Iraqi Bulletin of Geology and Mining Vol.15, No.2, 2019 p 51 – 70

DIAGENETIC HISTORY AND POROSITY TYPES OF THE BALUTI FORMATION (UPPER TRIASSIC), GALLEY DERASH, DUHOK GOVERNORATE, KURDISTAN REGION, NORTHERN IRAQ

Irfan Sh. Asaad[*1] and Muhamed F. Omer[1]**

Received: 11/ 11/ 2018, Accepted: 05/ 08/ 2019
Key words: Petrography; Diagenetic stages; Dolomite texture; Baluti Formation; Northern Iraq.

ABSTRACT

The Baluti Formation in the Galley Derash locality is comprised of 73 m brecciated dolomitic limestone in the lower part, alternating with thin bedded dolomitic limestone and dark gray shale in the middle part, then thin to medium bedded brecciated sandy limestone interbedded with dark grey shale in its upper part. The sum of 21 thin sections of the Baluti Formation carbonates are petrographically studied using polarizing microscope. The results show various types of skeletal grains including calcareous algae, ostracods, brachiopods, bivalves, benthonic foraminifera, gastropods, and echinoderms, while the non-skeletal grains include peloids, intraclasts, extraclasts and rare ooids. The Baluti Formation was subjected to differed diagenetic processes such as micritization, mechanical compaction, cementation, early dolomitization, neomorphism, stylolitization, late dolomitization, dedolomitization, silisification, soulution, fracturing and pyritization. These diagenetic modifications occurred during marine phreatic shallow burial stage and were activated during intermediate to deep burial and uplift in the late stages. Five kinds of dolomite textures are recognized: Unimodal very fine to fine-crystalline planar-s (subhedral) mosaic, unimodal very fine to fine-crystalline planar-e (euhedral) mosaic, unimodal fine to medium crystalline planar-s (subhedral) mosaic, medium to coarsecrystalline planar to non-planar-c (cement) mosaic and polymodal planar-s (subhedral) to planar-e (euhedral) mosaic. The petrographic study revealed that the secondary porosity is dominant. The paragenetic history of the Baluti Formation passed through four diagenetic environments which are: marine, meteoric, burial and uplift.

التأريخ التحويري وأنواع المسامية لتكوين بلوطي (الترياسي الأعلى) في مقطع كلي ديرش، محافظة دهوك، أقليم كوردستان، شمال العراق

عرفان شعبان اسعد و محمد فخري عمر

المستخلص

تتألف صخارية تكوين بلوطي في المقطع االمختار من 73 متر من االصخر الجيري المدلمت المكسور في جزئه السفلي والجزء الوسي تيتكون من طبقات رقيقة من الصخر الجيري المدلمت المتداخل مع السجيل الرمادي الداكن بينما يتكون الجزء الاعلى من الصخر الجيري الرملي المتكسر المتداخل مع السجيل الرمادي الداكن. اظهرت الدراسة البتروغرافية لـ 21 شريحة رقيقة من الصخور الكاربونيتية للتكوين العديد من انواع الحبيبات الهيكلية المتمثلة بالطحالب الكلسية والصدفيات وذوات القوائم الذراعية وذوات الصدفتين والفورامينيفيرا القاعية والرخويات وشوكيات الجلد، اما الحبيبات غير الهيكلية فتتضمن كل من الدمالق والسرئيات وقطع داخلية وخارجية التكوين. تأر تكوين بلوطي بعدة عمليات

[1] Department of Geology, College of Science, Salahaddin University-Erbil, Iraq.
[*]e-mail: irfan.asaad@su.edu.krd, [**]e-mail: muhfakhri2005@gmail.com

تحويرية متمثلة بالمكرتة والانضغاط الميكانيكي والكيميائي والسمنتة والدلمتة بنوعيها المبكرة والمتأخرة والتشكل الجديد والدلمتة العكسية والسلكتة والإذابة والتكسر وتكوين البايرايت. حدثت العمليات التحويرية في المرحلة المبكرة (الدفن الضحل) ونشطت في المرحلتين المتوسطة والمتأخرة (الدفن العميق وعملية الرفع اللاحقة). تم تشخيص خمسة انواع من انسجة الدولومايت في صخور تكوين بلوطي تضمنت كلا من **1)** النسيج ذو البلورات الدقيقة جدا الى الدقيقة المسطحة الناقصة الاوجه الأحادي النمط، **2)** النسيج ذو البلورات الدقيقة جدا الى الدقيقة المسطحة كاملة الاوجه الأحادي النمط، **3)** النسيج ذو البلورات الدقيقة الى المتوسطة المسطحة الناقصة الاوجه الأحادي النمط **4)** النسيج ذو البلورات المتوسطة الى الخشنة المسطحة الى غير المسطحة الناقصة الاوجه الاسمنتي و **5)** النسيج الناقص الاوجه الى كامل الاوجه متعدد النمط. بينت الدراسة البتروغرافية ان غالبية المسامية هي من النوع الثانوي. مر تكوين البلوطي بأربع بيئات تحويرية وهي: البحرية و المياه العذبة والدفن والرفع.

INTRODUCTION

The Late Triassic succession is widely expanded than the rest of the Triassic strata in the Arabian Peninsula (Jassim and Goff, 2006). The exploration of economic hydrocarbons in the Triassic rocks of the northern Arabian Plate gave these sediments more interest and importance, particularly the Baluti Formation units, which are a source rocks, reservoir and seals in the Triassic petroleum system (Aqrawi *et al.*, 2010; Balaky *et al*., 2016; Akram, 2016). The Baluti Formation was first introduced by Wetzel in 1950 and amended by Morton in 1951 in Bellen *et al*. (1959) in its type locality section in the Baluti village, south of Amadyia town, in the core of the Chia Gara Mountain as a gray and green shales, calcareous, dolomitic, with intercalations of thin-bedded limestones, silicified limestones and solution-recrystallization breccias. The exemplary development of the formation is limited to the High Folded, Imbricated, and Northern Thrust Zones of Iraq (Buday, 1980). While, in subsurface it was identified in wells: Jabal Kand-l, Khlesia-l, Atshan-l and W Kifl-l (Jassim and Goff, 2006). The formation is characterized by rare fossils, therefore, the age was regarded as Rhaetian based on its stratigraphic position between the lower part of the Kurra Chine Formation and the upper part of the Sarki Formation (Bellen *et al.*, 1959).

Diagenesis defined as a sedimentary phenomenon combining the whole physical and chemical modification, which occurs after deposition and before the emergence of metamorphism (Flügel, 2004 and Ahr, 2008). It ordinarily obscures the primary depositional features (Boggs, 2009) and in some situations, some evidence survives to aid pre-diagenetic environments interpretation (Swati *et al*., 2014). Significant changes in porosity and permeability are related to the diagenetic processes (Ahr, 2008 and Boggs, 2009). There are a few published data or reports about the Baluti Formation within the High Folded and Northern Thrust zones of Iraq. The Baluti Formation has been studied by many researchers {e.g., Bellen *et al*. (1959); Buday (1980); Jassim and Goff (2006); Hanna (2007); Aqrawi *et al*. (2010); Shingaly (2016); Al-Mashaikie *et al*. (2016); Al-Mashaikie (2017) and Al-Mashaikie and Abdul-Razzak (2017)}. The main objective of the present study is to determine the diagenetic history and dolomite texture of the carbonates succession in the Balluti Formation at the Galley Derash section.

METHODOLOGY

The work was done in two steps: firstly, fieldwork, which includes the general geology and structural relations of the Triassic – Jurassic units in the Galley Derash locality and the surrounding area and to choose the most suitable section for the study. The studied outcrop is described and measured in detail including logging the lithology, grain size, and mineralogy, in addition to collection of 21 samples from the carbonate rocks. The upper and lower parts of each sample are marked. Secondly, preparing thin sections for all collected samples and staining with Alizarin Red S (ARS) solution following the procedure of Friedman (1959) at the workshop of the Department of Geology, Salahaddin University – Erbil. The thin sections are examined for detailed petrographic study by polarizing microscope and several references were used for identifying the constituents, such as; Horowitz and Potter (1971); Scholle (1978); Sartorio and Venturini (1988) and Scholle and Scholle (2003).

GEOLOGIC SETTING

The Baluti Formation crops out as secluded patches in the core and limbs of anticlines in the High Folded, Imbricated and Northern Thrust Zones of Iraq (Fig.1), as well as in subsurface wells, such as Jabal Kand-l, Khlesia-l, Atshan-l, W Kifl-l, Bjeel-1, 2, 3, 7, Bakirman-1, Bekhma-1, and Gulak-1 (Buday, 1980; Jassim and Goff, 2006; Csató *et al*., 2014). The Galley Derash section, which is also called the Sarki section in some articles, was chosen for the present study. It is located in the Gara Mountain, about 4 Km south of Derash village, 9 Km east of Baluti village and 15 Km southeastern Amadyah town in Duhok Governorate (Fig.1). The studied section is located at Lat. 36° 59' 37" N and Long. 43° 32' 23" E, on the road of the Sarki village. It is located in the core of the Gara anticline in the High Folded Zone of the Zagros Fold and Thrust Belt. Structurally, several faults cut the area which comprises the northern flank of the Gara anticline and form deep narrow gorges through the Jurassic, Cretaceous, and Tertiary carbonate units. Generally, the dip of stratigraphic units in the area increases gradually towards the older units and abruptly increases in the Jurassic units to nearly vertical due to thrust faulting (Awdal *et al*., 2016).

