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Facies Analysis, Biostratigraphy, and Sequence Stratigraphy of the Lower Eocene Sinjar Formation, Duhok Area, Kurdistan Region, Iraq

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ABSTRACT

The Sinjar Formation in the Duhok area, Kurdistan region, Iraq, is characterized by lateral and vertical mixed carbonates and siliciclastic facies. Therefore, the main target of this work is to identify the diagnostic lithofacies and microfacies of the carbonate successions of the Sinjar Formation. The carbonate-predominant Sinjar Formation was deposited as patchy reefs that show interfingering, along with the siliciclastic-dominated turbidites facies of the Kolosh Formation (Lower to Upper Paleocene). The depositional environments of the Sinjar Formation have been recorded as inner to middle shelf deposition settings based on the micro and macrofossil associations and facies indications. The inner shelf successions included three microfacies, dolomitized mudstone and wackestone, which show alternations with proximal Turbidites facies (sandy conglomerates). In comparison, the middle shelf represents five microfacies: framestone, coral-algal wackestone, microbial bioclastic wackestone, packstone, and grainstone microfacies, and shows alterations with the middle to distal turbidite facies. The recorded shallow larger benthic foraminiferal biozones are: 1) *Orbitolites complanata –Saudia labrynthica – Opetorbitolites* Assemblage Zone; 2) Idalina *sinjraica- Alveolina globosa- Rotalia trochidiformis* Assemblage's zone. They are indicating Ypresian age. The mixed carbonates and siliciclastic parasequences evolutions have been used to identify the stacking patterns response to the eustatic sea level changes. The studied successions represent one complete third-order depositional system, started with sequence boundary type two at its base and capped by sequence boundary type one, manifested as an incised valley between the patchy reef-marine Sinjar deposits and the non-marine molasses of the Gercus Formation.

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الملخص

يتميز تكوين سنجار فى منطقة دهوك و كردستان –العراق بسيادة الترسبات الكلسية مع شعاب مرجانية غير مكتملة، وتتداخل مع سحنات التعكرات الفتاتية. الهدف الرئيسي من هذا البحث هو تحديد السحنات الدقيقة للتعاقب الكلسيه. تضمنت تتابعات ترسبت في منحدرات الرصيف الداخلي وهي سحنة الحجر الطيني والواكستوني، والتي تظهر تناوبًا مع ترسبات التعكرات القريبة. في حين أن منحدر الرصيف الأوسط يمثل خمس سحنات دقيقة وهى: سحنه البلفستون، سحنه الطحالب المرجانية، السحنه الدقيقة الحيوي، سحنه الحجر المرصوص وسحنه الحجر الجيري الحبيبي، وتظهر بصورة تعاقبات مع سحنات التعكرات المتوسطة والبعيدة. الانطقه الحياتية القاعية المسجلة هي: 1- *Orbitolites Complanata --Saudia labrynthica - Opetorbitolites Assemblage Zone* 2 - *Idalina sinjraica - Alveolina globosa - Rotalia trochidiformis Assemblage*، و تشير إلى عمر البيرسين. استنادًا إلى الدلائل المستقاه من الأحافير الصغيرة والكبيرة ،والدلائل السحنيه، تم استنتاج البيئات الترسيبية على أنها تمثل بيئه منحدر الرصيف الأوسط إلى الرصيف الداخلي. ان التعاقبات المدروسة مثلت نظام ترسيبي واحد كامل من الدرجة الثالثة، يبدأ بحدود تعاقبى من النوع الثاني، في قاعدته ويغطى بحدود تعاقبي من النوع الأول، ويتجلى ذلك في شكل واد محفور بين رواسب الشعاب المرجانية البحرية التابعة لتكوين سنجار ورواسب المولاس الفتاتية التابعة لتكوين جركس.

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Introduction

The recording of the Sinjar Formation in the Duhok region is of economic and scientific importance, as it serves as a reservoir for the underground industry and cement ore. Dramatic lateral and vertical lithological changes can be for regional stratigraphic correlation. Biostratigraphic studies are important in sequence stratigraphic analysis because they indicate the time of deposition and the time of gaps or erosions. So, they play an important link between the stacked sequence, sequence boundaries, age, and gap determination with their duration (Brasier 1980). Furthermore, they are useful in depositional environments and the subdivisions of the cycle's orders and stratigraphic subdivisions into different Parasequence and packages, the shallowing upwards and vice versa, as well as the forced regression (e.g., Catuneanu, 2022). The biostratigraphic analysis of this study uses microfossils of mainly benthonic foraminiferal assemblages in addition to environmentally indexed macrofossils such as algae (post predominantly red coralline algae), Mollusca (mainly gastropods and pelecypods), corals and other less common groups, such as bryozoa, and other shallow marine groups. The studied interval contains an important transition from Turbidite-predominated facies to reefal-predominated facies Accordingly, a lithostratigraphic, biostratigraphic, facie association and sequence stratigraphic analysis is conducted around the Barbuhar section in the Duhok area to shed some light on the origin and distribution of the Sinjar Formation in the region. This study covers three newly measured sections in the Bekhair anticline: Besre, Linava, and Perfat. The Barbuhar section has been reused here for lithostratigraphic correlation as the fourth section examined by Al-Qayim and Barzani (2021). Several previous studies about the microfacies, biostratigraphy, and sequence stratigraphy of the Sinjar Formation have been published by Shazayaa., 1980, Al-Qayim, and Salman 1986, Surdashy and Lawa 1993, Lawa 2004, Al-Sakry, 2006, Jaff 2008, Al-Sakry, 2006, Lawa and Al - Bayati., 2006, and Salih, 2012.).

Geologic Setting

The selected studied sections from Duhok governorate, Kurdistan region (Iraq) are considered tectonically a part of the High Folded-Thrust Zone, within the Bekhair anticline, where its southwestern limb is regarded as the boundary with the Low Folded Thrust Zone (Lawa et al., 2013) See (Fig. 1). The Bekhair anticline, which is about 70 km in length and 2-6 km wide (Stevanovic and Markovic 2003), displays the transition from the NW-SE major trend to the E-W trend. Al-Hubaiti (2008) mentioned that the axis of the Bekhair anticline coincides with the Zagros Range (NW-SE) in the Duhok area, which changes to the Taurus trend (E-W) near Zakho City. The Paleogene sequence exposed in the core of this structure is represented by1- Kolosh Formation (Paleocene) 2- Sinjar and Khurmala Formations (Lower Eocene), 3- Gercus Formation (Middle Eocene), 4- Avanah Formation (Middle to Upper Eocene), and 5- Pila Spi Formation (Upper Eocene) (Fig. 1). According to the modified geologic map of the Iraqi Geological Survey, the Paleogene sequence in the Duhok area, includes the following Formations: Kolosh, Sinjar, Gercus, and Pila Spi Formations (Al-Qayim and Barzani, 2021). This modification involves replacing the Khurmala Formation with the Sinjar Formation, with a lateral distribution of about 40 km along the main trend of the structure (Fig. 1). In the study area, the Kolosh Formation is overlain unconformably by the Sinjar Formation. which is in turn overlain unconformably by the Gercus Formation.

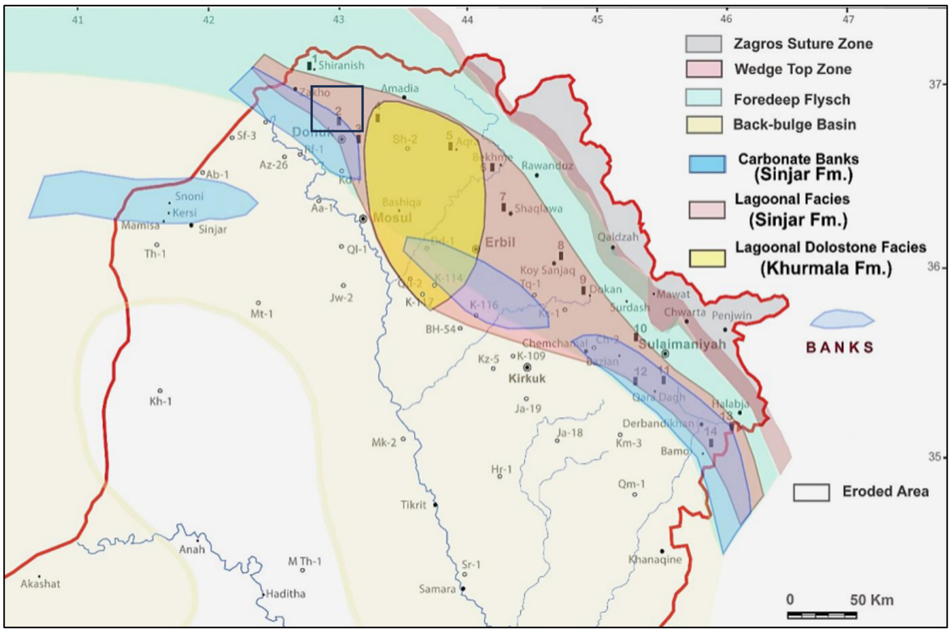

Fig. 1. Tectonic divisions map (From Fouad, 2015) showing the studying area with stratigraphic distribution of Sinjar – Khurmala Formations of the Zagros foreland basin (From Al-Qayim, 2023).

Material and Methods

Three well-exposed outcrops have been selected from the Duhok area, specifically Bekhair Mountain. These three localities are Besre (section 1), Perfat (section 2), and Linava (section 3; Fig. 2). They are described for stratigraphic relations, lithological characters, sedimentological features, and paleontological aspects. The three outcrops are well-exposed, with clear lower and upper boundaries. Therefore, thirty-three fresh rock samples were collected from the three measured sections to examine macro and micro sedimentary features and micro and macrofossil content. Based on the macro-textural properties, the lithofacies types were determined, while the more detailed characterization of the micro-fabric, using microscopic observations. The laboratory work included the preparation and description of slab samples for macro-sedimentary features. Petrographic analysis and interpretation were conducted on 28 thin sections for microfacies and biostratigraphic analysis. The carbonate rocks were classified according to Dunham's (1962), additions by Embry and Klovan (1971). The technique of Lirer (2000) was conducted on soft samples for retrieving calcareous microfossils. The foraminiferal assemblages of the current study are composed of different perforate and imperforate benthic large foraminifera and other fauna, which is a valuable tool for biofacies analysis and indicating depositional environments. The biostratigraphic study is based on the large benthic foraminiferal zonation described by Serra-Kiel et al., 1998, and Serra-Kiel et al., 2020. The third-order sequence boundaries, system tracts, are determined based on Catunneanu (2022).

