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# MICROFACIES STUDY OF MAASTRICHTIAN REEFAL LIMESTONES NORTHEAST AND NORTHERN KURDISTAN REGION-IRAQ

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## ABSTRACT

The Maastrichtian reefal limestone, which developed variably across the northern and northeastern Kurdistan Region of Iraq, includes the Aqra Formation, which formed extensive platforms in the Aqra-Barzan area throughout the Maastrichtian period. Additionally, bars and beds of reefal limestone in the upper part of the Tanjero Formation created longitudinal submarine ridges in the Arabian-Eurasian Foreland basin. This study selected three sections: the Aqra Formation in the type section and study the reefal limestone beds in the Upper part of the Tanjero Formation at the Kunamasi and limestone bars in the Balakaity. Focusing on lithofacies and microfacies to determine if these reefal limestones are part of the Aqra Formation. The type section of the Aqra Formation, located in the In Geli shekh Abdul Aziz significant reefal limestone approximately 700 meters thick, including rudists with bitumen and some dolomite content. This formation is widely deposited in the Aqra and Barzan areas, overlying the Bekhme platform stratigraphically, and extends geographically from Bujel to Chia Gara anticlines. Four submicrofacies identified in this reefal limestone are Miliolids packstone, Rudists floatstone, Peloidal grainstone, and Bioclastic foraminifera grainstone. In the Kunamasi area, the reefal limestone appears as thick deposits associated with marl and sandy claystone beds, more than 30 meters thick, and situated above the flysch Tanjero Formation. Key submicrofacies here include Omphalocyclus packstone, Rudists floatstone, and Echinoids grainstone. At the Balakaity section, the reefal limestone consists of a single, thick body exceeding 50 meters in thickness, directly overlying the Tanjero Formation and restricted to the Dar-Alsalam area. The submicrofacies in this section include Foraminifera packstone, Omphalocyclus packstone, and Rudists floatstone. Overall, the microfacies interpretation is the Aqra Formation is deposited as a large platform in inner and middle ramp settings. Conversely, the reefal limestone in the Balakaity and Kunamasi areas appears to be part of submerging islands within the flysch marine environment of the Tanjero Formation during the active Arabia-Eurasian Subduction. Based on depositional context and microfacies analysis can be concluded the reefal limestone in these areas is more likely associated with the Tanjero Formation rather than the Aqra Formation.

## 1. INTRODUCTION

During the Maastrichtian, two distinct facies developed in the Kurdistan depositional basin: (1) the clastic turbidites of the Tanjero Formation and (2) the reefal platform of the Aqra Formation located in northern Kurdistan. In the northeastern part of Kurdistan, numerous reefal bodies are observed intercalated in the upper part of the Tanjero Formation's clastic deposits (Lawa et al, 1998). The thickness, shape, repetition, and extent of these reefal limestone beds vary. Generally, they are found in the shallower parts of the foreland basin. (Lawa, 2018). 1 – 3 meter thick, rudistic limestone layers, forming 4 to 7 repetitive bundles intercalated within the upper clastic sequence of the Tanjero Formation, characterize these limestone beds. These beds ranging from 15 to 20 kilometers in length. In other areas, the reefal limestone appears as a 50-meter-thick elongated body. The main objectives of this article are to study these reefal limestone units from a tectonostratigraphic perspective and compare them with the present-day Aqra Formation. Previous studies have offered various interpretations of this phenomenon, primarily based on stratigraphic approaches without considering tectonic factors. Consequently, they are referred to as the Aqra Limestone Formation (Bellen et al., 1959). Later, following this idea Al-Mehaidi (1975) and Buday (1980) identified carbonate tongues within the Tanjero Formation as part of the Aqra Formation. More recently, Lawa et al. (1998) proposed that these carbonate tongues are inter-finger within the Tanjero Formation and were originally connected to the type section of the Aqra Formation. However, Karim (2004) proposed that it is part of the Tanjero Formation, a mixed carbonate-siliciclastic succession. He believes that variations in sediment influx rates and climate changes led to cyclic variations in the clastic-dominated shelf.

The lower contact of the Aqra Formation with the Bekhme Formation is described as disconformable by the presence of one hardground between them as observed in the Bekhme area. The Aqra Formation in the type section is disconformably overlain by the Kolosh Formation (Al-Karadaghy, 1989). The age of the base of the Kolosh Formation is the Late Paleocene. The Kolosh Formation above the Aqra Formation in the type locality is only 8 m thick.

The lower contact of the Aqra Formation with the Bekhme Formation is characterized as disconformable, marked by a hardground between them, as observed in the Bekhme area (Zebari, 2010). In the type section, the Aqra Formation is disconformably overlain by the Kolosh Formation (Al-Karadaghy, 1989), whose base dates to the Late Paleocene (Al-Qayim, 1989) and (Al-Omari et al., 1989). At the type locality, the Kolosh Formation above the Aqra Formation is only 8 meters thick and represents a transgressive lag beneath the much thicker Khurmala Formation (Lawa,1983) and (Aqrawi et al., 2010).

## 2. MATERIALS AND METHODS

In the studied location, two main methods are used. Firstly, fieldwork involved describing all outcrop phenomena, including bed thickness, color, and other physical characteristics. This also included examining the nature of the contact surfaces between beds, tracing the lateral and vertical changes, and documenting any sedimentary structures. Approximately 100 rock samples are collected from the exposed Aqra Formation. Secondly, about 50 thin sections were prepared from these samples for detailed petrographic analysis using a polarizing microscope.

## 2.1. Location of the study area and General Tectonic setting of Upper Campanian-Maastrichtian sequences

Iraq is located in the Western Asian continent and more particularly in the northern Arabian promontory (Figure 1). The study area is located in the northeastern Kurdistan Region of Iraq, approximately in the center of the Middle East. Fieldwork is conducted in the Zagros Fold and Thrust Belt, specifically in the High Folded Zone (Figure 1). This research focuses on areas where limestone beds are exposed as outcrops, including the type section of the Aqra Formation in the Aqra area. (Figure 1).

### 2.1.1. Azmar-Kunamasi area

This area is in the northeastern limb of the Azmar anticline and the Kunamasi area. The area exists of limestone beds interbedded in the Tanjero Formation (Aziz et al., 2001).

### 2.1.2. Balakaity area

The area occupies the extreme northeastern of the Imbrication Zone, geographically, between Balakaity and Choman areas, near the Dar-Alsalam, Gwizan, and Kawlan villages.

### 2.1.3. Aqra area

The area is in the Aqra anticline, near Aqra City, the area exists a thick thickness (exceeding 700 m thick) of reefal limestone of the Aqra Formation.

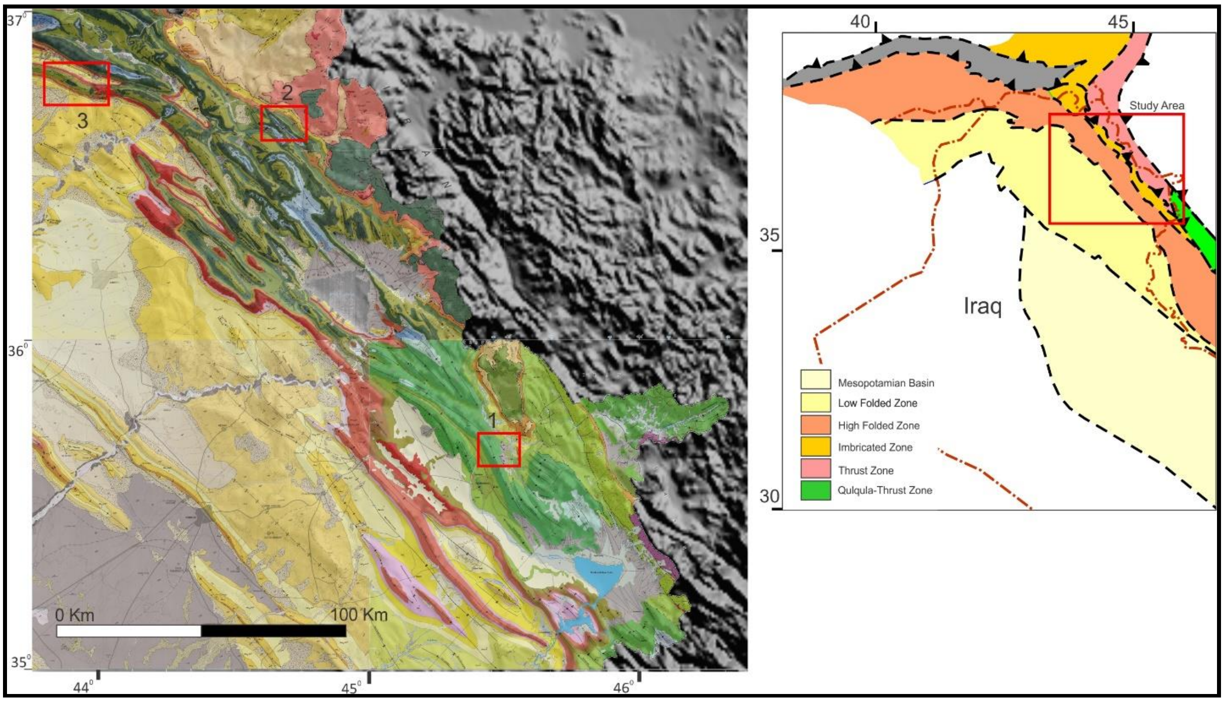


Figure 1: Tectonic subdivision of NW of Zagros Fold and Thrust Belt in Kurdistan Region-Iraq (modified from Aqrawi A. A.M., Gof, J.C., Horbury, A.D. and Sadooni, 2010); (Jassim & Goff, 2006). The geological map from (Sissakian, V.K., 2000) shows the locations of the study area. Three red rectangular are the study areas **1)** the Kunamasi area, **2)** the Balakaity area, and **3)** the Aqra area.

