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NEW ORIGIN OF THALASSINOIDES BURROWS (GASTROPOD DWELLING STRUCTURES) IN THE QAMCHUQA FORMATION (LOWER CRETACEOUS), KURDISTAN REGION, NORTHEASTERN IRAQ

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ABSTRACT

Thalassinoides burrows, commonly interpreted as dwelling structures, are widespread in marine and coastal environments. This study presents the first documented occurrence of a significant assemblage of *Thalassinoides ichnofossils* within the Lower Cretaceous Qamchuqa Formation in the Kurdistan Region of northeastern Iraq. These trace fossils are preserved in coarse-grained detrital limestones, terrigenous carbonates, and mixed sediments, and are associated with ichnofacies indicative of coastal to shallow-marine settings, particularly the *Skolithos* and *Cruziana ichnofacies.*

Numerous extensive burrow networks were observed. During the Mesozoic–Cenozoic, the likely producers of these burrows were decapod crustaceans, supported by the presence of the crayfish *Hoploparia* within the structures. Notably, crab trackways and gastropod bulldozing trails reaching lengths of up to 0.5 meters represent some of the longest known invertebrate cursorial traces in the fossil record.

The burrow systems consist of branching horizontal tubes connected to the sediment surface by vertical or inclined shafts. Swellings, typically eccentric, occur at branching points, and the burrows exhibit backfilled sediment indicative of active construction by the tracemakers. The tubes range from 5 to 20 mm in diameter and have smooth walls. Evidence of lateral movement suggests the potential emergence of crab-like forms and sideways locomotion during the Cretaceous. This study represents the first recorded occurrence of *Thalassinoides* in Iraq.

Keywords: *Ichnofossils*, *Thalassinoides*, Lower Cretaceous, Qamchuqa Formation, *Ichnofacies*, NE Iraq

1- INTRODUCTION

The Early Cretaceous period in Iraq is marked by the development of a widespread carbonate platform system across the northeastern margin of the Arabian Plate. This platform played a pivotal role in the regional sedimentary and tectonic evolution, and it is primarily represented by a thick succession of shallow marine carbonates. These carbonates are predominantly composed of reefal limestones and dolomites, and they constitute some of the most important hydrocarbon reservoirs in the Middle East. In Iraq, the key formations associated with this platform include the Qamchuqa, Shuaiba, Mauddud, and Garagu formations, while their equivalents in western Iran are the Fahliyan, Dariyan, and Sarvak formations (Alsharhan & Nairn, 1997; Jassim & Goff, 2006; Rashidi et al., 2022).

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The Qamchuqa Formation, in particular, occupies a central position within the Early Cretaceous stratigraphy of northeastern Iraq. This formation, dated from the Hauterivian to Albian stages, was first described in detail by Wetzel (1950, in Bellen et al., 1959). It was originally recognized as a thick carbonate unit, with an estimated type section thickness of approximately 650 meters. Wetzel described the formation as an alternation of massive grey dolomite and light grey limestone, indicative of deposition in a high-energy, shallow marine environment. Subsequent stratigraphic revisions by Hudson (1954), Dunnington (1958), and Chatton & Hart (1960) subdivided the Qamchuqa Formation into two major units based on fossil assemblages and lithological differences: a lower Barremian–Aptian unit and an upper Albian unit. These were later formally renamed the Shuaiba Formation (lower) and the Mauddud Formation (upper) by Fürst (1970, cited in Buday, 1980), primarily in central and southern Iraq. These subdivisions correspond to the Dariyan Formation (Aptian) and the Albian section of the Sarvak Formation in the stratigraphy of southwestern Iran.

Despite the economic and stratigraphic significance of the Qamchuqa Formation, most previous research has focused on sedimentological, tectonostratigraphic, and petroleum geological aspects of the unit. Important contributions in this regard include works by Al-Sadooni & Alsharhan (2003), Ameen (2008), Karim & Ameen (2009), Ghafor et al. (2020; 2023), and others. These studies have examined depositional environments, platform evolution, tectonic uplift events, and diagenetic features such as karstification and dolomitization. However, there remains a significant gap in the ichnological understanding of this formation. Specifically, trace fossil assemblages—such as the morphologically distinctive and environmentally diagnostic Thalassinoides burrow systems—have received limited attention in the geological literature of this region.

The Qamchuqa Formation exhibits a lateral facies transition into the Balambo Formation toward the north and northeast. This change reflects a deepening gradient from shallow carbonate platform environments to deeper marine hemipelagic settings. In the northeastern parts of the Kurdistan Region of Iraq, particularly within the High Folded Zone, the Qamchuqa Formation is well exposed and represents a classic example of an inner to mid-ramp reefal facies belt. The formation is particularly well developed in areas around Dokan, Ranyia, Surdash, Bingird, and northwestern Sulaimaniyah, where thick reefal limestone successions dominate the stratigraphic record.

To investigate the ichnological and sedimentological characteristics of the Qamchuqa Formation in this region, two key stratigraphic sections were selected for detailed study **(Figure 1):**

Asos Section: Located at coordinates 35° 04′ 40.14″ N and 45° 04′ 30.35″ E.

Sekanyian Section: Located at coordinates 35° 53′ 02.31″ N and 45° 08′ 42.47″ E.

Figure 1 illustrates the tectonic context of the Arabian Plate and highlights the study area, adapted from Al-Husseini, 2000; Ziegler, 2001; Haq & Al-Qahtani, 2005.

Wetzel's initial type section, located approximately 7 km east of Dokan town, near Qamchuqa village, remains the reference locality for the formation. This section consists of alternating massive and well-bedded dolomite and limestone units, indicating a complex depositional history influenced by marine chemistry, sea-level fluctuations, and biogenic activity. Hudson (1954) originally assigned a broader age

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range to the formation (Valanginian to Albian), but later revisions by Dunnington (1958) reassigned the Valanginian interval to the underlying Balambo Formation. The refined biostratigraphy and correlation with adjacent regions provided further resolution, leading to the recognition of widespread time-equivalent carbonate platforms in both Iraq and Iran.

Additional lithostratigraphic and paleoenvironmental insights have been provided by researchers such as Abawi & Hassan (1993), who reported the presence of shallow neritic orbitolinid microfacies within the lower Qamchuqa carbonates in the Kirkuk region. Al-Shdidi et al. (1995) estimated a pre-compaction thickness of nearly 1000 meters in some areas. Diagenetic features such as vuggy porosity, karstification, and stylolitization have been extensively documented (Al-Sadooni & Alsharhan, 2003), suggesting complex post-depositional processes that may affect reservoir quality.

Although substantial work has been conducted on the sedimentology, tectonics, and hydrocarbon potential of the Qamchuqa Formation (e.g., Ameen, 2008; Karim & Taha, 2009; Al-Zaidy et al., 2013; Al-Qayim et al., 2016; Daoud, 2021; Tahir, 2022), trace fossils and bioturbation features—especially those related to Thalassinoides burrows—have not been systematically investigated in this formation across northeastern Iraq.

This study seeks to address this gap by conducting a detailed ichnological and sedimentological analysis of the Qamchuqa Formation in the Asos and Sekanyian sections. These sections lie within an area of approximately 500 km², covering parts of Asos, Sekanyian Gorge, and the northern to northwestern outskirts of the Sulaimaniyah Governorate. The geographic layout forms a northwest–southeast trending belt across the northeastern edge of the Arabian Plate (see **Figure 2** for location and geological maps).

FIGURE 2. (a) Location map of the study area on the tectonic map of northern Iraq (Jassim & Goff, 2006). (b) Geological map of the study area (modified from Karim, 2020).

The Qamchuqa Formation in the study area consists primarily of hard, dense, grey to dark-grey massive limestones, often containing a rich assemblage of biogenic components such as corals, stromatolites, ooids, pelecypods, and gastropods. Multiple unconformities and erosion surfaces are identified within the sequence, some of which are marked by basal conglomerates, karstic voids, and solution-collapse breccias, indicating periods of exposure and subaerial weathering **(Figure 3).** Notably, Ghafor (2020) reported a complete absence of ostracods in the examined sections of this formation, suggesting specific paleoenvironmental conditions during deposition.

