Unconformity and Paleokarst in the Lower Part of the Qamchuqa Formation; An Example from the Arabian Carbonate Platform in the Zagros Belt NE Iraq

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Abstract
Northeastern Arabian Plate Margin is now part of the Zagros Collisional belt and extends nearly parallel to the Iraq-Iran border. The margin comprised, during the Early Cretaceous, of the Arabian Carbonate Platform which is poorly explored. This margin consists of thick carbonate succession and separates the Neo-Tethys Ocean (present Sanandaj-Sirjan Zone) from the Arabian Plate interior. The carbonate succession, as the Qamchuqa and Balambo formations, consists of more than 600 m of dolomite and reefal limestone. The present study focused on records and discussions of evidence of unconformity and paleokarst (UaPK) inside the Arabian platform in northeast Iraq. The study recorded this evidence inside the lower part of the Qamchuqa Formation and the pieces of evidence include limestone conglomerate, placeo-solution cavities, erosional surfaces, widespread coarse and fine grain detrital limestones, hardground, extensive burrows of Thalassiniodes, and mineralization. The solution cavities shaped a complex network, developed inside fine-grain limestone and filled with yellow to brown ooid and detrital limestones. Most of these features are observable over more than 500 km² in the Sulaymaniyah and traceable inside gorges and valley sides. Toward the north and northeast of the studied area, the unconformity changes to correlative conformity in the Neo-Tethys basin of the studied area where the sediments consist of laminated and graded detrital limestone (packstone-wackstone) and are deposited as a thick succession of calciturbidite that stratigraphically designated as the Balambo Formation. The result of the present study debates the previously claimed unconformities and uncovers many processes and features of the Northeastern Arabian Carbonate Platform Margin. Additionally, it reveals tectonic and paleogeographic settings of the Arabian Plate Margin that have application in searches for oil and better reconsideration of the geologic setting of the Zagros Belt in the future.

Keywords: Unconformity; Paleokarst; Qamchuqa Formation; Balambo Formation; Early Cretaceous Arabian Platform; Erosional surface

1. Introduction

In Iraq, the Early Cretaceous Arabian platform consists of a thick succession of reefal limestones and dolomites that occur as extensive outcrops or subsurface sections. This occurrence includes most of Iraq and some parts of southwestern Iran, the Arabian Gulf, and Saudi Arabia where it has given different stratigraphic names. The Qamchuqa, Suaiba, and Mauddud formations are the main DOI: 10.46717/igi.55.2A.9Ms-2022-07-25
constructing units of the platform during the Early Cretaceous. These units are an important reservoir for oil in the Middle East (Alsharhan and Nairn, 1997; Jassim and Goff, 2006; Rashid et al., 2020). The studied area constitutes a part of the northeastern Arabian Platform Margin, which needs more detail highlighting and exploration than before. In the studied area, the reefal Qamchuqa, deep basinal Balambo, and Kometan formations occur, among these three formations, the present study focused on the first one, which has thick and relatively well-exposed outcrops in the areas around Dokan, Ranyia, Surdash, and Bingird Towns in addition to northwest Sulaimani city (Fig.1). On the Margin, the reefal Qamchuqa Formation changes to deep marine Balambo Formation toward the north and northeast (Dunnington, 1958; Bellen et al., 1959; Karim, 2020).

Bellen et al. (1959) defined in detail the Qamchuqa Formation (Hautervian-Albian) and measured its thickness to be about 650 meters of alternation of well-bedded to massive, grey-colored dolomite and light grey limestone. The latter authors named the Qamchuqa Formation after the name of Qamchuqa village located directly to the southwest of the type section, about 7 km east of Dokan town. According to Furst (1970) (cited in Buday, 1980), the Upper and the Lower Qamchuqa Formation are renamed as Mauddud and Shuaiba formations, respectively in central and southern Iraq. The same author stated that, in Iran, the correlative formations are the Dariyan (Aptian) and the Albian part of the Sarvak Formation of the East Zagros Mountains.

Ameen (2008), Karim and Ameen (2008), Karim and Taha (2009), Karim and Khanaqa (2016), Al-Qayim et al. (2016), and Karim and Khanaqa (2017) studied stratigraphy, sedimentology environments, tectonics, and oil aspect of the Qamchuqa Formation. While Karim and Ameen (2009), Al-Zaidy et al. (2013), and Daoud (2021) studies microfacies analysis of the formation in different sections in Kirkuk and Sulaymaniyah, therefore the present study will not repeat the facies investigation.

In its type section, the formation comprised of alternation of thick beds of dolomite and limestone. The limestone units are relatively thin-bedded and have light color (white weathered color) while dolomite ones are thick, massive, and have a dark brown color. The stratigraphic position of these beds is not constant across the studied area; the same thing is true for the numbers of dolomite and limestone beds since the number of each one varies between 0-3 groups of beds. Ameen, (2008) divided the type section (650 m thick) into four units of dolomite and the same number of limestones while Zewe Gorge is totally built of one unit of limestone.