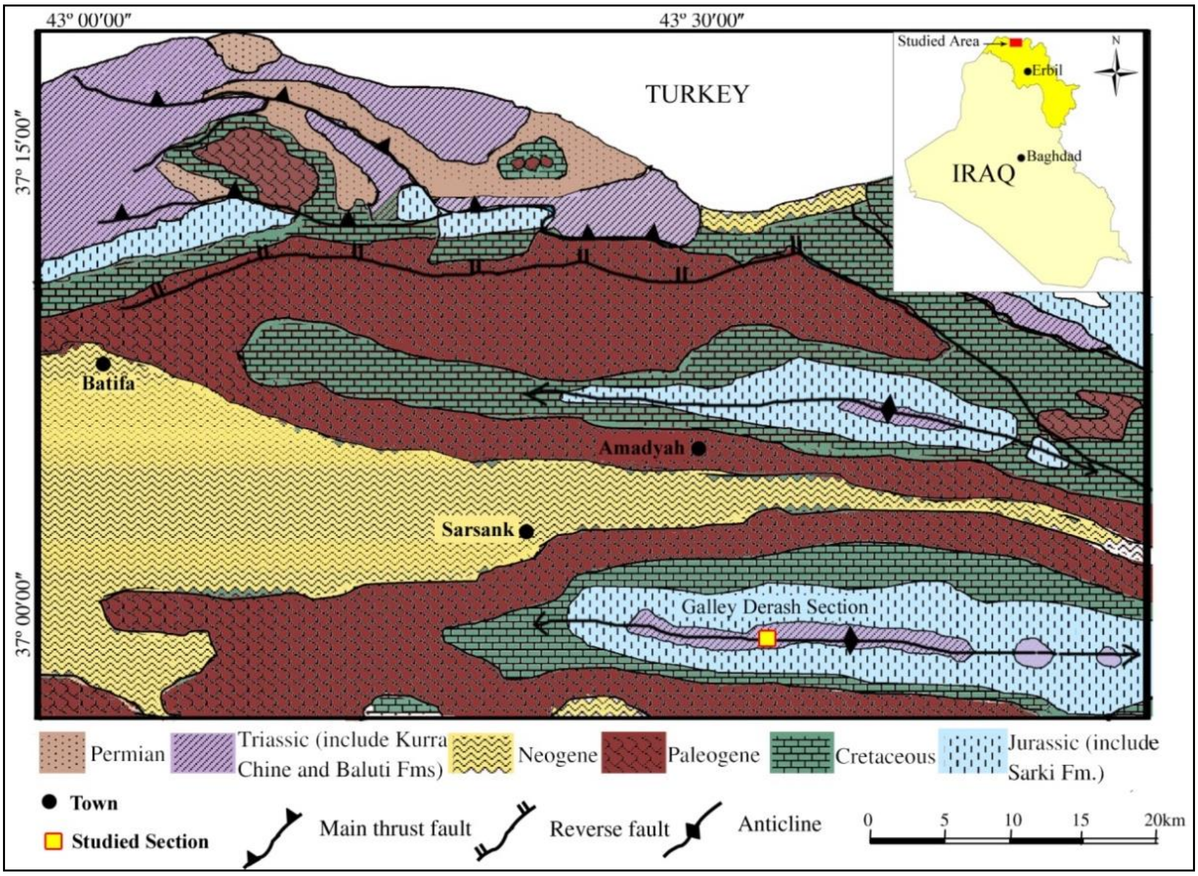


Fig.1: Location and geological map of the studied section
(After Sissakian, 2000)

The stratigraphy of the studied section includes stratigraphic succession, starting with the oldest rock; Kurra Chine, Baluti (Upper Triassic) and Sarki formations (Lower Jurassic) at the core of the Gara anticline. The latter is, in turn, overlain by the younger Sehkaniyan Formation (Lower Jurassic), followed by the Sargelu (Middle Jurassic), Naokelekan and Barsarin formations (Upper Jurassic). The Cretaceous and Tertiary units are also exposed farther north of the northern limb of the Gara anticline (Fig.1). Lithologically, the studied section comprises 73 m of brecciated dolomitic limestone in the lower part, alteration of thin-bedded dolomitic limestone with dark gray shale in the middle part and thin to medium bedded brecciated sandy limestone interbedded with dark-gray shale in the upper part (Fig.2). The nature of the lower and upper boundaries of the Baluti Formation is conformable with both the Kurra Chine and the Sarki formations (Fig.3).

RESULTS AND DISCUSSION

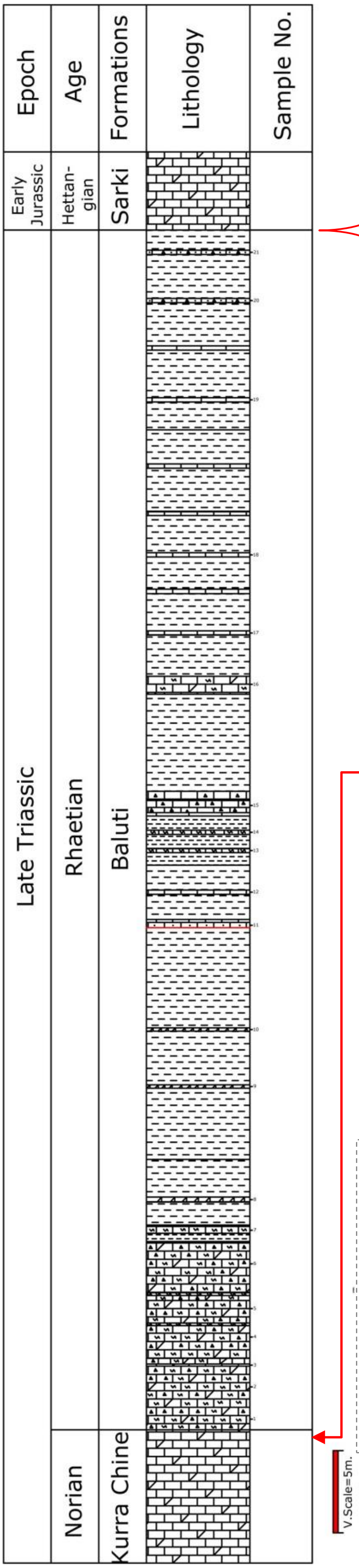
▪ Petrography

The petrographic study of 21 thin sections of the Baluti carbonates from the Galley Derash section shows that the compositional maturity of the Baluti carbonates are immature to mature in lower part, mature in middle part gradually change of the maturity into immature in upper part depending on number of limestone constituents (e.g. intraclasts, ooids, fossils, peloids, micrite matrix, and terrigenous minerals). Mature limestone contains a reduced number of these constituents (Smosna, 1987). In the Baluti Formation the following types of skeletal grains are found: calcareous algae (Fig.4c), ostracods (Fig.5b), bivalves (Fig.5d), echinoderms (Fig.5f), gastropods (Fig.6a), benthonic foraminifera (Fig.6d), and brachiopods (Fig.7b). Non skeletal grains include peloids (Fig.6b), intraclast (Fig.6c), extraclast (Fig.6c) and rare ooids (Fig.6c). The extraclasts contain cryptocrystalline quartz grains (Fig.6c). The groundmass of the in the studied samples is mainly micrite (Fig.5b), transformed into microspar (Fig.8b) and sparry calcite (Fig.7b) due to effective neomorphism and silicification.

▪ Diagenesis

The diagenesis of carbonate rocks is more variable than that of the siliclastics, due to the metastable nature of their minerals (Bathurst, 1975). The carbonates of the Baluti Formation in the Galley Derash is highly obliterated and the original features were changed by diagenesis. Shingaly (2016) discussed the diagenetic processes of the Baluti Formation and not considered as a completed face for the formation, Al-Mashaikhi and Abdul-Razzak (2017) studied the origin of the dolomites in the formation in the same studied section. In the present study dolomitization is studied as a diagenetic processes and the dolomite texture restudied and integrated to paragenetic history of the Formation. The most important diagenetic processes that had affected the formation over three main paragenetic stages: (early, middle, and late) are the following:

– **Micritization:** It is considered as an early diagenetic process, appears as micritic rim (or envelope), as a result of borer organisms such as endolithic algae activity or fungi in carbonate deposits (Bathurst, 1975). Micritic rim is produced at the early stages of micritization, while in the progressive stages the skeletal grains are overturned to peloids (Blatt, 1982). It is active in the stagnant marine phreatic zone (Longman, 1980). Micritization had influenced most fossils in the Baluti carbonates particularly thin shells (valves) of mollusks (Fig.4a).



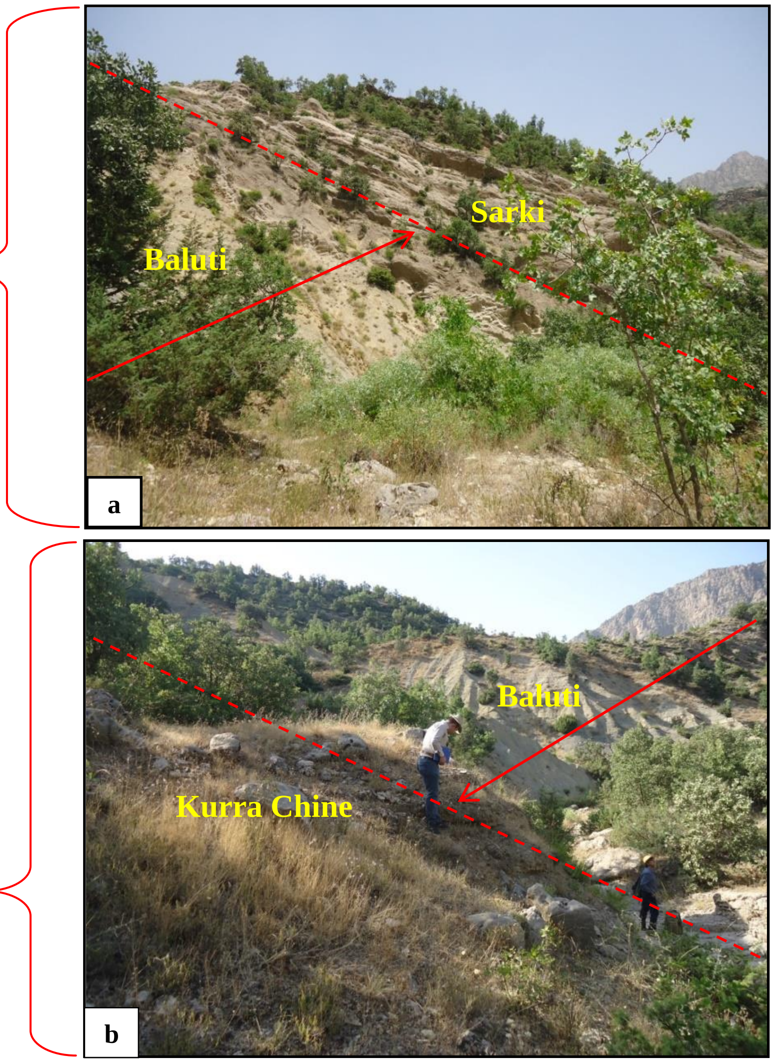


Fig.3: Field Photographs showing **a)** The boundary of Baluti Formation with the overlying Sarki Formation in the Galley Derash section. **b)** The boundary of the Baluti Formation with the underlying Kurra Chine Formation in the Galley Derash section