During the Late Cretaceous, the Subduction between the Arabian passive margin and the Eurasian plates in Kurdistan accelerated, leading to the emplacement of ophiolites onto the northern Arabian margin (Numan, 2001). The weight of the ophiolitic thrust sheets on the Arabian Platform created a narrow foreland basin that extended along the northeastern-northern margin of the Arabian Plate. The obducted ophiolites and associated deep-water sediments, mainly radiolarites, were elevated above sea level during the Campanian – Maastrichtian (Alavi, 1994). These materials subsequently eroded and re-deposited in the foredeep basin as flysch deposits, known as the Tanjero Formation in Iraq and the Amiran Formation in Iran. In northern Iraq, the Shiranish and Tanjero formations were deposited in this narrow foreland basin, with the Tanjero Formation representing an early foreland basin. The Tanjero Formation and the underlying Shiranish Formation are sometimes referred to collectively as the initial Zagros Foreland Basin. Within this basin, the Tanjero Formation is thought to have been deposited in the near-shore area, while the Shiranish Formation was deposited in the central part of the basin (Karim & Surdashy, 2005). Aqrawi et al., (2010) noted a gentle inversion at the end of the Cretaceous, which caused widespread partial erosion and an unconformity between Maastrichtian sediments and the base of the overlying Tertiary sequences.

In the north of Kurdistan, the the deposit of Aqra Formation mostly have been deposited in a platform as reefal facies. This formation was first described by Bennett (1945) in Bellen et al. (1959) near Aqra City along the Geli Sheikh Abdul Aziz. The thickness of the Aqra Formation in the type section is about 740m (the base of the formation is not seen), and composed of a reefal limestone complex with msassive rudists-shoal reefs, detrital fore-reef limestone, locally dolomitized, siliceous, and impregnated with Bitumen. The Aqra Formation forms the core of many anticlines in the western High Folded Zone, such as Aqra Dagh, Jebel Gara, Ser Amedia, and Shaikhan anticlines. The Aqra Formation is deposited in the reef, fore reef, and back reef environments. The fossils in the Aqra Formation are abundant, especially the rudists, foraminifera, and other microfossils.

In northern Kurdistan, the Aqra Reefal Platform Formation was deposited. This formation was first described by Bennett (1945) near Aqra City along the Geli Sheikh Abdul Aziz (Bellen et al., 1959) and (Lawa, 1983). The Aqra Formation is 740 meters thick at the type section, although its base is not visible. It consists of a reefal limestone complex with massive rudist shoal reefs, detrital fore-reef limestone, and sections that are locally dolomitized, siliceous, and impregnated with bitumen (Bellen et al., 1959). The Aqra Formation forms the core of many anticlines in the western High Folded Zone, such as Aqra Dagh, Jebel Gara, Ser Amedia, and Shaikhan anticlines. It was deposited in the reef, fore-reef, and back-reef environments (Buday, 1980); (Al-Omari et al., 1989); (Zebari, 2010). The formation is rich in fossils, particularly rudists, foraminifera, and other microfossils (Buday, 1980).

Throughout Kurdistan, the upper part of Tanjero Formation is Maastrichtian, while the lower part ranges from the top of the Maastrichtian to the base of the Campanian (Buday, 1980). Biostratigraphic studies indicate that the entire Shiranish and Tanjero formations generally belong to the Late Campanian-Maastrichtian interval (Kassab, 1976); (Kassab et al., 1986). In the Dokan area, the Tanjero Formation is dated to the late middle Maastrichtian or possibly younger (Aqrawi et al., 2010). The Tanjero Formation was deposited in a foreland basin, near the shore. Most of the sequence was deposited during a regression, primarily due to river and submarine turbidity currents (Karim, 2004); (Karim & Surdashy, 2005). The formation consists of flysch deposits in a rapidly subsiding foredeep basin, situated in front of the emerged lands formed by the thrust sheets obducted onto the southern margin of the Neo-Tethys (Jassim & Goff, 2006); (Aqrawi et al., 2010). It is turbidit facies within Kurdistan Foreland Basin (Lawa, 2018).

**2.2. Reefal Carbonate Lithofacies in the Kunamasi area**

The area lies between the northeastern flank of the Azmar anticline and the allochthonous units. It features several mountain ranges and valleys formed by a succession of anticlines and synclines. Tectonically, this region is located within the High Folded and Imbricated Zones (Fouad, 2016) (Figure 1) and affected by significant tectonic events, particularly in the Late Cretaceous obduction and the evolution of the Mesozoic sedimentary basins, as well as the Neogene folding and thrusting. To the northeast of the Azmar anticline, the Shiranish Formation directly overlies the well-bedded limestone facies of the Kometan Formation. The Shiranish Formation in this area is characterized by rhythmic alternations of marls and marly limestones. In the lower part of the Shiranish Formation, the thickness of marly limestone and marl in each bundle is roughly equal, while in the upper part, the thickness of the marly beds increases in each bundle. Previous studies have dated the Shiranish Formation to the Late Campanian – Maastrichtian based on foraminifera assemblages (Bellen et al., 1959); (Buday, 1980); (Jassim & Goff, 2006).

The Tanjero Formation outcrops extensively in the Tagaran and Qalachwalan areas. In these locations, the formation is characterized by alternating layers of marl and sandstone (Figure 2). The thickness of the Tanjero Formation in these areas can exceed one kilometer. In the upper part of the Tanjero Formation, massive reefal limestones exist as intercalate beds. These reefal limestone beds intercalated inside the Upper part of the Tanjero Formation reach to 15 m thick (Lawa & Qadir, 2023). We observed the repetition of 5 or 10 beds (Figure 2).