Recently Ghafur et al. (2020) studied nearly the same characteristic of the Qamchuqa Formation on the southwest limb of the Piramagroon-Sara anticline and found an unconformity between Kometan and Qamchuqa formations by which the upper part of the latter formation was removed during the Early Cretaceous. The present study aims to uncover the characteristics, features, and processes of the Qamchuqa Formation, as a unit of the Arabian Northeast Platform during the Early Cretaceous in Sulaymaniyah. Among these issues, the study focused mainly on unconformity and paleokarst inside the formation.

2. Location and Geology of the Area

The studied area includes the northern and northwestern parts of the Sulaymaniyah in northeastern Iraq. The area is comprised of more than 500 km² that embrace towns such as Ranyia, Bingird, Dokan, Surdash, Gapelon, and Mergapan. We indicated the location of the area as a northwest-southeast rectangle whereas its four corners are located, clockwise from north, at 36° 21’ 42” N, 44° 46’ 19.60” E; 35° 42’ 29” N, 45° 33’ 37.50” E; 35° 36’ 37” N, 45° 17’ 16”E; 36° 10’ 30” N, 44° 36’ 09.5” E (Fig.1). Dunnington (1958) described the area as Folded Zone while Buday (1980) considered it a High Folded Zone. Structurally, the area consists of chains of large anticlines and synclines which form high mountains and deep valleys respectively. The cores of most anticlines are eroded along their axes and
form subsequent valleys and gorges while the consequent or obsequent valleys dissected the anticline limbs. These folds trend northwest-southeast and have the general trend of the Zagros orogenic belt.

The Main Zagros Thrust Fault is passing directly to the northeast of the studied area and according to Koyi (1988), the area was part of the northeastern passive margin of the Arabian Plate during the Early and Middle Cretaceous on which a shallow carbonate platform was blooming, which was designated as the Qamchuqa Formation. During Early Cretaceous, the margin was bordered by the deep Neo-Tethys Sea to the north and northeast in which the Balambo Formation was depositing. The Qamchuqa Formation is the time equivalent and lateral facies change of the latter form in which Karim (2020) found more than 200 m of laminated and graded detrital limestones with conglomerates. He considered these limestones as calciturbidite that was sourced from erosion of the early Cretaceous platform. The area consists of many high amplitude anticlines in which soft sediments of Sarmord and Jurassic rocks are exposed while their inner and outer arcs are comprised of Qamchuqa and Kometan formations. Complementary synclines separate the anticlines and relatively soft sediments such as Shiranish and Tanjero formations occupy their troughs (Fig.1). The main anticlines are Piramagroon, Daban, Qaywan, Sara, Sarmord-Sargelu, Haladin-Yakhsamar, Kosrat, Asos, and Makok anticlines. Karim et al. (2020) studied some of these anticlines structurally and concluded that the axes of small folds (parasitic folds) deviate (shift) about 20 degrees northward from the axes of the main folds of the Zagros Belt. They attributed this deviation to facies change in the area in addition to the effect of the Mawat Core Complex.

### Table 1. The studied sections

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of section</th>
<th>Latitudes</th>
<th>Longitudes</th>
<th>No.</th>
<th>Name of sections</th>
<th>Latitudes</th>
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<tbody>
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<td>Kewa Rash</td>
<td>35° 16′ 54″</td>
<td>44° 52′ 40″</td>
<td>6</td>
<td>Sargelu Gorge</td>
<td>35° 52′ 34.77″</td>
<td>45° 09′ 59.48″</td>
</tr>
<tr>
<td>2</td>
<td>Ranyia Gorge</td>
<td>35° 16′ 54″</td>
<td>44° 52′ 40″</td>
<td>7</td>
<td>Babo mountain</td>
<td>35° 51′ 21.45″</td>
<td>45° 11′ 42.98″</td>
</tr>
<tr>
<td>3</td>
<td>Asos Mountain</td>
<td>35° 04′ 40.14″</td>
<td>45° 04′ 30.35″</td>
<td>8</td>
<td>Tabben Gorge</td>
<td>35° 50′ 14″</td>
<td>45° 06′ 52″</td>
</tr>
<tr>
<td>4</td>
<td>Qamchuqa Gorge</td>
<td>35° 54′ 04.13″</td>
<td>45° 01′ 17.46″</td>
<td>9</td>
<td>Zewe Gorge</td>
<td>35° 44′ 12″</td>
<td>45° 14′ 24″</td>
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<tr>
<td>5</td>
<td>Sekanyian Gorge</td>
<td>35° 53′ 02.31″</td>
<td>45° 08′ 42.47″</td>
<td>10</td>
<td>Qaywan Mountain</td>
<td>35° 42′ 34.94″</td>
<td>45° 24′ 15.70″ E</td>
</tr>
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### 3. Materials and Methods