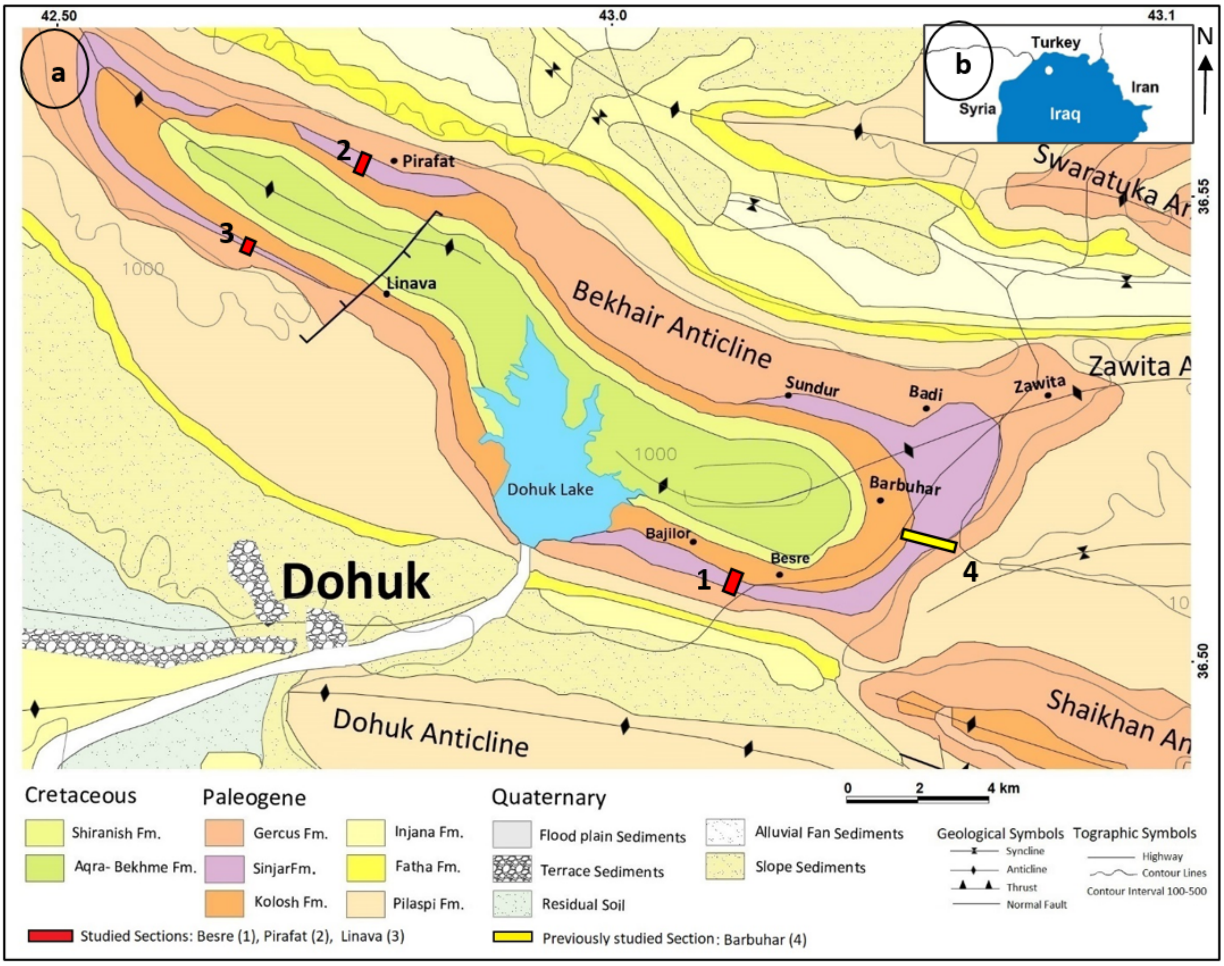

Fig. 2. a) Geological map of the study area, showing location the examined sections (Map after Sissakian, 2013 with slight modifications by Al-Qayim and Barzani, 2021). b) Map of north Iraq.

Results

Lithostratigraphy:

The three studied exposed sections were measured and described as follows:

Besre Section:

This section is selected from the SE plunge of the Bekhair anticline near Besre village, where the Sinjar Formation is recorded, for the first time in the present study at about 38.5m thick. This unit is overlain by the Kolosh Formation and underlain by the Gercus Formation (Figs.2and3). The Sinjar Formation is nominated due to its diagnostic lithological properties, which dominantly consist of limestone fossiliferous, thick-bedded massive coralline, more like those in its type of section. The Sinjar Formation in this section comprises two limestone units separated by a wide clastic unit. Lawa (2004) also recorded a similar succession from the Sulaimani area. According to this mixed carbonate and clastic succession, this section is subdivided into three units as follows: - The first unit (A) is composed of 3.5m of thickening upward brown to gray cherty argillaceous limestone, rich in gastropods (Fig. 6 B). This unit overlies the green flysch sediments of the Kolosh Formation through unconformable contact at the lower part (Fig. 6 b).

The second unit (B) is around 17m and consists of a mixture of soft green sandstone, siltstone and marlstone interbedded with thin to laminated chert beds (Fig. 3). The characteristic of this part is that it contains a lenticular lens of rugged sandstone in the middle green part. The unit (C) is 2m of argillaceous limestone, which becomes fossiliferous at the upper 0.5m, containing coral and large gastropod and pelecypod shells (Fig. 6 c-d). This unit is followed by unit (D) 14m, composed mainly of soft green sandstone. In the middle of this unit, it contains a thin bed of fossiliferous sandy limestone that includes fragments of reefs. This bed also contains medium-sized gastropod and pelecypod shells (Fig. 6 e) and another feature of this bed is the systematic joints on the bedding plain of the sandy limestone. The sandstone of this unit is getting coarser and tougher towards the top with increased fossil content. It contains some pebbles towards the upper part. Unit (E) is composed of 2m. The lower part is 1m tough, thickening upward fossiliferous green sandy limestone, and the upper part is also 1m thick dolomitic limestone (Fig. 6 f). This unit underlies the Gercus Formation unconformably through an intermixture of green and red sandstone, siltstone, shale, and a thin white-colored limestone bed.

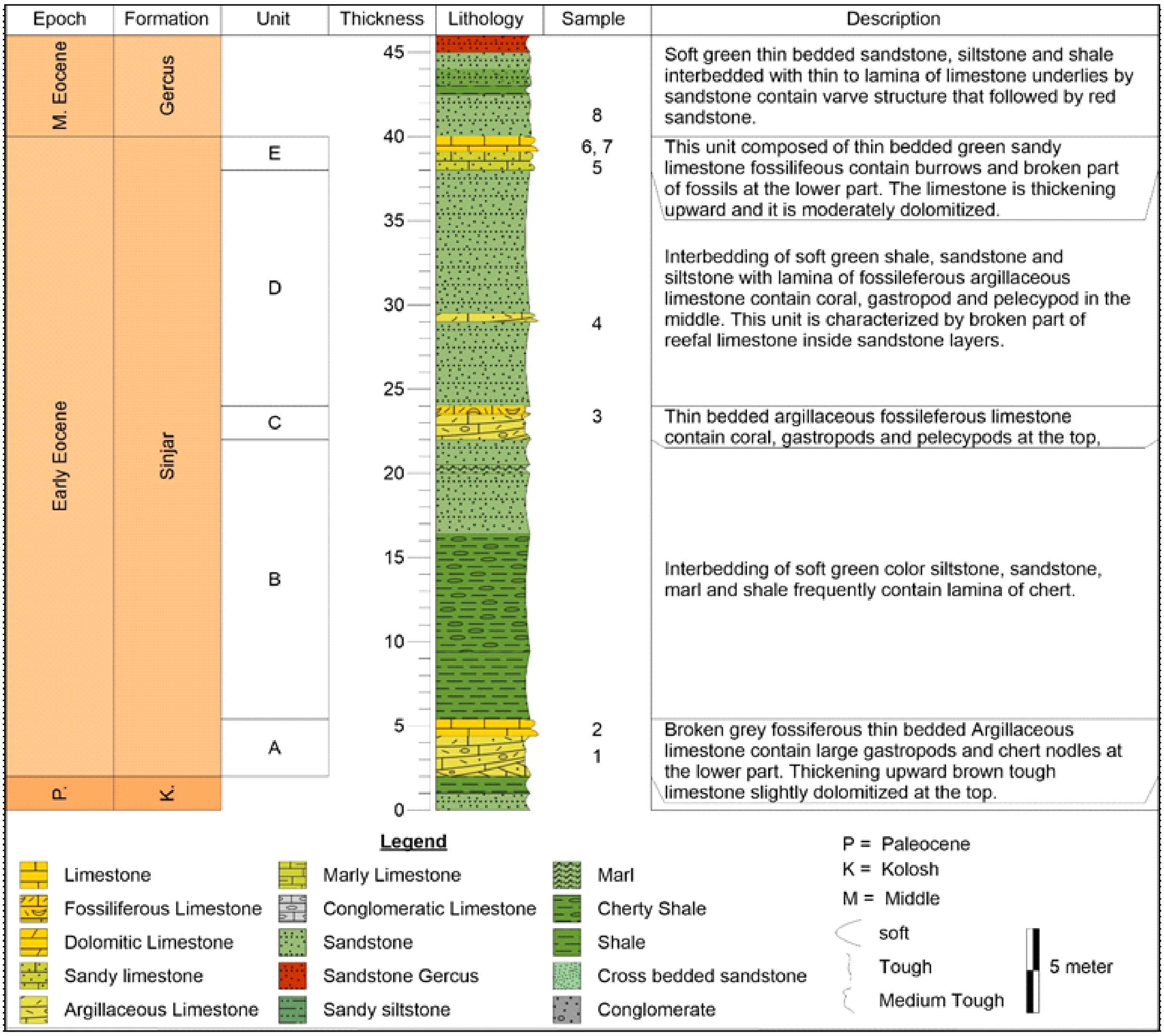

Fig. 3. Lithostratigraphic column of Sinjar Formation in Besre section.

Perfat Section:

The Sinjar Formation in this section is composed of massive fossiliferous limestone separated by clastic units, mostly sandstone, and some thin shale beds and conglomerates. The Sinjar Formation was subdivided into three informal lithostratigraphic units (Fig. 4). The first unit (A) is 14 m of massive reefal limestone. It is represented by two cycles of thin-bedded marly limestone. It turned into massive fossiliferous reefal limestone at the bottom (Fig. 7 d). The lower cycle consists of 5.5 m of massive gray to brown reefal limestone rich in algae. This part also shows a predominance of large gastropods and algal fragments. (Fig. 7 b-c). The upper cycle of this unit is 8.5m massive brown reefal limestone containing coral, shell fragments, and rich in algae at the middle part. The carbonates show alternation with thin (0.5m) soft, green, fine-grained sandstone interlayers.

The second unit (B) is composed of (5.5 m) green sandstone, siltstone, conglomerate, and a minor amount of shale. The conglomerate is gray to diverse colors, thick-bedded with poorly sorted fine and coarse-grained pebbles (Fig. 7 e). This conglomerate bed is rich in chert boulders.

The unit (C) comprises three intervals of thick to intermediate bedded gray and yellowish fossiliferous limestone, which is interbedded with sand and sandy limestone (Fig. 7 f). This unit's base is characterized by a tough thick bed of conglomeratic limestone with small, poorly distributed grains. They show shallowing upwards towards fossiliferous limestone. The last 1.5m of this unit is composed of reefal limestone. The whole thickness of this unit is 10m. This limestone unit is covered by pebbly sandstone of the Gercus Formation, characterized by the predominance of red to purple-colored shale, siltstone, and mudstone.