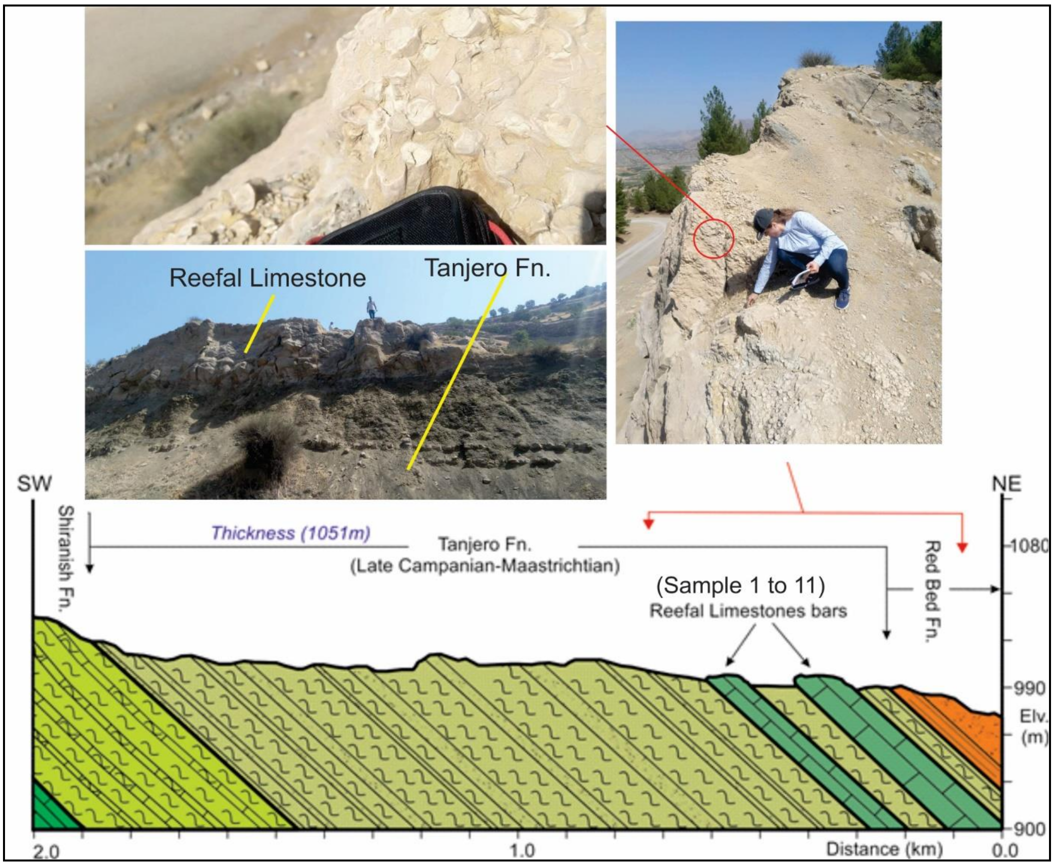


Figure 2: Stratigraphic cross-section showing Campanian – Maastrichtian sequences in the northeastern flank of the Azmar Anticline. The photos are the clear outcrops of the reefal beds stratigraphically located in the Upper part of the Tanjero Formation with Rudist existing in these reefal beds explaining the extremely shallowing.

In the upper section of the Tanjero Formation, there are thick-bedded reefal limestones arranged as intercalated beds (Lawa et al,2017). These reefal limestone beds, which range from three to 5 meters in thickness, are intercalated within the upper part of the Tanjero Formation. We observed the repetition of the reef beds (Figure 2). The thickness and frequency of these reefal limestone beds increase to the northwest of Qalachwalan Town (formerly known as Kunamasi village). Near Kunamasi village in Dolbeshk Valley, the reefal limestone beds have overthrust the Red Bed Series (Karim et al., 2017).

These reefal beds extend approximately 25 kilometers in length, stretching from Qalachwalan Village to the northwest of Kunamasi Village. They consist of well-bedded limestone rich in rudists (Figure 2) and various shell types, indicative of a shallow marine environment. These carbonate beds are intercalated within the clastic sediments of the upper part of the Tanjero Formation.

### 2.3. Maastrichtian Reefal Carbonate Lithofacies in the Balakaity area

The geological setting of the area is complex due to the presence of a series of thrust faults. Despite this, the Red Bed Swiss Group unconformably overlies the Maastrichtian sediments. The thrust zone, or Allochthonous Nappe, constitutes the northeastern part of the area (Figure 3).

In this region, the Tanjero Formation is characterized by alternating shales and sandstones, with some conglomerate layers. A notable feature of the Tanjero Formation is the thick reefal limestone body found in its upper section, with a thickness of approximately 50 meters.

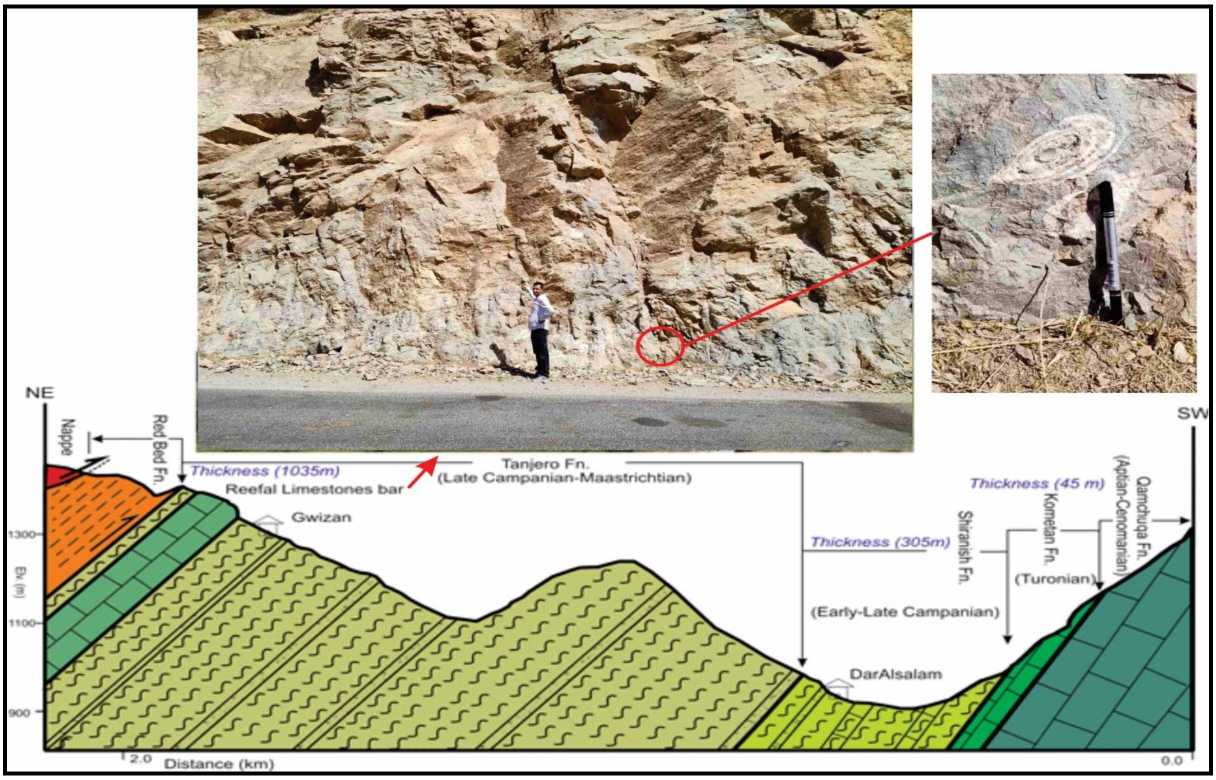


Figure 3: Geology cross-section of Campanian-Maastrichtian sequences in Dar-Alsalam. This section is located between Dar-Alsalam and Gwizan villages. The photo above shows the thick reefal limestone with contains macro fossils.

**2.4. Development of the Aqra reefal limestones Formation**

The Aqra Formation was first described near Aqra City along the Geli Sheikh Abdul Aziz (Bellen et al., 1959) (Figure 4). This formation comprises reefal limestones and includes various facies (Lawa, 1983); (Al-Qayim and Saadallah, 1994). Due to the challenges in distinguishing between the Aqra and Bekhme formations, Buday (1980) used the combined term Bekhme/Aqra. The Aqra Formation is entirely Maastrichtian in age (Al-Omari et al., 1989). At the type section in Aqra City, the formation consists of over 740 meters of shallow reefal limestones, which contain detrital shell debris, particularly rudists, and are impregnated with bitumen (Figure 5). In certain locations, such as the Gali Zanta Gorge near Dinarta, bitumen exists in layers 0.5 to 1 meter thick interbedded with the carbonate of the Aqra Formation (Figure 5).

In the northwest flank of Bekhme, near Nerwe Village (Figure 6), we observed that the marl and limestone of the Shiranish Formation overlie the reefal limestone of the Bekhme Formation. Above this, the clastic sediments of the Tanjero and Kolosh formations are present, with a total thickness of approximately 200 to 300 meters. The 50-meter-thick lagoonal limestones of the Khurmala Formation overlie the Kolosh Formation. The stratigraphic sequence in this section mirrors that of the Bekhme Gorge, with no occurrence of Aqra Formation facies.

In the gorge upstream from Qalat Village, situated on the southwestern flank of the Bekhme Anticline (Figure 6), the Shiranish Formation, with a thickness of approximately 5 – 10 meters, overlays the reefal limestones of the Bekhme Formation. This reefal limestone sequence, about 50 meters thick, is intercalated between the Shiranish and Tanjero formations (Figure 7). Lithologically, it closely resembles. In this section, the Kolosh Formation's clastic sediments overlie the Tanjero Formation, while the Khurmala Formation's lagoonal limestones cap the Kolosh Formation (Figure 6).

Near the Bjil villages (Figure 6), also on the southwestern flank of the Bekhme Anticline, the reefal limestones of the Aqra Formation are prominently exposed (Figure 8). Here, the Aqra Formation comprises a substantial sequence of limestone resting on the Bekhme Formation. The lagoonal limestones of the Khurmala Formation directly overlie the Aqra Formation's reefal limestones without any angular unconformity. Above the Khurmala Formation, the Cenozoic successions, including the Gercus, Pila Spi, and Fatha formations, are clearly visible (Figure 8).

