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Petrography, Mineralogy and Diagenetic history of the Sarmord Formation (Valanginian-Aptian) in selected areas, Northeastern Iraq

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Abstract

This research studies the petrography, mineralogy and diagenetic history of the Sarmord Formation at Sulaimani and Erbil Governorates in Northeastern Iraq. The Sarmord Formation consists mainly of alternated yellowish to bluish gray bedded marly limestone with yellowish gray soft marl beds. Petrographic investigations of the marly limestones were based on 270 thin sections and show that the skeletal grains include bioclasts, foraminiferas, radiolarians, calcispheres, echinoderms, ostracods and cephalopods. The groundmass is composed of micrite with light brown to gray colors, rich in organic materials and iron oxides. The X-ray diffraction analysis of the marls revealed that the abundant clay minerals in the Sarmord Formation are kaolinite and smectite -illite mixed layers, in addition to chlorite traces, which may indicate an increasing influx of detrital minerals from the continental weathering because of the humid Early Cretaceous climate. Non-clay minerals include calcite and quartz with subordinate feldspars. The main diagenetic processes affecting the Sarmord Formation carbonates are micritization, dissolution, cementation, compaction, dolomitization, dedolomitization and authigenic minerals (pyrite and silica). These belong to three diagenetic stages; early (shallow burial), middle and late (deep burial).

Keywords: Sarmord Formation, Marly limestones, Marl, Diagenetic history, Northeastern Iraq.

البتروغرافية والمعدنية والتاريخ التحويري لتكوين السارمورد (الفلانجينيان – الابتيان) في مناطق مختارة شمال شرق العراق

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الخلاصة

يتناول هذا البحث دراسة البتروغرافية والمعدنية والتاريخ التحويري لتكوين السارمورد (الفلانجينيان– الابتيان) في مناطق المختارة ضمن محافظتي اربيل والسليمانية شمال شرق العراق. يتألف تكوين السارمورد بصورة رئيسية من تعاقب الحجر الجيري الصلصالي المتطبق ذي لون الرمادي المصفر الى الرمادي المزرق مع طبقات

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الصلصال ذي اللون الرمادي المصفر . تتألف بتروغرافية الحجر الجيري الصلصالي من الحبيبات الهيكلية مثل الفتاتات العضوية, الفورامنفرا, الرديولاريا, الكرويات الكلسية, شوكيات الجلد,الاوستراكودا وراسية الاقدام. تتكون الارضية من الميكرايت ذي اللون البني الفاتح الى الرمادي الفاتح الغني بالمواد العضوية واكاسيد الحديد. أظهرت نتائج تحاليل الأشيعة السينية لنماذج الصلصال ان المعادن الطينية الرئيسة التي تظهر في المقاطع المدروسةهي: الكاؤلينايت والطبقات المختلطة من الألايت – السمكتايت ونسبة قليلة جداً من الكلورايت. تأثرت صخور الكاربونيت لتكوين السارمورد بعدة عمليات تحويرية كالمكرتة, الاذابة, السمنتة, الانضغاط , الدلمتة , الديدلمتة والمعادن موضعية النشأة (البايرايت والسليكا) و التي تعود الى ثلاثة مراحل التحويرية هي: المبكر (الدفن الضحل), المتوسط و المتأخر (الدفن العميق).

1. Introduction

The Sarmord Formation (Valanginian – Aptian) crops out in the southern part of the Imbrication Zone and the northern part of the High Folded Zone of northern Iraq and is regarded as one of the most widely outcropped Cretaceous formations in Iraq. It stretches from the Iraq-Iran border to the west of Rawanduz, frequently intersecting with the Balambo and Qamchuqa formations (Figure 1) [1]. The lateral equivalents of the studied formation in Iraq are the Zubair, Ratawi, Qamchuqa and Balambo Formations, whereas, in Turkey, it is equivalent to the Cudi Group and in Iran to the Gadwan Formation.

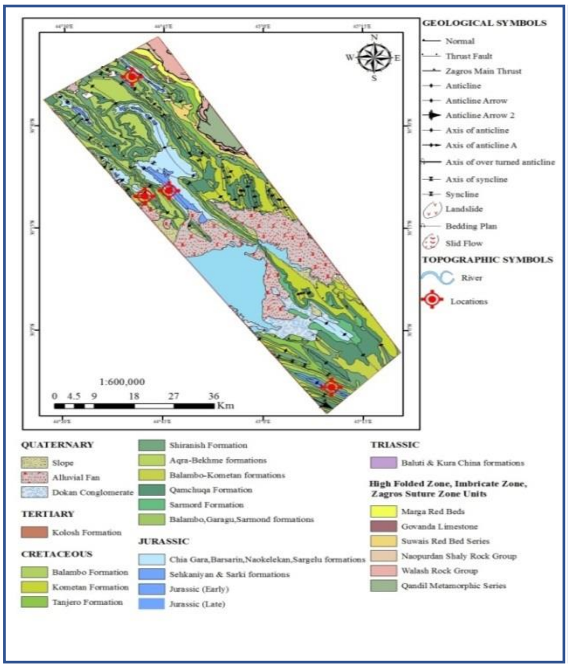
The Sarmord Formation was firstly described by Wetzel in Surdash anticline-Sulaimani area, in northern Iraq. The type locality is completed from two separate sections. The Qamchuqa Gorge part exposes the formation's upper 182 meters, with the lowest exposure at Sarmord village (Latitude 350 54' 18'' N, Longitude 430 02' 07'' E) and the highest exposure about 250 meters southwest of this village at the foot of the massive Qamchuqa Formation limestone scarp. The lower 273 meters are reported based on the part of the creek that flows north across Sargelu town. The top of this section (corresponding to the bottom of the section exposed at Sarmord Village) is sited about 1 km north of the village (Latitude 350 52' 54'' N and Longitude 450 09' 28'' E), while the base of the formation is located about 800 meters north of the village (Latitude 350 52' 54'' N and Longitude 450 09' 28'' E). The overall thickness of the studied formation is 455 meters, with considerable amounts of fossils in the upper 80 meters. The age of the formation was given as Barremian to Hauterivian [2]. The Sarmord Formation is comprised of the succession of neritic to deep-water environment deposits and brown and bluish marls, with alteration of marly neritic limestones.From surface and subsurface rock units of Tithonian to Albian age in the north and south parts of Iraq, They gave many ideas about the Sarmord Formation, vertical and lateral relationships with other related formations. They concluded that the Sarmord Formation is diachronous because it is the oldest in the southwest (Wasil area), there being Tithonian (Upper Jurassic) and Berriasian - Hauterivian in the Samarra Kirkuk area, and becoming diachronous younger into the basin, Hauterivian Barremian at Surdash and Aptian at Peramagroon [3]. The Sarmord Formation divided into three parts: - Lower Sarmord Formation (Tithonian Berriasian) - Middle Sarmord Formation (Valanginian Aptian), and Upper Sarmord Formation (Albian) [4]. The Sarmord Formation divided into two different formations; Lower Sarmord Formation, which refers to the Berriasian-Aptian sub-cycle. Upper Sarmord Formation, which refers to Albian sub-cycles [5]. The biostratigraphy of the Sarmord Formation consist of two biozones; the Choffoatella decipiens Range zone and Orbitolina discoidea Range zone that belong to Barremian –Aptian [6]. This study investigates the detailed aspects of the petrography, mineralogy and diagenetic history of the Sarmord Formation in selected sections of northeastern Iraq.

2.Location

The studied areas are located within Sulaimani and Erbil Governorates in northeastern Iraq (Table1) and (Figure 2). These areas constitute a part of the Western Zagros Fold-Thrust belt, directly to the southwest of the main Zagros Suture Zone [7, 5, 8, 9 and 10]. Structurally, the areas are located within the High Folded and Imbricated Zones of northeastern Iraq [8], where the axes of the anticlines trend in a northwest–southeast direction.

