron-rich fluids during diagenesis, possibly linked to redox changes or post-depositional fluid migration. The overall texture and composition of the dolomitic wackestone reflect complex diagenetic processes that have significantly altered its original mineralogical state.

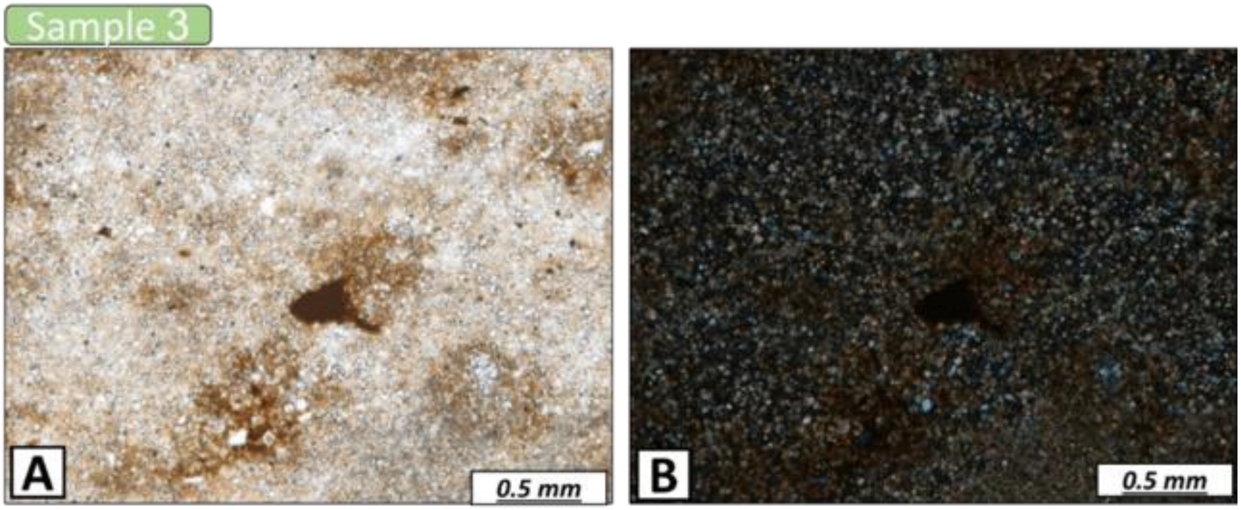

Fig.18. Photomicrograph showing A& B Dolomitic wackestone..

Sample no. 04: Foraminiferal bioclastic packstone

This microfacies is characterized by a matrix of cryptocrystalline lime mud (micrite) interspersed with brown, ferruginous, rounded materials. The groundmass is highly weathered and includes an argillaceous (clay-rich) component, indicating exposure to post-depositional alteration or subaerial weathering. The allochems are dominated by rudaceous-sized bioclasts, which are larger fragments of pre-existing skeletal material. These bioclasts include a diverse assemblage of fossil debris, such as ostracod shells, foraminiferal chambers, gastropods, bivalves, oysters, echinoids, bryozoans, and algae. The presence of this wide variety of marine organisms suggests a biologically active depositional environment. The occurrence of benthic foraminifera, particularly *Amphistegina cf. lessonii*, serves as a valuable paleoenvironmental indicator, as you seen in figure19. This foraminiferal species is typically associated with shallow, warm, and well-lit marine environments, such as reefal or lagoonal settings. The presence of rudaceous bioclasts, along with the diversity of fossilized marine fauna, implies deposition in a shallow, high-energy marine environment with sufficient water agitation to transport and accumulate coarse skeletal debris. The overall composition reflects a dynamic setting influenced by waves, currents, and biological activity.

