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# Sedimentology of Avanah Formation (Middle-Upper Eocene) from Selected Sections within Iraqi Kurdistan Region

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## ABSTRACT

Sedimentary features, petrography, and microfacies analysis of the Avanah Formation are investigated in the current study. Two exposed outcrops (Sartak-Bamo and Belula) for the Avanah Formation are studied in detail, located in the Zagros High Folded Zone (ZHFZ), and two subsurface sections (K90 and K306) within the Zagros Low Folded Zone (ZLFZ). The Avanah Formation is composed of multi-lithological sequences (limestone, dolomitic limestone, dolostone, and marly limestone). It has been subdivided into five units based on its composition. The Khurmala Formation underlies the Avanah Formation at all the studied sections unconformably. The Pila Spi Formation at the Sartak-Bamo section conformably overlies the Avanah Formation, but the Jaddala Formation conformably overlies the Avanah Formation at the Belula section. The Fatha Formation unconformably overlies the Avanah Formation at both subsurface sections. A variety of large benthic foraminifera species have been identified, such as Nummulite spp.; Orbitolite complanatus (Lamarck); Alveolina spp.; Discocyclina spp. and Assilina spp. In addition, some other small benthic foraminifera, such as Miliolids, Rotalids, a few Mollusca, and Algae with their bioclasts, are identified in the studied sections. Based on detailed microfacies analysis, four main microfacies (Mudstone, Wackestone, Packstone, and Packstone-Grainstone) and eleven submicrofacies are determined. Three facies' associations are identified, which lead to interpreting that the Avanah Formation was deposited in a semi-lagoon, shoal (bank) to shallow open marine environment of the inner ramp and extending to the middle ramp setting.

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# دراسة رسوبية لتكوين أفانا (الايوسين الاوسط- الاعلى) في مقاطع مختارة من اقليم كردستان العراق

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**الملخص**

تمت دراسة الخصائص الرسوبية، البتروغرافية، والسحنات الدقيقة لتكوين أفانا المنكشف في مقطعي (سارتك بمو وبيلولة) ضمن نطاق زاكروس للطيات العالية (ZHFZ) وكذلك بئري (K90-K306) ضمن نطاق زاكروس للطيات الواطئة (ZLFZ). إعتمادا على المكونات الصخرية، قُسم التكوين الى خمس وحدات، فالتكوين مؤلف بشكل رئيس من تتابعات صخرية تشمل صخور الحجر الجيري، الحجر الجيري المتدلمت، الحجر الدولوميتي والحجر الجيري الصلصالي. أظهرت الدراسة أن هناك سطح عدم توافق يفصل تكوين أفانا عن تكوين خورمالة الواقع اسفله ضمن المقاطع المدروسة، بينما سطحه العلوي مع تكوين بيلاسبي وجداله يعتبر سطحاً متوافقاً ضمن مقطعي (سارتك بمو و بيلولة)، بينما في مقاطع البئرين (K90-K306) فهو سطح عدم توافق مع تكوين فتحة. حددت الدراسة أنواعاً مختلفة من المنخربات القاعية الكبيرة الحجم، والتي تمثلت بالأنواع منها: Nummulite spp.; Orbitolite complanatus (Lamarck); Alveolina spp.; Discocyclina spp. and Assilina spp. بالاضافة الى ذلك تم تشخيص أنواع أخرى من متحجرات الفورامنيفيرا صغيرة الحجم مثل: المليوليد، والروتاليد وقليل من الرخويات والطحالب مع بقايا أحيائية. بناءً على تحليل السحنات الدقيقة، تم تحديد أربع سحنات دقيقة رئيسة (Mudstone، وWackestone، وPackstone، وPackstone-Grainstone) وإحدى عشر سحنَّة ثانويَّة. فسرت بيئة الترسيب لتكوين افانا بناءً على تجمعات السحنية facies associations))، ترسب تكوين أفانا في بيئة لاغونية شبه محصورة Semi restricted lagoon)، ومياه ضحلة (Shoal) إلى بيئة بحرية ضحلة مفتوحة للمنحدر الداخلي (shallow open marine environment of the inner ramp) وتمتد إلى بيئة المنحدر الأوسط (Middle Ramp).

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## Introduction

According to Sharland *et al.* (2004), the Avanah Formation belongs to the upper part of the AP10 tectonic mega-sequence of the Arabian plate (Early Paleocene-Late Eocene). McGinty (1953), in Bellen *et al.* (1959), first described the Avanah Formation (from Kirkuk well 116, Avanah dome). Lithologically, the Avanah Formation is composed of limestone beds, which are generally dolomitized, recrystallized, and intercalated with some beds of dolomitized limestone. This Formation is distributed along a relatively narrow belt (30-40 km) wide with different thicknesses, and lithologically it is rather uniform and can be correlated with the Dammam Formation in facies and age (Buday, 1980). Generally, the Avanah Formation represents a fore-slope marine platform facies (Al-Hashimi and Amer, 1985).