Table 1: Outcrops location through geographic coordinates, thickness and number of samples.

section	*Geographic co-ordinate*		*Thickness (m)*	*Number of samples*
	Latitude	*Longitude*		
Sargelu	*35º 51' 58"*	*45º 10 ' 19.2 "*	*360*	*89*
Rania (Dowawa)	*36º 19 ' 42.5 "*	*44º 42 ' 17.6 "*	*70*	*40*
Rania (Qala-Saida)	*36º 20 ' 31.4 "*	*44º 46 ' 01 "*	*63*	*40*
Barsarin	*36º 37 ' 12 "*	*44º 40 ' 20 "*	*144*	*100*



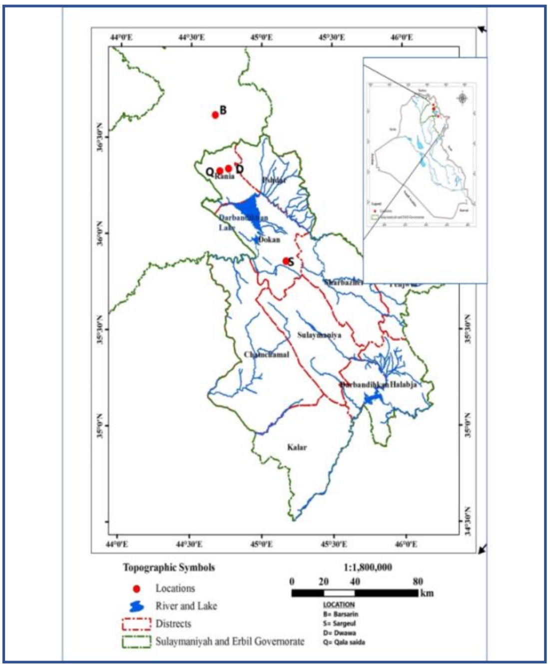
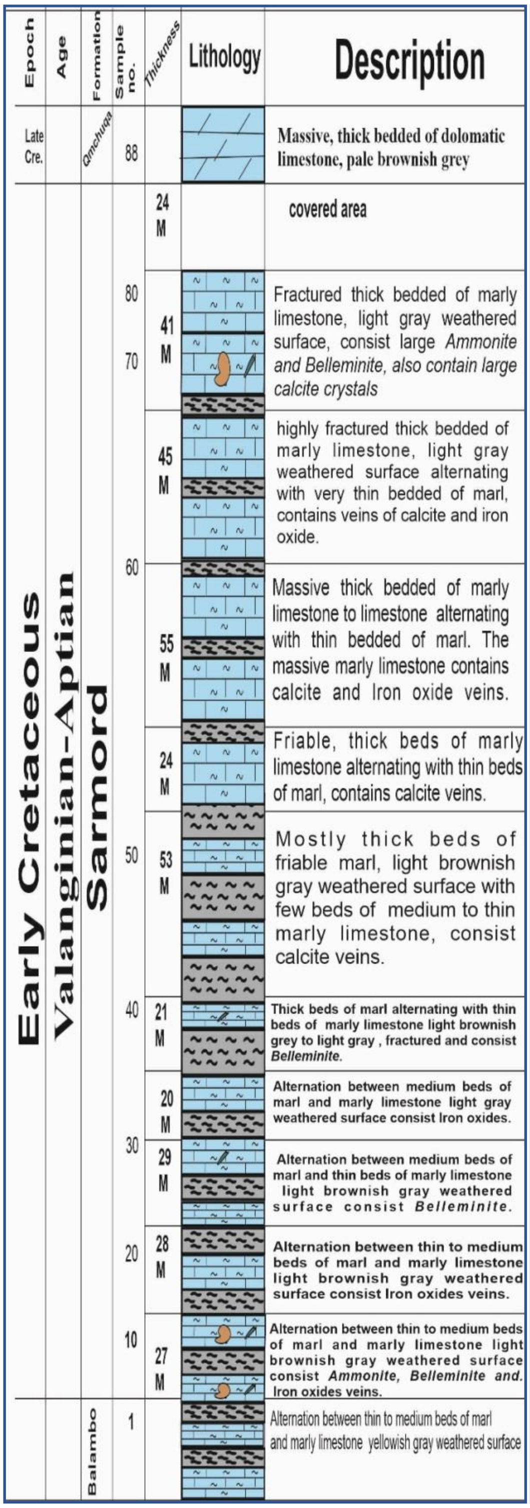


Figure 1: Geological map of the study area. **Figure 2:** Location map of the study area.

3.Methodology

The research work in the studied areas is divided into two stages: fieldwork and laboratory work. The fieldwork includes the description and sampling of four outcrops: Sargelu, Rania sections (Dowawa and Qala-Saida) and Barsarin (Figures 3, 4, 5 and 6). These outcrops are selected based on their thickness, location, and distance. The samples are described in the field according to the changing in lithology, hardness, color, texture, fossils content, sedimentary structure and nature of contacts.

The laboratory work involves performing thin sections (about 270 thin sections) prepared in the Department of Geology, College of Science, University of Baghdad workshop. Following Dickson's method, each thin slide was treated with Alizarin Red Solution and potassium ferricyanide for petrographic study (11]. The petrographic description was handled using a polarizing microscope to identify the constituents. In addition, ten marl samples are chosen for X-Ray Diffraction analysis (XRD) to distinguish between clay and non-clay minerals. These samples were analyzed at the laboratories of the Ministry of Science and Technology - Baghdad. From the X-ray diffractogram, there are two treatments (heating 550° and Ethylene Glycolation) in addition to normal for the studied samples.



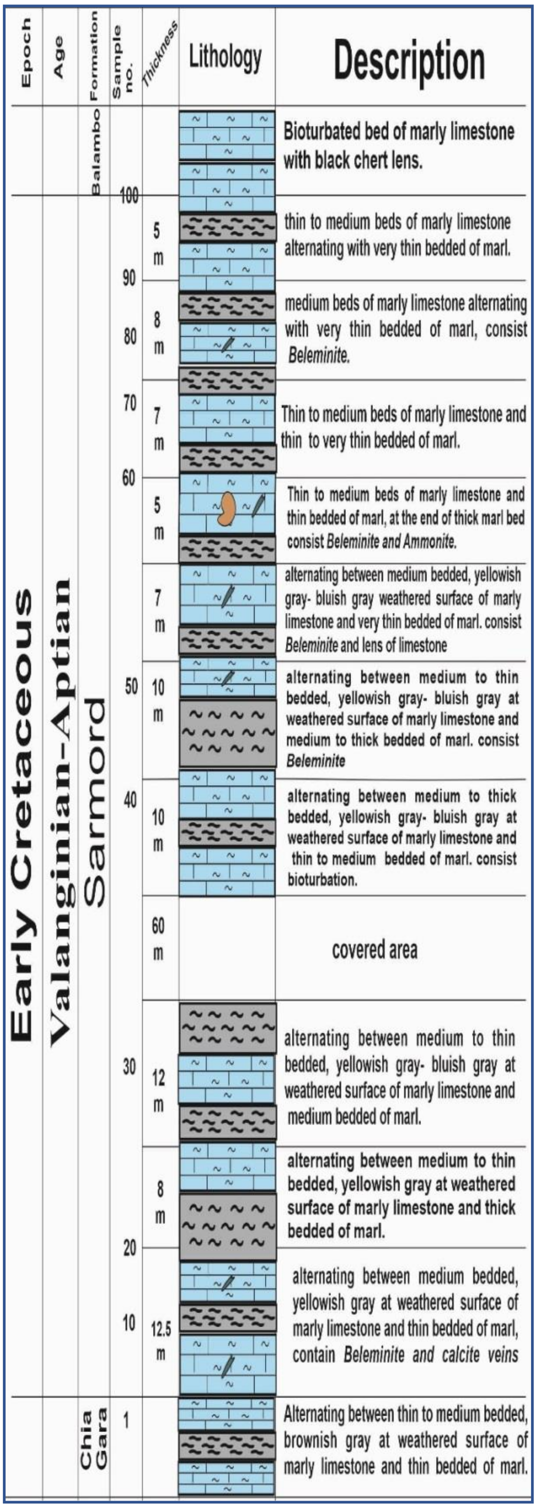


Figure 3: Lithological section for Sargelu section

Figure 4- Lithological section for Barsarin section.