The main materials of the study are the lower part of the reefal Qamchuqa Formation as a unit of the Early Cretaceous Arabian Platform and its time equivalent deep marine Balambo Formation in which a thick succession of detrital limestone, conglomerate, erosional surfaces, and paleokarst are found. The finding of these materials and features are dependent on the fieldworks in the studied area where outcrops of the above two units are well exposed and observable in deep valleys, gorges, and along mountainsides. During the fieldwork, we inspected more than 11 locations (sections) (Fig.2) for exploration of the features and textures of UaPK with an X10 hand lens and suitable samples are prepared for cutting 150 thin sections for petrographic studies. Additionally, our study reviewed all the previous works of literature and discussed their data objectively, and compared it with our results.
4. Results

We found the relics of the unconformity in 10 different localities inside deep gorges and valleys of the studied area. The unconformities manifested by a conglomerate, erosional surfaces, hardground, intense thalassiniodes burrows, and mineralization, and among these localities, the paleokarst are present in the four of them. In all sections of the Qamchuqa Formation, only the Zewe gorge is barren of signals of unconformity and its lithology consists mainly of fine detrital limestone which is barren of fossils. The evidence of subaerial erosion is more expressive in the limestone than in the dolomite successions of the Qamchuqa Formation. The rareness of the unconformity signals in the dolomite units is due to dolomitization and destruction of original textures and structures by crystallization. We found most of the clear pieces of evidence of unconformity always at the top of the fine-grain limestone beds (mudstone or wackestone) inside soft intervals at the top of the lower part of the Qamchuqa Formation (Figs. 3 and 4).
Fig. 2. Google Terrain Image shows the location of the inspected sections

4.1. Babo Mountain Unconformity and Paleokarst (UaPK)

The Babo Mountain is located between Sargelu and Haladin village northeast of Surdash Town where the lower part of the Qamchuqa Formation is comprised of three parts. The first is about 80 meters thick and consists of massive algal–coral limestone with some intervals of detrital and oolitic limestones Ameen and Karim (2009) and Karim (2020). Above this limestone, there are about 10 meters of pale yellow and bedded oolitic limestone in which we found the UaPK features on the mountain for the first time at 35° 51' 21.45" N, 45° 11' 42.98" E. Three signals of the UaPK between algal–coral and oolitic limestones beds are observable, the first is the presence of sharp but irregular contact between the two limestones. The light grey fine-grain limestone with coral and algae (at the base) changes rapidly to oolitic limestone succession at the top. The contact between the two limestones is sharp but undulating and erosional with irregular surfaces. The Irregular surface is underlined by spotty and spongy limestone that has a thickness of about one meter. The spongy limestone appears as a network of interconnecting paths or passages making an erosional maze filled with oolitic limestone (Fig. 4). These limestone mazes are interpreted as karstic solution cavities during regression and subaerial erosion which are later followed by sea transgression and filling the cavities with oolitic limestone (Fig. 5). In addition to the solution cavity, solution limestone breccia and conglomerate occurs on the unconformity surface and
the clasts are angular and derived from underlying fine-grain limestone (Fig. 5). The oolitic limestone occurs mostly as packstone on the top of the unconformity and has about 10 m thickness. The ooids are a superficial type characterized by few laminae around a nucleus of calcium carbonate lithoclast or bioclast. All the above characteristics and features are valid for the Sargelu Gorge which is located 1 km north of Sargelu village at 35° 52' 34.77" N, 45° 09' 59.48" E. However, there are a few minor differences; the first is the thickness of the ooid changes to 10 cm instead of 10 m while the conglomerate has less thickness and is finer in grain sizes (granule conglomerate) than the Babo mountain section (Figs. 6 and 7). The second is a composition of the lower part that is not pure limestone but intermittently intervened by dolomite and dolomitic limestone. The third is changing the facies of the lower part from algal-coral bindstone and mudstone to mostly lithoclast-bioclast packstone and wackestone.

Fig. 3. (a) Babo mountain photographed from Daban mountain shows the location of the UaPK (white line); (b) a close-up photo of the soft interval on the Babo mountain where we found the best signals of the karstification and unconformity.

Fig.4. (a) the vertical section shows solution cavities filled with oolitic limestone on the Babo mountain; (b) a close-up photo of the fresh surface of the previous photo shows sharp contact between host rock and filling ooids.