FIGURE 3. Lithostratigraphic column of the Qamchuqa Formation (after Tahir, 2022)

Objective of the Study

The primary objective of this study is to document and interpret the occurrence and distribution of *Thalassinoides* trace fossils and associated bioturbation structures within the reefal carbonate facies of the Qamchuqa Formation in northeastern Iraq. The findings aim to provide new insights into the paleoenvironmental conditions, depositional settings, and early diagenetic processes of this important Cretaceous unit.

2- GEOLOGIC SETTING

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The studied area lies directly southwest of the Main Zagros Thrust Fault, which, according to Koyi (1988), marks the boundary of the Zagros Fold-Thrust Belt. During the Early and Middle Cretaceous, this region formed part of the northeastern passive margin of the Arabian Plate and was occupied by a shallow carbonate platform known as the Qamchuqa Formation. This platform was situated adjacent to the deep-water Neo-Tethys Ocean to the north and northeast, where deeper marine deposits such as the Balambo Formation and Qulqula Radiolarian Formation were laid down (Ghafor & Baziany, 2009).

The Qamchuqa Formation is time-equivalent to, and represents a lateral facies transition from, the Balambo Formation. Karim et al. (2020) reported over 200 meters of laminated and graded detrital limestones and limestone conglomerates within the Qamchuqa Formation. These deposits were interpreted as calciturbidites of the Balambo Formation, derived from the erosion of the Qamchuqa platform carbonates (Ghafor & Mohialdeen, 2016, 2018).

Structurally, the area is marked by a series of high-amplitude anticlines, where the eroded cores frequently expose soft sediments of the Sarmord Formation and underlying Jurassic units. The limbs of these anticlines are dominated by the more erosion-resistant Qamchuqa and Kometan formations. In contrast, intervening synclines are filled with softer formations, particularly the Shiranish and Tanjero formations (Ghafor, 1988, 1993; Al-Shaibani et al., 1993; Bakkal et al., 1993; Ghafor, 2000; Sharbazheri et al., 2009a, 2009b, 2011; Al-Nujaimy et al., 2020; Ghafor et al., 2024) **(Figure 4).**

Figure 4. Stratigraphy of the Haladin-Yakhsamer valley (eroded anticline), indicating the location of the unconformity in the lower part of the Qamchuqa Formation.

Prominent anticlines in the region include Piramagroon, Daban, Qaywan, Azmar, Sara, Surdash-Sargelu, Haladin-Yakhsamar, Kosrat, Asos, and Makok. Karim et al. (2020) distinguish two categories of folding within the Qamchuqa Formation: major and minor folds. Notably, the axes of the minor folds are rotated approximately 20° northward relative to the major fold axes. This angular deviation is attributed to two main factors:

A facies shift from massive reefal carbonates to well-bedded deep-marine limestones of the Balambo Formation.

Tectonic influence from the uplifted and mechanically rigid Mawat Complex, situated northeast of the study area **(Figure 5).**

Figure 5. Deviation (~20°) of minor anticline axes (orange arrows) from major fold orientations (red arrows) due to facies variation and tectonic influence from the Mawat Complex (Karim et al., 2020).

The stratigraphic position of the Qamchuqa Formation within the regional geologic framework of northern and northeastern Iraq is presented in **Figure 6,** based on the works of Harland et al. (1990) and El Diasty et al. (2016). The Cretaceous successions have been the subject of extensive studies (e.g., Kassab, 1976–1979; Ghafor, 1988, 1993, 2004; Ghafor & Mohialdeen, 2016, 2018; Ghafor et al., 2012, 2023, 2024; Ghafor & Karim, 1999; Ghafor & Baziany, 2009).

Similarly, the Paleogene formations have received significant scholarly attention (Al-Fattah et al., 2017, 2018, 2020a, 2020b; Al-Taee et al., 2024a–c; Al-Qayim et al., 2014; Ghafor & Al-Qayim, 2021a, b; Karim

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& Ghafor, 2021; Al-Qayim & Ghafor, 2022; Ghafor & Muhammad, 2022a, 2023a, b, 2025). The transitional Cretaceous–Paleogene boundary units have also been investigated in detail (Kassab et al., 1986; Ghafor, 1988, 2000, 2020; Al-Shaibani et al., 1993; Sharbazheri et al., 2009, 2011; Al-Nuaimy et al., 2020; Ghafor et al., 2024).

Furthermore, Neogene units have been extensively documented (Ghafor, 2004, 2010, 2011, 2014, 2015, 2022a, 2022b; Ghafor & Muhammad, 2005, 2006a, b; Muhammad & Ghafor, 2008; Ghafor & Ahmad, 2019, 2021; Ghafor & Najaflo, 2022; Ghafor et al., 2014, 2023, 2025). Oligocene–Miocene sequences are considered equivalent to the Asmari Formation of Iran, as identified by Rashidi et al. (2022, 2023a, b, 2024), Rajabi & Ghafor (2024), Гафур и др. (2025), and Qafor et al. (2025).

Figure 6. Stratigraphic correlation chart showing the placement of the Qamchuqa Formation and related units across southern, western, and northern Iraq (Kurdistan Region), based on Harland et al. (1990) and El Diasty et al. (2016). Modifications applied to the Kurdistan area.

3- MATERIALS AND METHODS

This study focuses on the lower part of the reefal Qamchuqa Formation, a stratigraphic unit of the Early Cretaceous Arabian Platform. The formation is characterized by a thick succession of detrital limestone, conglomerates, erosional surfaces, and evidence of paleokarstification. To better understand its geological features, we also examined its time-equivalent deep marine unit—the Balambo Formation.

Fieldwork was conducted in the study area where these formations are well exposed, particularly in deep valleys, gorges, and along rugged mountain slopes. Extensive in-situ observations and sampling were carried out to document sedimentological and ichnological features, with particular attention given to the trace fossil *Thalassinoides*. For accuracy, only those occurrences of *Thalassinoides* found in situ within the Qamchuqa Formation were considered.

Two key field sections were selected for detailed study: the Ass and Seykanian sections **(Figure 7).** These locations were chosen due to their representative stratigraphy and accessibility to well-preserved exposures. However, both sites present significant logistical challenges due to their rugged terrain, including narrow, steep-sided gorges and high elevations.

Representative rock samples were carefully collected from both sections for further laboratory analysis. These samples were selected based on their visibility of trace fossils, lithological variation, and stratigraphic significance. Thin sections were later prepared for petrographic study to supplement field observations and support paleoenvironmental interpretations.

Figure 7. **Google Terrain Image showing the geographic locations of the Ass and Seykanian sections studied in this work.**

4- RESULTS AND DISCUSSION

Thalassinoides Burrow Systems

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The ichnogenus *Thalassinoides* represents one of the most characteristic biogenic structures attributed to arthropods in the marine sedimentary record (Seilacher, 1986). This holds true not only for the present study but also for comparable calcareous and siliciclastic successions in the Portuguese Mesozoic (e.g., Fürsich, 1981; Neto de Carvalho, pers. obs.).

In the studied sections, a dense network of *Thalassinoides* burrows has produced prominent ichnofabrics, imparting a nodular texture to the exposed strata. These biogenic structures are most often observed as predominantly horizontal tunnels, typically preserved at bedding plane interfaces and commonly appearing as convex hyporeliefs.