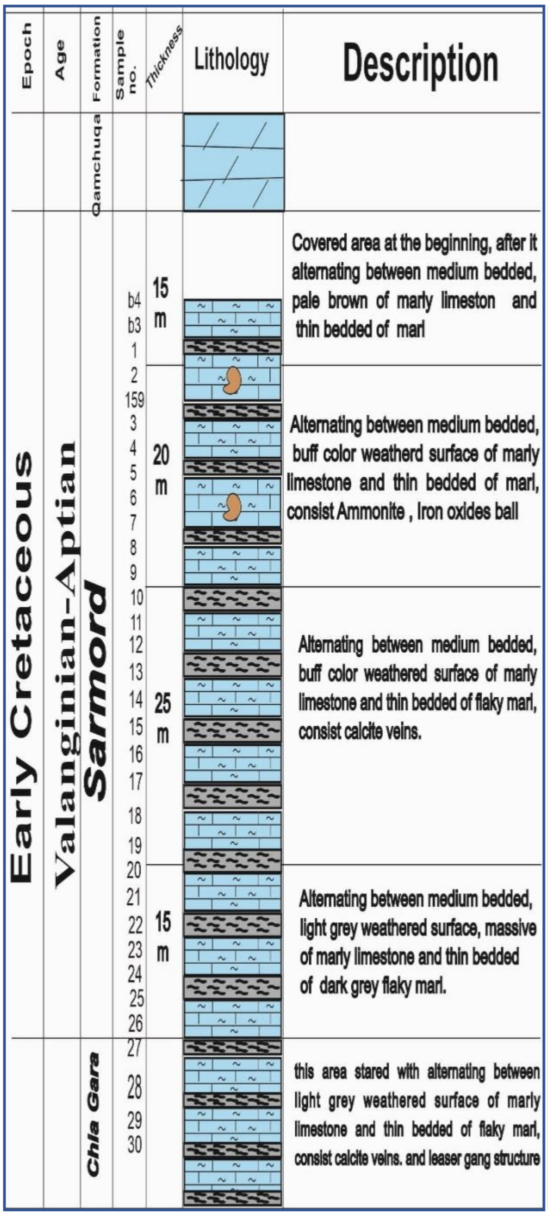


Figure 5: Lithological section for Dowawa section

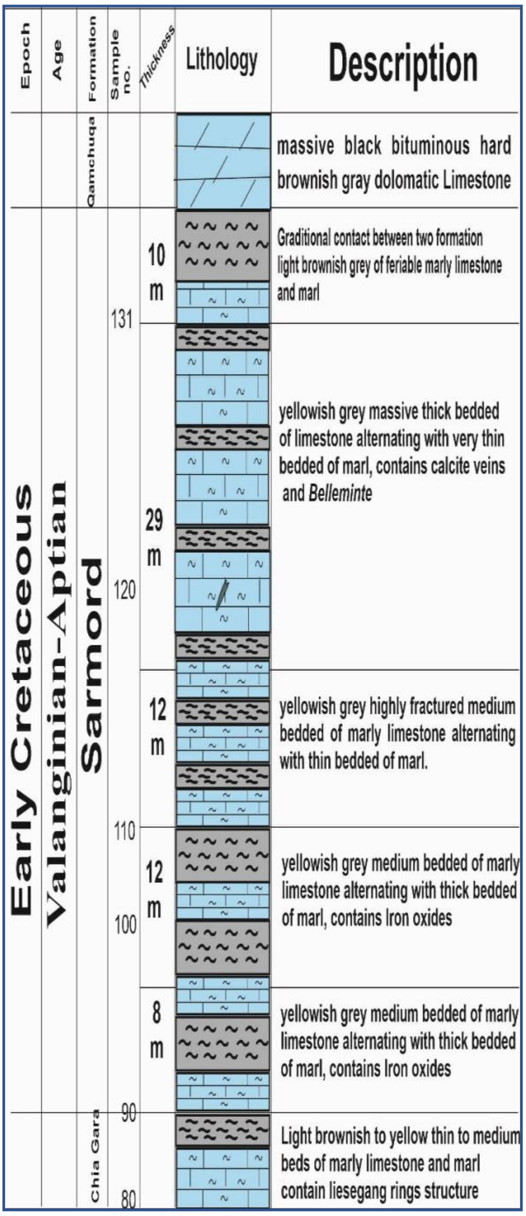
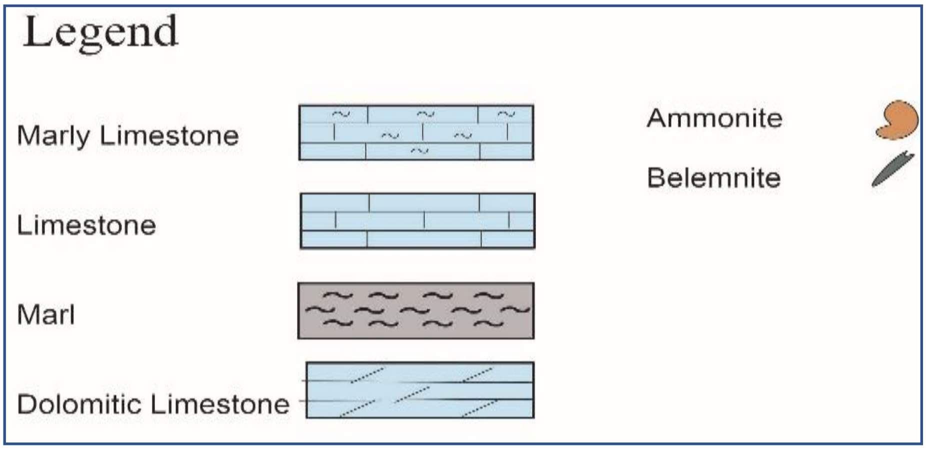


Figure 6: Lithological section for Qala Saida section.



4. Petrographic constituents

The Sarmord Formation is composed of alternated marly limestone and marls. Carbonate rocks, in general, consist mainly of groundmass and grains. The grains are divided into skeletal grains that include fossils and their clasts and non-skeletal grains [12]. The following petrographic constituents are observed in the studied sections carbonates:

4.1. Skeletal grains: -

The skeletal grains are mostly preserved hard pieces of fossil assemblages with broken particles (bioclasts) whose spatial and temporal distribution is influenced by water depth, bottom currents, climate, basin physiography, and nutrient supply. The poor preservation and alternation of some types of skeletal grains is due to the diagenetic effect which causes much difficulty in identifying some of these grains. Generally, different skeletal grains types are identified and distinguished, such as:

4.1.1 Foraminifera:

The foraminifera is the dominant type of protozoa, mainly occurring in marine and dominantly of microscopic size [13]. The foraminifera adopted two main life modes, benthic (on the sea floor) or planktonic [14]. Foraminifera of the Sarmord limestone are usually small–sized and calcite or pyrite–filled. Most Foraminifera was subjected to recrystallization and leaching. They are, thus, hard to identify. The identified foraminifera types include Heterohelix sp. Globigerinilloides sp., Rotalia sp., and miliolids (Plate1 A, B, C and D).

4.1.2 Bioclasts:

Bioclasts are the most common grain kinds found in the Sarmord Formation. These are derived from detritus of different macrofossils represented by bivalves and some other undefined macro and microfossils shell fragments. The general shapes of the bioclast grains are irregular with different sizes. Large bioclasts dominate the upper part of the studied formation at Sargelu and Rania sections. At the same time, fine grain bioclasts are scattered in all portions of the formation but have many occurrences in the Sargelu section and Rania sections (Plate 1E).

4.1.3 Calcispheres:

Calcispheres are organisms with a maximum dimension of less than 0.5 mm. A thin fine-grained layer surrounds the interior cavity in radiosphaerid calcispheres, with a radially prismatic outer layer. These are thought to be marine plankton [15]. Mesozoic calcispheres are abundant in pelagic limestones, typical basinal and basin edges [16]. The investigated sections show scattered unwalled and walled calcispheres, ranging in size (0.08-0.25 mm), in all intervals of all sections. Sparry calcite granular mosaic crystals fill all of the calcispheres that have been found. Calcispheres commonly accompany calcified radiolarian in the lower part of the Barsarin section; this can indicate that large numbers of calcispheres are spherical radiolaria replaced by sparry calcite (Plate 1F).