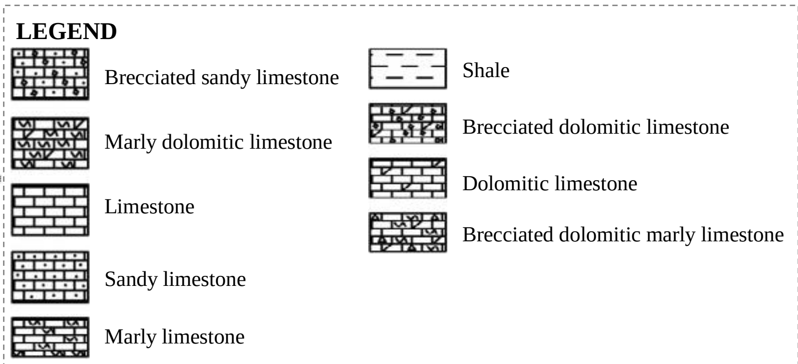


Fig.2: Stratigraphic column of the Baluti Formation (Upper Triassic), Galley Derash section, High Folded Zone.

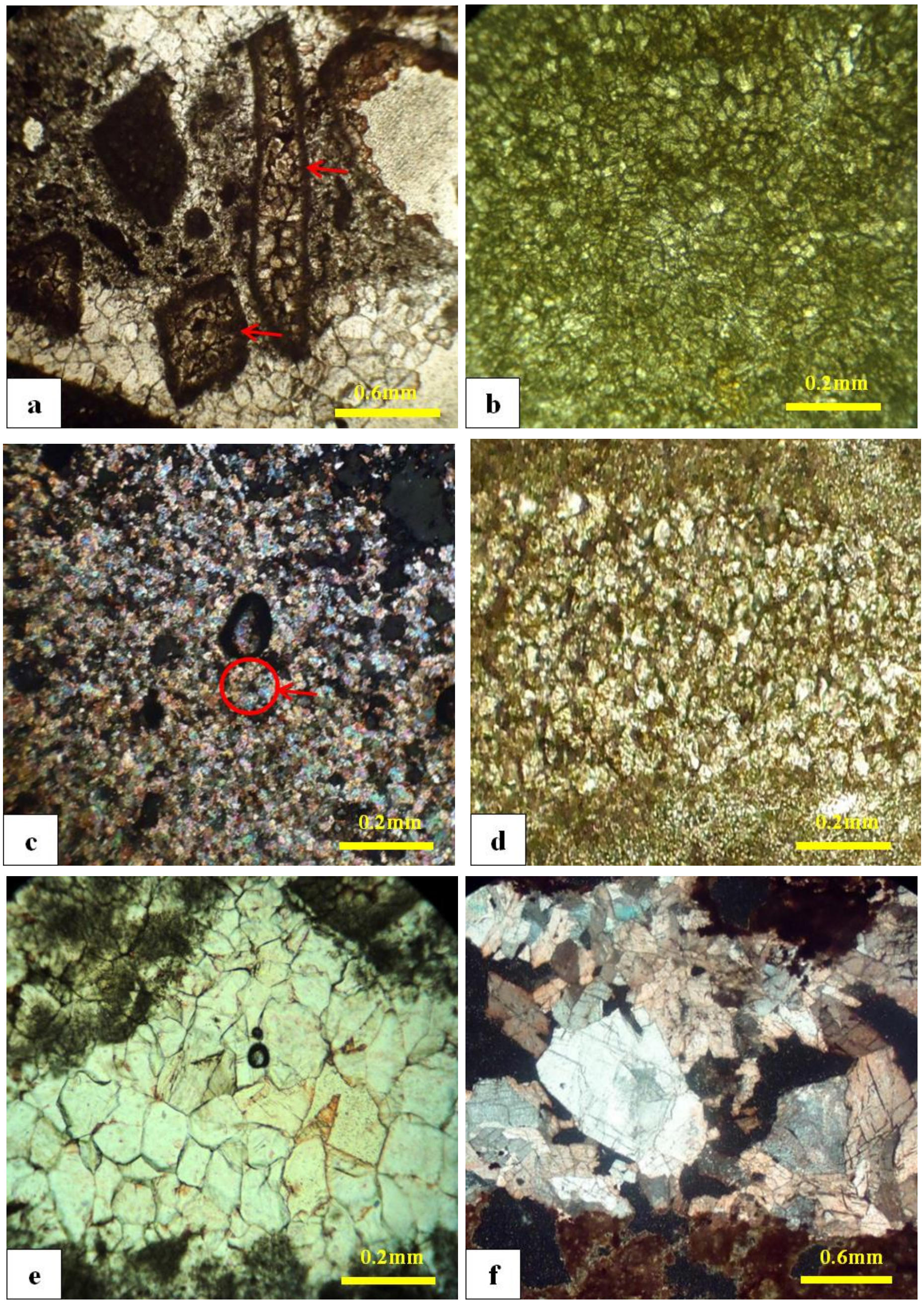


Fig.4: Photomicrographs of micritization and dolomitization showing:

a) Micrite envelops (rim) surrounding mollusks shell (red arrows). B4, P.P. **b)** Unimodal, very fine to fine-crystalline planar-s (subhedral) mosaic dolomite, which is formed in early-stage dolomitization. B2, P.P. **c)** Unimodal, very fine to fine-crystalline planar-e (euhedral) mosaic dolomite, Dasycladacean calcareous green algae affected by dolomitization (red arrow), (early dolomitization). B1, X.N. **d)** Unimodal, fine to medium crystalline planar-s (subhedral) mosaic dolomite. B2, P.P. **e)** Medium to coarse-crystalline planar to non-planar-c (cement) dolomite. B4, P.P. **f)** Polymodal planar-s (subhedral) to planar-e (euhedral) mosaic dolomite. B7, X.N.

B = Baluti Formation, P.P = Plane Polarized light, X.N = Crossed Nichols

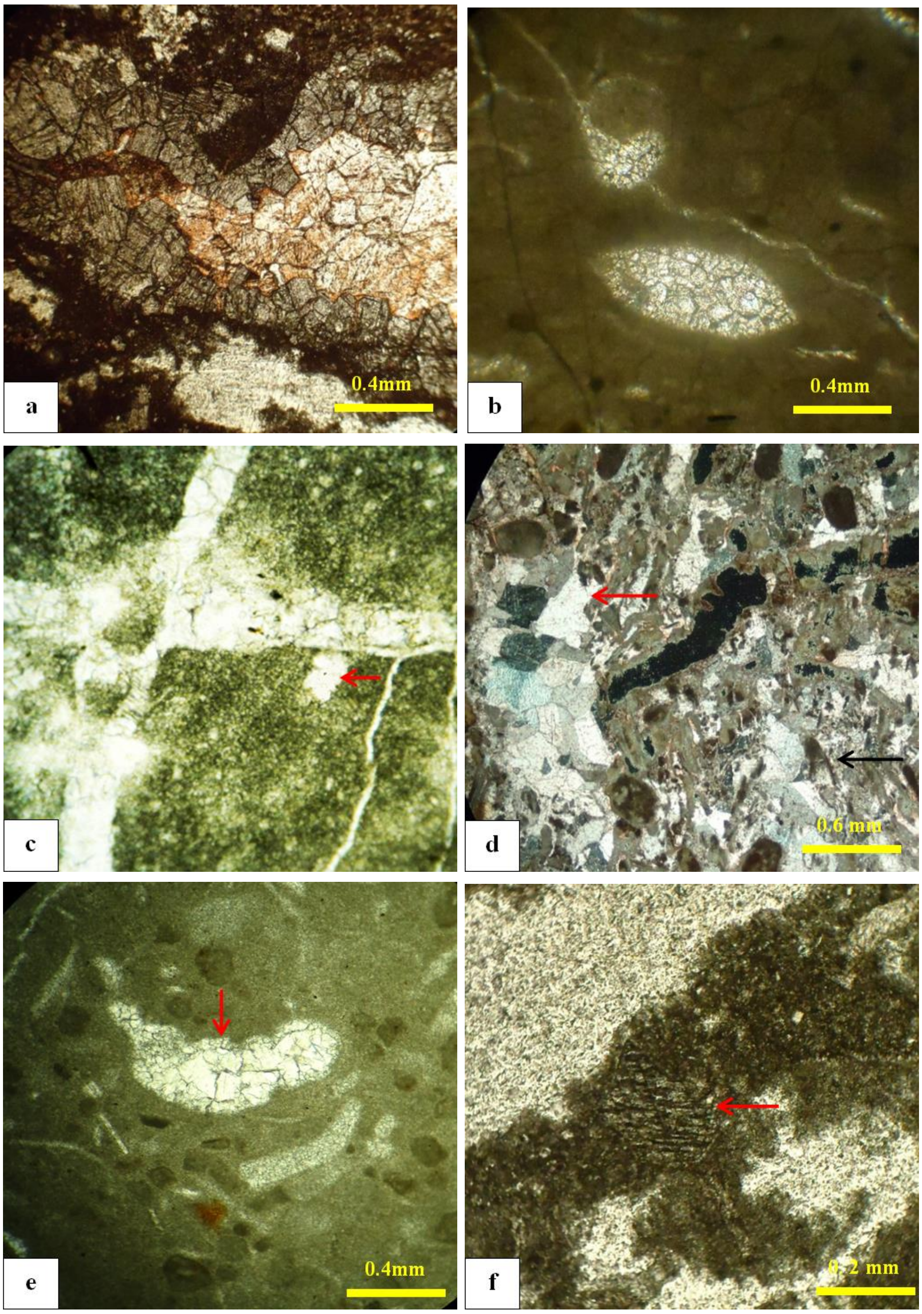


Fig.5: Photomicrographs of dedolomitization and cementation showing:

a) Dedolomitization of dolomite crystals caused by the effect of freshwater. B2, P.P., A.S. **b)** Articulated Ostracoda filled by granular cement (red arrow), B13 P.P. **c)** Compaction-related fracturefilled by granular cement with neomorphism of skeletal grains around it (red arrow). B13, X.N **d)** Blocky cement filling a fracture (vein) (red arrow) and articulated bivalve (black arrow), B11, X.N. **e)** Neomorphosed calcite within bioclastic grains filled by drusy cement (red arrow), B13, P.P. **f)** Syntaxial overgrowths cement on the echinoderm fragments (arrow), B2, P.P.