The burrows vary considerably in width—some exceeding 110 mm—and can extend over lengths greater than 1 meter. They exhibit characteristic Y-shaped branching patterns with acute-angle bifurcations and localized expansions at branching points, which likely functioned as turning or resting chambers. The burrow cross-sections are generally elliptical, with the major axis aligned parallel to bedding planes, reflecting the effects of post-depositional compaction. The burrow walls are smooth and unlined, suggesting passive filling, and their internal fill is notably distinct from the surrounding host matrix. This difference is attributed to more intense carbonate cementation within the burrow fill, which may consist of coarse sandy, bioclastic, or lime mud sediments **(Figure 8).**

Thalassinoides burrow systems dominate the ichnofabric of the Qamchuqa Formation and serve as strong evidence for the ecological success of mecochirid decapods—believed to be the primary trace makers—during the Early Cretaceous. Despite this, the fossil record of decapods remains sparse and taphonomically biased (Plotnick, 1990). This scarcity is often explained by the taphonomic model proposed by Stempien (2005), which suggests that the delicate cuticular structures of decapods decay rapidly and are rarely preserved, resulting in a low preservation potential.

Interestingly, all fossilized decapods observed in association with these burrow systems are preserved in lateral view and in a state of rigor mortis (Feldmann et al., 2002), deviating from the typical exuvial (ecdysis) positioning often seen in molted specimens. This pattern may reflect specific environmental or burial conditions that rapidly immobilized and preserved the organisms before significant decomposition could occur.

Figure 8. *Thalassinoides* burrow walls are smooth, unlined, and exhibit passive infill. The burrow fill differs markedly from the host limestone or fine sandstone matrix due to enhanced carbonate cementation (modified after Tahir, 2022).

Asos Mountain Section

The Asos section is located on the northeastern flank of Asos Mountain (an anticline structure) along the northern boundary of the Dokan Reservoir. This stratigraphic section is notable for its abundance of paleokarst features, erosional surfaces, and oolitic limestone beds. One of the key intervals, approximately 5 meters thick, is characterized by laminated and bedded bioturbated limestone as well as the presence of hardgrounds. Bioturbation in this section is predominantly horizontal, suggesting formation through either current-induced disturbance or biological reworking, indicative of an omission surface **(Figure 9).**

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Figure 9. Limestones of the lower part of the Qamchuqa Formation at Asos Mountain showing: (a) partially karstified, fine-grained limestone (dark gray) with cavities filled by detrital and oolitic limestone; (b) oncoidal floatstone directly underlying karstified layers at coordinates 35°04′40.14″N and 45°04′30.35″E .

The laminated bioturbated layer exhibits clear features of *Thalassinoides* burrows, many of which occur within an omission surface setting. This surface exposes brief interruptions in sedimentation and is marked by multiple overprinted excavations, burrow fills, and boring structures, consistent with the descriptions of Bromley (1975). These burrows are closely associated with thin dolomitized conglomeratic floatstone layers. The clasts within these floatstones show poor sorting and irregular margins, further supporting the interpretation of episodic reworking **(Figure. 11c).**

Figure 10. A 5-meter-thick bioturbated interval in the lower Qamchuqa Formation, densely populated with *Thalassinoides* burrows .

Figure 11. (a) Bioturbated interval (same as Fig. 10); (b) Close-up view of the rectangular zone showing *Thalassinoides* details; (c) Thin section photograph highlighting the hardground marked by a white arrow (after Tahir, 2022).

In most cases, bioturbation is manifested as elongated dark patches composed of coarse-grained dolomite. These structures range from 4–8 cm in length and 1–3 cm in thickness. In outcrop, the burrows exhibit positive relief and are commonly cylindrical or irregular in shape, with visible necking and widening along their lengths **(Figure 12a, b).** When compared with documented morphologies (Sheehan & Schiefelbein, 1984; Ekdale et al., 2012; Gingras et al., 2012), these traces are confidently assigned to the ichnogenus *Thalassinoides*.

Figure 12. Lower Qamchuqa Formation in the Asos section showing: (a) hardground surfaces, horizontal bioturbation, and erosional contacts; (b) erosional surface underlying a bioturbated horizon .

Dolomitization of the burrow fill is interpreted as a result of preferential fluid flow through the more permeable burrow-associated sediments, which acted as conduits for early diagenetic alteration. According to the literature, *Thalassinoides* are horizontal, branching burrow systems that connect to the sediment-water interface via vertical or inclined shafts. Swellings—often eccentric—occur at branching points and are believed to result from active infilling by the burrowing organism.

Typical *Thalassinoides* tubes range from 5 to 20 mm in diameter and possess smooth walls. However, Yanin and Baraboshkin (2013) observed shaft and tunnel diameters from 15 mm up to 60 mm, further illustrating the variability in these structures. These burrows are typically found in coarse-grained terrigenous, carbonate, or mixed sediment settings, and are associated with ichnofacies indicative of shallow-marine and coastal environments, including Skolithos and Cruziana assemblages.

Although many previous studies have interpreted *Thalassinoides* as crustacean-produced burrows, in this study, associated macrofauna are limited to small gastropods and pelecypods. Crustaceans are notably absent from the host rocks, suggesting that the observed burrows in the Qamchuqa Formation were more likely formed by these mollusks or similar invertebrates.

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In the Sekaniyan Gorge, where the strata of the Qamchuqa Formation are exposed vertically, two distinct *Thalassinoides*-rich horizons with associated hardgrounds are observed. The first occurs approximately 20 meters above the formation's base and is about 1 meter thick, while the second is found near the top of the lower Qamchuqa interval and is approximately 4 meters thick **(Figure 9).**

Sekanian Section

The Sekanian section is situated in the northeastern part of Asos Mountain (anticline), along the northern boundary of the Dokan Reservoir. This section is particularly significant due to a 5-meter-thick interval of bedded and laminated bioturbated limestone associated with hardground surfaces (Fig. 13).

Figure 13. Limestones of the lower Qamchuqa Formation in the Sekanian section showing partially karstified fine-grained limestone (dark), with cavities filled by detrital and oolitic limestone.

Bioturbation within the Sekanian section is predominantly horizontal, likely resulting from a combination of biological reworking and current activity. These burrows are commonly associated with omission surfaces that indicate short interruptions in sediment deposition **(Figure 14).**

Figure 14. Bioturbated succession in the lower Qamchuqa Formation, densely populated with *Thalassinoides* burrows

In the Sekaniyan Gorge, the Qamchuqa Formation is exposed in nearly vertical strata, where two distinct ichnological horizons are observed. The first horizon, located approximately 20 meters above the formation's base, is about 1 meter thick. The second horizon occurs at the top of the lower Qamchuqa unit and is 4 meters thick. Both horizons display well-developed *Thalassinoides* networks and hardground surfaces **(Figure 15).**

Figure 15. (a) Nearly vertical strata of the Qamchuqa Formation in the Sekaniyan Gorge exhibiting *Thalassinoides*; (b) Close-up of *Thalassinoides* and associated hardground; (c) Detailed view of branching and swollen burrows at coordinates 35°53′02.31″N and 45°08′42.47″E .

The omission surfaces in this section reveal multiple phases of biogenic activity, shown by superimposed borings, burrow infill, and reworking. These surfaces are commonly linked to thin dolomitized conglomeratic beds (floatstone facies), characterized by poorly sorted clasts with irregular boundaries **(Figures. 16–18).** Associated lagoonal biofacies—composed of nerineids, naticids, *Exogyra*, and other gastropods—further support a shallow-marine depositional environment **(Figures. 17, 18).**

Figure 16. Panels (a–f): Examples of *Thalassinoides* burrows from the vertical exposures of the Qamchuqa Formation in Sekaniyan Gorge.

Figure 17. Panels (a–e): Lagoonal biofacies with nerineids, naticids, and clustered *Exogyra*.

Figure 18. Panels (a–e): Continued examples of lagoonal fauna with nerineids, naticids, and clustered *Exogyra*.

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At both the Sekanian and Asos sections, *Thalassinoides* burrows can extend vertically and horizontally, often forming dense networks that define entire bedding planes. These burrow walls are occasionally lined, indicating they functioned as dwelling structures. While some *Thalassinoides* morphologies resemble *Ophiomorpha*, they differ by lacking fecal pellets in their walls. This transitional morphology is expected, as both structures are commonly attributed to burrowing shrimp or closely related arthropods.