The Gali Zanta Gorge, which cuts through the eastern limb of the Aqra Anticline (Figure 6), features a well-exposed Late Cretaceous carbonate sequence. However, distinguishing between the carbonates of the Bekhme and Aqra formations is challenging (Figure 9). In the northern part of the gorge, near Dinarta Town, clastic beds with some limestone layers overlie the reefal limestone beds of the Aqra Formation.

Figure 4: The limestone cliffs located behind Aqra City are part of the Aqra Formation.

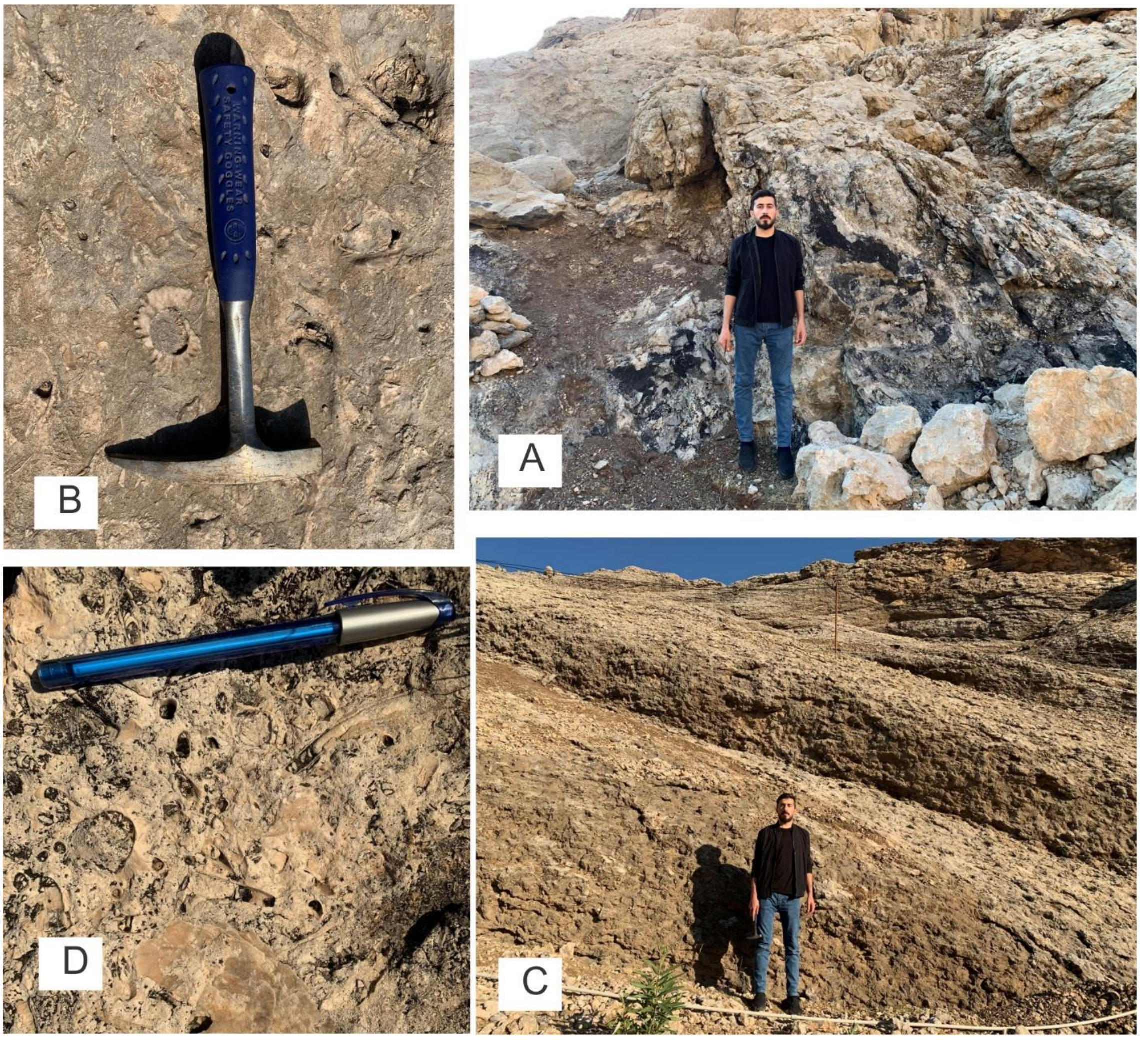


Figure 5: A) Bitumen occurrences within the Aqra Formation. B) Rudistic limestones of the Aqra Formation near Aqra City. C) Reefal limestone from the upper part of the Aqra Formation. D) Bitumen impregnation within the reefal limestones (near the Aqra area).


Figure 6: Google Maps illustrates the locations of four areas studied to examine stratigraphic successions, understand lateral continuities, and investigate the development of the Aqra Formation.


Figure 7: Late Cretaceous-Cenozoic successions in Qalat Valley in the southwestern flank of the Pirat (Bekhme) anticline.

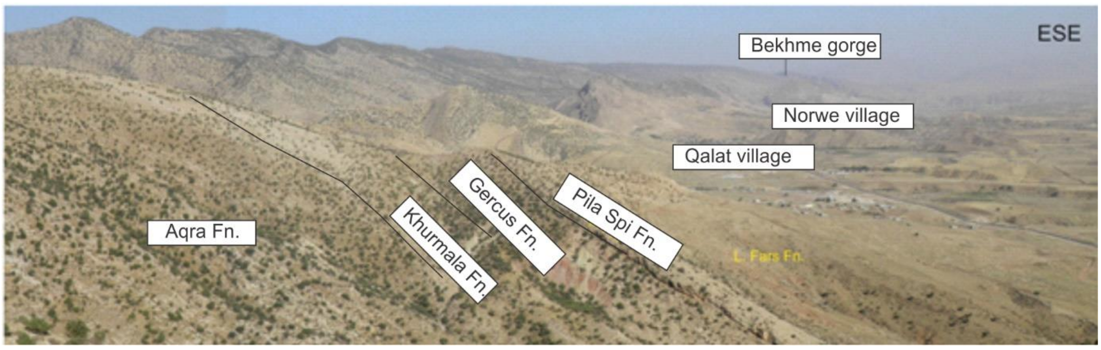


Figure 8: Late Cretaceous-Cenozoic succession enechelon plunging between Bekhme and Aqra anticlines. The photo was shot from the Bujel area directly to the southwestern flank of the Bekhme Anticline.

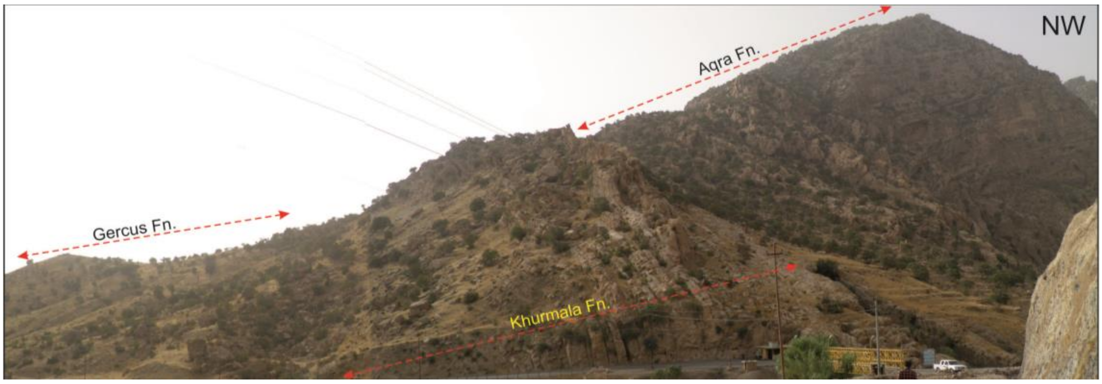


Figure 9: In the Gali Zanta Gorge, the thick lagoonal limestones of the Khurmala Formation lie atop the reefal limestones of the Aqra Formation.

The results from these four locations suggest that during the Early to Late Campanian period, the Bekhme-Barzan-Aqra region was submerged (Al-Ameri & Lawa, 1986), forming a large reefal platform associated with the Bekhme Formation. This reef facies had an extensive geographical reach, evident from the thick and massive limestones and dolomitic limestones, exceeding 300 meters in thickness, which overlie the Qamchuqa Formation. The majority of the area is covered by clastic sediments of the Tanjero Formation, while the Aqra area (including the Aqra Anticline and extending northwest) submerges under a well-developed shallow reefal environment of the Aqra Formation. The transition between these facies (Aqra and Tanjero formations) occurred in the restricted zone between the Aqra and Bekhme anticlines (Al-Ameri & Lawa, 1986). The Aqra Formation, which overlies the Bekhme Formation, consists of a thick sequence of reefal limestones containing various large bivalve shells, notably rudists.