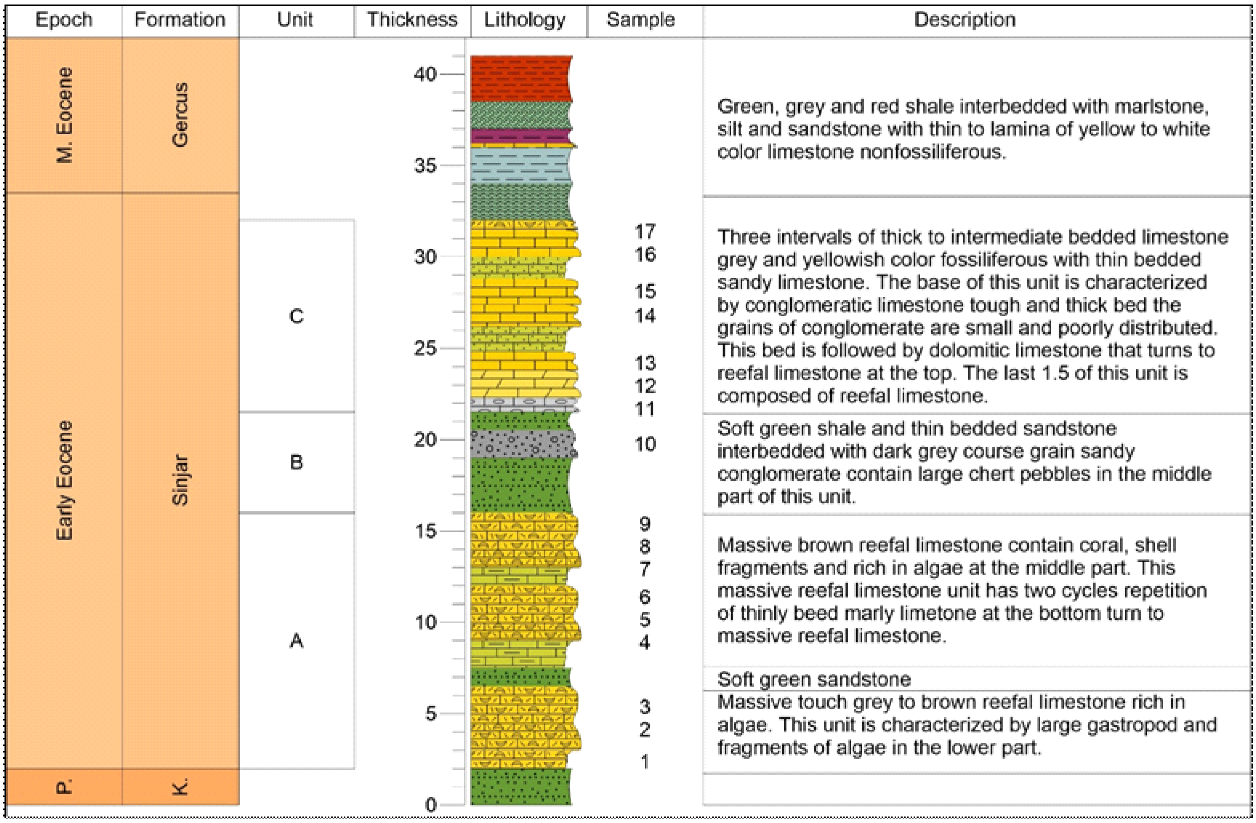

Fig.4. Lithostratigraphic column of the Sinjar Formation in Perfat section.

Linava Section:

This section is a few kilometers away from the Perfat section, but it has some significant variations regarding formation aspects of lithology and thickness. The recognized Sinjar Formation in this section is about 31 m thick and is subdivided from a lithological point of view into 3 informal lithostratigraphic units (Fig. 8 a). The first unit (A) is 4 m, thickening upward, massive, tough, and fossiliferous limestone. The lower part is argillaceous and characterized by a large gastropod horizon (Fig. 8 b). This unit is also rich in coral and algal fragments (Fig.8 c-d). The second unit (B) is the thickest (24.5 m wide) and is composed mostly of sandstone. This unit is often interbedded with the green soft and hard calcareous sandstone with green soft shale and occasionally with some thin beds of chert especially at the top. In the middle of this unit, there is a 1.5 m fossiliferous marly limestone, which is overlain by thin (0.1) cross-bedded. This unit at the upper part is interbedded with soft and hard calcareous sandstone with thin marlstone, limestone, and chert bed (Fig. 8 e). The sandstone beds changed to coarsening upward and changed to pebbly sandstone.

The third unit (C) consists of marly limestone, limestone, and dolomitic limestone with a thickness of about 12m thick (Fig. 8 d). This unit marks the end of the Sinjar Formation in this section. The upper boundary with the Gercus Formation, indicated by a diagnostic lithological variation to the red molasses, mainly consists of the intercalation of green, brown, and red sandstone with shale and marlstone.

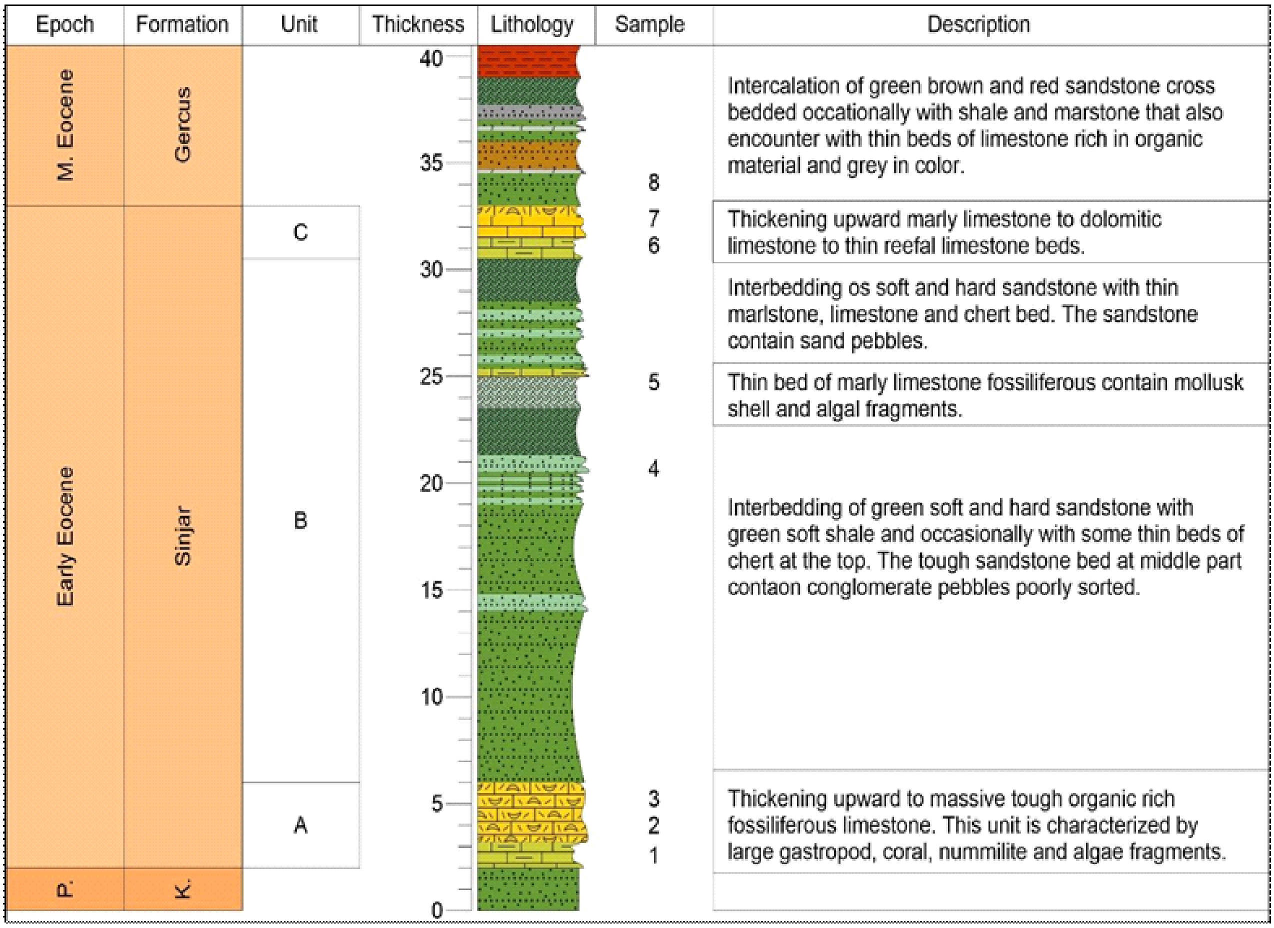

Fig. 5. Lithostratigraphic column of the Sinjar Formation at Linava section.

Fig. 6. Field photo of Sinjar Formation at Besre section. a. Field photo showing all units of Sinjar Formation in Besre section. b. Unconformable lower contact of Sinjar Formation with Kolosh Formation, green sandstone changes to brown thickening upward fossiliferous limestone. c. Coralline reefal limestone of unit C showing abundant of corals. d, e. Sandy limestone bed contains Gastropod and Pelecypods (Oyster) respectively. f. Thickening upward sandy limestone to dolomitic limestone followed by green sandstone of Gercus Formation. Red arrow indicates the place of scale. The blue bar scale is once centimeter. The yellow lines are showing the three units of carbonate.

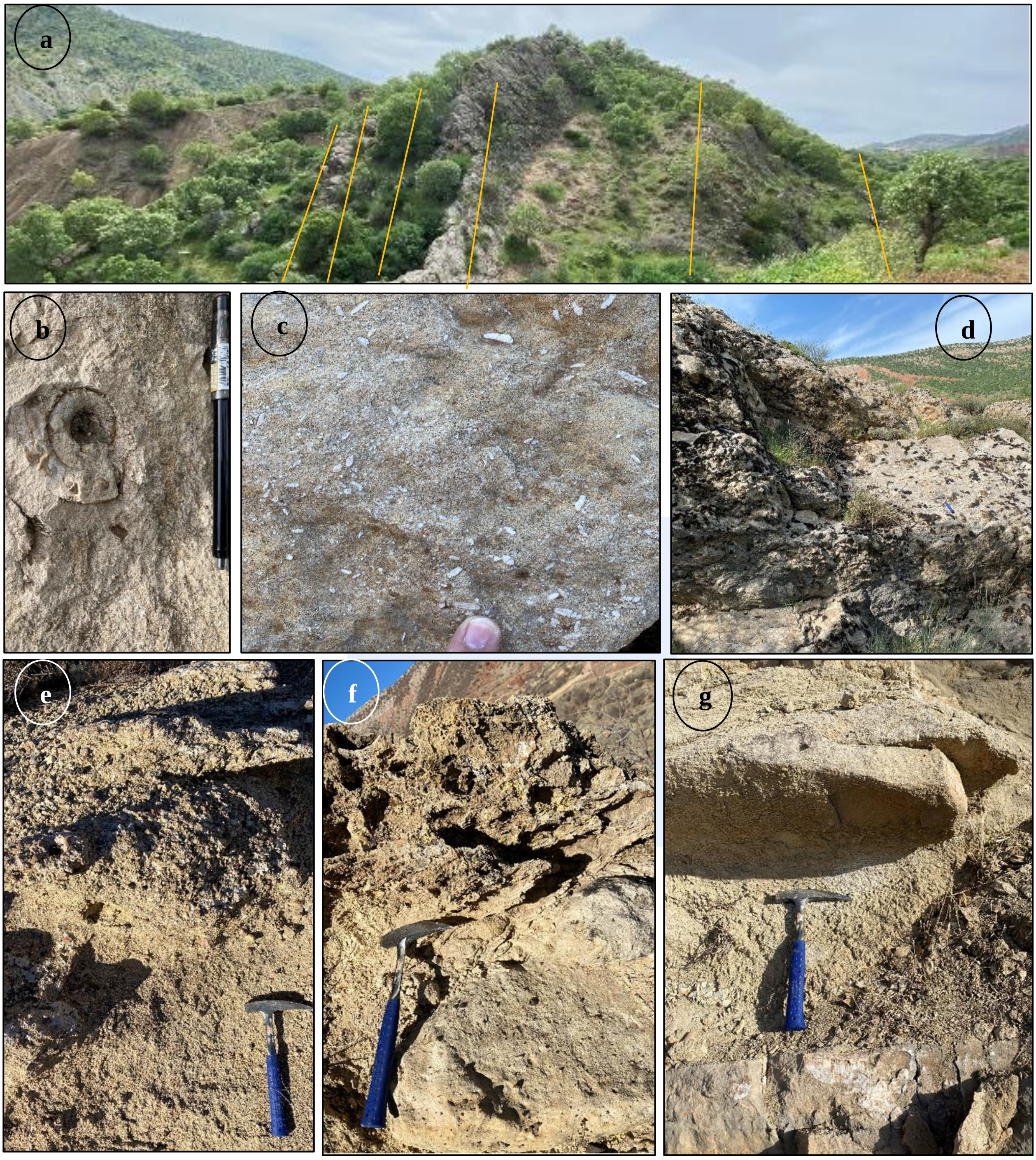

Fig.7. Field photo of Sinjar Formation at Perfat section. a. Field photo showing all units of Sinjar Formation in Per Fat section. b. Large gastropod shell from the bottom of first limestone unit. c. Thick bedded fossiferous limestone rich in nummulite from the lower part of the first limestone unit. d. Massive fossiliferous reefal limestone rich in algae in the middle part of unit A. e. thick bed of Conglomeratic sandstone contain large chert noddules. f. Conglomeratic limestone contain tafone structure 50 meters away from the section. g. Interbedding of sand with thick bedded fossiliferous limestone of the last unit C.