Similar burrow systems have been documented in both muddy and sandy sediments within the shallow-marine deposits of the San Joaquin Basin. The comparison supports the interpretation that these trace fossils reflect well-established, low-energy marine conditions favorable for long-term colonization by burrowing organisms **(Figure 19).**

Figure 19. A complex *Thalassinoides* burrow network from the Asos section, showing vertical and horizontal branching. Lined burrow walls suggest a dwelling function. While morphologically similar to *Ophiomorpha*, the absence of fecal pellets supports attribution to *Thalassinoides*. These structures are typical of burrowing shrimp activity in shallow-marine environments.

5- CONCLUSIONS

1. **Exceptional preservation of decapods within *Thalassinoides* burrow systems** The study documents a significant finding of fossil decapod populations, exceptionally preserved within well-developed *Thalassinoides* burrow networks. This association provides critical ichnological and paleoecological evidence of crustacean behavior in Early Cretaceous marine environments.
2. **High-quality preservation of *Mecochirus rapax* specimens** Hundreds of fossilized *Mecochirus rapax* carapaces were recovered, many exhibiting complete appendages and delicate morphological features, including saw-toothed crests and granulated textures. This exceptional preservation suggests rapid burial and minimal post-mortem transport.
3. **Obrution by flooding events in a shallow lagoonal setting** The widespread preservation of these decapods is interpreted as resulting from obrution—rapid burial during high-energy storm or flooding events. These episodic influxes of coarse, sandy mud into shallow back-reef lagoons likely occurred repeatedly during the lower Barremian, facilitating fossilization in situ.
4. **Focused ichnological analysis of the Qamchuqa Formation** This study centers on the Qamchuqa Formation in the Sulaimaniyah Governorate, aiming to characterize and interpret *Thalassinoides* trace fossils. Their abundance and complexity reflect significant bioturbation and support interpretations of a low-energy, shallow-marine depositional environment.
5. **Unconformity and diagenetic features in the lower Qamchuqa interval** The lower part of the Qamchuqa Formation reveals a prominent unconformity marked by paleokarst surfaces, conglomeratic layers, erosional truncations, *Thalassinoides* traces, chert nodules, and hardground surfaces. These features collectively indicate subaerial exposure, periods of non-deposition, and early diagenetic modification, emphasizing the complex paleoenvironmental history of the formation.

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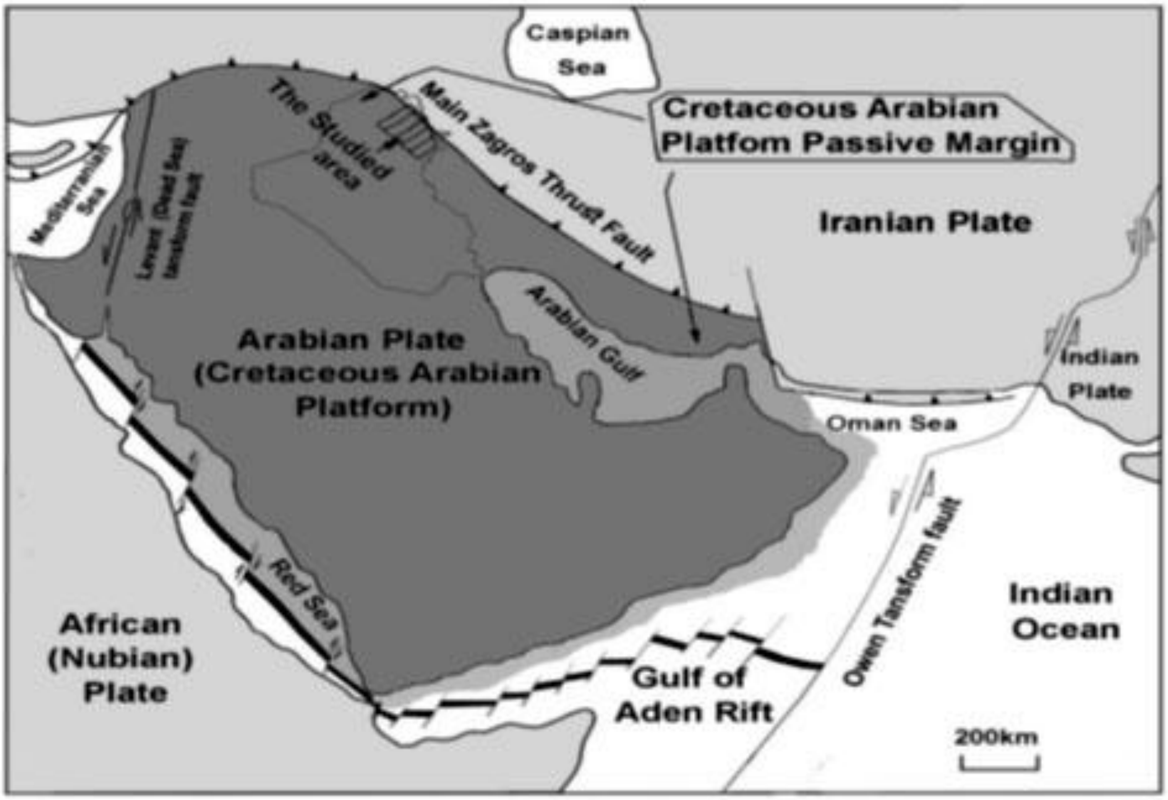

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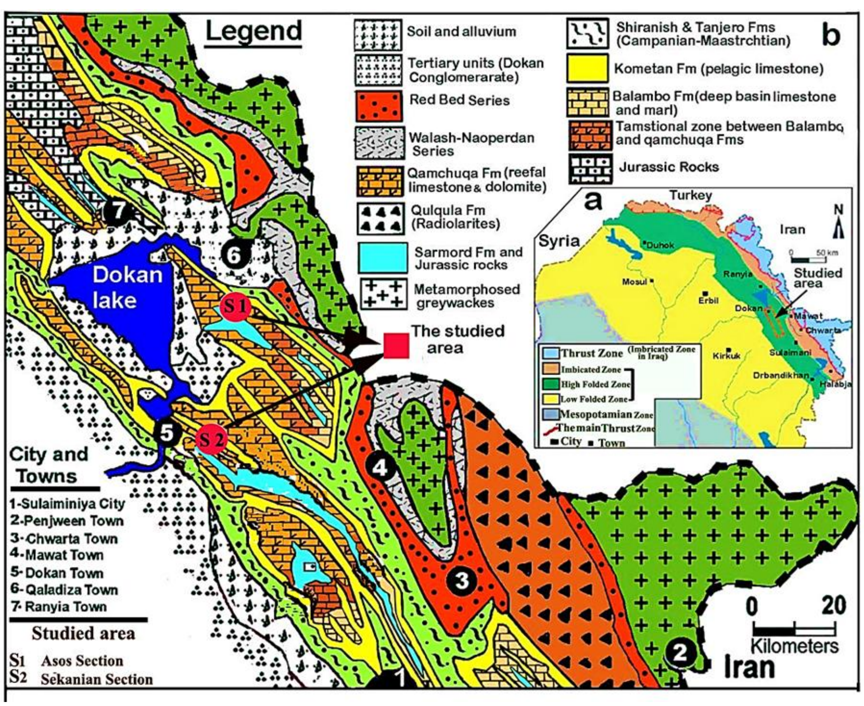

FIGURE 2. (a) Location map of the study area on the tectonic map of northern Iraq (Jassim & Goff, 2006). (b) Geological map of the study area (modified from Karim, 2020).