Based on the correlation between the Aqra type section and the Balakaity and Kunamasi sections (Figure 10), it can be concluded that these reefal beds correspond to the upper part of the Aqra Formation that formed during the Late Maastrichtian period. These reefal bed limestones are considered part of the Tanjero Formation and resulted from compristional faulting that created horsts and graben during the Maastrichtian (Ahmed et al., 2016). In contrast, the Aqra Formation represents a substantial platform that developed on top of the Campanian Bekhme platform.

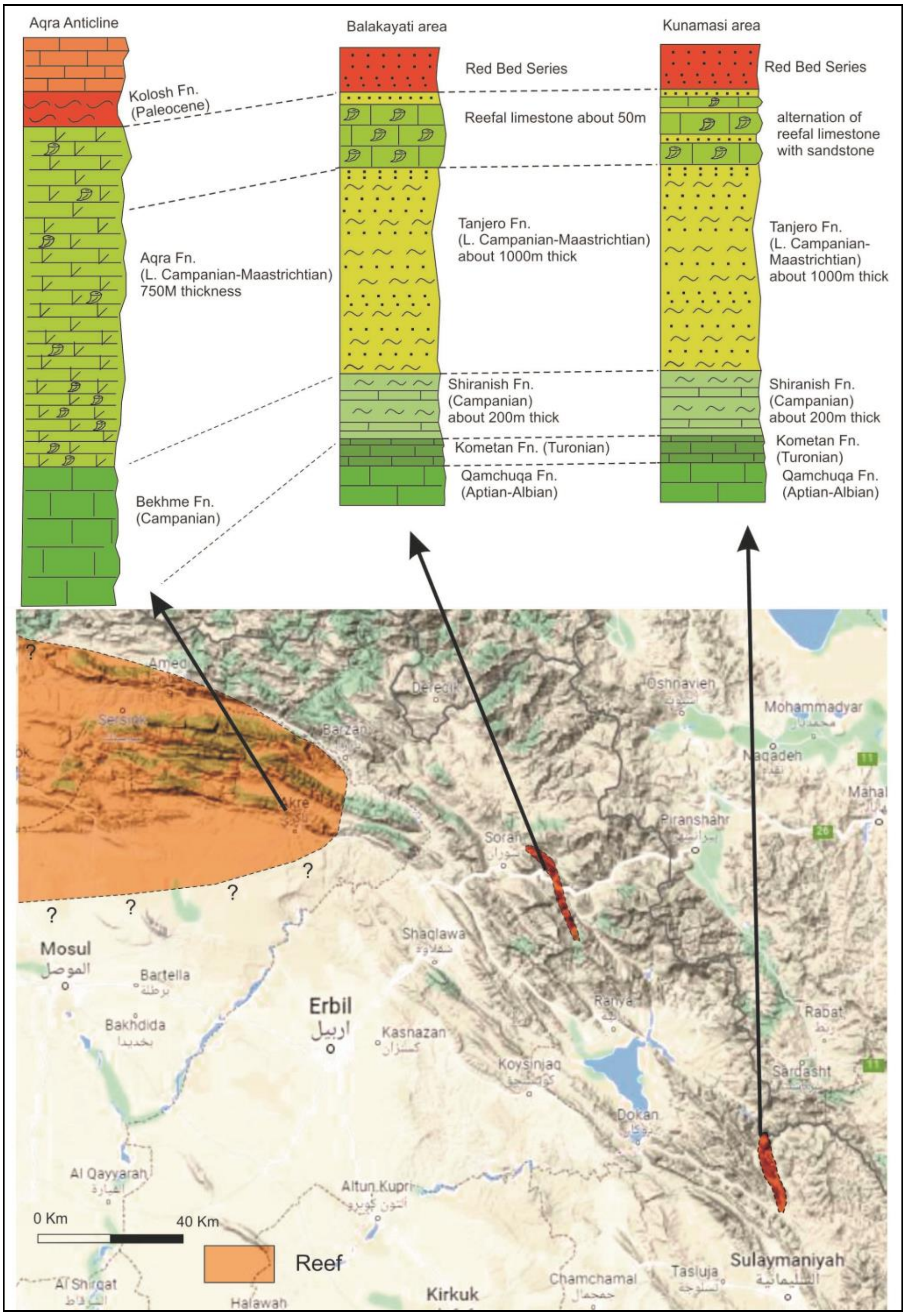


Figure 10: Lithofacies correlation of Late Cretaceous formations among Aqra, Balakaiaty, and Kunamasi sections. The orange represents the distribution of reefs during Late Maastrichtian in Kurdistan Region-North Iraq.

## 3. MICROFACIES ANALYSIS

Three main microfacies have been recorded and subdivided into several submicrofacies, depending on the percentage of the grains and groundmass types (Table 1):

Table 1: explain main and sub-microfacies, composition, diagenesis, and depositional environment found in the Aqra Formation and the reefal limestones in the upper part of Tanjero Formation (Aqra type Section, Kunamasi and Balakaiaty sections).

| Main microfacies | Sub-microfacies | Composition of sub-microfacies and percentages | Diagenesis processes | Depositional environment |
|---|---|---|---|---|
| Boundstone | Rudstone floatstone | Rudist fragments of Pelecypods and coral (20%), Miliolids (5%), Orbitoids (2%), Siderolites (1%), Rotaliids (2%), Loftusia (1%), Bolivians (1%), Dictyoconus (2%), Omphalocyclus (3%), Echinoids (6%), Valvulinds (4%), Bryozoa (1%), gastropods (2%), and green algae (2%). | Dissolution, cementation, and compaction | Reef (middle ramp) |
| Grainstone | Echinoids grainstone | Echinoids (40%), Omphalocyclus (2%), Fissoelphidium (1%), Valvulinids (3%), Rotaliids (2%), Loftusia (2%), green algae (2%), and fragments of Pelecypods (4%). | Dissolution, cementation, and micritization | Sand shoal (inner ramp) |
| | Bioclastic foraminifera grainstone | Bioclastic (30%), Loftusia (3%), Miliolids (7%), Orbitoids (5%), Dicyclina (2%), Valvulinids (3%), and green algae (1%). | Micritization and recrystallization | Sand shoal (inner ramp) |
| | Peloidal grainstone | Peloids (35%), Miliolids (8%), Peneroplids (1%), Orbitoids (1%), bioclastic of Echinoids (2%), Gastropods (1%), and Pelecypods (1%). | Micritization, compaction, and recrystallization | Sand shoal (inner ramp) |
| Packstone | Omphalocyclus packstone | Omphalocyclus (20%) Loftusia (8%), Orbitoids (7%), Siderolites (3%), Rotaliids (3%), Goupillaudina (1%), Salpingoporella (2%), Fissoelphidium (1%), Nummofollotia (2%), Miliolids (1%), Textularia (1%), Valvulinids (2%), Echinoids (3%), gastropods (1%), and fragments of pelecypods (3%). | Recrystallization, dissolution, compaction, and stylolites | Platform margin or forslope (outer ramp) |
| | Foraminifera packstone | Loftusia (8%), Orbitoids (7%), Siderolites (4%), Omphalocyclus (10%), Rotaliids (4%), fragments of Pelecypods (3%), crinoids spins (5%), and extra-clast grains (3%). | Dissolution, cementation, and micritization | Platform margin or forslope (outer ramp) |
| | Miliolids packstone | Miliolids (*Quinqueloculina* sp., *Pyrgo* sp., and *Triloculina* sp.) (25%), valvulinids (4%), gastropoda (4%), Pelecypods (3%), peneroplis (2%), bryozoan (1%), green alge (1%), bolivina (1%), and orbitoids (2%). | Dissolution, cementation, compaction, and micritization | restricted lagoon (inner ramp) |

### 3.1. Miliolids packstone submicrofacies

These submicrofacies is recognized in the lower part of the Aqra Formation at the Aqra section. Miliolids are the common grains in this submicrofacies and are associated with Orbitoids, Valvulinids, Peneroplids, green algae, gastropods, bryozoan, and pelecypods (Figures 11a, b, c, and d). These grains are scattered in dark gray micrite. This microfacies contain high bitumen and reddish-to-brown iron oxide. Micritization, dissolution, cementation, and compaction are major processes observed.

### 3.1.1. Interpretation

the highly diverse and greater number of Miliolids species are indicated deposit in the lagoon or back reef environments in tropical shallow, clean waters of normal salinity (Brasier, 1975). According to (Ghose, 1977), divers of Miliolids and Rotaliids dominate and point to protective environments in shoal back reef lakes and protected sections of reef platforms, but they never point to forereef environments. Micritic limestone with a high concentration of Miliolids, Valvulinids, and Peneroplids is thought to be found in lagoonal environments or back reef deposits ((Bismuth & Bonnefous, 1981) in (Lawa, 1983).