B = Baluti Formation, P.P = Plane Polarized light, X.N = Crossed Nichols

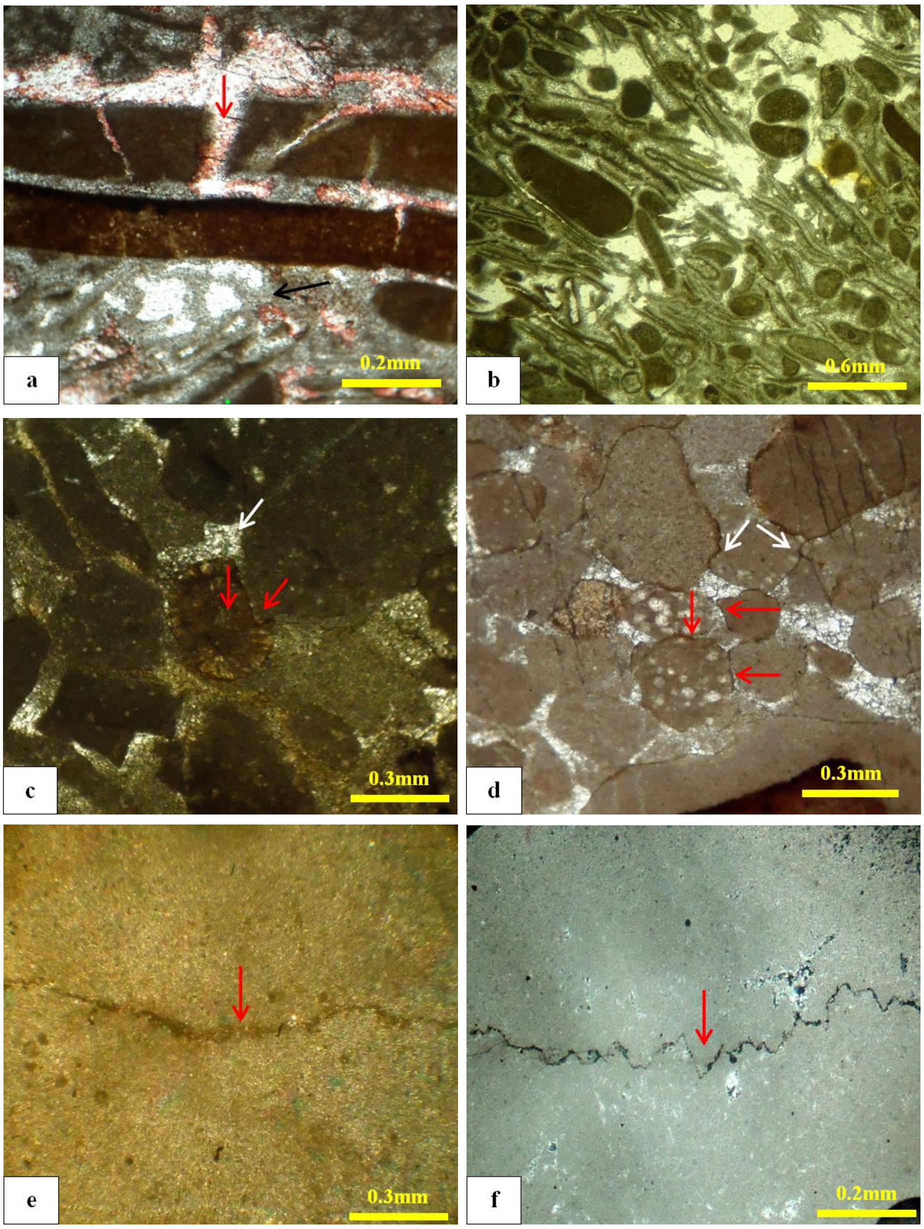


Fig.6: Photomicrographs of Physical and Chemical compaction showing:

a) Breakage of skeletal grain (red arrow) due to weight of overburden, Gastropods are intraparticle pores filled by cement (black arrow). B12, X.N. **b)** Over close packing of skeletal grain and deformation of peloids under the effect of compaction. B11, P.P. **c)** over close packing of grain mostly intraclasts, deformation of radial fibrous oolite by mechanical compaction (red arrow) and cryptocrystalline quartz above it (white arrow). B21, P.P. **d)** concave-convex suture between intraclasts grains (white arrows), benthonic foraminifera (*Glomospera*) (red arrows). B20, P.P. **e)** Sutured seam stylolite, irregular type with peaks of low amplitude, B16, P.P. **f)** Sutured seam stylolite, irregular type with peaks of high amplitude (columnar stylolite), B17, P.P.

B = Baluti Formation, P.P = Plane Polarized light, X.N = Crossed Nichols

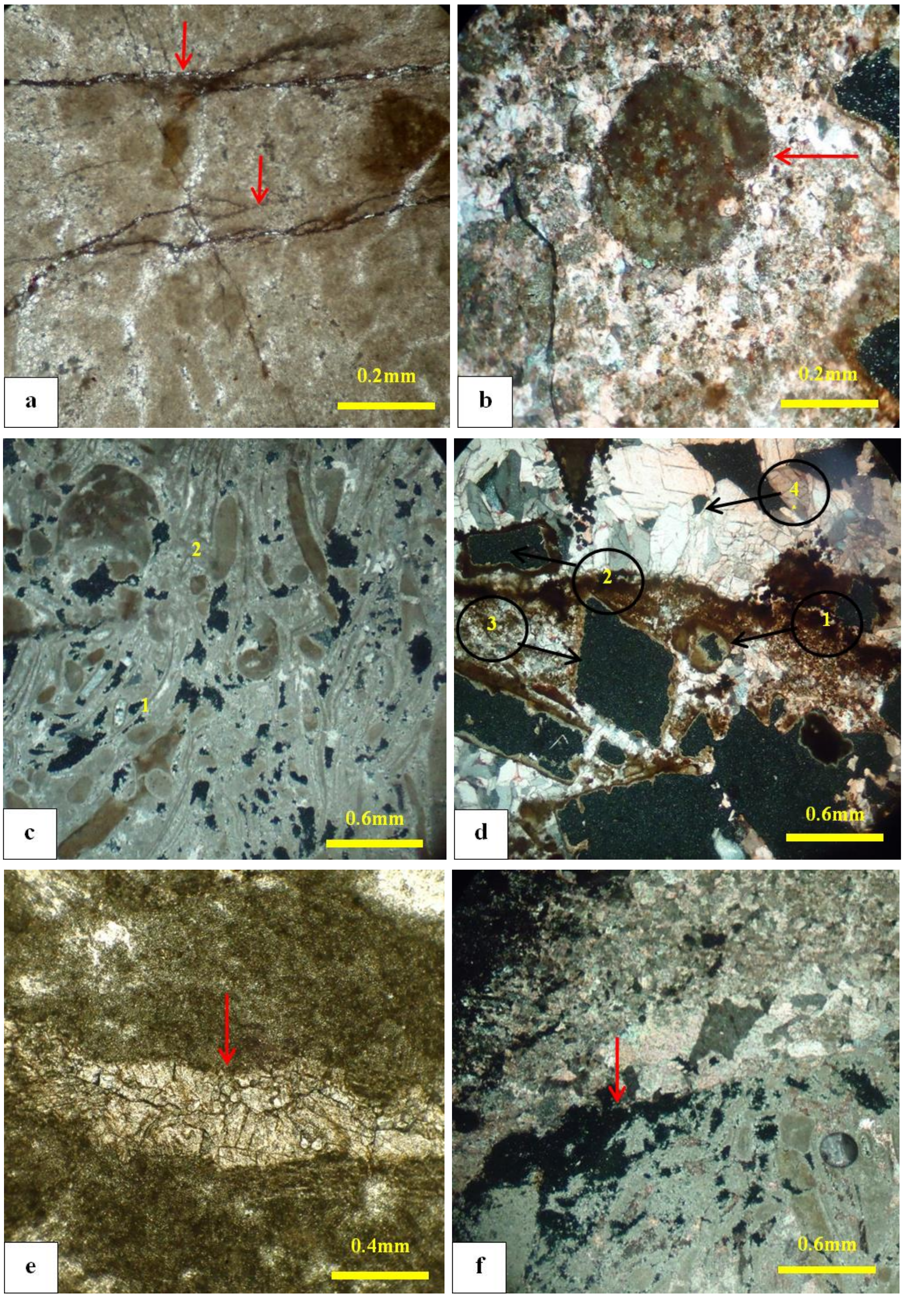


Fig.7: Photomicrographs of chemical compaction, silicification and porosity showing:

a) Non-sutured seam stylolite, anastomosing type, (parallel sets) (red arrows), in slightly neomorphosed micrite matrix. P.P. **b)** Selective silicification affecting brachiopod spine (arrow). B7, X.N. **c-1)** Interparticle porosity between peloids . **c-2)** Intraparticle porosity reduced by sparry calcite cement. B11. X.N. **d-1)** Intraparticle porosity reduced by sparry calcite cement. **d-2)** Moldic porosity, bioclast (calcareous algae) reduced by cement. **d-3)** Moldic porosity, dolomolds produced by selective leaching of dolomite crystals. **d-4)** Intercrystalline porosity between dolomite crystals. B7. X.N. **e)** Fracture porosity filled by dolomite cement (arrow). B2. P.P. **f)** Vuggy porosity (arrow) partially reduced by cement. B11, X.N.