Fig. 5. (a) thin section of karstified fine-grain detrital limestone (dark grey) and solution cavities filled with badly sorted oolitic limestone (light grey); (b) Oolitic and detrital limestones over the karstified limestone, the superficial ooids are observable, normal light, s.no. 3b, c) Hand specimen of the karstified limestone of Babo Mountain under normal light shows solution cavities filled with oolitic limestone.
**Fig. 6.** (a) A vertical section of the karstified bed of Qamchuqa Formation in Sargelu gorge in which the solution cavities, in dark grey limestone, are filled with milky detrital limestone; (b) A limestone conglomerate of the same gorge.

**Fig. 7.** (a) A limestone conglomerate of Sargelu gorge section in hand specimen and (b) thin section of the same conglomerate under normal light, s.no. 2s

4.2. **Qamchuqa Gorge Section**

This Gorge is located 6 km east of the Dokan Town and about 50 km northwest of Sulaimani city where Bellen et al. (1959) described the Qamchuqa Formation for the first time and designated it as a type section. Ameen (2008) divided its 650 m thickness into four units of dolomite and the same number of limestones units alternating with each other in the Gorge. The lower part has a thickness of 70 m and consists of a sequence of thick beds mainly of detrital limestone with subsidiary coral boundstone, rudist-gastropod floatstone, and mudstone. In the gorge, the signals of unconformity are located at 35° 54' 04.13" N, 45° 01' 17.46" E, and consist of erosional surfaces, mineralization, lenticular beds and hardgrounds in the lower part of the formation, while the present study did not find karst and conglomerates in this part (Figs. 8 and 9). In the gorge, several irregular erosional surfaces are present with the occurrence of hardground mineralization (chert nodules). One of the erosional surfaces is well expressed which most possibly represents significant unconformity on which paleokarstification occurred on other sections such as Babo mountain, Sargelu Gorge, and Asos Mountain sections. The hardgrounds have irregular shapes in vertical sections and are 5-30 cm thick consisting of light brown dolomite highlighted in light grey limestone background and mostly underlain and overlain by bioturbation (Fig. 9). The crowding of chert nodules in certain horizons is detectable on the hummocky bedding surface in the lower part of the formation near the unconformity. The chert nodules exhibit different morphologies with sizes ranging from 1-5 cm in height and 5-20 cm in diameter in some cases showing branching (Fig. 10).

Most possibly, these chert nodules are developed after seawater regression and subaerial exposure during which a part of the platform is saturated with freshwater promoting limestone dissolution and precipitation of silica. The Kewa Rash Mountain section is very similar to the Qamchuqa Gorge in characteristics and is located directly to the north of Ranya town at 35° 16' 54" N and 44° 52' 40" E. It
contains erosional surfaces, hardgrounds, and chert nodules in its lower part. The only difference is the occurrence of chert nodules along more than ten horizons in the interval of 5 meters (Fig.11). They are larger than those of Qamchuqa Gorge and in some cases coalesce laterally forming ribbons about two meters long. These horizons are in the same stratigraphic position of the bioturbation and hardground of the Asos mountain section.

![Fig. 8.](image1)

**Fig. 8.** a vertical section of the lower part of the Qamchuqa Formation manifesting two erosional surfaces with reworked sediments inside Qamchuqa gorge, 1km south of Sarmord village, at 35° 54'07.01” N and 45° 01’18.26” E.

![Fig. 9.](image2)

**Fig. 9.** The lower part of Qamchuqa Gorge manifests, (a) hardground, bioturbation, and erosional surface; (b) an erosional surface underlying a bioturbated horizon

![Fig. 10.](image3)

**Fig. 10.** (a) Lenticular bed of reworked detrital dolomitic limestone underlain by erosional surface in the lower part of Qamchuqa Formation at the northeastern outlet of the Qamchuqa Gorge; (b) Erosional surface crowded by different sizes and shapes of chert nodules at the same locality of the photo
Fig. 11. More than 10 successive horizons of chert nodules (5 m thick) in the Lower part of the Qamchuqa Formation in Kewa Rash Section at 1km northwest of Ranyia town.

4.3. Asos Mountain Section

This section is located on the northeastern part of Asos Mountain (anticline) at the northern boundary of Dokan reservoir. This section is very similar to that of Babo mountain intern of the paleokarst, erosional surface, and oolitic limestones except for the presence of 5 meters interval of bedded and laminated bioturbation and hardground (Fig.12). Opposite to the bioturbation of other sections, the bioturbation of the Asos section is mostly horizontal which most possibly resulted either from current or biological reworking as an omission surface (Fig.13). These bioturbations are associated with thin beds of dolomitized conglomerate (floatstone facies) in which the clasts manifest badly sorting and have ragged boundaries (Fig. 13c). Another difference with other sections is the occurrence of oncoid floatstone below the karstified horizon and they consist of a nucleus surrounded by many concentric laminae of fine-grain dark limestone and their diameters range 1 to 3cm. Their shapes manifest different distortions, which may be due to compaction or later current activity especially the oncoids developed in high-energy time and near the unconformity surface (Fig.13b). Karim et al. (2010) and Khanaqa et al. (2013) record large oncoids, with diameters ranging between 4 to 10 cm, on a recent lake coastal area (intertidal area), therefore, it is possible that those of Asos mountain belong to the similar environment as concerned to depth and energy.