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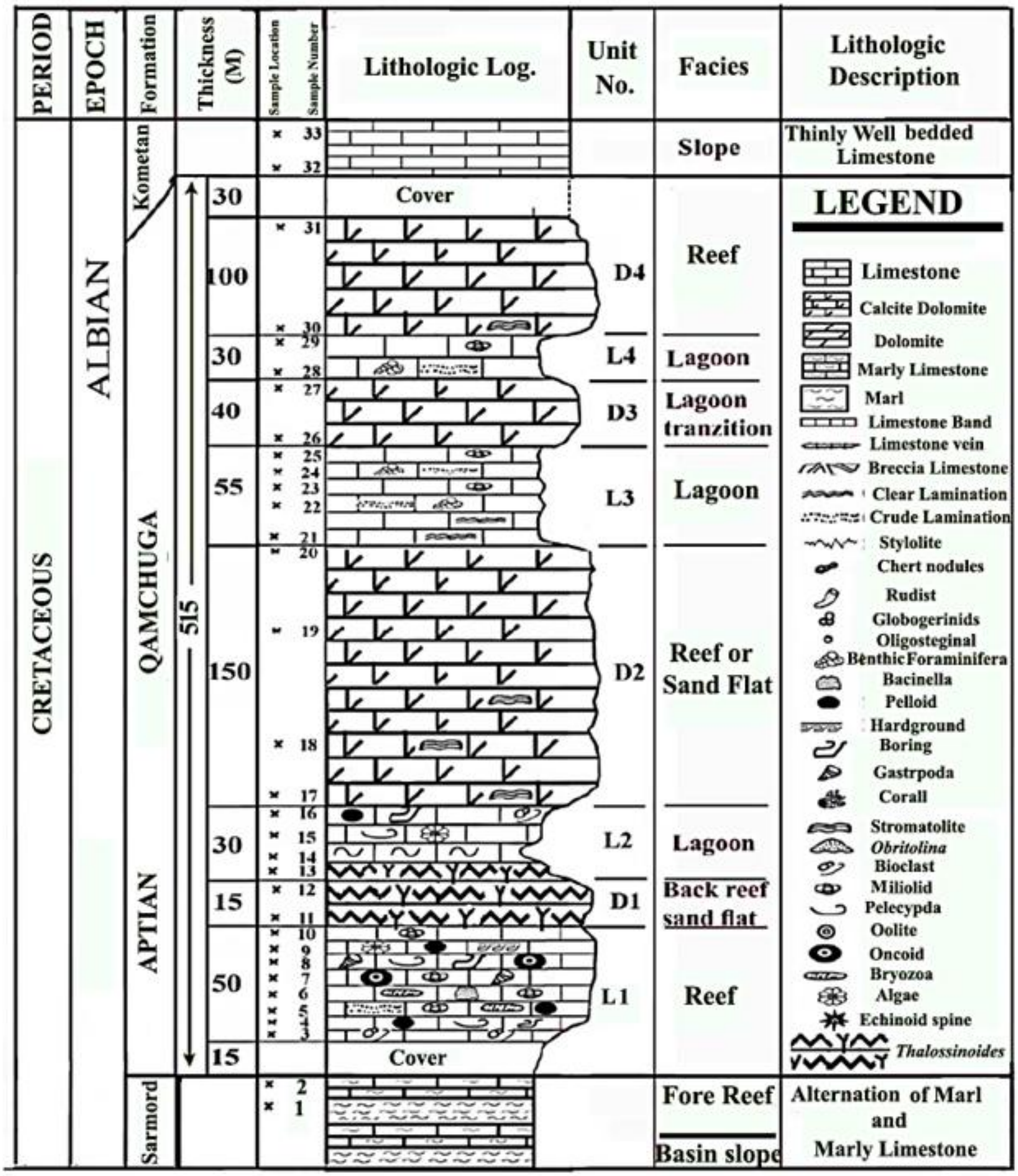

FIGURE 3. Lithostratigraphic column of the Qamchuqa Formation (after Tahir, 2022)

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Figure 4. Stratigraphy of the Haladin-Yakhsamer valley (eroded anticline), indicating the location of the unconformity in the lower part of the Qamchuqa Formation.

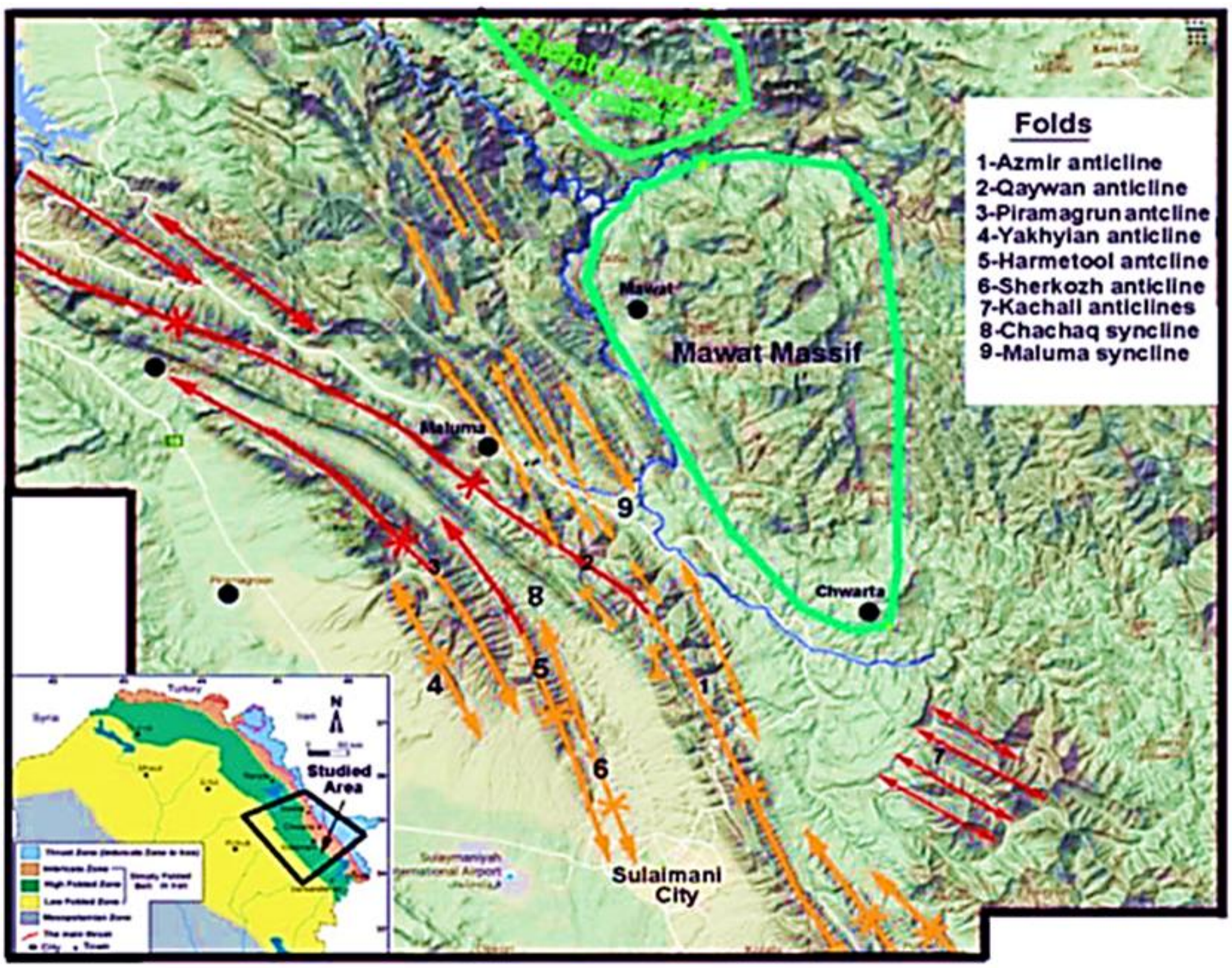

Figure 5. Deviation (~20°) of minor anticline axes (orange arrows) from major fold orientations (red arrows) due to facies variation and tectonic influence from the Mawat Complex (Karim et al., 2020).