B = Baluti Formation, P.P = Plane Polarized light, X.N = Crossed Nichols, A.S = Alizarin Stained

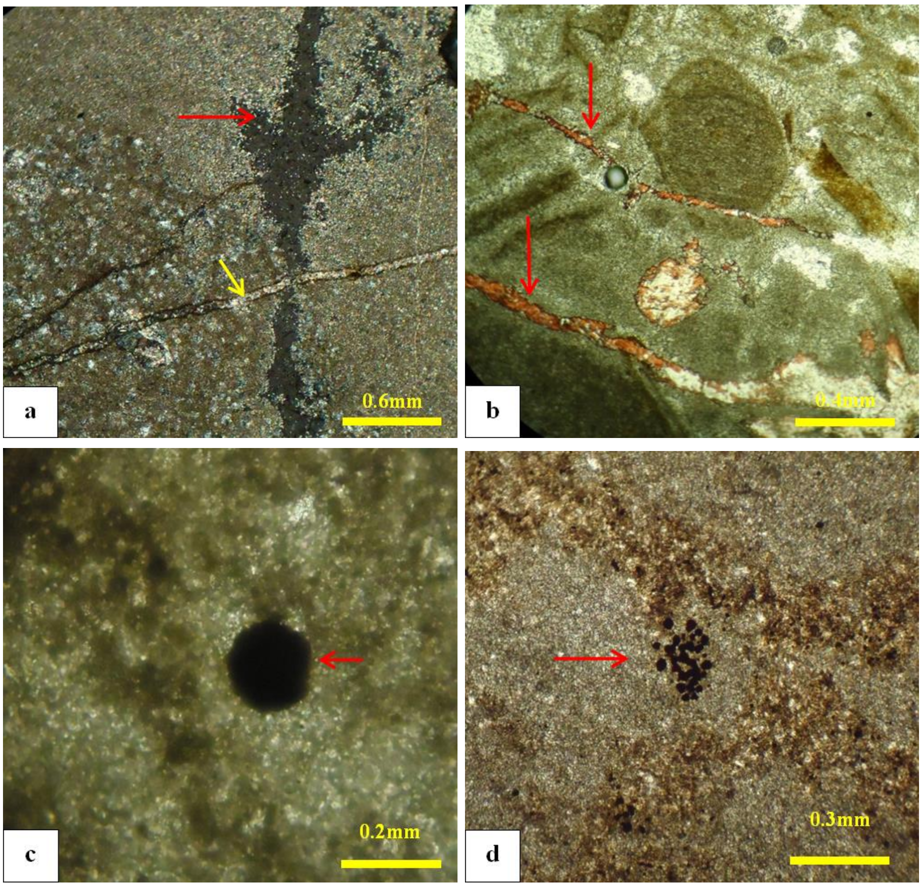


Fig.8: Photomicrographs of porosity and pyritization showing:

a) Boring porosity (red arrow) forming by macroborers during primary (biogenic) processes, fracture (yellow arrow) later and filled by calcite cement. B6, P.P. **b)** Stylolitic porosity (arrows), produced by solution enlargement of original stylolite surface and filled by sparry calcite cement (stained). B 12, P.P. A.S. **c)** Small cubic pyrite (arrow) in the neomorphosed micrite matrix. B17, P.P. **d)** Framboidal pyrite (arrow) in neomorphosed matrix. B5, P.P.

B = Baluti Formation, P.P = Plane Polarized light

– **Dolomitization:** It is the process which converts limestone or its precursor sediment, entirely or partly, to dolomite when magnesium carbonate replaces the original $CaCO_3$, by the influence of Mg - bearing water (Flugel, 2004). It requires augmentation of the Mg/Ca ratio in saline water that enters pores and interstices of carbonate rocks (Folk and Land, 1975). Dolomitization process is widely agreed to be classified into the following types:

- **Early diagenetic dolomitization:** Early dolomitization takes place before the lithification of sediments, which are yet in link with marine water and keeps their textures (Tucker, 1981). It results from the impact of Mg-rich marine water on the newly precipitated carbonates (Fuchtbauer, 1974). In the Baluti Formation, very fine crystals of early dolomites rhombs of crystals are found floating in the micrite matrix and abundant in the lower part of the studied section (Fig.4b and c).

- **Late diagenetic dolomitization:** This kind happens in post lithification of sediments under the effect of Mg-rich solutions and predominately damages the original texture of rocks (Chilingar *et al*., 1967; Tucker, 1981). It differs from the early diagenetic dolomite by its coarse crystals.

Dolomitization is a common process in the carbonates of the Baluti Formation. Most of the dolomitization in the studied section is of late diagenetic type and characterized by coarse crystals, that removed all the original sedimentary features of the rocks. On the other hand, the dolomitization process is probably selective, based on several factors such as pore-water and sediment chemistry and crystal size, and, occasionally, only the matrix or grains of particular mineralogy are replaced (Tucker, 1981).

– **Dolomite texture:** Based on the crystal size distribution and crystal boundary shape (planer or non-planer), Five types of dolomite texture are recognized and classified in the Galley Derash section using the classification of Sibley and Gregg (1987). This classification is descriptive but carries genetic implications because the size distribution is controlled by both nucleation and growth kinetics (Sibley and Gregg, 1987). A brief review of each type is provided below:

A. **Unimodal, very fine to fine-crystalline planar-s (subhedral) mosaic dolomite:** This type forms scattered dolomite crystals that are less than 60 μm of interlocking sub to planar-s crystals (Fig.4b). It is characterized by dense mosaics with milky white clear or cloudy texture and occasionally, micro-stylolites can be noticed. It is formed in the early-diagenetic stage replacing subtidal to intertidal carbonate muds. It occurs in both -the lower and upper- parts of the studied section.
B. **Unimodal, very fine to fine-crystalline planar-e (euhedral) mosaic dolomite:** This type of dolomite texture is dominant in the lower part of the Baluti carbonate, which is formed of crystals less than 60 μm. It is a dense mosaic with a light color of the very fine and dark color of fine crystals (Fig.4c). It is an early-diagenetic dolomite, differs from planers by occurring in micritic matrix and pores of dissolution. The latter is highly common in the studied section.
C. **Unimodal, fine to medium crystalline planar-s (subhedral) mosaic dolomite:** This type represents dense mosaics of subhedral to euhedral planar-s crystals (15 – 80 μm), that generally show milky white or cloudy texture (Fig.4d). It is interpreted as the end of early to intermediate diagenetic replacement dolomite. It is common in the lower part of the Baluti Formation, which is characterized by non-mimetic replacement of allochems particularly calcareous green algae (Dasycladaceae).
D. **Medium to coarse-crystalline planar to non-planar-c (cement) dolomite:** This type is dominant in the studied section particularly in lower part. It consists of medium to coarse crystals (80 – 400 μm), characterized by milky-white to clear color with sweeping extinction under crossednichols. Triangular surface irregularities can be observed under plane-polarized light (Fig.4e). It mainly fills the void and fractures in thin sections of the studied section and commonly forms in intermediate to late diagenetic stages, at elevated temperatures during burial and/or result from recrystallization of precursor finer dolomites in burial environments or near-surface meteoric to mixed meteoric-marine environments (Gregg and Sibley, 1984).
E. **Polymodal planar-s (subhedral) to planar-e (euhedral) mosaic dolomite:** It is a replacive dolomite with polymodal crystals (10 – 900 μm) (Fig.4f). It has a planar-e to planar-s texture with cloudy cores of the rhombs and clears an outer zone under plane-polarized light. It subjected to the dissolution and calcification in the studied section. It

forms by non-mimetically replacement of unimodal matrix and allochems in addition to dissolution of undolomitized matrix and allochems in the late diagenetic stage (Ozcan and Dinc, 2011).

– **Dedolomitization:** It is the process that takes place when partial to complete transformation of dolomite rocks to limestones, or partial to entire replacement of dolomite to calcite on the scale of individual crystals (Middleton *et al*., 2003). It considered as a near-surface or surface diagenetic phenomenon and thought to happen when the beds are exposed (Goldberg, 1967; Groot, 1967; Chafetz, 1972; Back *et al*., 1983; Lee and Harwood, 1989). Dedolomitization process is observed in the middle part of the Baluti carbonate in the studied section (Fig.5a).

– **Cementation:** Chemical deposition of calcium carbonate from saturated solutions is called cementation. It precipitates between or inside grains or in pores and cracks resulting from solution, all driving to the growth of spary calcite in these cavities (Larsen and Chilingar, 1979). The following cement fabrics are recognized in the carbonate rocks of the Baluti Formation based on the dominate occurrences:

1. **Granular cement:** This type of cement is characterized by small pore-filling calcite crystals that have no preferred orientation and no substrate control (Flugel, 2004). It is the most common cement type in the carbonate rocks of the Baluti Formation in the studied section. Granular cement is observed as infilling of fossil shells (Fig.5b) and compaction-related fractures (Fig.5c).
2. **Blocky cement:** This type of cement consists of medium to coarse-grained crystals (several micrometers) without preferred orientation and often shows distinct crystal boundaries (Fig.5d). It is the second most common type in the studied section of the Baluti Formation, forming a mosaic of crystals that have roughly the same diameter in all direction (Blatt *et al*., 1980). It is thought to form in a freshwater phreatic zone (Longman, 1980).
3. **Drusy cement:** This type of cement is characterized by pore-filling calcite crystals increasing in size towards the center of interparticle pores (Flugel, 1982) and is comprised of anhedral to subhedral calcite crystals that are commonly greater than 10 μm in size (Fig.5e).
4. **Syntaxial overgrowths cement:** It is a substrate-controlled overgrowth concerning a host grain formed by a single crystal, which is commonly high-Mg calcitic echinoderm fragment. This overgrowth is predominantly continueous within the host grain in the crystallographic lattice. In the echinoderm case, it is often zoned with manifested color differences between the skeletal grain and the overgrowth. This type of cement is inclusion-rich and cloudy in near-surface marine, vadose-marine and meteoric-phreatic environments, while it is a clear overgrowth in deep burial environments (Flugel, 2004). It is not common in the studied samples of the Baluti Formation and observed in the lower part of the section (Fig.5f).