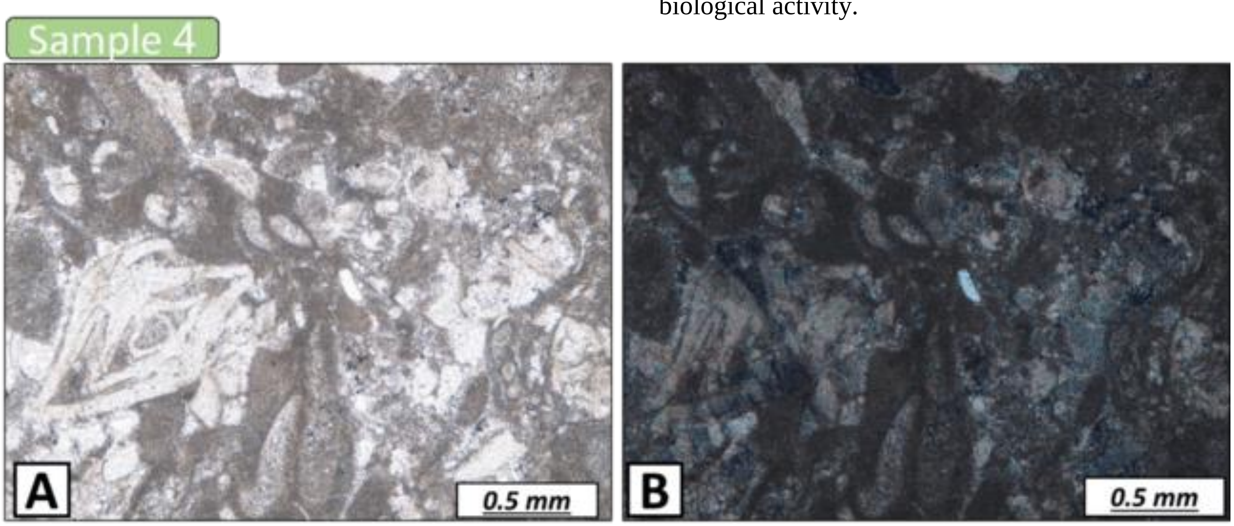

Fig.19. Photomicrograph showing A& B Foraminiferal bioclastic packstone. the benthic foraminifera are *Amphistegina cf. lessonii.* Sample no. 05: Echinoidal, foraminiferal, algal packstone

This microfacies is composed of a tightly interlocking mosaic of dolomite crystals and a micrite (fine-grained lime mud) matrix. The groundmass serves as a supporting framework that binds the allochems together. The allochems are diverse and abundant, consisting of skeletal and non-skeletal grains. These include echinoid spines, concentric oolites, peloids, bryozoans, algae, foraminifera, ostracods, bivalves, and various shell fragments, as you seen in figure 20. The wide range of allochem types suggests a biologically rich and dynamic depositional environment. Cementation occurs through sparry mosaic calcite and crystallized dolomite, which fill pore spaces between the allochems, enhancing lithification.

The diagenetic processes that affected this microfacies are significant. The original micritic matrix underwent dissolution, creating secondary porosity that was subsequently filled by coarse-grained sparry calcite and well-formed dolomite crystals. This process reflects substantial post-depositional alteration, likely involving fluid migration and chemical changes that facilitated the replacement of original carbonate components with larger, more crystalline dolomite and calcite. The presence of well-developed dolomite points to dolomitization, which could be linked to changes in salinity, magnesium-rich fluids, or fluctuating redox conditions. This microfacies provides valuable insight into the diagenetic history and fluid dynamics of the depositional environment.