4.1.4 Ostracods:

environments [12]. In the Sarmord Formation, they were recognized in the middle and upper part of the studied succession at the Sargelu section and in the middle part of the Rania sections. Throughout their lives, ostracods are predominantly benthic or pelagic; pelagic forms have thin shells and an ovate to sub-circular lateral profile. As with other planktons, the pelagic ostracods thrive in regions of current upwelling, rich in phosphates and nitrates [14]. Ostracods are recognized in the Sarmord limestones; some articulated type is micrite–filled or sparry calcite, and others are articulated (single valve) (Plate 1G).

4.1.5 Radiolaria

Radiolarians are microscopic one-celled organisms that secrete a siliceous (opal) shell that is typically less than 1 mm in diameter but more commonly between 0.1 and 0.2 mm. The shell morphology varies considerably, although it is usually shaped like a hollow perforated spherical or vase [17]. Radiolarians are planktonic organisms living in open marine environments found in pelagic limestone [18 and 19]. In the Barsarin section, a high fraction of radiolarian, particularly in the lower and middle sections, are found. In other sections, they were also seen at the lower contact with the Chia- Gara and Balambo formations. The majority are spherical (globular) in shapes conical and star (Plate 1; H and I). The radiolarian ranges in size between (0.08-0.2 mm), not preserved siliceous shell mostly replaced by calcite resulting calcitized radiolarian. The spherical radiolaria is hardly distinguished from calcispheres. They commonly dissolve, leaving empty mold of radiolaria which may become calcite and pyrite filled in later stages.

4.1.6 Echinoderms

The phylum echinoderms include echinoids in the reef and associated environment and crinoids in deep marine [20]. The echinoderms types in the Sarmord Formation mostly belong to crinoids. The echinoderm fragment shapes are primarily circular, semicircular, and star-shaped (Plate 1J). In the Sarmord Formation, the occurrence of echinoderms is few but scattered in the forms of plates and spines all over the whole part of the studied formation. They indicate open normal marine conditions [21].

4.1.7 Sponge spicules

Sponge spicules commonly live in water less than 100-meter-deep on the hard bottom where some water circulations exist [21]. Sponge spicules can be recognized only in the upper part of the Sarmord Formation in the Sargelu section associated with planktons and bioclasts indicating deep an outer ramp and basinal environments (Plate 1K).

4.1.8 Cephalopods

Cephalopods are molluscs that live in the sea and have evolved to swim. Ammonoids usually have a plan spirally coiled shell comprising early Devonian to Cretaceous ammonoids with extinct belemnites (Carboniferous to Eocene but most abundant in the Jurassic and Cretaceous, where the group is used as index fossils). Depositional depths of the Paleozoic and Mesozoic open-marine ammonoid limestones are debated, ranging from tens of meters to thousands of meters [22]. Mesozoic cephalopod wackestones exhibit ammonoids, thin-shelled pelagic bivalves and ostracods, and radiolarians [23]. They were wholly marine (open marine) animals with a dominantly nektonic or nekto- planktonic mode of life [12]. Ammonoids being relatively less common in all the studied sections of the Sarmord Formation except in the upper part of the Sargelu section, abundant ammonites are replaced by iron oxides (Plate 1 L). On the other hand, the belemnites are common in the Sarmord Formation at the Barsarin section compared with other sections of the Sarmord Formation (Plate2; A and B). The other type of Mollusca that seen in the upper part of the studied formation in all studied sections is pelecypods (Plate 2C).

4.2 Non-skeletal grains

Non-skeletal grains are inorganic particles of carbonates. They are divided into coated grains such as (ooids and pisoids) and non-coated grains such as (Intraclast and extraclast) [24]. In the studied sections, rare occurrence of intraclasts is observed only (Plate 2D).

4.3 Matrix (groundmass)

The term matrix refers to the interstitial material between larger grains. Some authors use the terms matrix and groundmass similarly to refer to fine-grained interstitial material (micrite) and coarse interstitial crystal fabrics sparite created by cementation or neomorphic processes [23]. In this study, it is recorded in most of the studied thin sections of the Sarmord Formation. The micrite of the Sarmord thin sections is dark and opaque, rich with organic matter and iron oxide material (Plate 2; E and F). The micrite shows little or no evidence of significant transportation [25 and 26]. While the positions of the dominant marls and micrites are above the CCDL and suggest an environment between the lower part of the slope and the abyssal plain [27]. The main primary source of the Sarmord Formation's micrite may be precipitated microcrystalline calcite from the dissolution of aragonite [28], bacterial activity, decomposition of organic substance, the shell of micro-organisms, and accumulation of the calcareous tests and fragments of pelagic micro-organisms.

4.4 Non-Carbonate lithoclasts

Non-carbonate lithoclasts are rock fragments derived from the erosion of previous rocks. The main lithoclasts constituents in the Sarmord Formation are quartz and phosphatic grains, from silt to medium sand in size and rounded to sub-rounded. Lithoclasts are recorded in the lower part of all the studied sections (Plate 2; G and H).

5. Mineralogy of the marl

In this study, X-ray diffractometry is used to diagnose the clay and non-clay mineral constituents in selected marl samples of the Sarmord Formation. Ten (10) marl samples were chosen from the Sargelu and Rania sections. The samples were digested with weak acetic acid (5%) to estimate the carbonate continent (Table 2). Depending on XRD analysis for selected marl samples of the Sarmord Formation, the bulk rock mineralogy indicates abundant calcite with minor quartz and feldspar contents (Figure 7). Calcite is the most abundant non-clay minerals in the studied sediments. It is recorded with high abundance in the bulk samples mineralogy and the petrographic study. The existence of clay minerals in sediments or sedimentary rocks can be attributed to one of two sources:- detrital or authigenic [29]. The existing clay minerals in the studied samples were identified according to first reflection (001) and other reflections. The main clay minerals that were detected in the Sarmord Formation by x-ray diffractograms are kaolinite, illite, illite-smectite mixed layers and traces of chlorite (Figure8).

Table 2: Insoluble residue in marl samples

Sample No.	Section	IR* (%)
159	Dowawa	38%
21	Dowawa	48%
24	Dowawa	54%
107	Qala Saida	50%
128	Qala Saida	60%
3	Sargelu	52%
10	Sargelu	48%
35	Sargelu	60%
71	Sargelu	60%

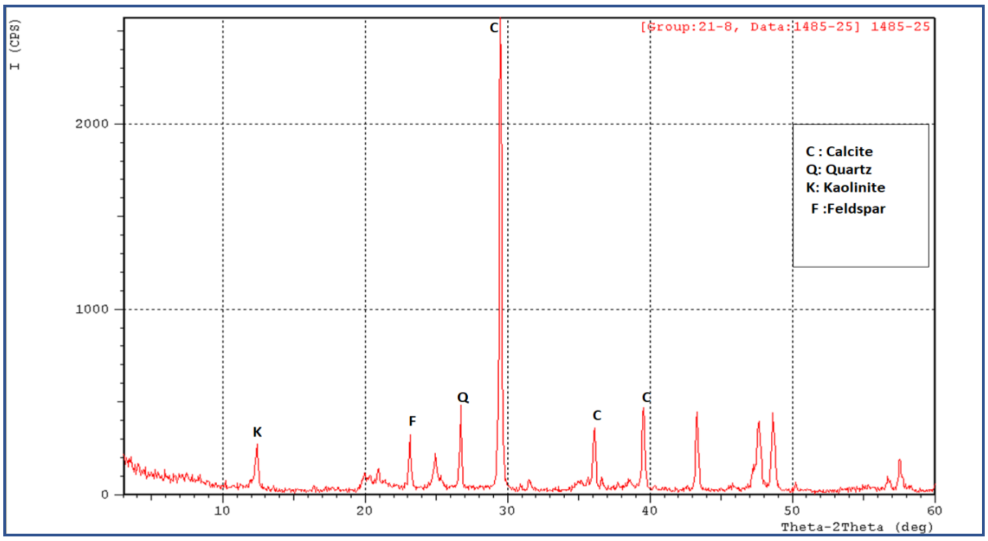


Figure7 : X-ray diffractogram for bulk sample showing minerals in the middle part of Sargelu section (sample No.35).