**3.2. Foraminifera packstone submicrofacies**

Submicrofacies type recorded in the reefal beds at the Balakaity section. The majority content of skeletal grains is diverse of Loftusia, Orbitoids, Siderolites, Omphalocyclus, Rotaliids, fragments of pelecypods, crinoids' spins, and extra-clast grains (Figure 11e, f, and g). All these grains are scattered in the micritic groundmass. Diagenesis processes observed in this submicrofacies are Micritization, dissolution, and cementation.

**3.2.1. Interpretation**

large foraminifera associations, such as Rotaliids, Siderolites, Orbitoids, and Loftusia are good indicators of outer shelf environment (Vecchio & Hottinger, 2007), and high energy zone and strong water action in typical reef-flank facies (Flugel, 2004). The characterized submicrofacies when correlated with standard microfacies, are represented for slope environment (Wilson, 1975) and (Flugel, 2010), and recorded from distal middle ramp to proximal outer ramp settings.

**3.3. Omphalocyclus packstone submicrofacies**

Submicrofacies type recorded in the upper beds of reefal limestone at Kunamasi and Balakaity sections. The main components of this submicrofacies are represented by Omphalocyclus. Other components like Loftusia, Orbitoids, Siderolites, Rotaliids, Goupillaudina, Salpingoporella, Fissoelphidium, Nummofollotia, Miliolids, Textularia, Valvulinids, Echinoids, gastropods and fragments of pelecypods (Figures 11h, I, j, k, L, and m). All skeletal fauna is distributed in the micrite groundmass. The extra-clasts of chert, quartz, igneous, and metamorphic rock fragments with reddish-brown iron oxides are irregularly distributed in the groundmass. Almost all the clasts are poorly sorted, angular to subangular with various-size clasts. Recrystallization, dissolution, compaction, and stylolites are common diagenetic features. The dissolution process affected the groundmass and grains and produced moldic and vug porosity within this submicrofacies.

**3.3.1. Interpretation**

The presentation of Omphalocyclus, Orbitoids, and Siderolites in this submicrofacies indicated a high energy zone and strong water action in atypical reef flank facies (Flugel, 2010), and fore reef environment (Bou Dagher, M.K. and Fadel, 2008). The co-existence of Omphalocyclus, Orbitoids, Rotaliids, and Loftusia are good indicators of forereef environments (Ali, 2010), and are reflected as outer shelf environments (Zebari, 2010). Additionally, the presence of extra-clast grains in the facies indicates the final stage of carbonate platform evolution before transitioning back to a clastic-dominated environment (Catuneanu, 2006).

**3.4. Peloidal grainstone submicrofacies**

This submicrofacies are observed in the upper part of the formation in the Aqra section. The common grains are Peloids. The occurrence of Miliolids, Peneroplids, Orbitoids, bioclastic Echinoids, Gastropods, and Pelecypods is rare (Figures 11n and 12o). All these grains are embedded within sparry calcite cement. The groundmass of this microfacies is rich with bituminous and reddish to brown iron oxide materials. The common diagenesis processes observed are recrystallization, compaction, and micritization.

### 3.4.1. Interpretation

This submicrofacies of grainstone with sparry calcite cement and low micrite indicated the deposit in a high-energy shoal environment (Wilson, 1975) and (Flugel, 2010). The faunal assemblage of Miliolids, Peneroplids, Orbitoids, bioclastic Echinoids, Gastropods, and Pelecypods characterizes the inner of the platform (Corda & Brandano, 2003) and indication in deposit in a high-energy sand shoals or bed setting (Tucker, 2001); and (Yazdani, 2014).

### 3.5. Bioclastic foraminifera grainstone submicrofacies

This submicrofacies is identified in the upper part of the formation at the Aqra section. It comprises bioclastic materials and a diverse array of benthic foraminifera, including Loftusia, Miliolids, Orbitoids, Dicyclina, Valvulinids, and green algae (Figures 12a-h). Some grains are surrounded by micrite envelopes, causing them to appear undermined. All grains are dispersed within sparry calcite cement. Common processes observed in this submicrofacies include micritization, compaction, and recrystallization.

### 3.5.1. Interpretation

The presence of bioclastic grains in this submicrofacies suggests a shelf lagoon back reef characterized by open circulation and calm waters below the wave (Flugel, 2010). The co-existence of bioclastic and Loftusia, Miliolids, Orbitoids, Dicyclina, Valvulinids, and green algae was indicated in the back reef area (Ali, 2010).

### 3.6. Echinoids grainstone submicrofacies

This submicrofacies is recognized in the middle part of the formation at the Kunamasi section. The major constituents of this submicrofacies are represented by fragments of echinoids with less amount of Omphalocyclus, Fissoelphidium, Valvulinids, Rotaliids, Loftusia, green algae, fragments of pelecypods and Rudists (Figures 12i, j, and k). All types of particles are embedded in coarse crystalline calcite cement. Groundmass and skeletal grains affect dissolution, cementation, and micritization.

### 3.6.1. Interpretation

The properties of this submicrofacies indicate deposits in high-energy back-reef environments (Flugel, 2010). The occurrences of a high number of echinoids in sparry calcite indicate moderate to high energy shallow water environment (Wilson, 1975) and (Flugel, 2010). Moreover, Beavington-Penney & Racey (2004) that the existence of pelecypods, echinoids, in marine cement indicates a high-energy environment.

### 3.7. Rudist floatstone submicrofacies

This submicrofacies were found in the lower reefal beds of the upper Tanjero Formation at the Kunamasi section but at the Aqra and Balakaity sections recognized in the middle part of the Aqra formation. This submicrofacies is mostly composed of rudist fragments, pelecypods, coral, and a size of more than 2mm at the Kunamasi section. While at the Aqra and Balakaity sections the composition differs which consists of rudist fragments of pelecypods and corals and association with Miliolids, Orbitoids, Siderolites, Rotaliids, Loftusia, Bolivians, Dictyoconus, Omphalocyclus, Echinoids, Valvulinds, Bryozoa, gastropods, and green algae (Figure 13). All these particles are scattered in the micritic groundmass. The main diagenesis types that affect the grains and groundmass are dissolution, cementation, and compaction.

### 3.7.1. Interpretation

The great diversity of organisms’ properties within this microfacies with a concentration of encrusting organisms indicate deposits in the slope toward the toe of slope environments. It represents the reef flank beds and the wind-facing side against the open sea. It is distinguished by the existence of large-sized reef detritus (Schlager, W., 2002). Also, the presence of Orbitoids, Siderolites, Rotaliids, Loftusia, Bolivians, Dictyoconus, and Omphalocyclus in this microfacies indicates forereef environment (Al-dulaimi & Abdallah, 2019).