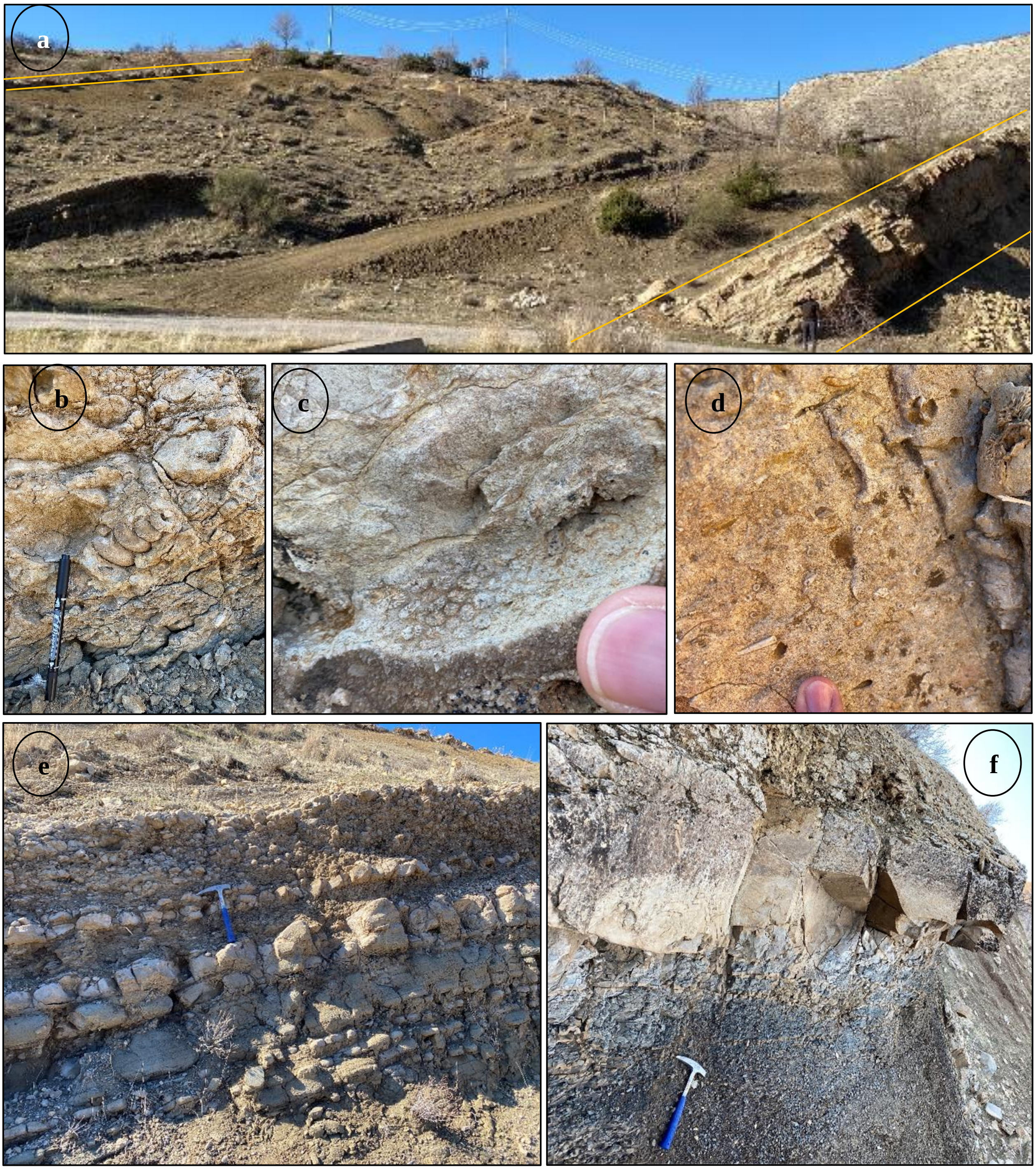

Fig. 8. Field photo of Sinjar Formation at Linava section. a. Field photo showing all units of Sinjar Formation in Linava section. b. Large gastropod shell from the bottom of first argillaceous limestone unit. c. Thick bedded fossiferous limestone rich in coral. d. fossiliferous limestone rich in algae in the middle part of unit A. e. Interbedding of green sandstone with shale, the beds are thinning upward and contain chert nodules. f. Highly porous limestone bed of the last unit C.

Facies and Depositional Environments

Mixed Clastic Lithofacies:

These lithofacies are recognized in all sections. Mixed clastic lithofacies are characterized by various lithologies ranging from mudstone, siltstone, and sandstone, mostly dark green, and have soft to moderate hardness. It also contains thin beds of argillaceous limestone and marlstone. It occurs in the Besre section with a thickness of up to 31 m. The sandstone is barren with no fossils, and a few beds of fossiliferous limestone contain some reworked fossils. These facies are also thick in the Linava section, up to 24.5 m. It is in the middle of both sections.

Sandy Conglomerate Lithofacies:

This lithofacies is recorded only in the Perfat section. It is intercalated between unit (B) clastic rock and occurs as a thick two-meter moderately hard dark gray-color sandy conglomerate. This conglomerate bed is composed of light-colored chert and carbonate boulders, cobbles, and pebbles. The grains are poorly sorted, and their rounding is usually poor to moderate. The conglomerate bed has a massive amount of coarse-grained sandstone. The main feature of this unit is lateral discontinuity. It extends more than 300 meters towards the west (Fig. 9 d). This conglomerate represents one of the submarine fan deposits, almost representing proximal turbidites.

Conglomeratic Dolomite Lithofacies:

These lithofacies only appear in the upper part of the Perfat section. It is characterized by a light gray, 40 cm thick, tough dolomite bed containing a few dark-colored conglomerates grain and ended by 50 cm of irregular surface with large pores and a mixture of a conglomerate-like tafone structure at the top. It is around 1 m thick and dies out laterally, so it's almost lensoidal channel lobes and mostly represents inter-tidal channels.

Limestone lithofacies:

It has been recorded in all sections and it represents the dominant lithofacies of Sinjar Formation. It is represented by two main facies as below:

I) Back Reef Facies (Inner Ramp Facies)

These facies are recognized in both the Besre and Linava sections. These facies are associated with argillaceous limestone and dolomitized limestone. The thickness reaches 6m in Besre and 2m in the Linava section. It is characterized by thin to medium-bedded argillaceous limestone containing many sizes of pelecypod shells and a few coral fragments. The limestone is mixed with clays, forming a dark color marl. It includes two microfacies types as below:

1) Wackestone Microfacies

These microfacies represent the argillaceous limestone within the lower part of Besre and the upper part of Linava sections. Petrographically, three different wackestone classes are distinguished based on the percentage of skeletal particles and all others. They are foraminiferal wackestone, coralline wackestone slightly dolomitized, and algal wackestone microfacies. Other recorded skeletal particles are pelecypod fragments, echinoids, and different foraminiferal forms such as miliolid and rotaliid species (Fig. 9 a). The algae have relatively limited occurrences in these microfacies.

2) Dolomitized Mudstone

This microfacies is very restricted in all three sections. Its thickness ranges from 0.5 to 0.9 m, especially in the bedded gray dolomitic limestone. It appears mainly at the uppermost part of Besre and Linava sections while in the Perfat section, it exists in the middle part. Petrographically, it is composed of fine to medium dolomite crystals of subhedral to euhedral fabric. The texture of the dolomite is unimodal. The faunas are less diverse, both skeletal forams and non-skeletal grains. Lamination is one of the characteristics of these microfacies (Fig. 9b, c).

II) Reef Facies

This is the dominant facies of Sinjar Formation in the examined sections. It consists of light brown, massive, fossiliferous limestone, rich in corals, algae, and their bioclast. It is dominant in the Perfat section with a remarkable thickness of about 11 meters and at the lower part of the Besre and Linava section about 2-2.5 meters in thickness. It includes five microfacies as below:

1) Framestone

Framestone microfacies in the field are characterized by 5m, massive reef limestone containing coral and large pieces of algae. It is worth mentioning that the red calcareous algae are the predominant type that binds the coral reefs and supports the reef buildup. Petrographically, it is composed of a large colonial framework of coral skeletons. The coral fragment can be seen in hand specimens of the studied sample and present as patchy reef bodies (see Fig. 9 f).

2) Coral-algal floatstone

This microfacies is very rare in the studied sections. It is mainly observed at the upper part of unit (A) of the Perfat section, composed mainly of algae, including large coral fragments and coarse bioclastic debris floating in mud-supported matrix texture. (Fig. 9 f).

3) Microbial Bioclastic Wackestone

This microfacies is recognized in the middle part of the first reefal unit (A) of the Perfat section which is composed mostly of micritic matrix and microbialites with some red algae. Fragments of mollusk shells are observed but rarely. Sample no.7 represents these microfacies (Fig. 9 g, i).

4) Packstone

This facies marks the lower part of the Sinjar Formation in the Linava and Perfat section. It is composed of a 5m, massive fossiliferous bed rich in forams and algal fragments. Coral fragments are common too. Large-size gastropod shells exist too within this limestone. Petrographically, it consists of various types of forams such as rotalid, miliolid, and textularid. The second widely distributed organism is red algae (Fig. 9 j). A few species of green algae such as *Dasycladacea* are also noticed, in addition to a few Ostracod tests.

5) Grainstone Microfacies

These microfacies appear at the upper part of the Perfat section. It differs from the other facies by its high percentage of grains. It comprises thin to thick-bedded gray and yellow fossiliferous limestone. The most common skeletal bioclasts are benthic foraminifera-like (rotalid, miliolid, and textularid). Green calcareous algae are common too with few ostracod tests. This microfacies is composed of abundant forams and green calcareous algae of variable size. The microfauna is getting large upward and surrounded by a sparry calcite cement. Pelecypods bioclasts are rare (Fig. 9 k, l). At certain parts pelloides and a few ooids are noticed with the miliolids forams (Fig. 9 i).