– **Neomorphism:** The term Neomorphism was first introduced by Folk (1965) to involve all transformations between one mineral and itself or a polymorph. Meteoric phreatic conditions are thought to be a lineage of neomorphism in marine sediments (Longman, 1980). The effect of Neomorphism on the carbonate rocks of the Baluti Formation in the Galley Derash section is distinct and have obliterated most depositional features, especially in the upper part of the formation. It has affected the shells of most types of fossils (Fig.5e) and extended to the micritic groundmass (Fig.6f).

– **Compaction:** It includes any processes that result in the reduction of bulk volume, thickness or porosity of the sediments due to the increase in weight of the overlying material, or to the pressure produced from earth movements within the crust (Flugel, 1982 and Mclane, 1995). Tucker (1981) subdivided compaction into two kinds:

1. **Physical compaction:** It begins directly after deposition and is led by the effective stress enforce on the sediments (Croizé *et al*., 2010). The mechanical compaction in the Baluti Formation is very intensive and the common criteria related to mechanical compaction noticed in the studied samples are the following:
   1) Fractures usually filled by sparry calcite cement derived from pressure solution and of post-compactional late diagenesis (Fig.5c and d).
   2) Breakage of grains (Fig.6a).
   3) Over close packing of grains and deformation of peloids and ooids (Fig.6b and c).
   4) Concavo-convex contact occurring between grains (Fig.6d).

2. **Chemical compaction (pressure solution):** It is well observed in grains which were subjected to dissolution under applied stress (overburden) giving rise to pressure solution effect (Bathurst, 1975). Stylolites are the major product of chemical compactions which are pressure solution lineaments along seams that are laterally expanded on the size of hand specimen (or greater) and they cut numerous grains, mud, and cement.

– **Stylolites:** They are thin ambits of discontinuity within rocks and, in a thin section, they are manifested as undulated to zig-zag sutures (Flugel, 1982). They have toothed sub- planar surfaces in which the material has been removed by pressure dissolution, causing a reduction in the total volume of the rock (Middleton *et al*., 2003). Stylolites appear to be a dominant feature in the Baluti carbonates in the studied section.
The following stylolite types of Wanless (1979) are recognized:

A. Sutured-seam stylolite: This kind forms within structural resistance units with little or no platy insoluble minerals (Wanless, 1979). The most common stylolites in the study section are irregular type, commonly with peaks of low amplitude (Fig.6e), and others of high amplitude (Fig.6f).

B. Non-sutured seam stylolite: Occurs in limestone units that contain a considerable amount of clay and platy silt (Wanless, 1979). It is characterized by low relief and are thinly undulated. Most stylolites of this subdivision noticed in the studied section are anastomosing (Fig.7a).

– **Silicification**: The silicification of carbonate rocks is either carbonate replacement by silica or precipitation of pore-filling silica cement (Flugel, 2004). It is obvious in different parts of the studied section, particularly in the upper part where it has selectively affected the skeletal grains (Fig.7b).

– **Porosity:** Porosity in carbonate rocks are products of many processes, both depositional and post-depositional processes (Murray, 1960). Porosity study is important in perception of diagenetic processes as well as it is highly considered in evaluating reservoir rocks (Flugel, 2004). The reduction of the pores is complex and may include cementation, compaction, or combinations of both (Tucker, 2001; Machel, 2005; Ahr, 2008).

The petrographic investigation of the Baluti carbonates reveal that there is a lot of porosity which is mainly of the secondary type. Based on Choquette and Pray (1970) classification the following types are recognized:

A. *Fabric-selective*: Four types of porosity were recognized:

1. **Interparticle porosity:** It is the spaces or voids between particles (Fig.7c-1). There are various shapes of this type in the carbonate rocks according to the type of particles present and their modification later by compaction and cementation (Reeckmann and Friedman, 1982; Lucia, 2007). Interparticle porosity is restricted to the peloidal- rich limestones in the middle part of the studied section and it is often reduced by cementation processes.
2. **Intraparticle porosity:** The primary pore space within the skeletal grains is the pores that are not filled later by diagenetic processes (Choquette and Pray, 1970). They are usually formed with the disappearance of the soft organic parts from the carbonate skeleton (Reeckmann and Friedman, 1982). In the Baluti Formation, this type of porosity is common and seen within the cavities of different fossils shell (Fig.7c-2 and d-1).
3. **Moldic porosity:** This kind of porosity is common within the rocks of the Baluti Formation in the Galley Derash section. It is formed by the selective removal of primary constituents from sediments or rocks. Two types of moldic porosity are recognized in the Baluti Formation:
   - **i.** Molds of fossils, such as those of mollusks and calcareous algae (Fig.7d-2).
   - **ii.** Dolomite molds or dolomolds (Fig.7d-3). They are commonly formed by the influence of freshwater on their initial susceptible mineralogy.
4. **Intercrystal porosity:** This type of porosity is formed in the voids that occur between microsucrosic (dolomite) crystals and is common in the lower part of the studied section in lithofacies which are subjected to dolomitization (Fig.7d-4).

B. ***Non-fabric-selective*****:** Two types of this division were recognized in the rocks of the Baluti Formation:

1. **Fracture porosity:** The main causes for the formation of this type of porosityare eithertectonic activity or compaction. It is recognized in several thin sections of the studied section where most of the pores are filled by drusy and granular types of cement (Fig.7e).
2. **Vuggy porosity:** This type of porosity results from dissolution and has no criteria of the initial rock texture (Reeckmann and Friedman, 1982). Many vugs may be solution-enlarged molds and fractures that generally form at the vadose zone of the fresh phreatic environment (Longman, 1980). This porosity type is less common in the Baluti Formation and found in the upper part of the studied section (Fig.7f).

C. ***Fabric selective or not*****:** Only one type of this division is recognized in the studied section which is **Boring porosity**. It is developed bys very small to centimeter-sized borings formed by micro and macroborers during primary (biogenic) processes though some of these pores can thereafter be modified by cementation and de-cementation (solution) (Flugel, 2004; Boggs, 2009). This type of porosity is less common in the Baluti carbonates and is observed in the middle part (Fig.8a)

D. Solution (leaching): Solution in the calcareous metastable minerals, such as the high-Mg-calcite and aragonite, is faster compared to normal, low-Mg calcite (Friedman, 1964). The effect of freshwater is higher than marine water in this process (Asaad, 2014). Solutionis seen in the rocks of the Baluti Formation in the studied section and had affected the groundmass (Figs.7f and 8b) and most of the fossil shells (Fig.7c-2).

E. Fracturing: The carbonates of the Baluti Formation were considerably affected by fracturing, and most of the fractures were mainly filled with calcite cement (Fig.7e).

F. **Authigenic mineral (pyrite):** Pyrite is a predominant precipitate mineral in the sediments, which were subjected to diagenesis in an alkaline reducing environments (Honjo *et al*., 1965). These favourable environments are probably enhanced by organic matter decay,driven by anaerobic bacteria, or sulfate solution by reducing bacteria, producing different crystal forms of pyrite (Hudson, 1982). The indispensable reducing conditions for pyritization are obtainable during early burial stages when anaerobic bacteria become active (Larsen and Chilingar, 1979). Pyrite is frequent in the Baluti carbonate and the most common pyrite forms observed in the studied samples are small cubic pyrite (Fig.8c) and framboidal pyrite (Fig.8d).

DIAGENETIC SEQUENCES

Depending on the results of the petrographic investigation, the diagenetic history of the Baluti Formation in the Galley Derash section had passed through four stages: marine, meteoric, burial and uplift (Fig.9).

- **Marine diagenesis**

Marine phreatic diagenesis in the Baluti Formation includes only early micritization of allochems. Micrite envelops are developed around most thin valves of mollusks and shells of calcareous green algae. The early marine cementation (isopachous fibrous cement) is not notice within the rocks of the studied section. This suggests that it did not seal the primary porosity predominantly but early compaction reduced it during this stage. Micritization in the Baluti Formation is supposed to have formed in a stagnant marine phreatic zone by boring algae, which occurs at the sediment-water interface to 1 m below the interface (Longman, 1980). The fine crystalline dolomites are subsequently formed by marine diagenesis in the vadose zone which is supposed to be in the meteoric-marine mixing zone. The mechanical compaction is more intensive in this stage (Fig.5c and 6a) and continues from marine to the meteoric stage. It is dominated by overclose packing of grains (Fig.6b and 6c) which simultaneously reduced the primary porosity in the carbonate succession of the Baluti Formation.

- **Meteoric diagenesis**

This stage starts with meteoric vadose diagenesis precisely with the vadose solution zone, which extends tens to hundreds of meters below the surface (Longman, 1980), where metastable skeletal and non-skeletal grains are dissolved. As a consequence, secondary fabric- and non-fabric selective porosity are formed. Subsequently, phreatic diagenesis occurred when pores spaces were filled by meteoric waters. That started with an active undersaturated meteoric phreatic zone forming, by solution, both moldic and vuggy porosity. Other characteristics features of this type of porosity are the observation of different types of cement fabrics (e.g drusy granular, blocky and syntaxial overgrowth cement) which are good evidence of active saturated freshwater phreatic zone. Occasionally the secondary cements progressively reduced primary pore spaces and gained, aggrading neomorphism found in mud-supported limestones.