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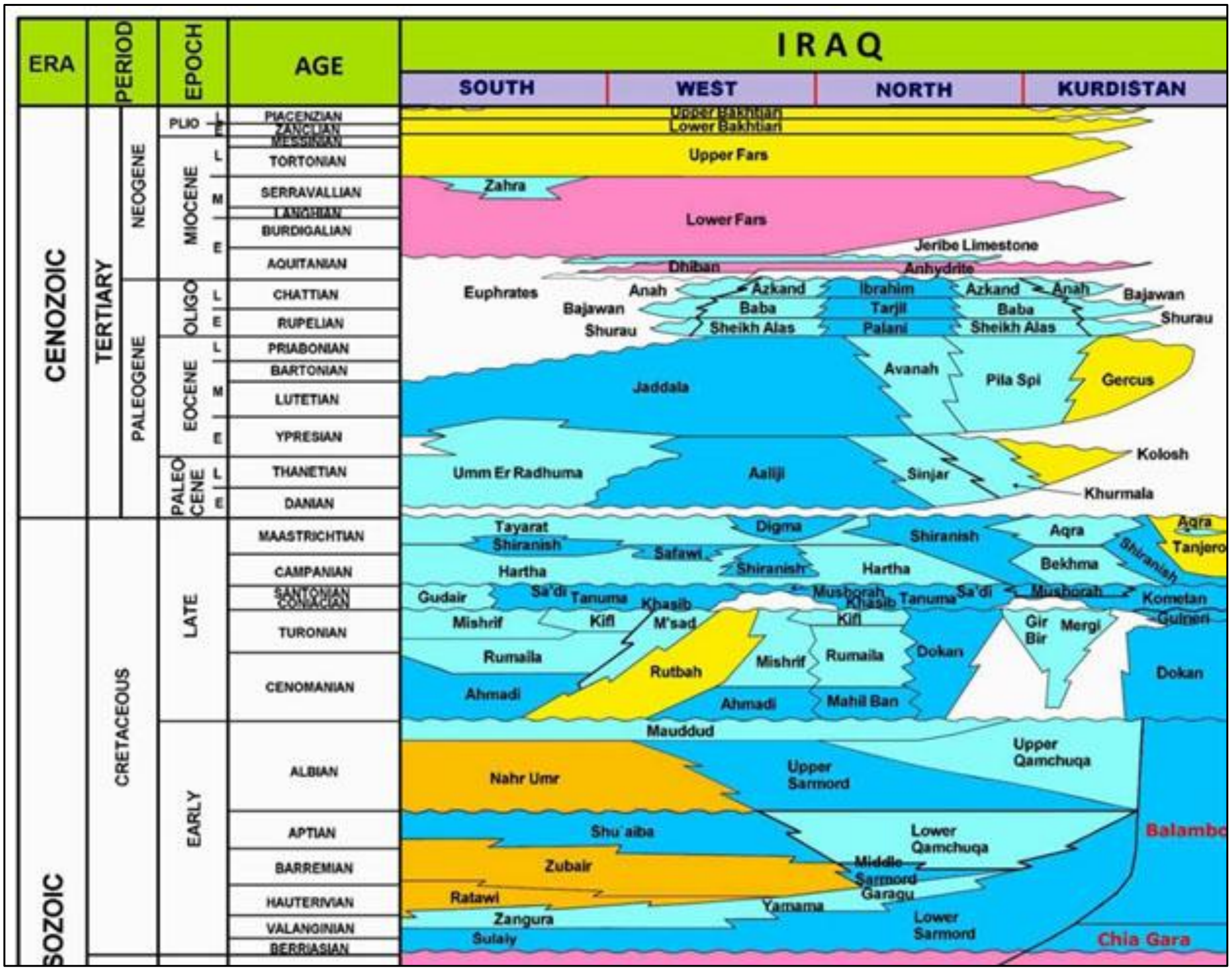

Figure 6. Stratigraphic correlation chart showing the placement of the Qamchuqa Formation and related units across southern, western, and northern Iraq (Kurdistan Region), based on Harland et al. (1990) and El Diasty et al. (2016). Modifications applied to the Kurdistan area.

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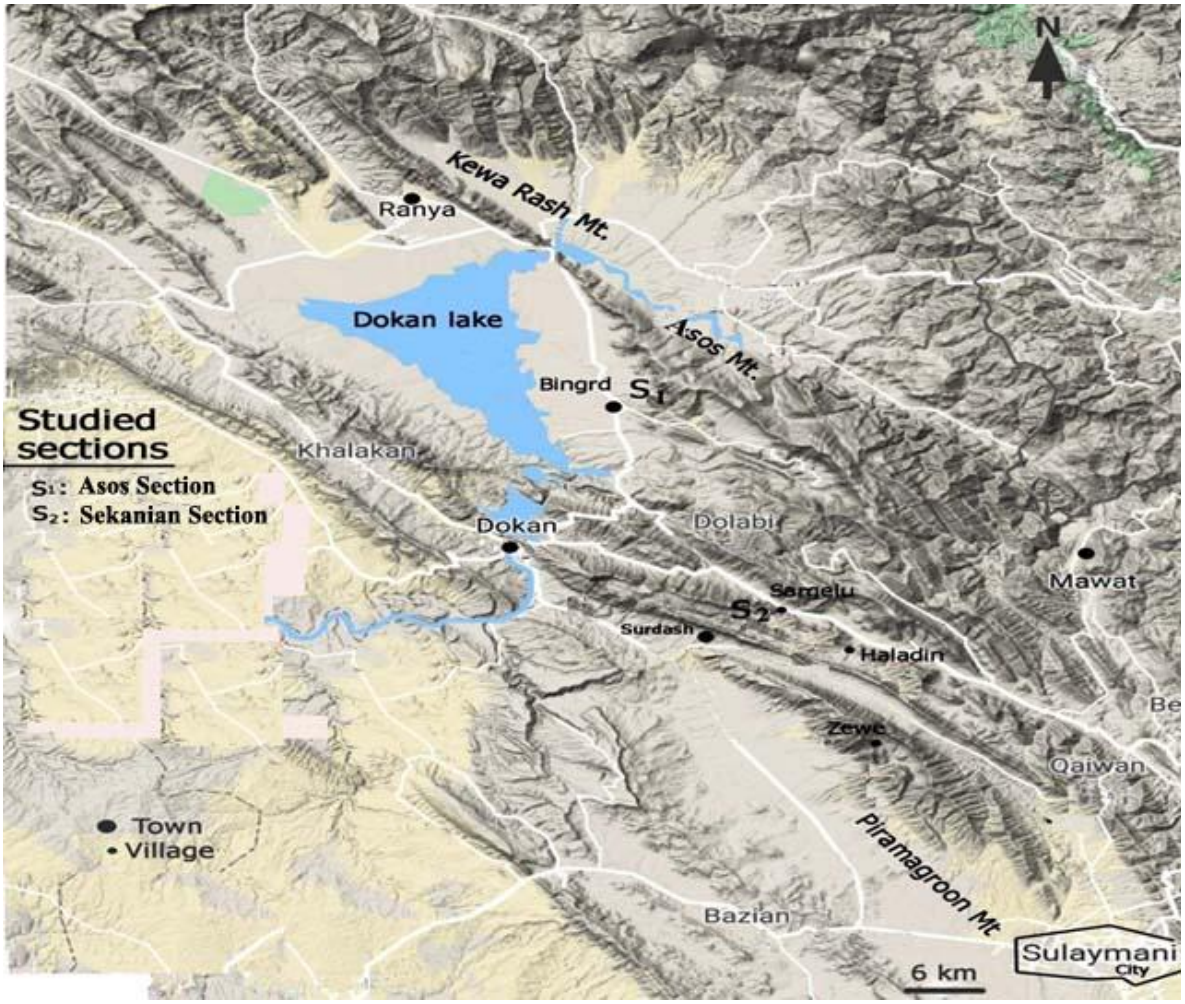

Figure 7. **Google Terrain Image showing the geographic locations of the Ass and Seykanian sections studied in this work.**

Figure 8. *Thalassinoides* burrow walls are smooth, unlined, and exhibit passive infill. The burrow fill differs markedly from the host limestone or fine sandstone matrix due to enhanced carbonate cementation (modified after Tahir, 2022).