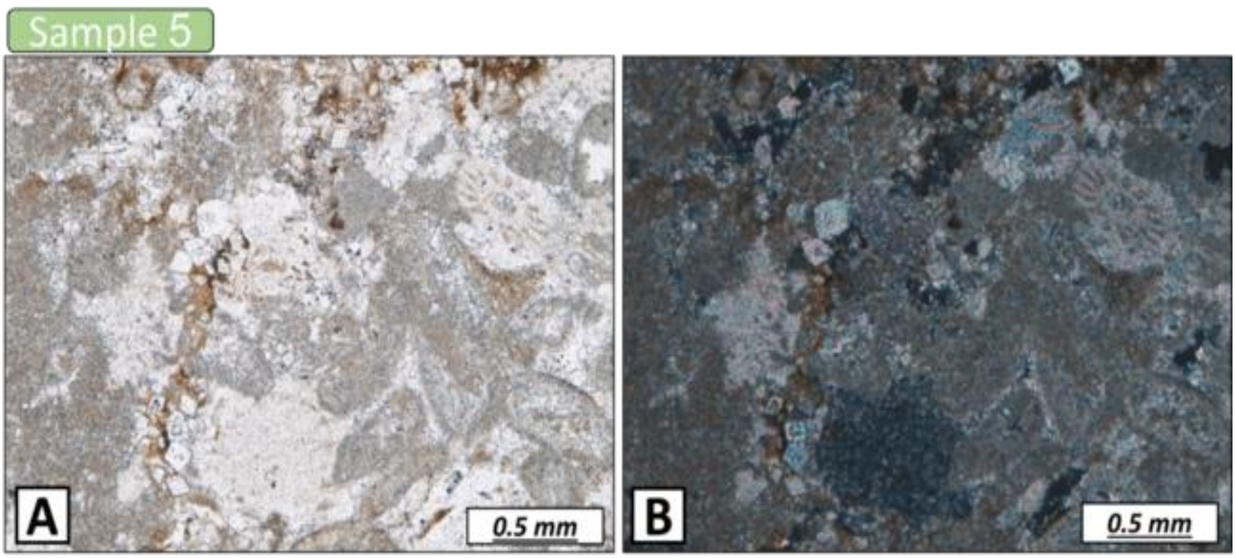

Fig.20. Photomicrograph showing A& B Echinoidal, foraminiferal, algal packstone.

4. Discussion:

4.1. Minerals Analysis:

The Abraq Formation, represented by sample1, has been taken from the sector's base They found that Dolomite is distinguished by the main peak 2ϴ (30.9°) Al Faidiyah Formation It was found that calcite and Dolomite are the most common and dominant carbonate minerals in all analyzed rock cliffs.The stable carbonate mineral form calcite can be found in a variety of environments, but aragonite and high-magnesium calcite are typically found in temperate, shallow marine environments where they are directly precipitated from seawater or the skeletons of various organisms (Lippmann, 1973; Rao, 1996; Chang et al., 1998). Kaolinite mineral was detected in sample 3 based on its characteristic peaks at d-spacing of 7.03Aº (001). While Kaolinite is generally not affected by transportation so that when it enters the basin of deposition, its composition and amount remain the same (Perrin, 1971). Al Jaghbub Formation It was found that calcite is the most common and dominant carbonate mineral in this formation.

4.2. Microfacies

1. Depositional Environments and Sedimentological Implications

The microfacies analysis of the studied samples reveals a range of depositional environments, from low-energy, protected lagoonal settings to relatively high-energy inner shelf and shallow marine conditions. Sample 1 (Dolomite wackestone) illustrates the characteristics of a low-energy depositional system, likely a restricted lagoon or tidal flat. The dominance of homogeneous, medium-grained, equigranular euhedral dolomite crystals and the presence of densely packed foraminiferal microfossils within a micritic matrix support this interpretation. Such environments are typical of arid, evaporitic settings where dolomitization is a common process due to the influx of hypersaline water. The abundance of foraminiferal microfossils, coupled with the fine-grained nature of the matrix, indicates a nutrient-rich environment with limited water agitation, promoting the growth and preservation of calcareous microorganisms. The close packing of microfossils in this facies also suggests periodic influxes of organic matter, fostering microbial activity that may have played a role in dolomite precipitation.

2. Diagenetic Processes and Mineralogical Transformations

Diagenetic alterations are evident in several of the analyzed microfacies, particularly in Samples 2, 3, and 5. In Sample 2 (Foraminiferal bioclasts packstone), early diagenesis is marked by the replacement of micritic matrix with coarse sparry calcite, indicative of increased porosity and fluid movement within the sediment. The dissolution and re-precipitation of carbonate material reflect changes in geochemical conditions, such as fluctuations in pH and saturation states of carbonate minerals. This diagenetic process enhances the visibility and preservation of the allochems, including echinoid spines, bryozoans, foraminiferal tests, and bivalve shell fragments. Similar diagenetic features are observed in Sample 5 (Echinoidal, foraminiferal, algal packstone), where dissolution of micrite and carbonate fragments results in the development of well-formed coarse sparry calcite and dolomite crystals. This transformation points to meteoric diagenetic influence, likely associated with subaerial exposure or changes in the hydrological regime. The presence of ferruginous staining in the dolomitic wackestones (Sample 3) further suggests suboxic to anoxic diagenetic conditions, potentially linked to the influx of iron-rich fluids during burial or early lithification stages.