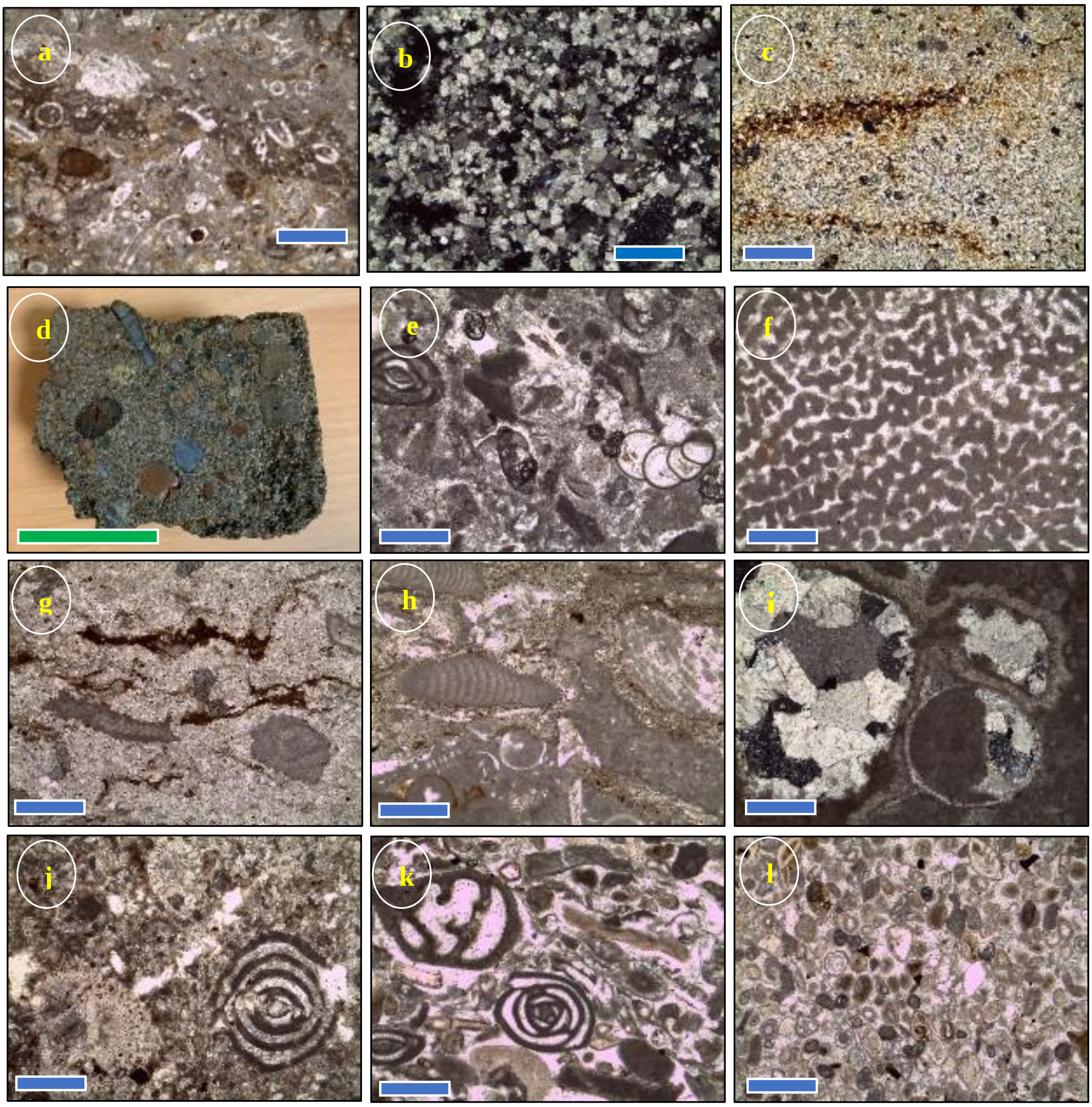

Fig. 9. (a) wackestone microfacies; (b, c) dolomitized mudstone microfacies; (d) conglomerate lithofacies;(e) packstone microfacies; (f) framestone microfacies; (g) microbial bioclastic wackestone; (h,i) coralgal intraclstic wackestone; (j) packstone; (k-l) grainstone microfacies rich in Valvulinds – Miliolids, pelloides and few ooides. Scale details: green bar =2 cm, blue bar= 500 µm.

Correlation

The upper part of the Kolosh Formation (Paleocene) is commonly associated with a marine carbonate unit that is often considered an equivalent to either the reefal limestone of the Sinjar Formation or the dolostone of the penecontemporaneous units of the Khurmala Formation (Bellen *et al.*,1959; Buday, 1980; Al-Qayim *et al.*, 1988; AL-Surdashy and Lawa 1993; Lawa 2004; Lawa and Albayati, 2006; Al-Banna *et al.*, 2006; Sissakian *et al*. 2013; Omer *et al*., 2014; Karim, 2016). Al-Qayim and Barzani (2021) recognized reefal facies of the Khurmala Formation at the southeastern tip of Bekhair Mountain, Duhok area. This exposed section shows evidence of clear outcrops characterized by a predominated reefal carbonate mixed with the siliciclastic sediments and considered a lens or tongue from the Sinjar Formation rather than the Khurmala Formation (Fig. 10).

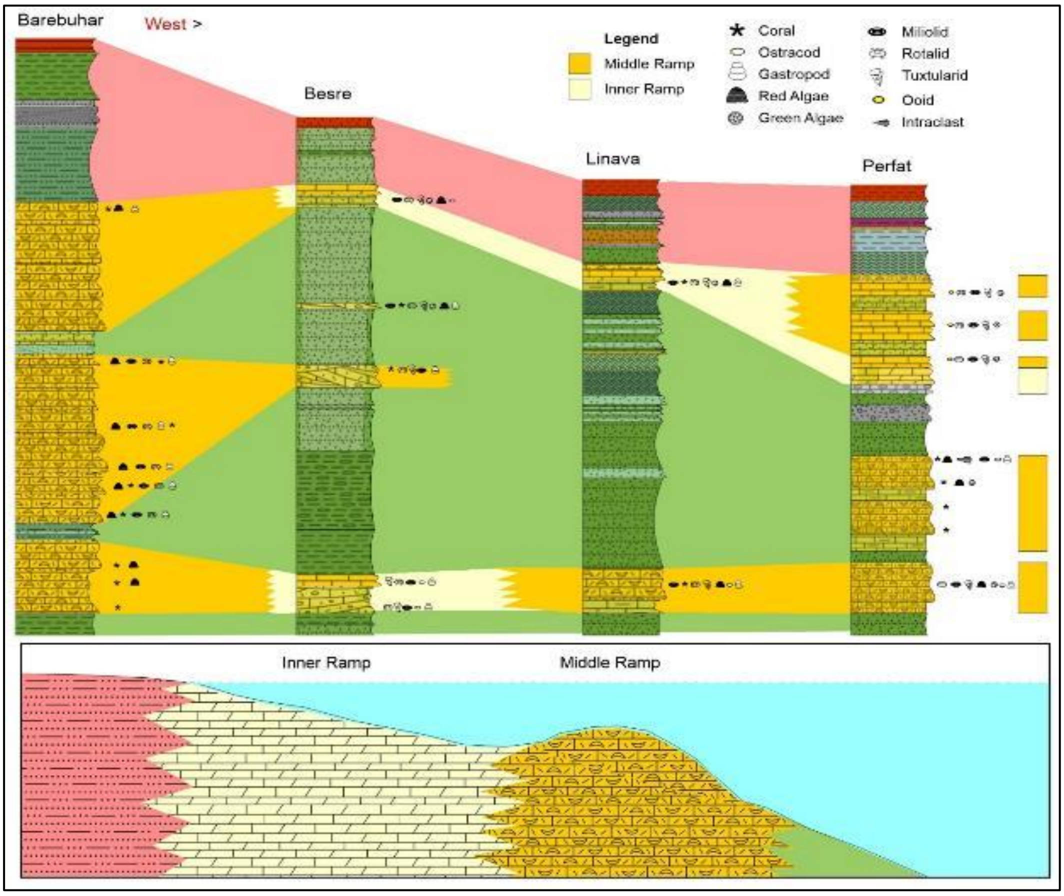

Fig. 10. Correlation of all the studied sections of Sinjar Formation at Bekhair Anticline showing vertical facies variation.

The Lower Eocene Sinjar Formation appears at Bekhair Anticline discontinuously from the east at Barbuhar village toward west Zewa Shafiq village.

The Sinjar Formation is getting thin or disappearing in some areas, such as in Qar Qarava, Pero Mara, and especially around the dam near the core of the anticline. On the other hand, it gets thick in some areas like Barbuhar, Bade, and Perfat village. The Barbuhar section had been examined by Al-Qayim and Barzani (2021). It is composed of massive coral-algal reefal limestone horizons associated with mollusk-rich limestone layers.

The reefal limestone bodies are intercalated with the marine Kolosh Formation proper siliciclastic sediments of green shale and sandstone (Al-Qayim and Barzani, 2021). Comparing the lithostratigraphic characters of this section with the Besre, Linava, and Perfat sections, shows a close similarity between them, especially the Barbuhar and Perfat sections. Parallels include facies, microfacies, stratigraphic position, nature of boundary conditions, lithologic characteristics, and fossil contents.

All three sections are composed of two or three fossiliferous carbonate units and separated by non-fossiliferous sandstone marlstone or shale horizons. This reveals that the carbonate horizons are getting thin towards the west of Duhok, indicating the main reef body is to be developed towards the eastern part of the study area, mainly in the Barbuhar area.

Faunal content:

The recorded genera and species are described and listed below:

1- Red algae: The calcareous red algae are dominated by genera and species of corallinaceae families, with the subfamilies of mastophoroideae, melobesioideae, and the family of Sporolithaceae. Six genera were found: *Lithoporella*, *Lithothamnium, and Mesophyllum. Lithophyllum Sporolithon*, while the recorded species are: *Amphiora iraquensis Lithothamnium* sp., *Sporolithon aschersoni* (Schwager), *Lithophyllum zonatum* Johnson, and Ferries. *Sporolithon*, which prefers warm and shallower depositional environments (Prica, 2005), indicates that the coral-algal bioconstruction in the Sinjar Formation is formed in warm and illuminated water. The red algae are common in the Perfat section and occasionally present in the Lenova and Besre sections.

2- The corals are diverse and lyshared in the middle-lower and middle parts, with high abundance in both the Besre and Barbahar sections and poorly developed in the Linava section. The zooxanthellate and azooxanthellate groups represent them. Zooxanthellate corals are dominated mainly by faviids and poritids. The principal genera recognized are Porites and Favit. The common coral is related to Portidae; the common species is *Monostraea nodosa. Favia favoides*(Fig.1.b).