In most cases, the bioturbation appears as elongated dark patches of coarse grain dolomite and they have a length of 4- 8 cm and thickness of 1-3cm while on outcrops sections they have positive relieves (Fig.9). A single trace has a cylindrical or irregular shape and is mostly characterized by both necking and widening along its length. When the shapes of these traces are compared to the pieces of literature such as Sheehan and Schiebelbein (1984) (Figs. 2-5); Ekdal et al. (2012) and Gingars et al. (2012), (Fig.3), they belong to Thalassinoides traces. They attributed dolomitization of their sediment fill to more permeable traces-related sediments relative to the host rocks, which act as privilege zones to the circulation of seawater. According to the above authors, Thalassinoides are burrow networks consisting of horizontal and branching tubes connected to the surface by vertical or inclined shafts. The swellings take place at points of branching of the burrows, they are normally asymmetrical (eccentric) and sediments fill results from active filling by the burrowing organisms. The tubes are 5–20 mm in diameter and smooth-walled.

Although most of the previous literature interpreted Thalassinoides as crustaceans burrow however only small gastropods and pelecypods are associated with present traces while their host rocks are barren of crustaceans. Therefore, in Qamchuqa Formation, we think that they most possibly the borrowing activity of the former organisms, not the latter ones. In the Sekaniyan Gorge, the strata of the Qamchuqa
Formation are vertical and manifest two horizons of the Thalassinoides and hardground, the first one is about 20m above the base and one meter thick. The second is located at the top of the lower part and 4-meter-thick (Fig. 14).

**Fig. 12.** limestones of the lower part of the Qamchuqa Formation in Asos mountain section contain, (a) partially karstified fine-grain limestone (dark) in which the cavities filled with detrital and oolitic limestone; (b) oncoids floatstone directly under the karstified horizons at 35° 04′0.14″ N and 45° 04′30.35″ E

**Fig. 13.** (a) 5 m of bioturbated succession crowded with *Thalassinoides* burrows in the lower part of the Qamchuqa Formation; (b) Close-up photo of the rectangular area; (c) thin section photo of the hardground indicated by the white arrow

### 4.4. Signals of Unconformity on the Slope and in the Basin of the Early Cretaceous

The facies map Dunnington (1958); Buday (1980); Jassim and Goof (2006) depicted lateral facies changes of the platform (Qamchuqa Formation) toward north and northeast to deep marine ones of Balambo Formation. Karim (2020) surveyed the outcrops between the two formations and concluded shedding of the voluminous amount of fine and coarse detrital limestones, as thick succession, from the platform into the basin of the latter formation. He stated the involvement of limestone conglomerate and sand-sized limestone clasts in the buildup of succession with the presence of interbed pelagic marls. The latter author found these sediment as channelized debris flow, graded and cross-bedded packstone limestone which considered them as sediment of calciturbidite derived from Qamchuqa Formation and deposited in the basin after bypassing the slope. Ali et al. (2020) discussed and refuted the record of calciturbidite deposition in the Balambo Formation while the present study confirms its occurrence and found new localities where it is clearly observable. These localities are such as 35° 42′34.34″ N and...
45° 24' 15.91" E, 35° 44' 39.10" N, 45° 24' 33.05''E and 35° 30' 37.91" N, 45° 52' 00.95''E where Bouma sequences are observable which include graded bedding, lamination, basal rip-up clasts, and debris flow conglomerates (Figs.15 and 16).

The signals of reworking and calciturbidite are widespread at 60 km away from the platform, where the autochthonous (pelagic limestones) and allochthonous (platform derived) lithologies are distinguishable. The sand- and gravel-sized clasts are dark grey in color while the host rocks (pelagite) are light grey (Fig. 15a) and their thickness is more than 200 m. The recorded thickness, clast types, stratigraphic position, structures, and textures in the Balambo Formation agree with pieces of evidence found in the Qamchuqa Formation for the occurrence of the unconformity and paleokarst. We recorded the evidence in both formations in the same stratigraphic position, which coincides with their lower part. In the platform, the UaPk occurs at the 60-100 m thickness from the base of the Qamchuqa Formation while in Balambo Formation, the conglomerate and Bouma sequence are observable at 30-50 m. These two thicknesses agree with the rate of sedimentation of the platform and basin modeled by Hunt et al. (2002) for the famous Capitan Reef in New Mexico, USA. The age of the unconformity is more or less uncertain due to the high energy of the lower part and the barrenness of index fossils. However, when the age of Hauterivian-Albian by Bellen et al. (1959) and the thickness of the Qamchuqa Formation are considered, the age of Late Barremian is most possible. The duration of the unconformity is more than