- **Burial diagenesis**

This stage begins when the sediments are buried under the reach of surface-related processes (reference?). It involves the mesogenetic or deeper burial settings and may face low-grade metamorphism in the deeper extension of some sedimentary basins, whereas, the regional confined meteoric aquifers are treated as surficial environments in the shallow subsurface due to surface meteoric recharge (Moore, 2001).In the carbonate rocks of the

Baluti Formation, it is produced by increasing overburden stress and pressure solution. Breakage over close packing of grains, produced concavo-convex contact between grains, deformation of grains and silicification of some skeletal grains. The primary and secondary porosity are reduced by compaction in the lack of cementation. As well as, the coarse crystalline dolomite and authigenic minerals such as pyrites are formed.

- **Uplift**

The last stage of the Baluti Formation diagenetic history is caused by uplift which resulted from the Alpine orogenies and caused folding and fracturing of the formation. Uplift, with exposure to freshwater in younger periods, resulted in the de-dolomitization and more dissolution which produced vuggy porosity in the Baluti Formation rocks.

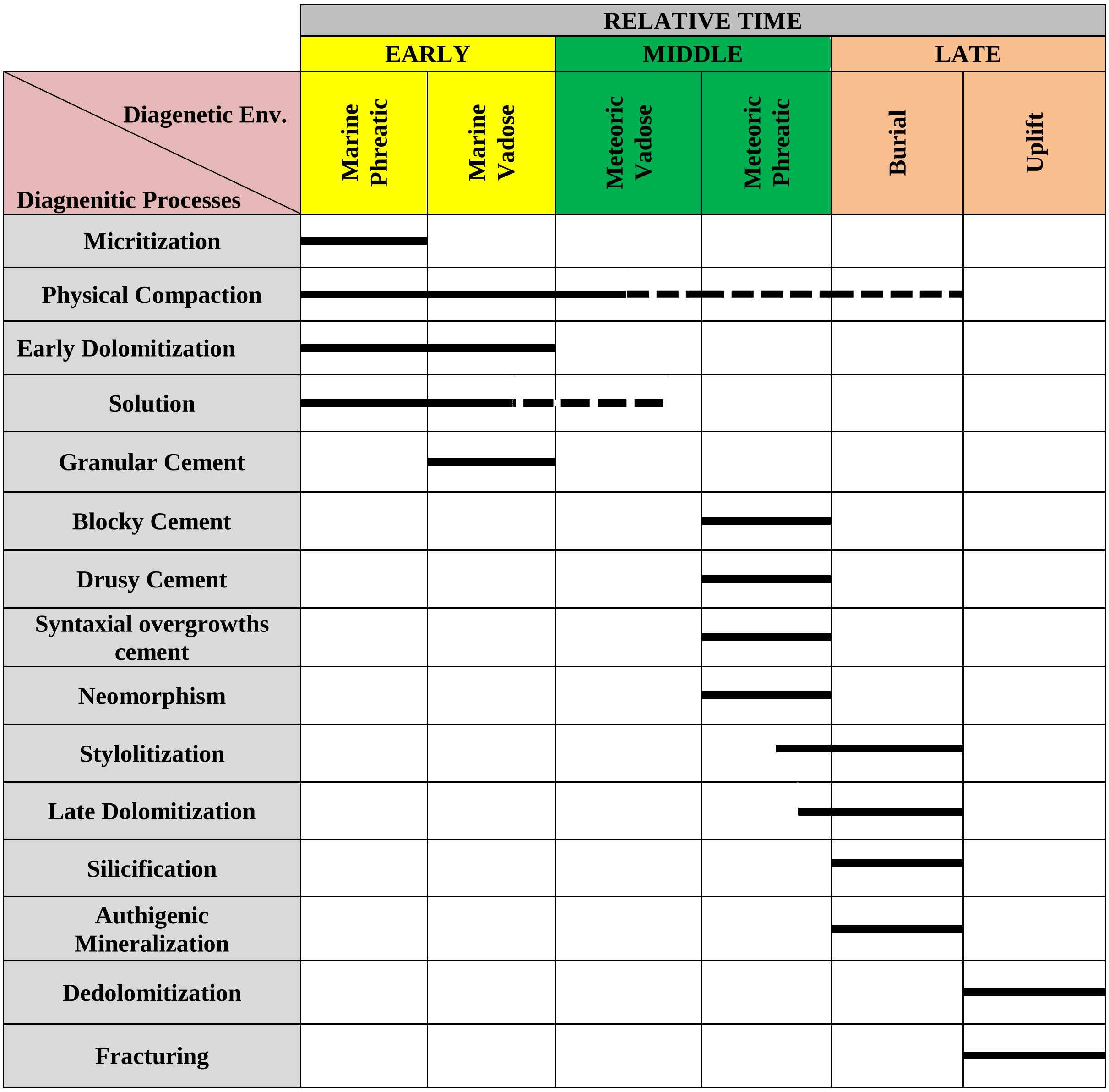


Fig.9: Paragenetic sequence of the diagenetic modifications in the carbonate succession of the Baluti Formation (Upper Triassic) in the studied section

CONCLUSIONS

- The present study of the Baluti Formation in the Galley Derash section revealed different diagenetic processes, they include (arranged in order of significance): micritization, dolomitization, de-dolomitization, cementation, neomorphism, compaction, silicification, solution, fracturing, and pyritization.
- The diagenetic processes, which have affected the Baluti carbonates in the studied section, belong to three diagenetic stages; early (shallow burial), middle and late (deep burial). Processes belonging to the early-stage are less common, while those of the late-stage are dominant.
- According to size distributions and crystal boundary shapes, five kinds of dolomite textures are recognized in the studied section. They include: **1-** Unimodal, very fine to fine-crystalline planar-s (subhedral) mosaic, **2-** Unimodal, very fine to fine-crystalline planar-e (euhedral) mosaic, **3-** Unimodal, fine to medium crystalline planar-s (subhedral) mosaic, **4-** Medium to coarse-crystalline planar to non-planar-c (cement) mosaic and **5-** Polymodal planar-s (subhedral) to planar-e (euhedral) mosaic.
- Seven types of primary and secondary porosities are recognized in the Baluti Formation carbonate rocks include Interparticle, Intraparticle, Moldic, Intercrystal, Fracture, Vuggy and Boring porosities. Most of the primary pores are diminished due to mechanical compaction.
- The diagenetic history of the Baluti Formation in the studied section passed through four diagenetic environment which are: marine, meteoric, burial, and uplift.

AKNOWLEDGMENTS

This paper is based on part of the first author M.Sc. thesis undertaken at the Department of Geology, College of Science, Salahaddin University. The authors would like to thank Mr. Haidar Hazim Al-Jaff for his help in the field work. Thanks also go to Mr. Wria Jabbar at Salahaddin University, College of Science and Mr.Waad Sh.Asaad for computer facilities.

REFERENCES

Ahr, W.M., 2008. Geology of Carbonate Reservoir: The Identification, Description, and Characterization of Hydrocarbon Reservoirs in Carbonate Rocks. Hoboken, New Jersey: A John Wiley and Sons, INC., Publication. 350pp.

Akram, R.K., 2016. Palynofacies and Source Rock Evaluation of Baluti Formation (Late Triassic) in two selected wells, in Duhok Governorate, Iraqi Kurdistan Region. Unpublished (M.Sc.) Thesis, University of Salahaddin-Erbil, Erbil, Kurdistan region, Iraq.

Al-Mashaikie, S.Z., Abdul-Razzak, S.K. and Naser, M.E., 2016. Sedimentology of the Baluti Formation in the Galley Derash, Amadiya, North Iraq: insight on carbonate turbidite facies and their depositional environmental, Arab Jour. Geosci., Vol.9, No.19. https://doi.org/10.1007/s12517-016-2703-4.

Al-Mashaikie, S.Z.A., 2017. Tectonostratigraphic Study of Carbonate breccias (Calciturbidites) in the Upper Triassic Baluti Formation (Northern Iraq): New insights on Tethyan Geodynamics. In: F., Roure, A., Amin, S., Khomsi and M. Al Garni (Eds.) Lithosphere Dynamics and Sedimentary Basins of the Arabian Plate and Surrounding Areas. Frontiers in Earth Sciences. Springer, p. 67 – 86.

Al-Mashaikie, S.Z. and Abdul-Razzak, S.K., 2017. Origin of Dolomites in the Baluti Formation (Late Triassic), Galley Derash Area, N-Iraq: Petrography, textural and diagenetic properties. Iraqi Journal of Science, Vol.58, No.1B, p. 237 – 251.

Aqrawi, A.A.M., Goff, J.C., Horbury, A.D. and Sadooni, F.N., 2010. The Petrolum Geology of Iraq. Statoil Scientific Press. 424pp.

Asaad I.Sh., 2014. Sedimentology and Stratigraphy of Kometan Formation (Upper Turonian – Lower Campanian), in the Kometan Village-Imbricated Zone Iraqi Kurdistan Region, Higher Diploma Dissertation (Unpublished), Salahaddin University-Erbil, 76pp.

Awdal, A., Healy, A. and Alsop, G.I., 2016. Fracture patterns and petrophysical properties of carbonates undergoing regional folding: A case study from Kurdistan, N Iraq. Marine and Petroleum Geology, Vol.71, p. 149 – 167.

Back, W., Hanshow, B., Plummer, L.N., Rahn, P.H., Rightmire, C. and Rubin, M., 1983. Process and rate of dedolomitization: Mass transfer and C dating in a regional carbonate aquifer. Geol. Soc. Amer. Bull., Vol.94, p. 1415 – 1429.

Balaky, S.M., Swrdashy, A.M. and Mamaseni, W.J., 2016. Permian – Triassic lithostratigraphic study in the Northern Thrust Zone (Ora), Iraqi Kurdistan region. Arab Jour. Geosci, Vol.9, No.5. [CGS-K1] https://doi.org/10.1007/s12517-016-2352-7.

Bathurst, R.G.C., 1975. Carbonate Sediments and Their Diagenesis, 2nd enlarged ed., Elsevier, Amsterdam, 658pp.