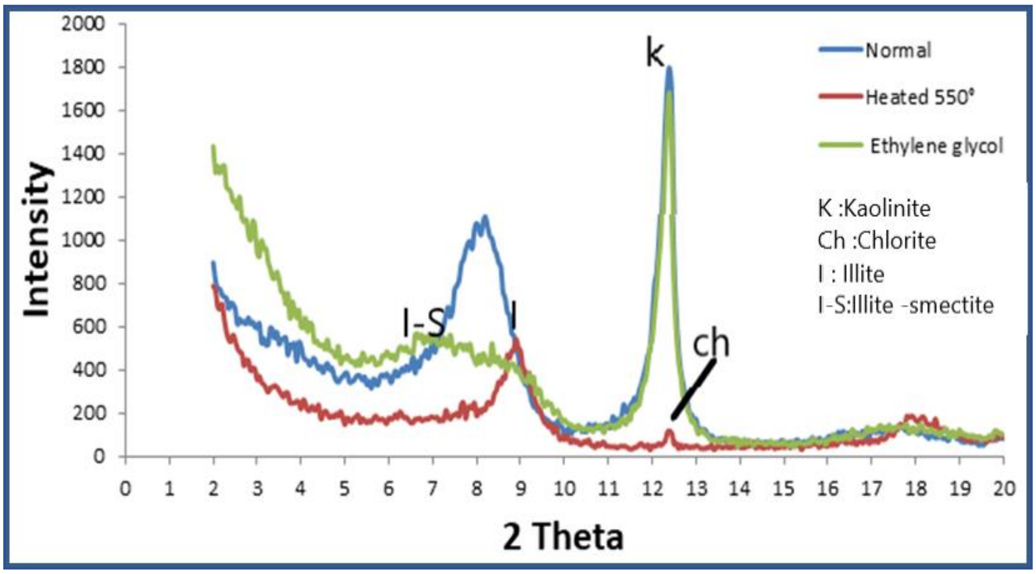


Figure 8: X-ray diffractogram shows the clay minerals in the middle part of the Sargelu section (sample No.35).

All XRD diffractogram samples infer that the kaolinite occupied a significant amount of clay minerals in all studied marl samples. Kaolinite is formed easily in warm and humid environments [30] or may indicate an increasing influx of detrital minerals from continental weathering [31]. The kaolinite possibly developed at high latitudes and cold conditions, under CO2 -enriched palaeoatmospheres, or by unusual acidic weathering linked with dry climates is misleading palaeoenvironment for palaeoclimatic reconstruction. The palaeoclimatic interpretations of marine clay assemblages yield broad palaeoclimatic information. Clay minerals assemblage cannot give the same degree of resolution as other paleoenvironment techniques such as isotope or microfossil studies [32]. The climate in the Cretaceous period was generally warmer and more humid, probably because of active volcanism associated with unusually high rates of seafloor spreading [33]. The kaolinite in the Sarmord Formation may reflect the humid early Cretaceous climate with an increasing influx of detrital minerals from the continent.

In Sarmord Formation, illite- smectite minerals mixed layers also existed. The presence of mixed-layer clays in the studied samples of the Sarmord Formation are basically of detrital origin. Because illite is the most common clay mineral in shales; it is produced mainly from pre-existing shales, whereas smectite is a hydrated, expandable clay that is found in soils and as an alteration result of volcanic glass, and it changes to illite during burial [34]

6. Diagenetic history of the Sarmord Formation

Diagenesis includes all physical, chemical, and biological changes in sediments during deposition and lithification under normal pressure and temperature before weathering and metamorphism [35]. Diagenesis of carbonate rocks is more varied than that of clastic rocks particularly, because of the metastable nature of carbonate minerals [25]). These processes are either destructive, caused by solution and pressure, or constructive, caused by cementation and neomorphism. Diagenetic processes that affected the rock of the Sarmord Formation in the studied sections are:

6.1 Micritization

Micritization (or micritic rim) is an early diagenetic phenomenon caused by borer organisms such as endolithic algae activity or fungi in carbonate deposits [25]. Micritic envelopes result in the early stages of micritization, while in the advanced stages, the skeletal grains are inverted to peloids [36]. The present study shows that micritization preferentially affects thin tests of foraminifera and shells of echinoderms and ostracods (Plate 2 I).

6.2 Dissolution

The effect of dissolving processes is more visible in the skeletal grains of the Sarmord Formation than in the micritic groundmass (especially at the lower and middle part of the studied formation). This is because the micrite is more resistant to dissolution than the skeletal grains [37]. In general, dissolution of $CaCO3$ can occur in environments under–saturated with carbonates. Low water temperatures, high partial pressures of $CO2$ or low pH, and increasing hydrostatic pressures are all significant controlling conditions for under saturation with carbonates [26]. This process is responsible for forming the porosity in carbonate rocks.

Porosity types

Two main types of porosity can be observed according to their time of formation; primary porosity and secondary porosity. These are the basic porosity types, according to Choquette and Pray classification, that are used to classify porosity in the present study. Many types of pore spaces can be recognized microscopically in the studied formation. They are divided into fabric selective and non-fabric selective pores [38].

1-Fabric- selective pores, which is controlled by the components of the original rock, such as: intraparticle porosity (Plate 2; J) and moldic porosity (Plate7; K)

2-Non – fabric selective pores: This term is used where the pores are developed independently of original textures, such as vugs (Plate2; L), fractures, and veinlets. Fracture and veinlet porosity are observed in different sizes, some reach 1 cm, and most fractures are filled by calcite. The fracture porosity in the studied section is most probably formed by tectonic movement (Plate3; B and D).

3-Fabric-selective such as breccia porosity, this type of porosity is rare and noticed in the middle part of Sarmord Formation (Plate2; D) and burrow porosity this type of porosity observed in the middle part of Sarmord Formation in the studied Sargelu section and the lower and upper parts of the formation in Barsarin section (Plate3; A).

6.3 Cementation

Cementation is the chemical precipitation of calcium carbonate between or inside grains and in pores and fissures resulting from the solution [34]. In the studied sections, several types of calcite cement have been recognized, including the following in order of dominance:
1- Granular cement: This cement type seems to be the most common in the studied samples of the Sarmord Formation. Granular cement type is observed in the infilling bivalves, calcispheres and foraminifera (Plate1; A and G).
2- Blocky cement: The presence of this type is common in sections of the Sarmord Formation. It is mainly located in fractures and cracks (Plate3; D). It confirms its late diagenetic occurrence. Similar to granular cement, the blocky type have formed in the freshwater phreatic zone [39].
3- Drusy cement: - This cement type seems less common (rare) in the studied samples of the Sarmord Formation. Drusy cement was observed filling the chambers of fossils (Plate1; F and Plate3; C) in the studied sections.

6.4 Compaction

Compaction refers to any process that reduces the bulk volume of rocks. [26]. There are two types of compaction: mechanical and chemical (pressure solution) [13]. The activated types of compaction in the Sarmord Formation in the studied sections are mechanical and chemical. The common criteria for recognizing mechanical compaction in the Sarmord Formation are fractures usually filled with sparry calcite cement derived from pressure solution and of post-compactional late diagenetic origin, breakage of grains (Plate3; B) and a crystal with strong development of twinning (twin lamellae) in calcite (Plate3; D). Intense twinning is caused by burial pressure or tectonic deformation and usually involves dissolution and crystal dislocation. Calcite develops twin lamellae significantly more easily than dolomite and can be used to identify between the two minerals without staining or analytical data [40].

Nodules are scattered or densely packed within a matrix of like or unlike the character in nodular fabrics of limestones. These nodules are typically centimeter in diameter and have rounded margins. Indistinct (showing bioturbation and diagenetic overprint) or sharp (indicating mechanical transport and sorting of nodules, pebbles, or lithoclasts) contacts between nodules and matrix or between neighboring nodules are occasionally emphasized by darker seams (caused by pressure solution) [23]. In this study, these nodules are seen in the Sarmord Formation, in the lower part of the Barsarin section, and may be related to the connection with burrowing (Plate 3A).