**Fig. 14.** (a) Thalassinoides in the Sekaniyan Gorge where the strata of the Qamchuqa Formation are nearly vertical; (b) Thalassinoides and hardground in close-up view, (c) detail of branching and swelling Thalassinoides burrows at 35° 53' 02. 31"N and 45° 08' 42.47"E.
half a million years which is estimated based on the thickness of the conglomerate and coarse limestone detritus succession which is more than 30 m thick, this succession is derived from the subaerial unconformity. While the rest of the Balambo Formation especially the middle part consists of fine detritus succession, which, according to Karim (2020), are not related to the unconformity but derived from normal wave and current erosional actions on the shallow parts of the platform reef.

**Fig. 15.** (a) part of 3 m conglomerate inside Balambo Formation on the Qaywan mountain at 35° 42’ 34.94” N, 45° 24’ 15.70”E; (b) erosional surface and rip-up clasts in the same latter locality, c) graded bedding and rip-up clasts in the same latter locality.

**Fig. 16.** Units of the Bouma sequence inside Balambo Formation on the Qaywan mountain at 35° 42’ 34.94” N, 45° 24’ 15.70”E

### 4.5. Tectonism and Environment of Deposition

Previously, Ameen and Karim (2009); Karim (2020) considered the environment of the formation as a reefal setting on which different facies of boundstone, bufflestone, grainstone, wackestone, and mudstone are deposited in its sub-environments (Fig. 17). The platform of the Qamchuqa Formation, at least in the studied area, was a rimmed shelf and it descended steeply northeastward to the deep basin of the Balambo Formation (Fig. 18). This platform was developed at the expense of the deep marine hemipelagic Sarmord Formation after its tectonic uplift as a flexure fore bulge. According to Karim and Taha (2009) underthrusting of the northeastern edge of the oceanic part of the Arabian Plate under the Iranian Plate with subsequent tectonic loading had uplifted the studied area.

The acceleration of the uplift was continuous up to emerge of the reef crest of the Qamchuqa Formation to subaerial erosion and karstification due to the wet climate with possible torrential rainfalls. These processes developed the type one sequence boundary during Late Barremian and it is possible
that it contained type two and three boundaries too since several horizons with the erosional surface, hardground and bioturbation are observable. Daoud (2021) studied microfacies of the upper part of the Qamchuqa Formation and observed detrital limestone in the form of lithoclast and bioclasts packstone-grainstone with ooids as main facies. Karim (2020) and Mirza et al. (2021) depicted the Platform as the western and southwestern boundary of the gigantic Neo-Tethys Ocean. Therefore, deposition, reef growth, and erosion were common processes on the platform while the erosion product mostly bypassed its attached slope and was deposited in the basin (Fig. 18). This newly formed island, in the mid of the giant Neo-Tethys Sea, imposed certain properties on the unconformity. The first one is the absence of paleosol and calcrite due to the washing and reworking of the weathered materials by tide waves and heavy climate storms. A second is prone of the reef to tsunami and hurricanes by which limestone conglomerate had transported about 60 km far from platform edge to the deep basin of Balambo Formation (Karim, 2020).

**Fig. 17.** Paleographic and environment setting of Early Cretaceous Arabian Platform (Qamchuqa Formation) with plotted facies (Ameen and Karim, 2009)

**Fig. 18.** Environmental and paleogeographic model of the lower part of the Qamchuqa Formation during Early Cretaceous (Late Barremian)
5. Discussion

According to our field works, there are three proven subaerial erosional unconformities in Northern Iraq, the first one is the present unconformity and associated paleokarst inside the Lower part of the Qamchuqa Formation. The second one is found inside the Tanjero Formation during which 300 m of chert conglomerate was deposited during Campanian-Maastrichtian (Karim et al., 2011). The third is Upper Oligocene unconformity and associated paleokarst inside carbonate succession of Kirkuk Group (Karim et al., 2020). The latter article recorded well-developed paleokarst in the boundary between the High and Low Folded Zones in Northwestern Iraq. The chert (siliciclastic) conglomerate filled the Oligocene solution cavities and was associated with paleosol. Whereas the present one is associated with limestone conglomerate, hardgrounds, oolitic and detrital limestone, *Thalassinoides* burrows in addition to paleokarst. According to Strasser (2015), the dropping of sea level below the pre-existing sediment surface results in erosion and cementation of the soft sediments in the fresh-water lens and later will stabilize the sediments, and karstified them. He stated recognizing of karstified surface as the first sequence boundary and the sea-level rise leads to flooding of the karst surface. He added that in this time, water depth is ideal to produce ooid dunes, shifted by tidal currents.