Blatt, D.A., 1982. Sedimentary Petrology. Freeman, San Francisco, 564pp.

Blatt, H., Middleton, G. and Murray, R., 1980. Origin of Sedimentary Rocks. Prentice – Hall, VSA. 782pp.

Bellen, R.C., Van Dunnington, H.V., Wetzel, R. and Morton, D., 1959. Lexique Stratigraphic International. Asie, Fasc. 10a, Iraq, Paris, 333pp.

Boggs, S.J., 2009. Petrology of Sedimentary Rocks. 2nd ed. Cambridge press. USA. 600pp.

Buday, T., 1980. Regional Geology of Iraq: Vol.1, Stratigraphy: I.I.M. Kassab and S.Z. Jassim (Eds) GEOSURV. Baghdad, Iraq, 445pp.

Chafetz, H.S., 1972. Surface diagenesis of limestone. Jour. Sed. Pet., Vol.42, No.2, p. 325 – 329.

Chilingar, G.V., Bissell, H.J. and Wolf, K.H., 1967. The Diagenesis of carbonate rocks. In: G. Larsen, and G.V. Chilingar. (Eds.), Diagenesis in Sediments, Development in Sedimentology, 9A, Elsevier, Amsterdam, 471pp.

Choquette, P.W. and Pray, L.C., 1970. Geologic nomenclature and classification of porosity insedimentary carbonates. AAPG. Bull., Vol.54, p. 207 – 250.

Croizé, D., Ehrenberg, S.N., Bjørlykke, K. Renard, F. and Jahren, J., 2010. Petrophysical properties of bioclastic platform carbonates: Implications for porosity controls during burial, Mar. Pet. Geol., Vol.27, No.8, p. 1765 – 1774.

Csató I., Kiss K., Toth S. and Varga M., 2014. Upper Triassic-Jurassic depositional systems in the Akri-Bijeel exploration block, Iraqi Kurdistan. MOL group Scientific Magazine, Vol.1, p. 54 – 72.

Flugel, E., 1982. Microfacies Analysis of Limestones, Springer – Verlag, Berlin, 633pp.

Flugel, E., 2004. Microfacies of Carbonate Rocks: Analysis, Interpretation and Application .Springer, Berlin, 976pp.

Folk, R.L., 1965. Some aspects of recrystallization in ancient limestones. In: L.C. Pray and R.C. Murray, (Eds.), Dolomitization and Limestone Diagenesis: a symposium – SEPM, specialpub. No.13, p. 14 – 48.

Folk, R.L. and Land, L.S., 1975. Mg/Ca ratio and salinity: two controls over crystallization of dolomite. AAPG. Vol.59, No.1, p. 60 – 68.

Friedman, G.M., 1959. Identification of carbonate minerals by staining methods. Jour. Sed. Pet., Vol.29, No.2, p. 87 – 97.

Friedman, G.M., 1964. Early diagenesis and lithification in carbonate sediments. Jour. Sed. Pet., Vol.34, No.4, p. 777 – 813.

Fuchtbauer, H., 1974. Sediments and Sedimentary Rocks, Schwiebartsch Verlagsbuch, Stuttgart, 464pp.

Goldberg, M., 1967. Supratidal dolomitization and dedolomitization in Jurassic rocks of Hamakhtesh Haqatan, Israel. Jour. Sed. Pet., Vol.37, No.3, p. 760 – 773.

Gregg, J.M. and Sibley, D.F., 1984, Epigenetic dolomitization and origin of xenotopic dolomite texture. Jour. Sed. Pet., Vol.54, No.3, p. 908 – 931.

Groot, D.K., 1967. Experimental dedolomitization. Jour. Sed. Pet., Vol.37, No.4, p. 1216 – 1220.

Hanna M.T., 2007. Palynology of the upper part of Baluti Formation (Upper Triassic) and the nature of its contact with the Sarki Formation (Lower Jurassic) at Amadyia District, Northern Iraq, Ph.D. thesis, University of Mosul, Mosul, Iraq.

Honjo, S., Fischer, A.G. and Garrison, R., 1965. Geopetal pyrite in fine grained limestones. Jour. Sed. Pet., Vol.35, No.2, p. 480 – 488.

Horowitz, A.S. and Potter, P.E., 1971. Introductory Petrography of Fossils. Springer – Verlag, Berlin. 302pp.

Hudson, J.D., 1982. Pyrite in ammonite-bearing shales from the Jurassic of England and Germany. Sedimentology, Vol.29, No.5, p. 639 – 667.

Jassim, S.Z. and Goff, J.C. 2006. Geology of Iraq. Dolin, Prague and Moravian Museum, Brno, Czech Republic. 341pp.

Larsen, G. and Chilingar, G.V., 1979. Introduction Diagenesis of Sediments and Rocks, in G. Larsen and G.V. Chilingar, (Eds.), Diagenesis in Sediments and Sedimentary Rocks. Development in Sedimentology 25 A. Elsevier Publ. Co. Amsterdam, p. 1 – 29.

Lee, M.R. and Harood, G.M., 1989. Dolomite and calcitization and cement related to uplift of the Raisby Formation (Zechstein Carbonate), Northeast England. Jour. Sed. Geology, Vol.65, p. 285 – 305.

Longman, M.W. 1980. Carbonate diagenetic textures from near surface diagenetic environment. AAPG. Bull., Vol.64, No.4, p. 461 – 487.

Lucia, J.F., 2007. Carbonate Reservoir Characterization. (2nd Ed.) Berlin Heidelberg New York: Springer. 266pp.

Machel, H.G., 2005. Investigation of burial diagenesis in carbonate hydrocarbon reservoir rocks. Geoscience Canada, Vol.32, No.3, p. 103 – 128.

Mclane, M., 1995. Sedimentology. New York, Oxford, Oxford Uni. Press, 423pp.

Middleton, G.V., Church, M.J., Coniglio, M., Hardie, L.A. and Longstaffe F.J., 2003, Encyclopedia of Sediments and Sedimentary Rocks. Springer, Netherlands, 928pp.

Moore C.H., 2001. Carbonate Reservoirs: Porosity Evolution and Diagenesis in a Sequence Stratigraphic Framework. Elsevier Science, 460pp.

Murray, R.C., 1960. Origin of porosity in carbonate rocks: Journal of Sedimentary Petrology, Vol.30, No.1, p. 59 – 84.

Ozcan A.M and Dinc S., 2011. Petrographic characteristics of the Hacialabaz Formation dolomites (Upper Jurrassic) in the Bagbast (Hadim-Konya/ Turkey) area. Ozean Journal of Applied Sciences. Vol.4, No.3, p. 209 – 226.

Reeckmann, A. and Friedman, G.M., 1982. Exploration for Carbonate Platform Reservoirs. Elf – Aquitain, 212pp.

Sartorio, D. and Venturini, S., 1988. Southern Tethys Biofacies, Agip Stratigraphic Department, 231pp.

Scholle, P.A., 1978. A Color Illustrated Guide to Carbonate Rock Constituents, Textures, Cements, and Porosities. AAPG, Memoir 27, USA, 241pp.

Scholle, P.A. and Ulmer-Scholle, D.S., 2003. Petrography of Carbonate Rocks: Grains, Textures, Porosity, Diagenesiss. AAPG, Memoir 77, USA, 459pp.

Shingaly W.S., 2016. Lithology and diagenetic processes of the Baluti Formation (Upper Triassic) from the Amadyia Area, Kurdistan Region, North-Iraq. Journal of Zankoy Sulaimani, Special Issue, GeoKurdistan II, p. 39 – 50.

Sibley, D.F. and Gregg, J.M., 1987. Classification of dolomite rock textures, Jour. Sedim. Petrol., Vol.57, p. 967 – 975.

Sissakian, V.K., 2000. Geological Map of Iraq. Sheet No.1, scale 1: 1000 000, 3rd edit. GEOSURV, Baghdad, Iraq.

Smosna R., 1987. Compositional maturity of limestone-A review. Sedimentao' Geology. Vol.51, Elsevier Science Publishers B.V., Amsterdam. p. 137 – 146.

Swati, A.F., Haneef, M. and Ahmad, S., 2014. Diagenetic analysis of the Early Eocene Margala Hill limestone, Pakistan: A synthesis for thin section porosity. Journal of Himalayan Earth Sciences, Vol.47, No.2, p. 49 – 61.

Tucker, M.E., 1981. Sedimentary Petrology, An Introduction, Blackwell Scientific publications, 252pp.

Tucker, M.E., 2001. Sedimentary Petrology: An Introduction to the Origin of Sedimenatry Rocks. Blackwell Publishing Company, 260pp.

Wanless, H.R., 1979. Limestone response to stress: Pressure solution and dolomitization. Jour. Sed. Pet., Vol.49, No.2, p. 437 – 462.

About the authors

Mr. Irfan Shaaban Asaad is a member of the geologic staff of Salahaddin University, Erbil. He is an employer in the same university since 2009. He has held past positions as Field Geologist with Kalegran Co. Subsidiary of MOL Group for Oil and Gas from 2008 to 2009. He holds B.Sc. in Geology (2007) from Salahaddin University, Erbil, Higher Diploma in Sedimentology and Stratigraphy in 2015 and M.Sc. in Sedimentology and Stratigraphy in 2019 from the same university.

e-mail: irfan.asaad@su.edu.krd

Dr. Muhamed Fakhri Omer is a sedimentology lecturer at the Department of Geology, Salahaddin University in Erbil, Iraq since 2004. He obtained his M.Sc. and Ph.D. degrees from the University of Baghdad, Iraq in 2000 and 2012, respectively and he got postdoctoral scholarships for one year at Warsaw University – Poland in 2016. He is Assistant Professor since 2017. He published many papers in international journals with impact factors and participated in many local and international conferences and workshops with oral presentations. His major interests are Sedimentology and Sedimentary Petrology with particular reference on Paleozoic formations exposed in northern Iraq.

e-mail: muhfakhri2005@gmail.com