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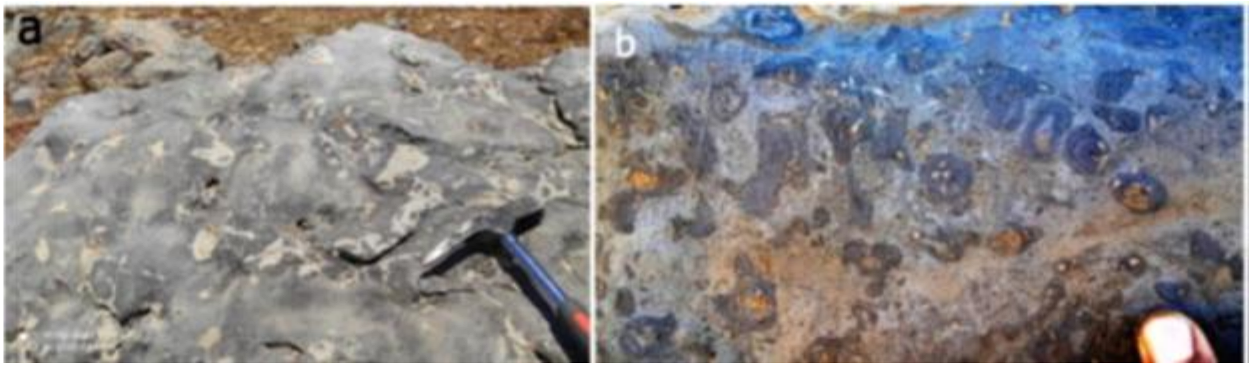

Figure 9. Limestones of the lower part of the Qamchuqa Formation at Asos Mountain showing: (a) partially karstified, fine-grained limestone (dark gray) with cavities filled by detrital and oolitic limestone; (b) oncoidal floatstone directly underlying karstified layers at coordinates 35°04′40.14″N and 45°04′30.35″E .

Figure 10. A 5-meter-thick bioturbated interval in the lower Qamchuqa Formation, densely populated with *Thalassinoides* burrows .

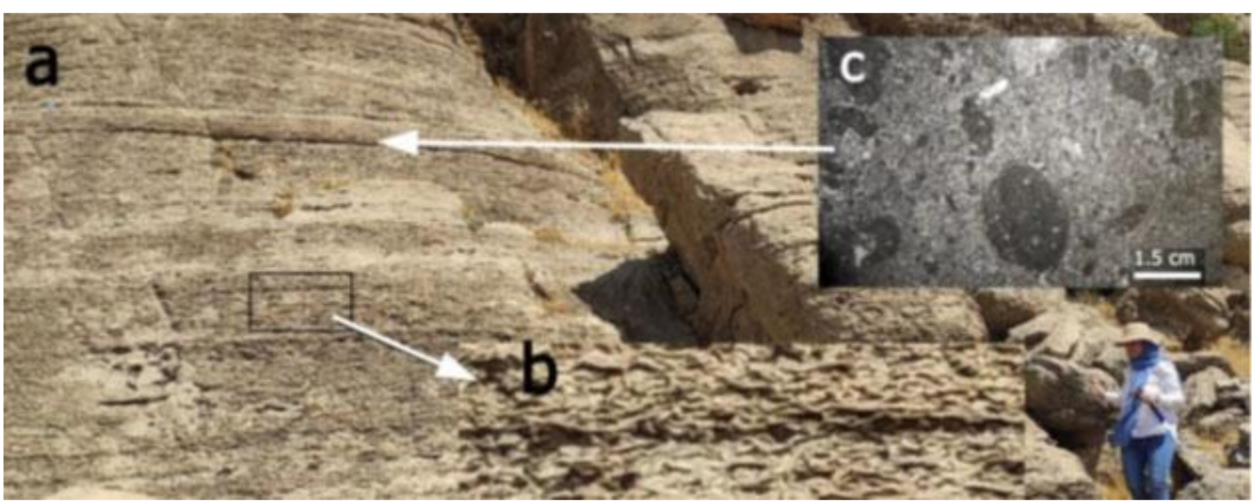

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Figure 11. (a) Bioturbated interval (same as Fig. 10); (b) Close-up view of the rectangular zone showing *Thalassinoides* details; (c) Thin section photograph highlighting the hardground marked by a white arrow (after Tahir, 2022).

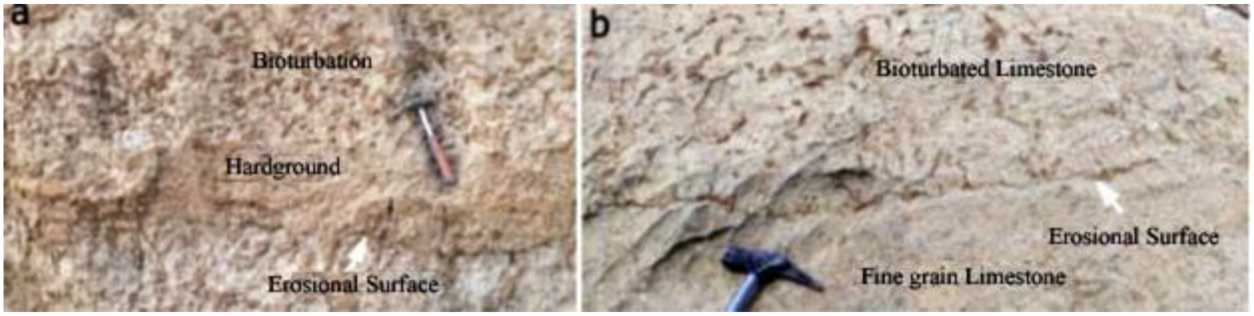

Figure 12. Lower Qamchuqa Formation in the Asos section showing: (a) hardground surfaces, horizontal bioturbation, and erosional contacts; (b) erosional surface underlying a bioturbated horizon.

Figure 13. Limestones of the lower Qamchuqa Formation in the Sekanian section showing partially karstified fine-grained limestone (dark), with cavities filled by detrital and oolitic limestone.

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Figure 14. Bioturbated succession in the lower Qamchuqa Formation, densely populated with *Thalassinoides* burrows