3- The larger benthic foraminifera is an important component of tropical shallow-water carbonates, and they are considered major sediment producers and powerful tools for stratigraphic and environmental studies (Serra-Kiel et al. 1998; Beavington-Penney and Racey 2004; Boudagher-Fadel 2008). They represent the most abundant and diverse group in the carbonate units of the Sinjar Formation. Both hyaline and porcelaneous forms represent the small and large benthic foraminifera. The hyaline foraminifera are dominated by *Kathina selveri Smout, Rotalia trochdiformis, Rotalia spp., Operculina sp., Ranikothalai sp., and Lockhartia* sp., and the porcelaneous forms are represented by miliolids (*Idalina sinjarica Grimsdale), Quinquloculina, Pyrgo spp., and Spiroloculina* spp. The most porcelaneous wall groups fall into two families: the Soritidae and the Alveolindae. Brasier (1980) mentioned that the Soritidae have thrived in reefal and carbonate habitats since the late Triassic, with all-embracing, annular chambers in addition to forms like *Orbitolites complanatus* Lamarck (U. Paleocene-L. Eocene). They are common in the carbonates of the Sinjar Formation, especially in units b and c in the perfect section, in addition to other species and genera like *Saudia labyrinthica* Grimsdale and *Pertorbitolites douville* Nuttall. The Alveolinds are present too, but in less diversity and represented by Alveolina globose (Leymerie) and *Alveolina spp.* Martin *et al. (*2021 mentioned that the predominance of larger benthic foraminifera (LBF) in the shallow marine carbonate environments of the Tethys throughout the Eocene was favored by high temperatures. The other benthic foraminifera forms are represented by *Textularia* sp. *and* Valvulinids (*Valvulamina picaradi* SMOUT).

4- Mollusca and other macrofossils are represented by the giant gastropod genera *Campanile* (Bayle in Fischer 1884), recorded at the lowermost part of the Sinjar formation in all the studied sections. It is also recorded by Al Essa (1983) and Al-Banna *et al*. (2006) from the lowermost part of the Khurmala formation in Shaqlawa and Bade Duhok, respectively, as well as at the base of the Sinjar formation in the Sulaimani area by Lawa (2004). The giant gastropods in all studied sections (Fig. 5 d, Fig. 6 b, and Fig. 7 b) are known as *Campanile* *zakhoense* and were recorded by Harzhauser *et al. (*2013 from the upper part of the Kolosh Formation as indicators of the Thanetian age in the Bahre section, Zakho, Kurdistan region, and from the Late Thanetian to Early Ypresian in Turkey. It's worth mentioning that Harzhauser *et al. (*2013 assumed the existence of the following species in the Thanetian/Ypresian Mediterranean Region of the Tethys Realm, represented by molluscan faunas from western Turkey and northern Iraq, Including several new recorded gastropod species like: - *Campanile zakhoense*, *Pyrazopsis hexagon pyramidalis*, *Pachymelania islamogluae*, and *Pseudoaluco mesopotamicus* from Bahare section, Zakho area. Based on the above-recorded macro and micro associations, with particular attention to the large benthic foraminifera, the recorded assemblages are *Campanile zakhoense* and *Pyrazopsis hexagonpyramidalis*.

Biostratigraphy

The larger benthic foraminifera (LBF) are important components of tropical shallow-water carbonates, and they are considered major sediment producers and powerful tools for stratigraphic and environmental studies (Serra-Kiel et al. 1998; Beavington-Penney and Racey 2004; Boudagher-Fadel 2008). They represent the most abundant and diverse group in the carbonate units of the Sinjar Formation. The biostratigraphic analysis focuses on LBF biozonation using index fossils and following Serra-Kiel et al., 1998; Serra-Kiel et al., 2020, (Table 1). Below is a brief review of these zones in the study area: -

Table 1. Paleocene–Eocene correlation of deep-water and shallow-water biostratigraphic schemes and platform stages in the Tethyan realm, from Scheibner, and Speijer (2008), with the recorded LBF zones in the Sinjar Formation of Duhok area.

Series	Age: Berggren et al. (1995/2000)	Age: Serra-Kiel et al. (1998)	Age: Scheibner et al. (2005)	P Zone: Berggren and Pearson (2005)	P Zone: Berggren et al. (1995)	NP Zone: Martini (1971); Okada and Bukry (1980); Aubry (1995); Aubry et al. (2005)		B Zone: Berggren and Miller (1989)	SB Zone: Serra-Kiel et al. (1998)	SB Zone: Scheibner et al. (2005)	Platform Stages: Scheibner et al. (2005)	Present Study	
Early Eocene	Ypresian	Ilerdian	Ilerdian	E4	P6b	NP10	d, c	BB2	SBZ8	SBZ8		SBZ 7	Ypresian
				E3	P6a		b		SBZ7	SBZ7			
				E2	P5		a				?	SBZ 6	
				E1		NP9	b		SBZ6	6, 5	III		
Late Paleocene	Thanetian		Thanetian	P5			a	BB1	SBZ5, SBZ4	SBZ4	II	SBZ 5	Thanetian
				P4c	P4c	NP7/8			SBZ3	SBZ3	I		
				P4c	P4b							Not Studied	
				P4a		NP6							
	Selandian												

1- *Orbitolites complanata –Saudia labyrinthica – Opetorbitolites* Assemblage Zone (SBZ 5)

The lower limit of the zone is determined based on the lowest occurrence (LO) of the above species and was identified according to the coexistence of other benthic foraminifera like Kathina *selveri* and *Dictyokathina* simplex. This zone is mostly recorded in Iraq as an indicator of Shallow benthic zone five (SBZ 5), which is of the late Paleocene age (Thanetian) (e.g., Grimsdale 1952; Al- Hashimi and Amer 1985; Lawa and Surdashy 1993; Lawa 2004; Scheibner and Sperijer, 2009; and Boudagher, 2008). Scheibner and Speijer (2009), in their recalibration of the Tethyan shallow-benthic zonation across the Paleocene-Eocene boundary, mentioned that SBZ5 and SBZ6 in this study are combined and not separated because index species of both biozones co-occur. Serra-Kiel et al. (1998) Mentioned that the SBZ 4 biozone is characterized by the assemblage formed by *Glomalveolina levis, Hottingerina lukasi, Miscellanea meandrina, Daviesina garumnensis, Dictyokathina simplex, Nummulites* catari, and *Assilina azilensis*. Such an assemblage is not recognized in the studied sections.

In addition to that, the same author mentioned SBZ5 is of late Paleocene age (Thanetian). This zone was also recorded in alternation successions between the marl-dominated sequence and carbonates, which include planktic foraminifers of the Late Paleocene *Morozovella velascoensis* Zone by Lawa (2004). Serra-Kiel *et al.*, 2020 in their study about Paleocene Larger Foraminifera from the Pyrenean Basin with a recalibration of the Paleocene Shallow Benthic Zones Recorded this zone from the Early Eocene age. Recently, Kakemem *et al.* (2023) considered this zone part of the Early Eocene age strata in their litho and bios study on the Zagros foreland basin in Iran. Therefore, this study is also considered an Early Eocene Ypresian age indicator.

2- *Idalina sinjraica*, *Alveolina globosa*, and *Rotali trochidiformis* Assemblages Zone (SBZ6)

This zone is identified depending on the LO to the highest occurrence (HO) of *Idalina sinjarica*, *Alveolina globosa*, and *Rotali trochidiformis.* Serra-Kiel *et al*. (1998) recorded that the first occurrence of the genus *Orbitolites* and *Alveolina globosa* is in SBZ 5 and SBZ 6, and mentioned that the species *Idalina sinjarica* extends from shallow benthic zone three (SBZ.3) to Shallow benthic zone six (SBZ.6). In this work, the associated large benthic index has been taken into consideration, as has their stratigraphic position. The *Nummulites precursor* is restricted to SBZ 7. The *Nummulites preacursor* is recorded from the upper part of this zone, which is recorded in association with *Idalina sinjarica*; therefore, this zone may extend to SBZ.7, but it's not well distributed and not recorded in all sections, as well as not extending for a long period because it's truncated by the incised valley. Both zones (SBZ.6 and SBZ.7), almost indicate the Ypresian age and that is the early Eocene. Those zones are recorded by Al-Sayyab and Al-Saddiki (1970); and Lawa (2004) from Sinjar formations from sections in Mosul and Sulaymaniyah areas. This biozone was recorded from the Perat and Burbahar sections. They are associated with the predominance of different algae species like *Amphori iraqiensis* and green calcareous algae like *Trinocladus sp.* The base limit of the zone was identified according to the coexistence of the three species. The thickness of this zone at Perfat Station is about 7m, 5.5 m at the Besre Section, and only 1.5 m at the Linava Section. This foraminiferal assemblage terminates below the boundary with the overlying Gercus Formation when all foraminifera and all other micro- and Macrofossils have disappeared. Therefore, this assemblage indicates part of the Ypresian age, that is, the early Eocene, which is also assigned the same age by Al-Hashmi and Amer (1985) and Lawa (2004). Taking into consideration the stratigraphic position above the shallow benthic zones 5 and 6 in correlation with those by Serra Kiel 1998, and Boudagher 2008.The age of the Sinjar Formation in all three sections studied of the Early Eocene (Ypresian). The Ypresian bio-assemblages show mass extinction of almost all macro and microfauna, which points to the fact that the upper part of the Ypresian is represented by SBZ 8 and 9 at the boundary with the overlying red continental clastics of the molasse unit that is the Gercus Formation.

Sequence Stratigraphy

The Sinjar Formation in the three studied sections is comprised of mixed carbonates and clastics, so they reflect the interplay between the ramp carbonates and proximal turbidites facies along the Paleocene/Eocene boundary (extending from the Thanetian to the Ypresian) and mark the turnover from syn sedimentary tectonic disturbance to a time of quiescence suitable for patchy reefal facies. Accordingly, the sediment sources show remarkable interplay between external sources supplied from the hinterland area to the Kurdistan foreland basin (e.g., siliciclastic) or born within the sedimentary basin (e.g., mainly biochemical and chemical carbonates). In their overall context, these data indicate a shallowing upward sequence from the outer shelf to the middle, then to the inner shelf, and finally, the closing of the carbonate factory by the influx of red clastic continental and deltaic facies of the Gercus Formation (Middle Eocene). The recorded third-order depositional systems in the studied section are almost bounded or underlain by the sequence boundary of type two and overlain by the sequence boundary of type one.

The boundary between the Kolosh and Sinjar formations is associated with a gap and subaerial erosional surface on the basin margin (Lawa, 2004). In the present study sections, the Kolosh and Sinjar formational boundary is characterized by the first appearance of giant gastropods and oyster beds in all the studied sections, so they represent key surfaces in this concept and mark the turnover in the accommodation space to intertidal from the inner shelf to coastal turbidites facies. The following system tracts are recognized within the studied sequence:

The Shelf Margin System Tracts (SMST) extend for short periods and mostly consist of mixed siliciclastic and sandy carbonates. It is also represented by the low-stand wedge deposits, which are rapidly flooded by the retrograded stacked sediments of the TST, where the carbonate production is still in intercalation conditions with siliciclastic. The temporal variation in siliciclastic supply often results in alternations between siliciclastic and carbonate-dominant systems at the same position in a basin. The late situation is considered for the Ypresian Sinjar Formation tracts (mixed sequence), which result from the alternate drowning and emergence of siliciclastic sources attached to carbonate shelves. The reefal carbonates show alternations with the clastics, and they reflect the interplay between stability conditions (patchy reef time) and unstable conditions (turbidity time) during the depositions in the same section. Therefore, the sandy-conglomeratic limestone and grain stone dominated by re-sedimented carbonate deposits in lower portions of the Sinjar Formation are restricted to the base level of this package and correspond to an unconformable but relatively sharp sequence boundary between the Kolosh and Sinjar formations during a drop in the relative sea level. This sequence represents the new transgression after the last HST of the Kolosh Formation. This sequence is characterized by the retrogradational stacking pattern where relatively deep shelf ramp facies built a parasequence, in an up-dipping setting with relatively new accommodation space by the early most Ypresian.