Micro-stylolites are the main result of chemical compactions, which are pressure solution characteristics along seams that are laterally extensive on the scale of a hand specimen (or larger) and cut several grains of mud and cement. Stylolites are zones of discontinuity within rocks. In the thin section, they appear as undulated to zigzag sutures [26]. Among stylolite types [41], the main types of stylolites that occurred in the Sarmord Formation are:
1-Non–sutured seam stylolite (anastomosing): It can be found in limestone with a lot of clay and platy silt. They are lightly undulated and have low relief. Non-sutured seam stylolites have been found in carbonates from the Sarmord Formation as anastomosing sets in the Sargelu section (Plate 3; E).
2-Sutured–seam stylolite: This kind develops in structurally resistant units with few or no platy insoluble minerals. The current study shows that the most common stylolites in the Sarmord Formation at Barsarin and Rania sections are irregular types (a subdivision of sutured seam stylolites), mostly with peaks of low amplitude, with others of high amplitude (columnar stylolite) (Plate 3; F and G). Some irregular stylolites are accompanied by intensive dolomitization (Plate10; H). It was observed that stylolites were parallel to bedding, they are formed due to a load of overburden [12 and 42].

6.5 Dolomitization

The rhombic crystal shape of dolomite is easily identifiable in rocks of various eras. On the other hand, the Dolomites commonly occur in ancient rocks as a mosaic of anhedral crystals with uneven intercrystalline boundaries and undulatory extinction. [43]. Dolomite has also been recognized primarily as a replacement mineral [36]. Dolomitization requires a rise in Mg/Ca ratio in saline water that enters the pores and interstices of carbonate rocks [44].

The dolomitization process is widely agreed to be classified into the following types:

1- Early diagenetic dolomitization

Early dolomitization resulted from the effect of Mg-rich marine water on newly precipitated carbonates [45]. Micrite is the most favorable substrate for dolomitization because its surface area is high and promotes nucleation sites for dolomitization [46]. Early dolomites possess crystals of very fine size, which was abundant in the upper parts of the studied formation, informing of rhombs of dolomite crystals found floating in micrite matrix (Plate 3; I). These crystals are of early diagenetic origin. The Sarmord Formation in the studied sections is mostly related to this type. The upper part of the formation in the Barsarin section differs from other sections; the floating dolomite alteration resembling accentuates zonal variations in the iron contents. The grains' rusty color shows the original ferroan composition. Dolomitization occurred due to fracturing and reducing conditions, most likely during mesogenetic diagenesis. (Plate3; H) [40].

2- Late diagenetic dolomitization

This type occurs due to post lithification of sediments under the influence of Mg-rich solutions, mostly spoiling the original texture of rocks [47 and 12]. Unlike early dolomite, late diagenetic dolomite has coarse crystals. This type of dolomitization is not common in the Sarmord Formation. The Late diagenetic dolomitization is only seen in the Barsarin section, characterized by coarse size and euhedral crystals (Plate3; J). In the middle part of the formation at Barsarin sections, some beds have undergone complete dolomitization with coarse crystals, which removed all original sedimentary features of these rocks and made them friable.

6.6 Dedolomitization

Dedolomitization is the process of calcite replacing dolomite. The dedolomitization refers to the early or late diagenetic replacement of dolomite by calcite [23]. It is believed to have taken place while the beds were exposed. This process is not common in the studied sections and is restricted in the middle part of the Sarmord Formation in the Barsarin section (Plate3; J).

6.7 Authigenic minerals

1-Pyrite

Pyrite is a common precipitate in sediments, which underwent diagenesis in alkaline reducing environments [48]. Reducing conditions necessary for pyritization are available during early burial stages when anaerobic bacteria become active [35]. The most common pyrite forms in all studied sections are small cubic pyrite globular pyrite and moldic or fill pyrite (filled the micro-fossils) (plate 3; K).

2-Silicification and Idomorphic Quartz

Silicification of carbonate rocks entails the substitution of silica for carbonate and the precipitation of pore-filling silica cement. Idiomorphic quartz crystals are anhedral quartz crystals that are commonly found in carbonates exposed to salty or hypersaline pore fluids [23]. Siliceous tests and skeletal elements of animals, river input of solutions from continent weathering in semi-arid climates, and silica supplied in solution by hydrothermal volcanic systems are the principal sources of silica in sediments [12]. The authigenic quartz process is less common in the Sarmord Formation than observed in the upper part of the Sargelu and Rania sections (plate 3; I). As previously mentioned, some siliceous skeletal grains, such as radiolarians, well presented in rocks of studied sections, might be the most probable source for silica in these rocks.

7. Diagenetic sequences

The diagenetic history of the Sarmord Formation can be divided into four stages based on the results of a petrographic investigation (Figure 9): marine, meteoric, burial, and uplift.

1-Marine diagenesis: This marine phreatic diagenesis involves early micritization of allochems. Micrite envelops developed around most thin shells of foraminifera. On the other hand, during the early stage, compaction gradually reduces primary porosity. Finely crystalline dolomites are also formed. This was followed by marine diagenesis in the vadose zone.

2-Meteoric diagenesis: meteoric vadose diagenesis began with the dissolution of metastable skeletal and non-skeletal grains, resulting in secondary fabric- and non-fabric selective porosity. When meteoric waters filled the pores spaces, phreatic diagenesis happened. Types of cement with various fabrics (granular, blocky and drusy cements) were precipitated. These second-generation cements progressively occluded primary pore spaces. Dedolomitization also happened as a result of the percolation of meteoric waters.

3-Burial diagenesis: - Increased overburden stress and pressure solution characterized this stage. Breakage, deformation, over-close packing and some skeletal grains are silicified. Primary and secondary porosity was formed due to compaction without cementation. The coarsely crystalline dolomite and authigenic minerals such as pyrites are precipitated.

4-Uplift: - Cretaceous rocks were uplifted due to late Alpine orogenies. Folds and fractures were found in the Sarmord Formation. In the Quaternary, uplift and exposure to meteoric water led to further dissolution and vuggy porosity formation.

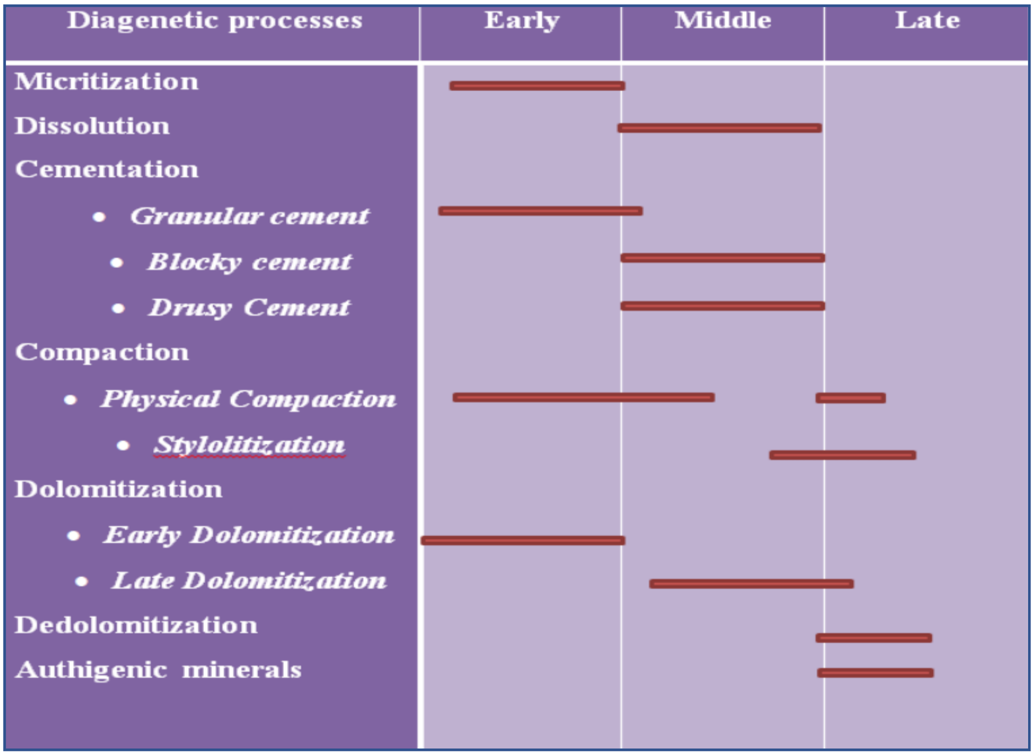


Figure 9: Diagenetic sequence of the Sarmord Formation in the studied sections

8. Conclusions:

The study has revealed the following conclusions:

1. The General lithology of the Sarmord Formation is carbonate rocks with siliciclastics in a rhythmic manner between marly limestone and marls with different thicknesses.