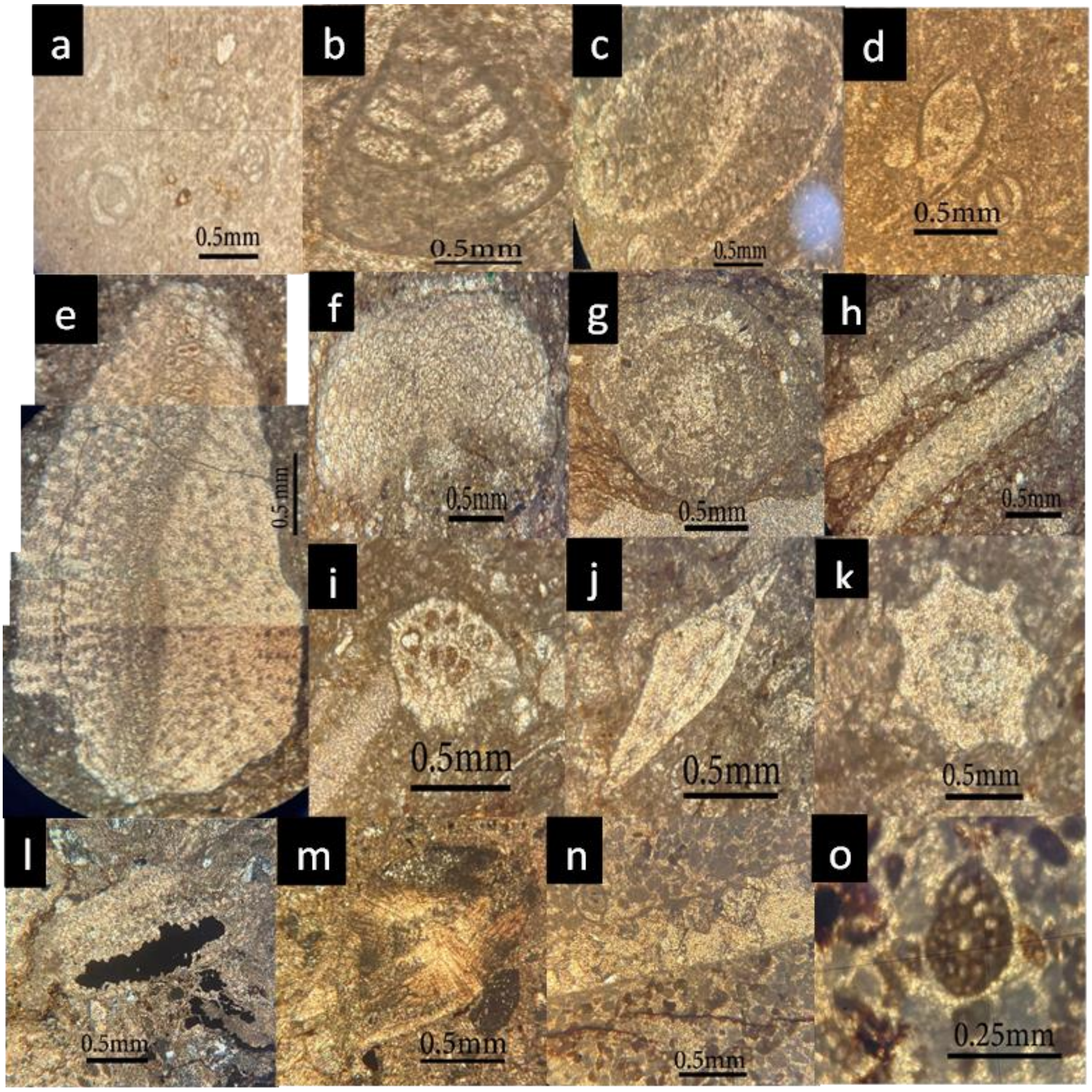


Figure 11: **a)** Miliolids packstone, S. no.1, Aqra section, ppl; **b)** Bolivina, S. no.2, Aqra section, ppl; **c)** gastropods fragment, S. no.3, Aqra section, ppl; **d)** pelecypods fragment, S. no.4, Aqra section, ppl; **e)** *Orbitoides* sp. S. no.1, Balakaity section, ppl; **f)** *Omphalocyclus* sp. S. no.1, Balakaity section, ppl; **g)** *Loftusia* sp. S. no.1, Balakaity section, ppl; **h)** Omphalocyclus packstone S. no.6, Balakaity section, ppl; **i)** *Rotaliids* sp. S. no.6, Balakaity section, ppl; **j)** *Nummofollotia* sp. S. no.10, Balakaity section, ppl; **k)** *Salpingoporella* sp. S. no.10, Balakaity section, ppl; **l)** dissolution processes S. no.7, Kunamasi section, xp; **m)** *Fissoelphidium operculiferm* SMOUT, S. no.7, Kunamasi section, xp; **n)** Peloidal grainstone, S. no.14, Aqra section, ppl; and **o)** *Peneroplis* sp., S. no.14, Aqra section, ppl.

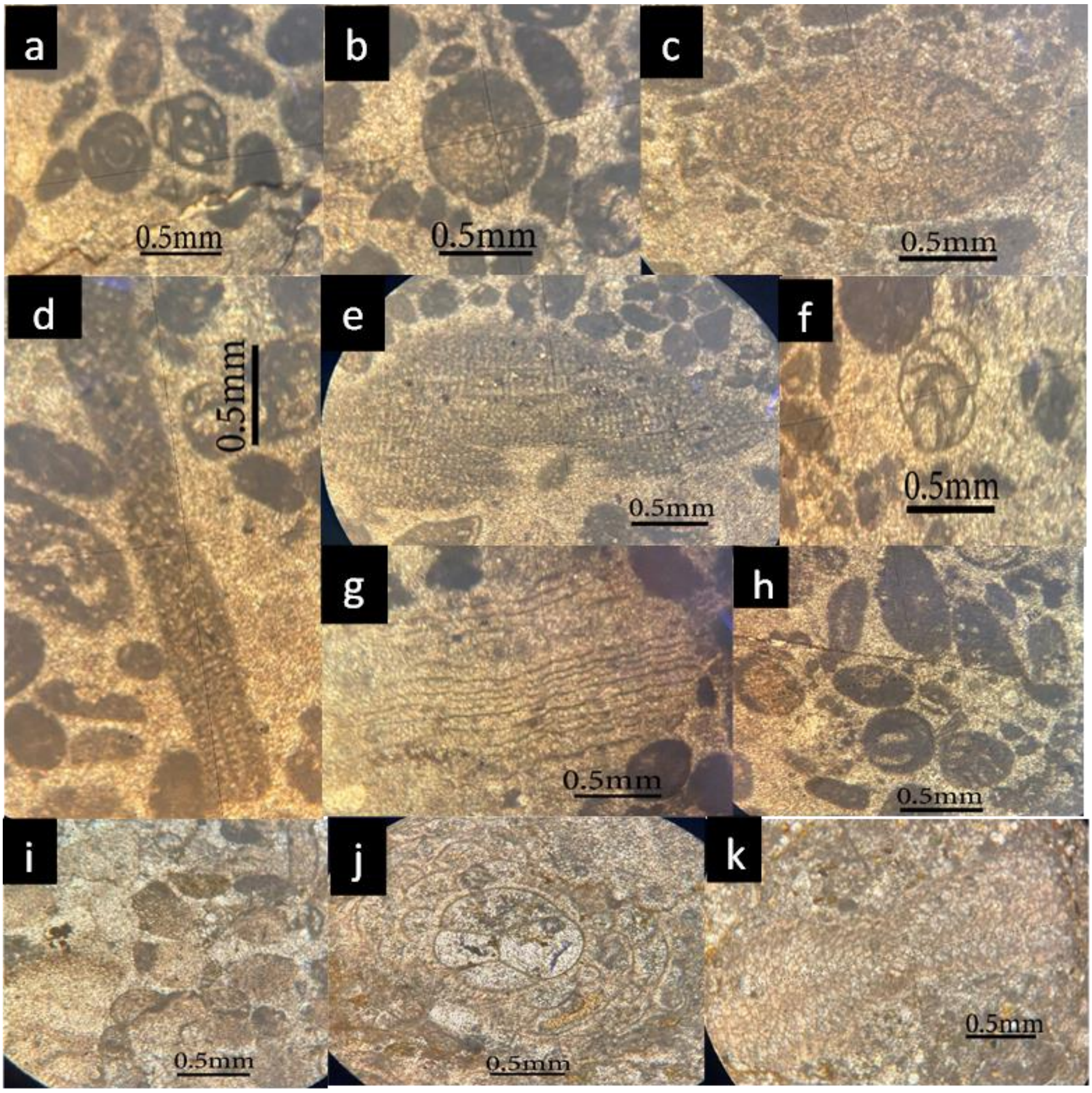


Figure 12: **a)** Miliolids within Bioclastic foraminifera grainstone, S. no.18, Aqra section, ppl; **b)** *Omphalocyclus cideensis* sp. nov., S. no.18, Aqra section, ppl; **c)** *Orbitoides* sp., S. no.18, Aqra section, ppl; **d)** *Pesedorbitolina cf marthae* (DOUVILLE) S. no.18, Aqra section, ppl; **e)** *Pesedorbitolina* sp., S. no.18, Aqra section, ppl; **f)** Valvulinids S. no.18, Aqra section, ppl; **g)** green algae S. no.18, Aqra section, ppl; **h)** Bioclastic foraminifera grainstone, S. no.18, Aqra section, ppl; **i)** Echinoids grainstone S. no.3, Kunamasi section, xp; **j)** *Omphalocyclus anatoliensis* sp. nov., S. no.4, Kunamasi section, xp; and **k)** *Omphalocyclus macropora* LAMARCK. S. no.5, Kunamasi section, xp.