The Transgressive System Tract Is recorded from all the studied sections of the Sinjar formation. The transgressive system tract is built up of *Orbitolites (Sudia labrynthica), Opertorbitolites,* and *Alveolina* facies with abundant Rotalids. In this condition, the rate of accommodation overwhelmed the rate of sediment supply. The transsystemic tract is represented by the predominance of the Patch Reef Facies Association (Including microfacies: frame stone, Coral-algal Intraclastic wackestone, and floatstone). Microbial Bioclastic Wackestone (grainstone and boundstone) of well-developed massive carbonates in per fat section and less in Linava and Besre sections. The appearance and abundance of the larger porcelaneous wall benthic foraminifera suggest shallow, well-illuminated, warm, oligotrophic waters with suitable substrate and normal marine salinity (Pomar *et al*.,2014). The higher degree of turbulence with mobile substrate and fauna indicates Turbidite conditions, which is also shown by robust and thick-walled tests of foraminifera (Nebelsick et al., 2000; Fournier *et al*., 2004). So, the paleodepth in this condition doesn't exceed 40 meters (Beavington-Penney and Racey, 2004). This system tract is restricted by the maximum flooding interval at the top with the small benthic mudstone, red-algae packstone, and grain stone sub-facies of Perfat. During the greenhouse conditions prevailing in the early-middle Eocene, larger benthic foraminifera (LBF) spread out on carbonate platforms worldwide (Beavington-Penney and Racey, 2004), while Rhodolith red algae beds were scarce, so the Maximum Flooding Surface (MFS) in Besre and Linava sections is placed at the top of the limestone bed very rich in red algae and bioclastic that is overlain by the siliciclastic deposit.

The early aggradation stacking pattern of the fossiliferous massive limestone with the proximal turbidites siliciclastic manifests the Highstand System Tract (HST). Here, the late HST is represented by the lagoonal-reefal carbonates in the Perfat section, which are composed mainly of large benthic foraminiferal packstone and grainstone microfacies. Sakar and Rao (2018) concluded that the coralline red algae dominated by the Melobesioid and Sporolithacean forms of the Late Palaeocene–earliest Eocene community from this Eastern Tethyan realm is characterized by encrusting, warty, lumpy, fruticose, and unconsolidated growth forms. The Eocene was a transient period between greenhouse and icehouse conditions (Norris et al., 2013; Mudelsees *et al*., 2014; Anagnostou *et al*., 2016). Global temperature rose in the early Eocene up to the highest values ever reached during the Cenozoic; the so-called early Eocene climatic optimum (EECO). The relative distribution of different foraminifera across the carbonate shelf is used as a valuable tool in paleoenvironmental and paleobathymetric reconstructions (Beavington-Penney et al., 2006; Barattolo *et al*., 2007). The predominance of porcelaneous foraminifera (*Idalina sinjarica* and others) and green calcareous algae, also associated with the remarkable disappearance of the hyaline-walled LBF like *Orbitolites* and *Nummulites,* points to shallowing and sea level fall by the late HST. As a result, the transgressive systems tract (TST) of the mid-shelf facies associations is followed by the inner ramp associations representing the high-stand systems tract (HST), whereas the MFS between them can be placed at the top of the large benthic Nummulites and red algae-rich beds. According to Sharland *et al.* (2001), the Pg20 MFS is preceded by a short-lived LST hiatus during the early Eocene and late Ypresian, as indicated by the presence of *Nummulites globulus* and *Coskinolina balsillei*. This marker in this section can be detected in the middle part of the Sinjar Formation. The late HST is characterized by the total disappearance of all marine fauna and flora of the Ypresian age (Sinjar Formation) and the first appearance of the red clastic molasses deposits of the Gercus Formation. Therefore, it is considered an unconformity that forms under subaerial conditions due to fluvial erosion, bypass, or pedogenesis. They are formed as a result of river rejuvenation in the incised valley and are filled by polymictic conglomerate beds of lensoidal shapes, mostly composed of gravels of badly sorted roundness, in the Linava and Perfat sections. They are mostly formed as channels in braided rivers. This boundary terminates the Ypresian carbonate factory and marks a major sea-level fall, possibly combined with the Arabian-Eurasian continent collisions during the middle Eocene (Lawa 2004). This suggests that the lower part of the Gercus Formation was deposited during a major sea-level fall, which coincides with the total exposure of the shelf.

Discussion

The lithological properties, stratigraphic positions, and microfacies analysis with facies interpretation suggest the occurrence of the Sinjar Formation at the three studied sections of the Duhok area, but with alternations of siliciclastic deposits. The carbonate units of the studied sections show evidence of an intergrowth of frame-building corals and algae (esp. coralline algae) as patchy reef developments near the top of the clastic-dominated Kolosh Formation. Inter-mixing between the two lithologic types is displayed by the subdivision of the carbonate reef body into a few subunits similar to the situation elsewhere in northern Iraq, such as Kolosh type area (Kassab, 1976); Sulaymaniyah area (Shathaya ,1980; Mallick and Al-Qayim, 1985; Al-Surdashy, 1988; Lawa and Al-Bayaiti, 2006; and Daoud, 2012); Darbandikhan area (Al-Dulaimi, and ALDulaimi, 2017; Karim, 2016); Bekhme area (Al-Qayim and Al-Shaibani, 1995; Al-Banna *et al.*, 2006); Daigala area (Agha *et al.*, 2015); and Duhok area (Al-Qayim and Barzani, 2021). The formation is determined by their lithological properties and their stratigraphic position. In different sections of Iraq, the Sinjar formation shows an extending age from the Upper Paleocene to the Lower Eocene (Bellen et al., 1959, Shazaya 1980, Surdashy and Lawa 1993, Lawa 2004, Daoud 2012). However, due to the fact the study part does not represent the type section and doesn't include or involve all the succession of Sinjar formation, the studied part represents the Lower Eocene based on Large benthic Foraminifera zonation. The boundary is placed at the first appearance of Massive, fossiliferous limestone However, the lensoidal shape and limited lateral extent of these reef bodies and organic limestone suggest patch reef development over the inner-middle ramp environment (Burchett and Wright, 1992). These carbonate units belong to the Sinjar Formation and are not developed until basin shoaling reaches the proper environmental conditions of shallow depth and limited clastic influx. These conditions, seemingly, developed around the Ypresian. Thus, the lower carbonate boundaries show no significant break but sudden lithological changes of sequence boundary type 1. The upper boundary, on the other hand, shows evidence of unconformity as the subcontinental red siliciclastic sediments of the Gercus Formation cover the carbonate unit in all the examined localities, making it a sequence boundary of type 1. The overall sequence of these carbonates (Sinjar Formation) in the studied sections represents a third-order cycle with system tracts passing from progradationally developed SMST to thicker retrogradational TST, followed by relatively thicker and aggradational to progradationally developed HST (Fig. 11). Further lower-order subdivision among the studied sections is not clear enough to be decided; however, in the Perfat section, the triple subdivision of the Sinjar Formation and the well-developed reef build-up in each division suggest the possible occurrence of three fourth-order cycles.The Palaeocene/Eocene boundary is represented by the boundary between the Thanetian and Ypresian stages of the International Commission Stratigraphic. It shows mostly the remarkable changes in dating in the last decades, but the most recent one deals with the selection of the

Dababiya section as a new stratotype section from Egypt (Aubry *et al*., 2001). The more significant foraminiferal turnover (LFT) was located between shallow benthic Zones 4 and 5. The boundary between the Paleocene and Eocene is located between SBZ5 and SBZ6 (Scheibner and Speijer, 2009). The Palaeocene-Eocene boundary in northern Iraq is almost considered a gradational, transitional boundary (Bellen et al., 1959; Buday, 1980; Shatthya, 1980; Al-Surdashy, 1988; Al-Qayim and Salman, 1988; Ghaffoor et al., 1999). Lawa (2004), Ameen and Mardan (2018) recorded an incised valley between the Kolosh and Sinjar Formations in Sulaimani and approved that by the disappearance of SBZ5 and SBZ6 between the Paleocene and Eocene in Sulaimani area. According to the most recently published article by Serra-Kiel et al. 2020, the boundary between the shallow benthic zones SBZ 4 and SBZ 5 is considered the Paleocene-Eocene boundary event (ca. 56.0 ma). In all the studied sections, red algae, coral, bryozoa, echinoids, and pelecypods (especially oysters) represent common macrofossils. Among the microfossils, the benthic foraminifera are common and are represented by the Miliolids, Sortied, and Rotalids groups. This study also coincides with the result by Aurby et al 1999, and Alhejoj et al 2020, about the Depositional sequences and sea-level changes of the upper Maastrichtian-middle Eocene succession in central Jordan: Evidence from foraminiferal biostratigraphy and paleo-environments. The P/E boundary is characterized by a great flourishing of reef communities, especially of larger foraminifera, red and green algae, pelecypods, gastropods, echinoids, and to a lesser extent coral and bryozoans. In the study area of Duhok, the Paleocene/Eocene boundary occurs within the Kolosh/Sinjar Formational boundary.

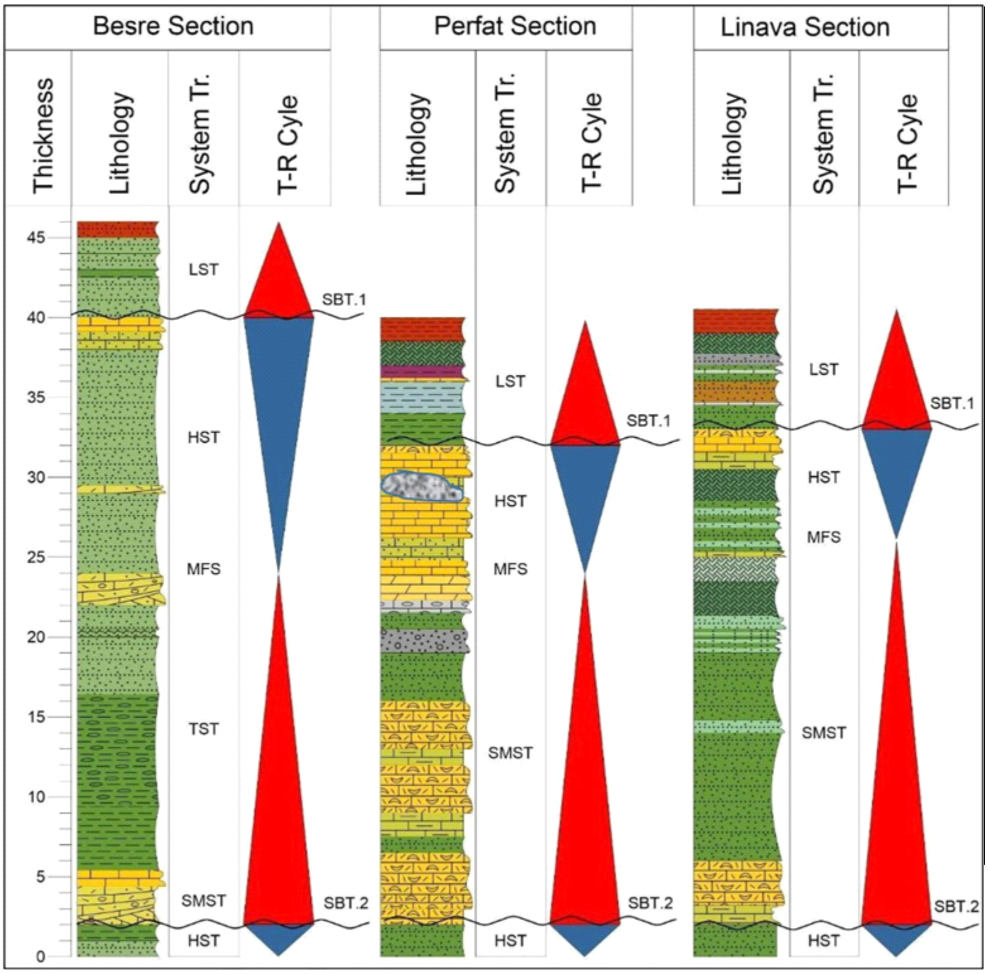

Fig. 11. Lower Eocene depositional sequence and their system tracts of the Sinjar Formation at Besre, Perfat, and Linava sections, Duhok area, Kurdistan Region, North Iraq.