5.1. Previously Recorded Unconformity on the Arabian Northeastern Plate Margin

As mentioned before, we found unconformity in the lower part of the Qamchuqa Formation on the platform interior (Fig. 19). Recently Ghafur et al. (2020) indicated unconformity in the upper part of the Qamchuqa Formation in the Piramagrun-Dokan area. However, our pieces of evidence from the field and lab results contradict the presence of findings of the latter authors. Therefore, the present study tries to reconsider stratigraphic and sedimentologic claims attributed to the Qamchuqa Formation in the latter area. This area is very important for the present authors since it is part of our county and the area is a place where BS and MSc students are trained geologically for tens of years. The published article of the latter authors discussed sedimentology and stratigraphy of the Early Cretaceous Qamchuqa Formation as a stratigraphic unit of the Northeastern Arabian Plate Margin. In the article, the authors recorded about 4-30 million years of the unconformity between Qamchuqa and Kometan Formations on which the sediments of Aptian, Albian, and Cenomanian are missed at the upper part of the Formation.

These authors established this unconformity neither on-field signals nor on index fossils biozonation. Their proof for the unconformity is based only on circumstance shreds of evidence, not direct ones, and depended on subjective and biased ideas in the discussion. We discuss, in this section, objectively the claimed unconformity and other results of Ghafur et al. (2020). Our field and laboratory evidence refute the presence of an unconformity between Qamchuqa and Kometan Formations (Upper part of Qamchuqa Formation). The stratigraphic interval of the claimed unconformity is barren of conglomerates, paleosol, paleokarst, erosion relief, erosional surface, and mineralization.

5.2. Zewe Gorge

The most concerning issue in Ghafur et al. (2020) is their establishment of the 30-million-year unconformity between the Kometan Formation (Turonian-Campanian) and the Qamchuqa Formation (Hauterivian-Cenomanian) in the Zewe Gorge at the southeastern part of Piramagroon anticline (Fig. 20a). They indicated sediment erosion of Aptian, Albian, and Cenomanian on this unconformity during later ages below the Kometan Formation (Fig. 21). In this figure, they indicated increasing time of the unconformity laterally toward the southeast where it increased from 7 to 13, 25, and 30 million years at the Qamchuqa, Jasana, Tabben gorges, and Zewe gorges (or sections) respectively. Their maps show that this increase occurred along 27 km, which represents the length of the line on which they sampled four sections along the southwestern lower limbs of the latter anticline. In their article, there is not any justification or proof for this unconformity and it is not clear if the unconformity is based on biozonation.
or isotope aging. They did not mention the presence of conglomerates, erosional surfaces, mineralization, and paleosols.

The revisiting and checking of the Zewe Gorge manifested the absence of any unconformities even on the scale of one million years (Fig. 21a). In this gorge, the thickness of the Qamchuqa Formation is more than 170-meters and consists of an alternation of the partially recrystallized mudstone and fine grain detrital dolomitic limestone that is located between the Sarmord and Kometan Formation at the base and the top. The accurate inspection of the present study, meter by meter, failed to find any signals of 30 ma erosional unconformity mentioned in the later article. The lithology and staking pattern of the Qamchuqa Formation at the Zewe gorge are similar to the middle part of the Qamchuqa Gorge photographed and described by the latter authors in Fig. 5 and present Fig. 20b. They titled this figure as “The strata consist of relatively well-indurated, more resistant lime-mudstone layers interbedded with recessive, somewhat argillaceous mudstone layers with a thickness of nearly is 80 m”, this description is also valid for the Zewe Gorge but with more thickness (170 m) and not know why they ignored this high thickness and considered it as an unconformity.

In the Zewe section, similar to the Qamchuqa Gore section, they considered the time span of the Gulneri and Dokan Formations (Cenomanian) as unconformity too. Conversely, the present study found the three formations in the gorges by lateral field tracing from areas where their occurrence is provable paleontologically. These areas such as the Dokan Dam site and Harmetool anticline (near Sutga village) where a Qamchuqa, Dokan, and Gulneri formation is traceable to Zewe gorge laterally. Karim and Khanaqa (2017) mapped the area, including, the Zewe gorge, and proved the presence of both Gulneri and Qamchuqa Formations. The detailed study of Al-Qayim et al. (2016) did not record any unconformity in the gorge, on the contrary, they recorded about 300 m thick of limestone and marly limestone between Sarmord and Kometan Formations but they considered this thickness as interfingering of Kometan and Balambo Formation.