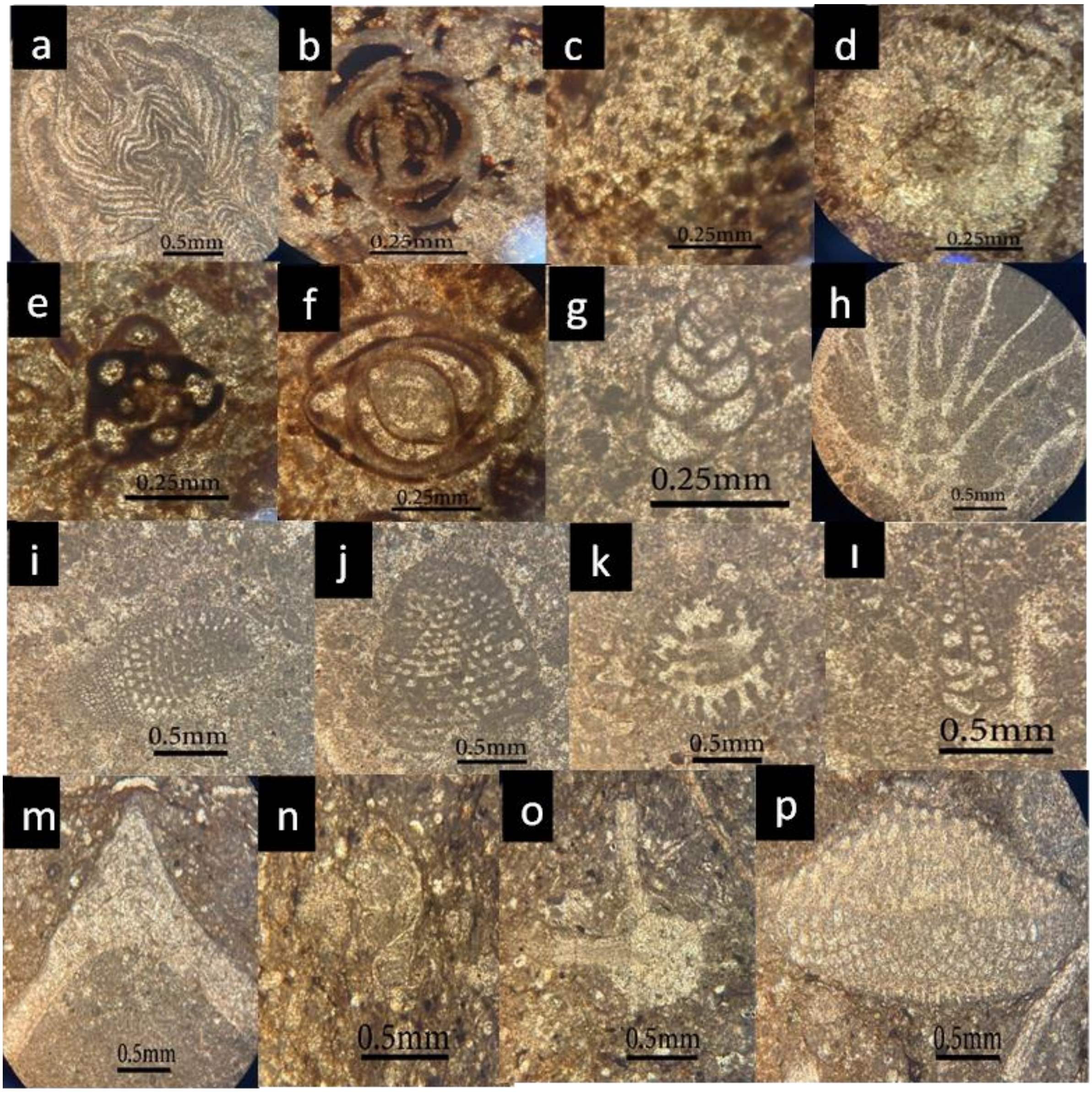


Figure 13: **a)** Rudist floatstone S. no.3, Kunamasi section, ppl; **b)** Miliolids sp., S. no.8, Aqra section, xp; **c)** Bryozoa S. no.10, Aqra section, xp; **d)** green algae S. no.10, Aqra section, ppl; **e)** Triloculina sp., S. no.10, Aqra section, xp; **f)** Miliolids sp., S. no.10, Aqra section, xp; **g)** Bolivina S. no.12, Aqra section, ppl; **h)** Coral S. no.12, Aqra section, ppl; **i)** *Dictyoconus Bakhtiari* sp. S. no.12, Aqra section, ppl; **j)** *Dictyoconus* sp. S. no.13, Aqra section, ppl; **k)** *Dictyoconus* sp. S. no.13, Aqra section, ppl; **l)** Valvulinids S. no.12, Aqra section, ppl; **m)** Rudist (pelecypods) S. no.4, Balakaity section, ppl; **n)** gastropods fragment, S. no.5, Balakaity section, ppl; **o)** Sidero calcispher S. no.4, Balakaity section, ppl; and **p)** *Orbitoides* sp., S. no.5, Balakaity section, ppl.

## 4. DEPOSITIONAL ENVIRONMENT

Lagoons, shoals, reefs, and proximal slope settings include several carbonate systems found in marine environments (Tucker, 2008). The most dominant microfacies are predominantly found in the inner ramp (lagoon and sand shoal environments) and the middle ramp (reef and slope environments) (Burchette & Wright, 1992). The submicrofacies types of the Aqra Formation deposited in the inner ramp setting (lagoon and sand shoal) within the studied sections include miliolid packstone, Foraminiferal packstone, peloidal grainstone, echinoid grainstone, and bioclastic foraminiferal grainstone. The dominated miliolids with micritic groundmass are common in shallow restricted low turbulence water (Lawa, 1983), (Geel, 2000), and (Safari et al., 2020). Also, miliolids packstone submicrofacies are compared with standard microfacies, revealing that this submicrofacies were deposited in restricted shelf lagoon environments (Wilson, 1975) and (Flugel, 2010). Omphalocyclus packstone and Foraminifera packstone submicrofacies most often deposit in settings between the distal middle ramp and proximal outer ramp that were calm, low energy hydrodynamic, and deep normal saline water (Buxton & Pedley, 1989). Many skeletal grains such as Omphalocyclus sp. which occur in the packstone microfacies are indicative of the outer platform environment (Gaddo, 1959). Peloidal grainstone and echinoid grainstone are abundant in the microfacies of the upper and middle parts of the Aqra Formation in Balakaity sections, respectively deposited in a high-energy shoal of the outer Platform margin (Flugel, 2010). The occurrence of peloids, echinoids, gastropods, and pelecypods clearly shows a high wave energy environment (Beavington-Penney & Racey, 2004). The co-existence of bioclasts with a diversity of large benthonic foraminifera in bioclastic foraminifera grainstone submicrofacies almost indicates the deposition in high-energy sand shoals or bed environments (Tucker, 2001); and (Yazdani, 2014) specifically indicates inner ramp environment. Other types of microfacies are distributed in the middle (reef and fore reef environments) ramps such as Rudist floatstone submicrofacies. Rudist floatstone submicrofacies represent the reef character, where the rudists form the main reef framework. The restricted and random distribution of the rudists indicates most probably a reef of local extension reflecting a submarine high land, which is genetically a secular warred environment. Such an element from a complementary system through a certain time extent, mainly intercontinental movement. The reef proper which is built by rudists is of biostrome type (Embry & Corp, 2015), (Bein, 1976) at the Kunamasi section. While this microfacies in the Aqra and Balakaity sections are represented forereef properties (Wilson, 1975) and (Flugel, 2010). The co-existence of a large fragment of bivalve, corals, Miliolids, Orbitoids, Siderolites, Rotaliids, Loftusia, Bolivians, Dictyoconus, Omphalocyclus, Echinoids, Valvulinds, Bryozoa, gastropods, and green algae indicates middle to proximal outer ramp setting (Al-Dulaimi, 2011).

From all petrographic, facies, and texture evidence, it is concluded that the reefal beds in the Upper Tanjero Formation (Aqra beds) at Kunamasi section were deposited in the inner to the middle ramp and proximal outer ramp setting but at Balakaity section were deposited in the middle to proximal outer ramp setting. However, the Aqra Formation in the Aqra section is mostly deposited in the inner and middle ramp settings.

## 5. CONCLUSION

- This study agreed with the previous studies that the reefal limestones lithofacies exist in the upper Tanjero Formation in the Kunamasi and Balakaity areas, and in the upper part of the Aqra Formation, they are deposited at the same period.
- The Aqra Formation represents an extensive reefal platform that developed as a continuation of the Bekhme Platform. However, the reefal limestone beds in the Balakaity

and Kunamasi areas deposit on small, locally submerged islands within the depositional environment of the Tanjero Formation and related to Aqra Formation.

- Based on the petrographic study, three major microfacies are identified and further divided into seven submicrofacies: miliolid packstone, foraminiferal packstone, Omphalocyclus packstone, peloidal grainstone, echinoid grainstone, bioclastic foraminiferal grainstone, and rudist floatstone.
- The submicrofacies of the Aqra Formation at the Kunamasi section deposit in settings ranging from the inner to the middle ramp and proximal outer ramp. In contrast, the Balakaity section's submicrofacies deposit in the middle to proximal outer ramp settings. The Aqra section deposits primarily in the inner ramp setting, with some deposits extending into the middle ramp setting.

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