2. The petrographic investigations of marly limestone of the Sarmord Formation show skeletal grains such as; bioclasts, foraminifera, radiolarians, calcispheres, echinoderms, ostracods and cephalopods.

3- X-ray diffraction analysis of marls revealed that the main clay minerals in the Sarmord Formation are kaolinite, illite-smectite mixed layers and traces of chlorite. The kaolinite and smectite minerals may indicate an increasing influx of detrital minerals from continental weathering due to the humid climate during the Lower Cretaceous period. Non-clay minerals include calcite and quartz with low feldspar contents.

4- The described diagenetic processes affected the Sarmord carbonates belonging to three diagenetic stages; early (shallow burial), middle and late (deep burial). Diagenetic processes include micritization, dissolution, cementation, compaction, dolomitization, dedolomitization and authigenic minerals (pyrite and silica).

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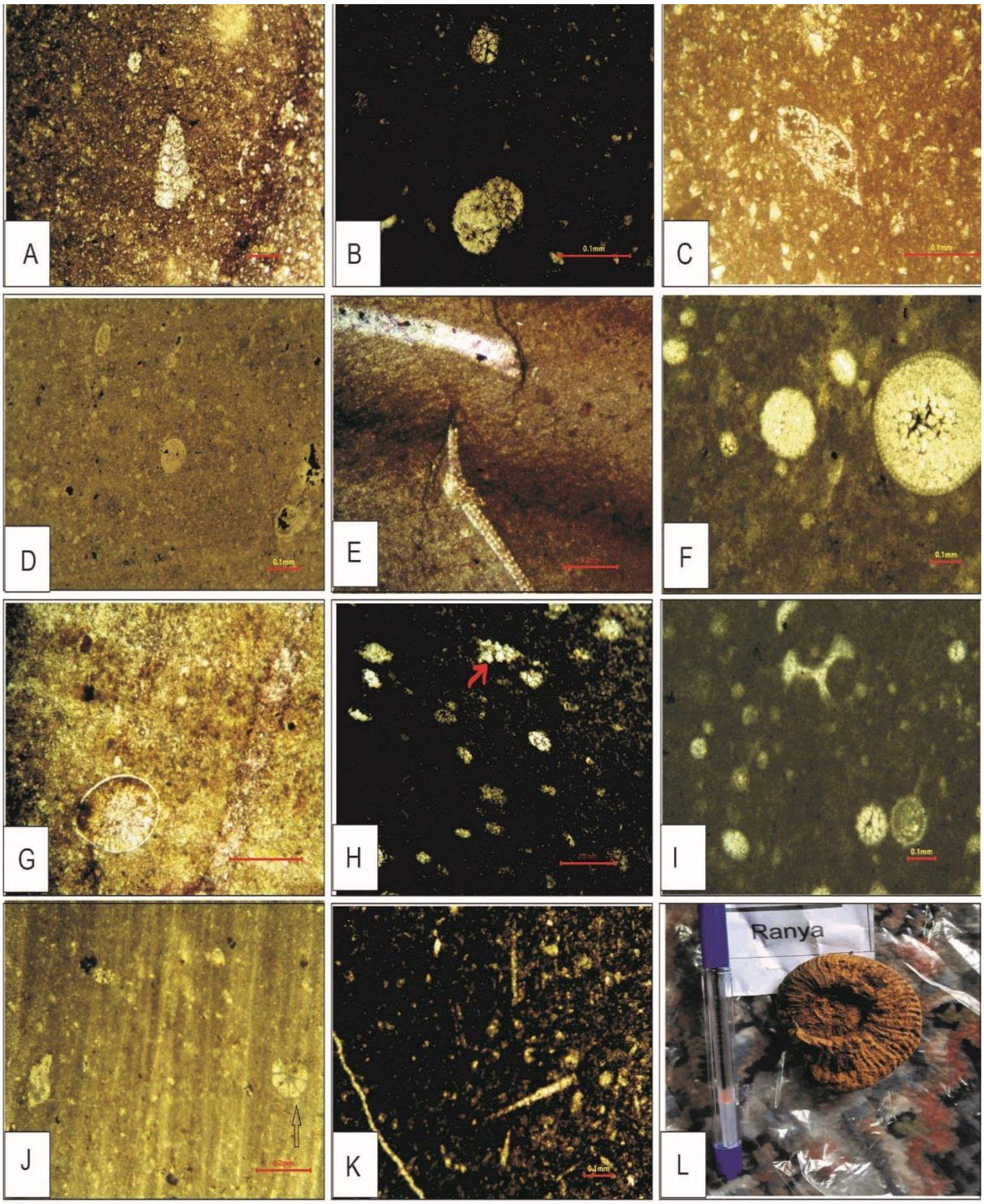

Plate 1

A. Heterohelix sp. planktonic foraminifera filed by granular calcite cement at Sargelu section, sample no.53 (PPL)
B. Globigerinid sp. planktonic foraminifera at Sargelu section, sample no.54 (XPL).
C. Rotalia sp. foraminifera at Sargelu section, sample no.73 (PPL).
D. Planispiral foraminifera in the center and miliolid foraminifera in the upper left, Sargelu section, sample no.85 (PPL).
E. Bioclast at Sargelu section, sample no.8 (XPL).
F. Calcispheres at Barsarin section, sample no.50 (PPL).
G. Articulated ostracoda filed by granular calcite cement at Sargelu section, sample No.22 (PPL).
H. Conical calcitized radiolaria, the tests are replaced by spary calcite cement. Sargelu section, sample No.2 (XPL).
I. Many types of Calcitized radiolaria, the tests are replaced by spary calcite cement. Barsarin section sample No. 43 (XPL).
J. Echinoid spines at Qala Saida section, sample No. 127 (PPL).
K. Calcic sponge spicules at Sargelu section, sample No. 66 (XPL).
L. Ammonite replacement by iron oxides at Dowawa section.