Fig. 19. (a) The stratigraphic column of the Babo mountain of the present study shows the location unconformity at the Lower Part of Qamchuqa Formation; (b) column of Zewe gorge section which contains only an erosional surface. It does not show the unconformities recorded by Ghafr et al. (2020) in the Fig. 21.
Fig. 20. (a) The outlet of Zewe Gorge shows 70 m of Kometan Formation in addition to Gulneri, Dokan, and Qamchuqa Formations. (b) Photo of part of the lower division of Qamchuqa Formation by Ghafur et al. (2020) who described it as a “succession of well-bedded lime mudstone interbedded with argillaceous mudstone layers with a thickness of nearly is 80 m”, it can be seen that this part is similar to the Qamchuqa Formation in the Zewe Gorge.

Fig. 21. Stratigraphic column of by Ghafur et al. (2020) on which the indicated 30 million years unconformity in Zewe gorge (the age of unconformity added by red fonts in the present study)

5.3. The Previous Increase in the Time Span of the Unconformity from the Platform Interior to the Adjacent Basin

The most surprising issue in the work of Ghafur et al. (2020) is the dramatic time span increase of their unconformity from the platform interior to the slope of the adjacent deep basin (Fig.21). This increase contradicts the principle of unconformity which is always characterized by a decrease of its amplitude toward the deeper part of the basin. This decrease is observable in the models of sequence stratigraphy by Catuneanu (2002, 2006). The increase of the erosional gap toward the southeast is opposite to their paleogeographic map (their Fig.15). This map shows the deepening of the basin toward the southeast and the facies shifted to Balambo Formation (slope and basinal facies) (Fig.23). It is clear that the latter author’s unconformity contradicts their adapted map (taken from Jassim and Goof, 2006) due to the increase in the unconformity amplitude in the basinal facies. In the title of their Fig. 15, they oppose their selves by confessing that the land is toward the west while their widest gap of the unconformity is located at the southeast at Zewe Gorge where they claimed that the whole Qamchuqa, Gulneri, and Dokan formations are missed and has a period of about 30 m.y. (Fig. 21). The southeast deepening is also confirmed by the facies map of the Dunnington (1958), according to the location of
the studied area of Ghafur et al. (2020) the Zewe section is located inside the “basinal marl, globigerin-al-radiolarian facies” of the former author (Figs. 22 and 23).

Unfortunately, the latter article does not justify this inconsistency of deep basin and wide gap of unconformity and decreases of the gap toward the platform interior (Qamchuqa gorge section). They claimed that the gap decreases in the Qamchuqa Gorge to 7 m.y in the shallowest section according to their map in Fig. 22 (see it below) and that of the Dunnington (1958, Fig. 23). Karim (2020) studied the area of the Zewe gorge in detail and proved the occurrence of the Qamchuqa Formation (or its time equivalent deep facies Balambo Formation). He did not find large unconformities in the transitional zone between the latter two formations near the latter gorge. Ghafur et al. (2020) recorded a minimum gap of 7 million years in Qamchuqa Gorge and mentioned and modeled the missing of both Gulneri and Dokan formations but revisiting and checking the gorge several times proved the presence of the two formations in the gorge (Fig. 24). Lateral tracing, by authors, proved the presence of the two formations from Dokan town (where their type localities are located) to the Qamchuqa Gorge which is only 8 km far from their type section. The facies of the Gulneri Formation laterally change from marly limestone to limestone.

Fig. 22. Paleogeographic facies distribution of Iraq by Ghafur et al. (2020) during the Aptian (a) and Albian (b). Their studied area is indicated by a red rectangular which is divided into equal parts one part located on the platform (Qamchuqa Formation) and the other in the basin (Balambo Formation)

Fig. 23. (a) Paleogeographic and facies map of northern Iraq by Dunnington (1958) on which the studied area of Ghafur et al. (2020) is plotted in this study, it can be seen that quarter of their studied area is located in a relatively deep basin. (b) Cross-section of the same map by the same author on which the section of the later article is plotted, 1, 2, 3, and 4 are Zewe, Tabeen, Jasana, and Qamchuqa sections respectively.
Fig. 24. Exposed Cretaceous stratigraphic unit of the upper part of the Qamchuqa Gorge where there are no signals of unconformities.

6. Conclusions

The present study found many pieces of evidence of unconformity and paleokarst inside the lower part of the Qamchuqa Formation, as part of the Arabian platform, in Sulaimaniya. These pieces of evidence are limestone conglomerate, paleokarst (solution cavities filled with ooids), erosional surfaces, hardgrounds, high-density Thalassinoides burrows. The study found thick analogous limestone conglomerates and coarse detrital limestones in the attached deep basin of the Balambo Formation denoting transportation of the eroded unconformity-related materials by turbidity currents and deposition as calciturbidites. In contrast to previous studies, this study did not find any evidence of the 30ma unconformity in the upper part of the Qamchuqa Formation (Zewe section of Ghafur et al. (2020). This is true for unconformities previously stated in the upper part of the Qamchuqa Formation in the Tabeen, Jasana, and Qamchuqa gorge sections.

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References