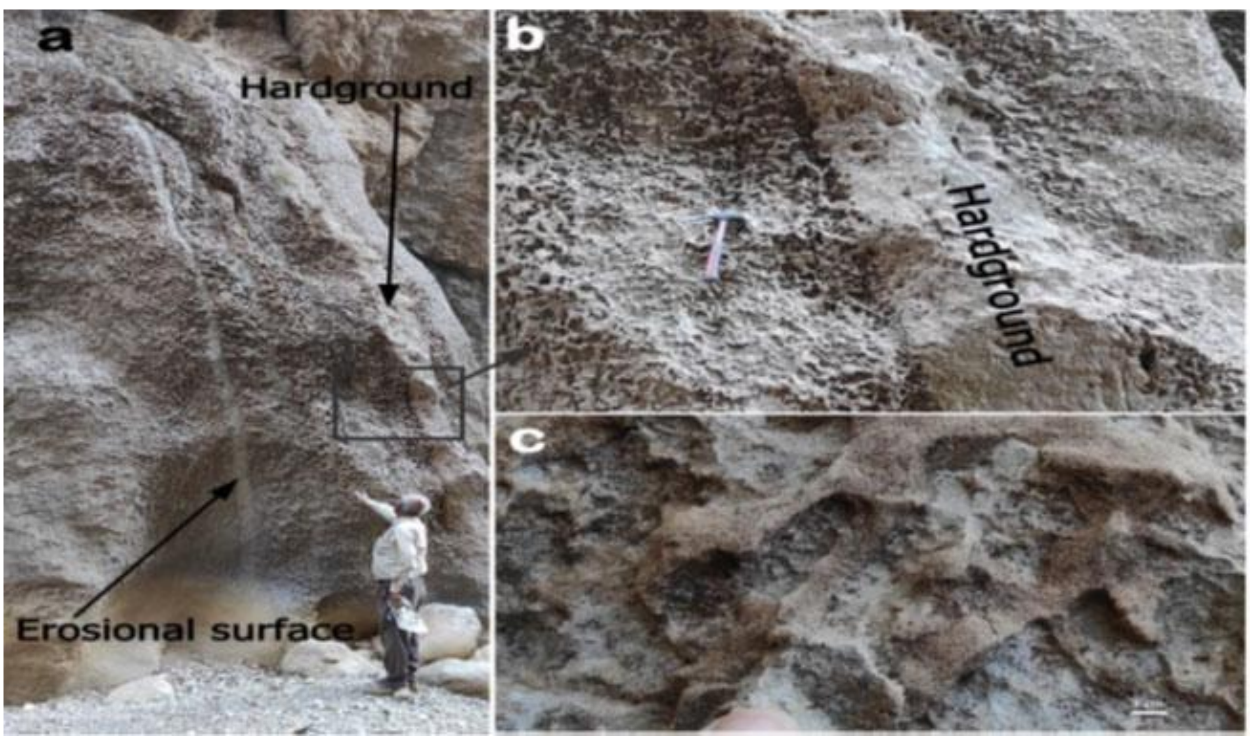

Figure 15. (a) Nearly vertical strata of the Qamchuqa Formation in the Sekaniyan Gorge exhibiting *Thalassinoides*; (b) Close-up of *Thalassinoides* and associated hardground; (c) Detailed view of branching and swollen burrows at coordinates 35°53′02.31″N and 45°08′42.47″E .

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Figure 16. Panels (a–f): Examples of *Thalassinoides* burrows from the vertical exposures of the Qamchuqa Formation in Sekaniyan Gorge .

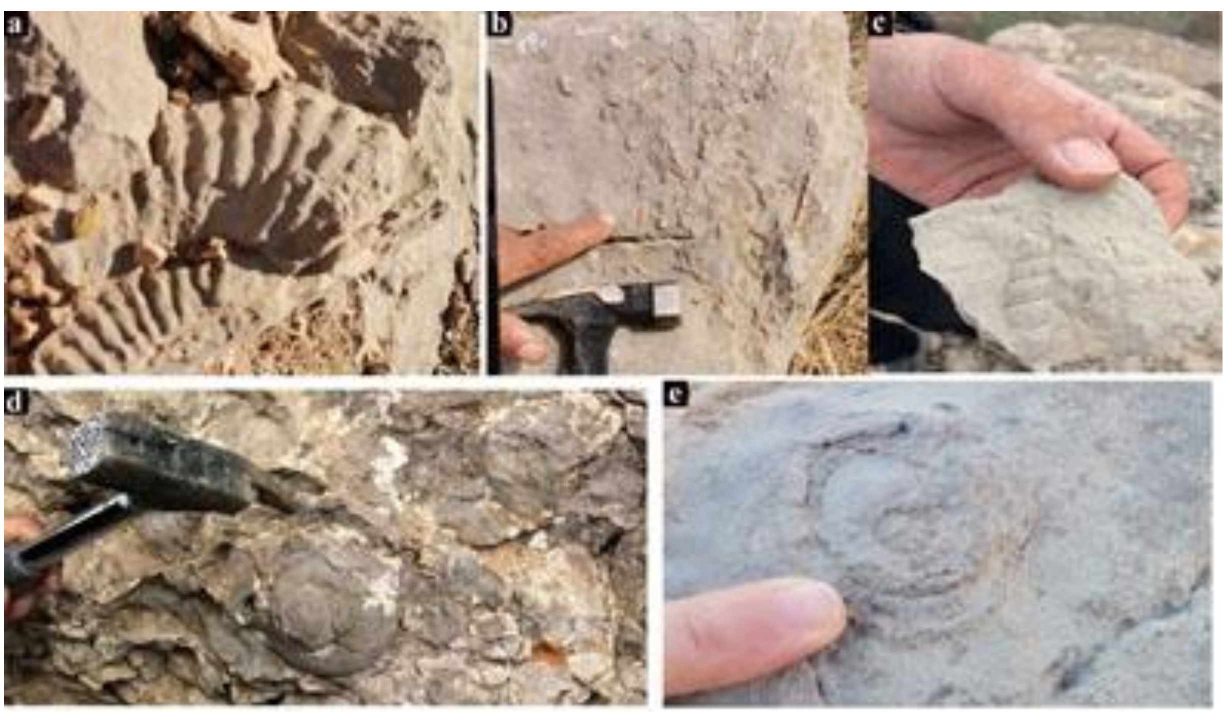

Figure 17. Panels (a–e): Lagoonal biofacies with nerineids, naticids, and clustered *Exogyra* .

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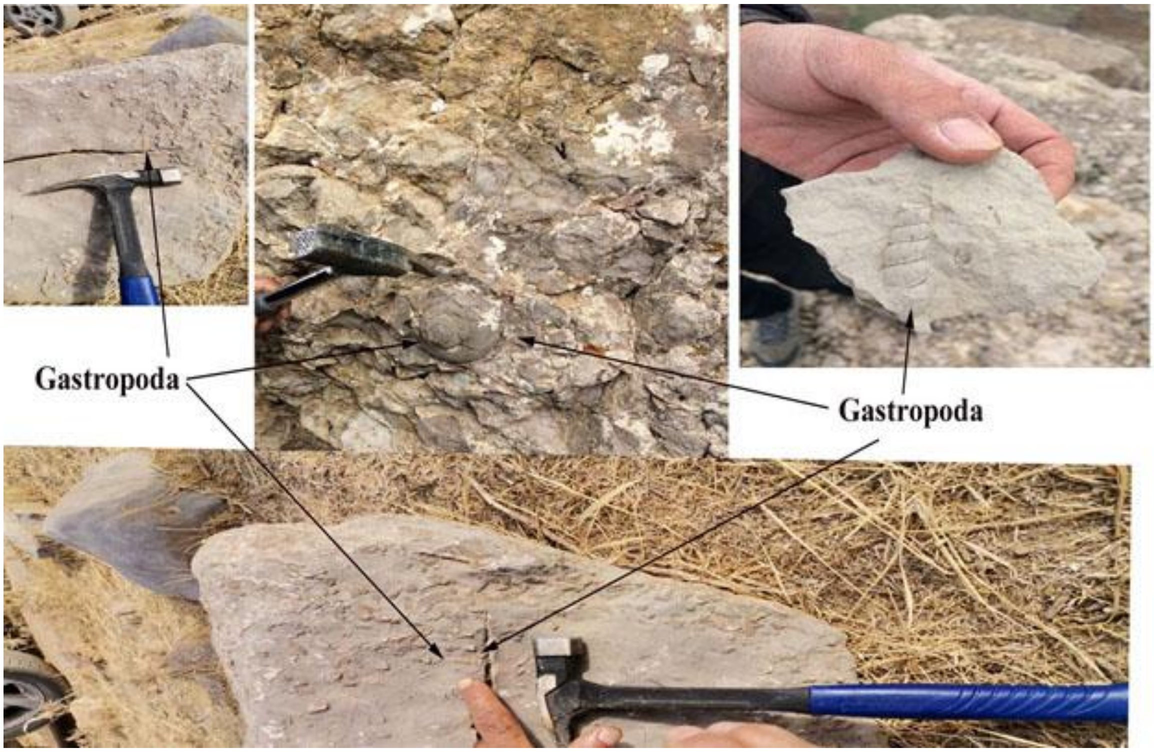

Figure 18. Panels (a–e): Continued examples of lagoonal fauna with nerineids, naticids, and clustered *Exogyra* .

Figure 19. A complex *Thalassinoides* burrow network from the Asos section, showing vertical and horizontal branching. Lined burrow walls suggest a dwelling function. While morphologically similar to *Ophiomorpha*, the absence of fecal pellets supports attribution to *Thalassinoides*. These structures are typical of burrowing shrimp activity in shallow-marine environments.

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