Conclusions

The exciting results of the facies development and sequence stratigraphy are summarized below:

The Sinjar Formation of the studied sections shows typical mixed carbonate-clastic units with variable lateral facies and thickness.

The carbonates are organically rich, and reef build-ups of small extensions indicate patch reef fauna associations that start with gastropods in the coquina band and terminate with red molasses.

Facies analysis indicates that the deposits of Sinjar carbonate that have been developed over an unstable shelf margin show fluctuation between middle and inner shelf settings with coastal classics, lagoonal limestone, organic limestone facies in the internal shelf, and patch-reef and lime mud facies.

The Foraminiferal assemblages are 1) *Orbitolites complanata, Saudia labrynthica, Opetorbitolites* Assemblage Zone (SBZ5), and 2) *Idalina sinjraica. Alveolina globosa-Rotalia trochidiformis* Assemblage Zone (SBZ6) indicates Ypresian.

The studied Sinjar Formation constitutes a complete third-order cycle of shelf margin system tract (SMST), which is built on the normal regression surface, followed by the transgressive surface at the base of the Transgressive system tracts (TST), capped by the Maximum Flooding surface (MFS), then followed by the Highstand System Tract (HST).

The lower sequence boundary with the Kolosh Formation is of Type 2 (SBT.2), and the upper boundary with the Gercus Formation is unconformable and of Type 1 (SB. T1).

The staking patterns and depositional system developments during the early to middle Eocene manifest inversion from marine warm conditions in the Sinjar reefal facies to, more excellent conditions characterized by non-marine red molasses in the Gercus formation, which is controlled mainly by the evolution of the Kurdistan Foreland Basin from deep moraine turbidites (Kolosh Fm.) to reefal facies (Sinjar Fm.) and finally to molasses facies (Gercus Fm.) by the middle Eocene.

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Plate 1

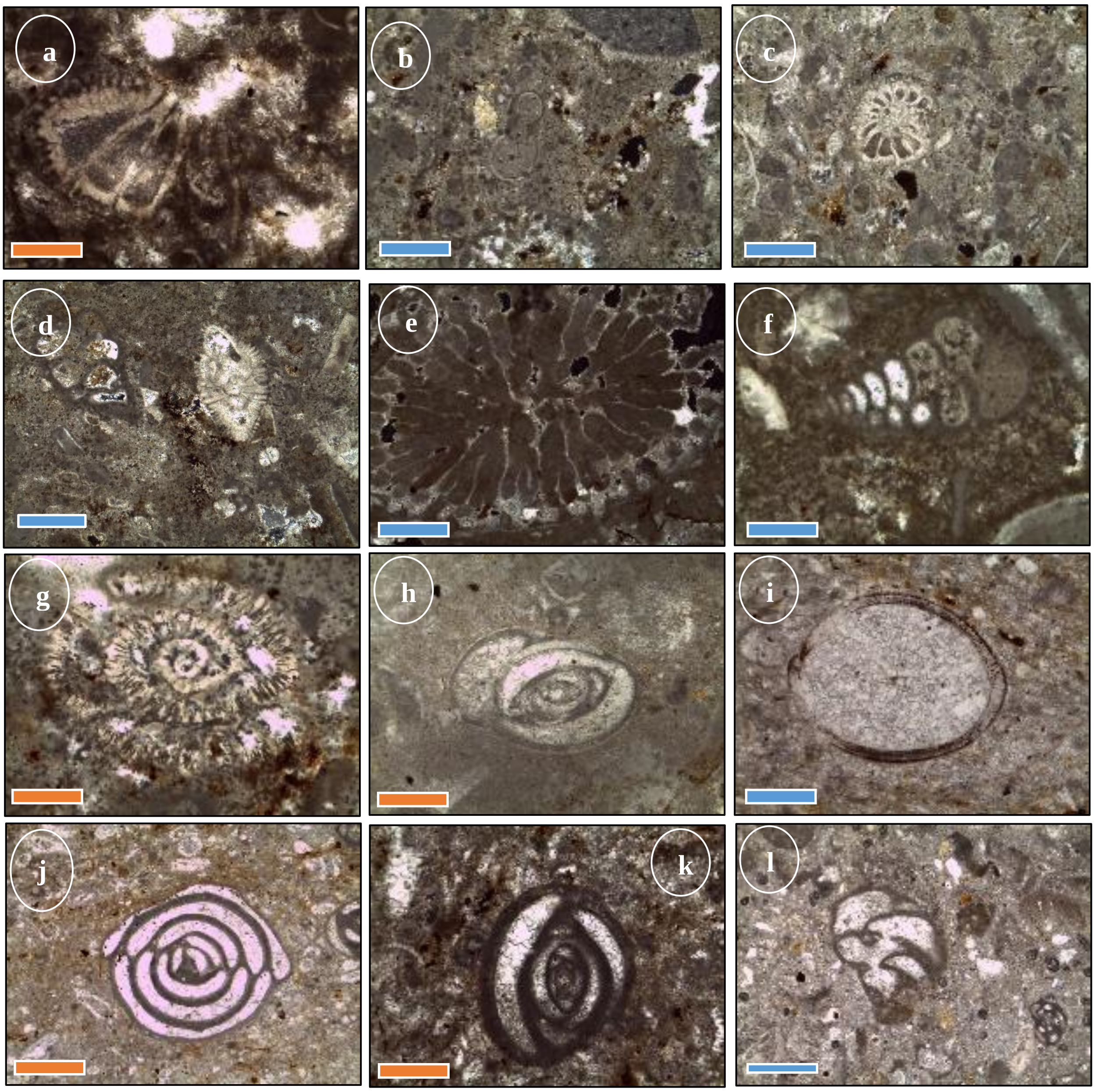

Plate 1. Photomicrograph of microfacies: (a) lockhaartia and kathina major Smout, (b) Pseudohatigerina SP. (c) r Ranikithalia antillea (Hanzawa). (d) Rotalia trochidiformis (Lamarck) (e) Coral. (f) Valvulina (g) Rotalids. (h) Idalina Sinjarica. Grimsdale (i) ostracod. (j) Miliolid (Pyrgo sp.). (k) Quincuoculina (i) Vulvulina SP. Scale details: blue bar= 500 µm. Orange bar scale= 200 µm.

Plate 2

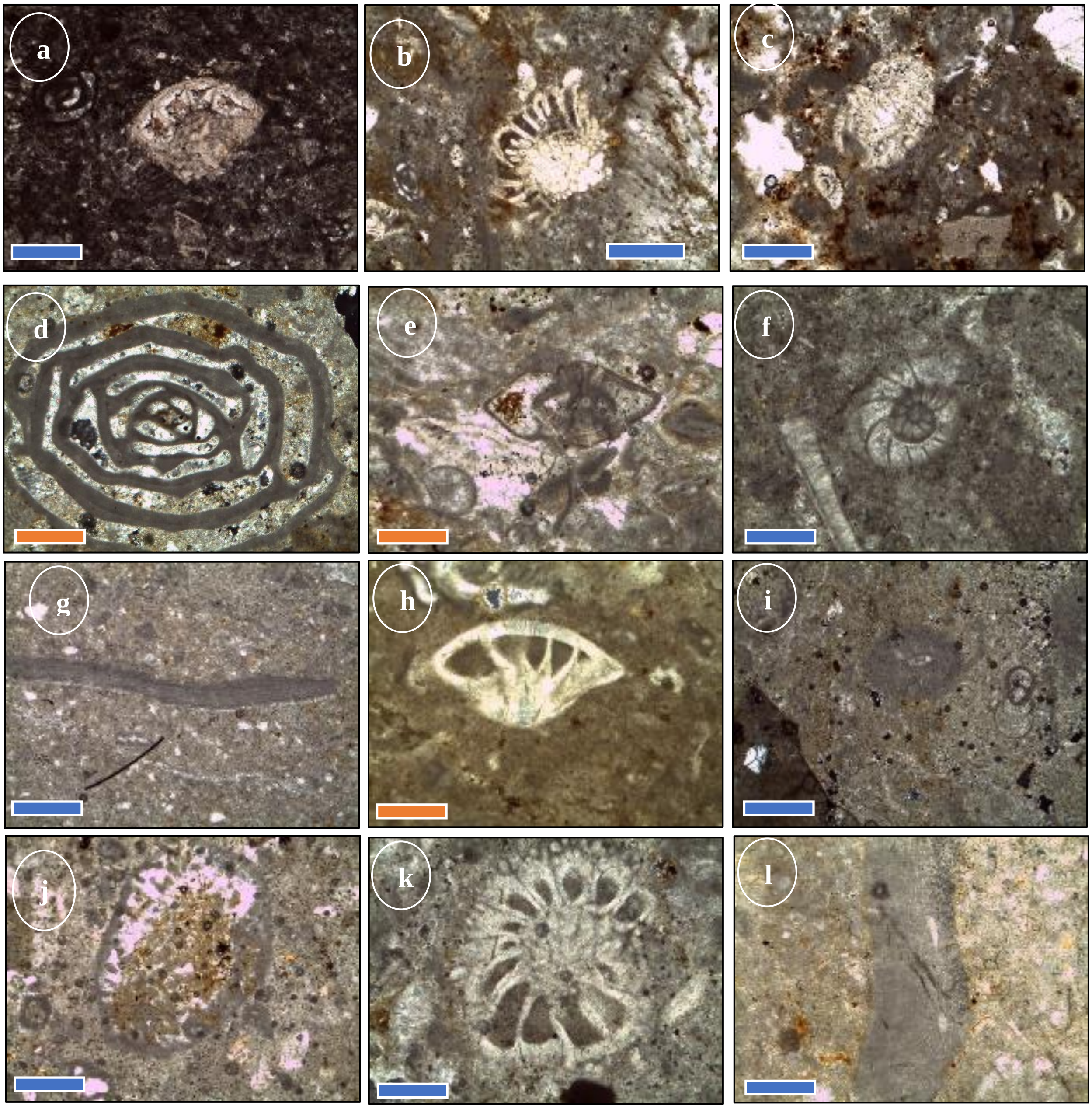

Plate 2. Photomicrograph of microfacies: (a) rotalid, (b,c) rotalid trochidiformis.(Lamarck) (d) Miliolid Pyrgo (e,h) *Lockhartia.* (f) *Peneroplis* sp. (g) *Orbitolites complanatus*; Lamarak (i) *Globanomalina* sp. (j) *Dictyoconus* sp. K) (l) Red algae *(Amphiroa* sp.).