3. Paleoenvironmental and Paleoecological Interpretations

The microfacies assemblages provide critical insights into the paleoenvironmental conditions during deposition. The predominance of benthic foraminifera, including *Borelis melo melo* (Sample 2) and *Amphistegina cf. lessonii* (Sample 4), points to shallow, tropical to subtropical marine conditions. These larger benthic foraminifera are indicative of warm, clear, and photic-zone habitats typically associated with inner shelf or lagoonal environments. The diversity of allochems, such as bryozoans, echinoids, algae, and molluscan fragments, reflects a biodiverse marine ecosystem with sufficient nutrient availability to support a wide array of calcareous organisms. Samples 2, 4, and 5 exhibit textural characteristics of packstone microfacies, suggesting episodic sedimentation, possibly related to storm events or shifting hydrodynamic conditions. The intermixing of cryptocrystalline lime mud, bioclastic debris, and allochems in these samples supports deposition in an energetic marine environment, where wave action periodically reworks the sediment. The presence of concentric oolites and peloids in Sample 5 implies a shallow, high-energy marine setting conducive to grain movement and carbonate precipitation, further affirming the dynamic nature of this depositional environment. Collectively, the evidence from these microfacies suggests a spectrum of depositional settings, from tranquil lagoons to more turbulent inner-shelf marine environments, with diagenetic processes overprinting the original sedimentary features.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper. The research was conducted independently, and no financial or personal relationships influenced the outcomes of the study.

Conclusion:

The mineralogical and microfacies analysis of the studied rock samples of the Al Gaghbub, Al Faidiyah, and Al Abraq Formations reveals significant insights into the depositional environments, diagenetic processes, and mineralogical composition of the formations. The mineralogical composition highlights a dominance of carbonate minerals, particularly calcite and dolomite, with trace amounts of evaporite and detrital minerals such as halite, quartz, and kaolinite. The variability in mineral distribution across the samples reflects distinct depositional conditions. For instance, the dominance of dolomite in Al Abraq Formation suggests deposition in arid tidal flats, while the high calcite content in Al Faidiyah, Formation and Al Jaghbub Formation is indicative of shallow marine conditions with strong carbonate precipitation. Evaporitic minerals, notably halite, are present in small quantities, pointing to intermittent evaporative conditions. The presence of detrital minerals like kaolinite and quartz in Al Faidiyah, Formation further supports the influence of terrestrial input and potential fluvial influx into the depositional environment. These findings underscore the role of environmental factors in controlling the mineralogical composition and depositional characteristics of these formations. The microfacies analysis identifies a range of depositional environments, from low-energy, restricted lagoons to high-energy shallow marine and inner-shelf settings. The dolomite wackestone facies observed in Sample 1, with its homogeneous dolomite crystals and dense packing of foraminiferal microfossils, reflects a lagoonal or tidal flat environment, where dolomitization is driven by the influx of hypersaline water. In contrast, the foraminiferal bioclast packstone (Al Faidiyah, Formation and Al Jaghbub Formation) represents shallow marine conditions characterized by the presence of diverse allochems, such as foraminifera, gastropods, bryozoans, and echinoid fragments. These high-energy environments, influenced by waves and currents, facilitated the accumulation and lithification of skeletal debris. The presence of benthic foraminiferal species like *Borelis melo melo* and *Amphistegina cf. lessonii* serves as valuable paleoenvironmental indicators, further confirming shallow, warm, and well-lit marine conditions. The dolomitic wackestone (Al Faidiyah, Formation) reflects diagenetic processes, as evidenced by ferruginous staining and the presence of subhedral to euhedral dolomite crystals. These diagenetic alterations are indicative of fluid-rock interaction, likely driven by post-depositional changes in geochemical conditions. The combined analysis of mineralogy and microfacies highlights the dynamic interplay of depositional and diagenetic processes within the Al Gaghbub, Al Faidiyah, and Al Abraq Formations. The dominance of calcite and dolomite, coupled with the occurrence of foraminifera-rich packstones, points to a carbonate platform setting influenced by fluctuations in sea level, salinity, and energy conditions. The presence of evaporitic minerals and terrigenous inputs underscores the role of episodic evaporative conditions and terrestrial influx. Diagenetic processes, such as dolomitization and the precipitation of sparry calcite, have significantly modified the primary mineralogy, as seen in the replacement of micritic matrix and the formation of secondary porosity. This study provides a comprehensive understanding of the geological history, depositional environments, and diagenetic evolution of the formations, offering valuable insights for future research and potential applications in hydrocarbon exploration, sedimentology, and paleoenvironmental reconstruction.

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