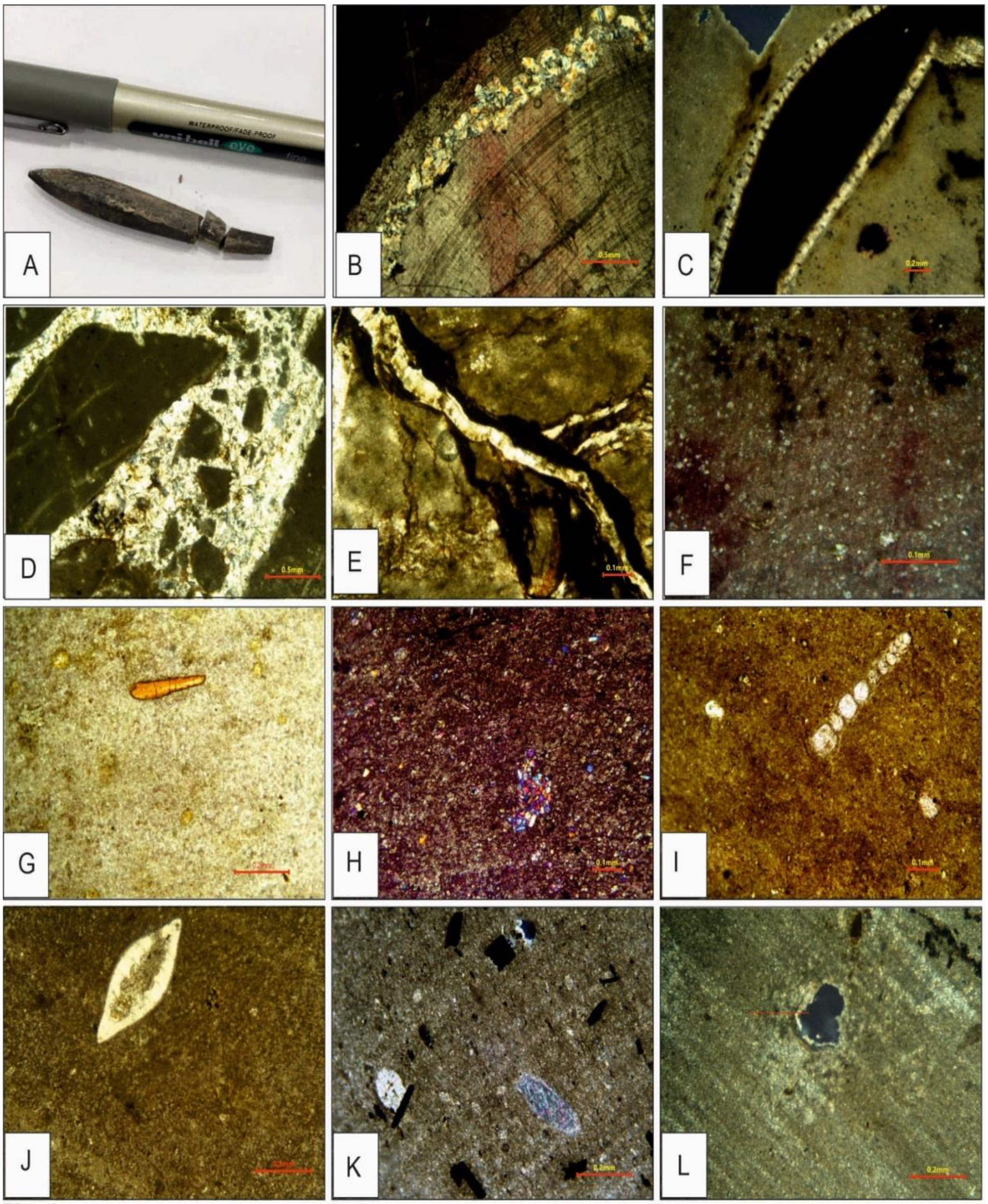

Plate 2

A. Belemnite sample at Barsarin section.
B. A transverse section through part of the wall of belemnite. the shell is composed of three layers, the middle layer contains silica.at Barsarin section, sample No. 5 (XPL).
C. Pelecypoda valves at Dowawa section, sample No. 8 (XPL).
D. Intraclast at Barsarin section, sample No. 59 (XPL).
E. Micrite contains Bitumen filled fracture at Barsarin section; sample No. 27 (XPL).
F. Newmorphism of micrite to microspare at Sargelu section, sample No. 31 (XPL).
G. Phosphatic grain at Sargelu section, sample No. 6 (PPL).
H. Quartz grains in micrite matrix with using accessary plate, Sargelu section, sample No. 63 (XPL).
I. Micrite envelope around the foraminifera test at Sargelu section, sample No. 51 (PPL).
J. Intraparticle porosity in radiolaria reduced by cementaion, Qala Saida section, sample No. 130 (XPL).
K. Moldic porosity Produced by dissolution process Qala Saida section, sample No. 106 (XPL).
L. Vug porosity at Dowawa section, sample No. 9 (XPL).

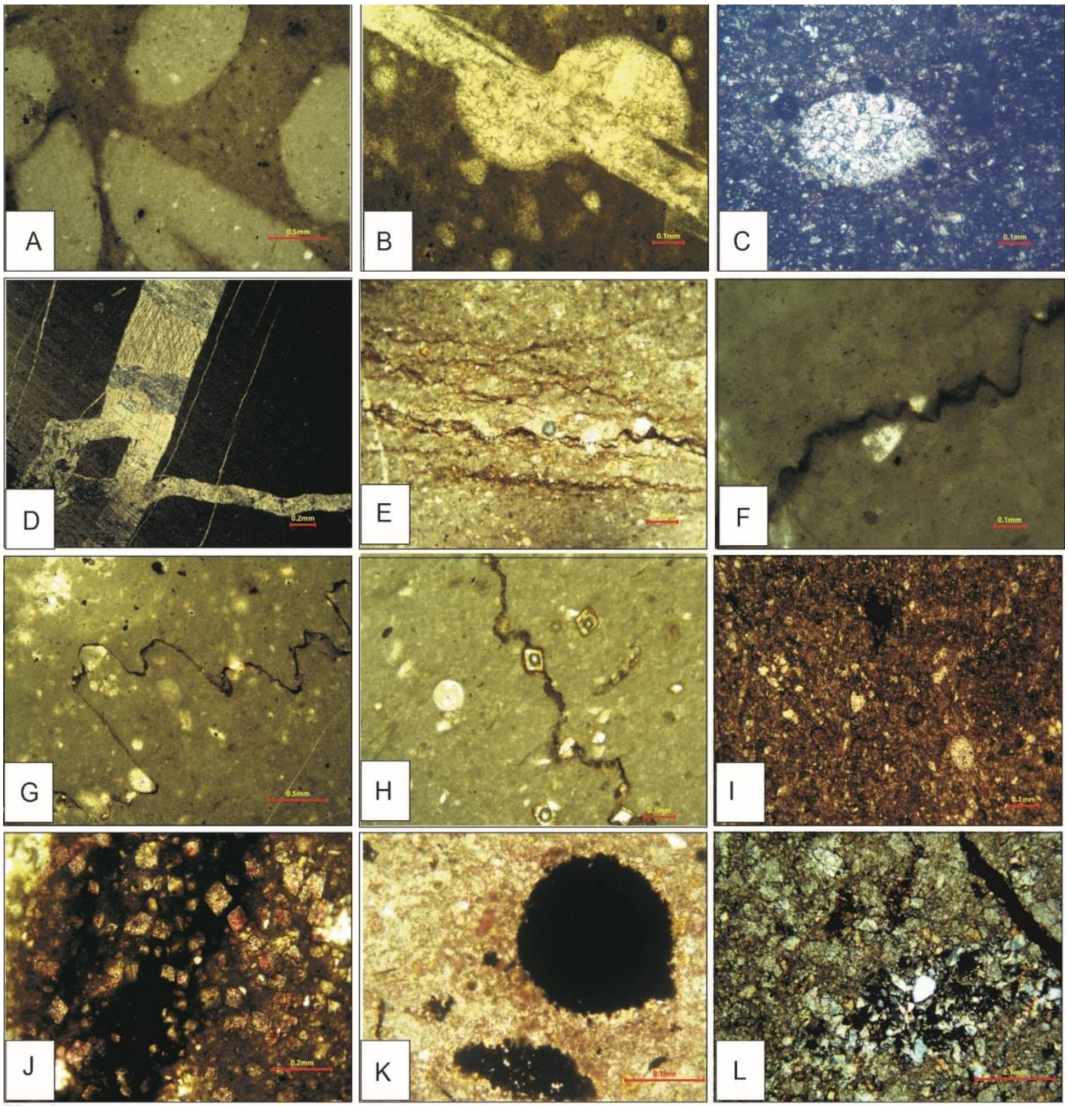

Plate 3

A. Burrow porosity at Barsarin section; sample No. 83 (XPL).

B. Calcisphere filled by granular calcite cement and effected by micro faulting(breakage of grain) due to compaction. Barsarin section, sample No. 50 (PPL).

C. Bivalve filled by drusy cement at Sargelu section, sample No. 64 (XPL).

D. Twin lamellae in calcite crystals typically a result of burial loading or tectonic deformation. Dowawa section, sample No. 5 (XPL).

E. Non- sutured seam stylolite, anastomosing type. Sargelu section, sample No. 60 (XPL).

F. Sutured seam stylolite, irregular type with peaks of low amplitude. Barsarin section, sample no. 67 (XPL).

G. Sutured seam stylolite, irregular type with peaks of high amplitude (columnar stylolite). Barsarin section, sample No. 92 (PPL).

H. Sutured seam stylolite, irregular type with peaks of low amplitude with dolomitization. Barsarin section, sample No. 82 (PPL).

I. Unhedral dolomite crystals found floating in micrite matrix. Sargelu section sample No. 83 (XPL).

J. Coarse size and euhedral crystals of dolomite and dedolomitization at Barsarin section, sample No. 45 (PPL).

K. Authigenic pyrite filled the fossils. Sargelu section, sample No. 80 (PPL).

L. Authigenic quartz at Sargelu section, sample No. 68 (XPL).

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