Several large benthic foraminifera have been reported from the Avanah Formation, such as Alveolina sp., Nummulites sp., Discocyclina sp., Operculina sp., *Orbitolites complanatus*

(Lamarck), *Lockhartia Alveolata* (Silvestri), *Assilina exponens* (SOWERBY) (Bellen et al., 1959; Al-Hashimi and Amer, 1985; Abawi and Sharbazheri, 1987; Ameen Lawa and Ghafur, 2015 and Pirot, 2017). The typical shoal realm's fossils are the most abundant ones (Buday, 1980). According to Karim (1997), the Avanah Formation interfingers with the Pila Spi Formation in the Sartak-Bamo area. Different microfacies and shallow depositional environments (nummulitic bank and shoal) were suggested for the Avanah Formation (Al-Temimi, 2002; Al-Mutwali and Al-Banna, 2005, and Barzani, 2016). While semi-restricted, shoal to open marine platform and ramp settings have been proposed for the Avanah depositional environment (Sharbazheri, 1983; Abdullah *et al.*, 2020; and Asaad, 2022). The Avanah Formation contains numerous species of larger benthic foraminifera that flourished and developed in the photic zone of tropical to subtropical seas. Large benthic foraminifera provide significant indications for the reconstruction of sedimentary paleoenvironments (Rahmani *et al.*, 2009; Amirshahkarami *et al.*, 2010). Nummulitic facies of the Avanah Formation form the middle to upper Eocene shelf margin, passing basinward into marls of the Jaddala Formation (Bellen *et al*., 1959; Aqrawi *et al.*, 2010).

To achieve the aims of this study, two outcrops, Sartak-Bamo and Darband Belula, and two subsurface sections (Kirkuk wells K-90 and K-306) are selected (Fig. 1). The subsurface sections are drilled at depths ranging from 846 to 973 m and 807 to 993 m, respectively (Table 1). Tectonically, the Sartak-Bamo and Darband Belula sections are located close to the boundary between the Zagros High Folded Zone (ZHFZ) and the Zagros Low Folded Zone (ZLFZ). According to Aqrawi *et al.* (2010), the boundary is sharp, and it is probably controlled by a basement lineament.

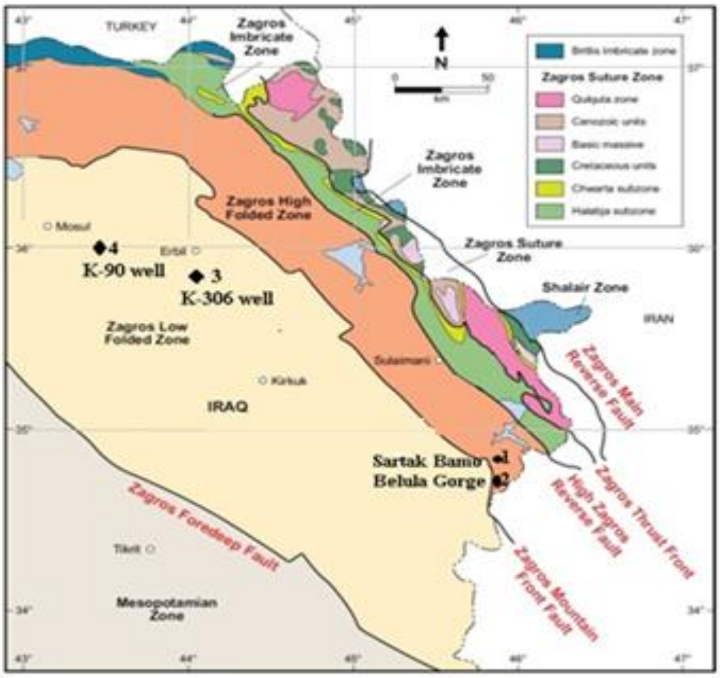



**Fig. 1. Tectonic map of northern Iraq showing the locations of the studied sections (After Al-Qayim, *etal.*, 2012).**

The beds at Sartak-Bamo are vertical but sometimes inclined, especially near the top of the Avanah to Pila Spi formations. Due to extensive tectonic activity, different sets of normal and reverse faults have been observed within the rock units of the Belula section. While the two subsurface sections (K-90, K-306 wells) are tectonically located within the Zagros Low Folded Zone (ZLFZ) (Fig. 1), the main objectives of the current study are to identify the sedimentological characteristics, stratigraphy, petrographic analysis, and microfacies assemblages, and to interpret the depositional environments of the Avanah Formation from the selected sections.

**Table 1: Geographic coordination, names, thicknesses, and locations of the studied sections.**

| Sections | Types | Latitude | Longitude | Thickness | Locations |
|---|---|---|---|---|---|
| Sartak-Bamo | Outcrop | 34°56'53.08" N | 45°43'40.93" E | 64 m | 35 km southeast of Darbandikhan town, (The SW limb of the Bamo Mountain). |
| Belula Gorge | Outcrop | 34°51'58.52" N | 45°43'50.54" E | 75 m | 48 km southeast of Darbandikhan town, (The SW limb of the Kawella mountain). |
| Well K-90 | Subsurface | 35°47'28.99"N | 43°59'06.34" E | 127 m | Avanah Dome/Kirkuk structure. |
| Well K-306 | Subsurface | 35°59'01.65" N | 43°42'44.68" E | 186 m | Avanah Dome /Kirkuk structure |

## Methodology

Executing detailed field investigation within Sulaimani Governorate, northeastern Iraq, looking for well-exposed outcrops of the Avanah Formation. This work is based on field observation and data collection for determining the textural and compositional characteristics of the carbonate rocks, facies association, thickness of the beds, and nature of lithological contacts with the overlying and underlying formations. Documenting the microfacies types, their constituents, the faunal abundance, and their diversity has all been taken into consideration (especially benthic foraminifera).

Accordingly, 102 slices of thin sections from Sartak-Bamo and Belula Gorge were prepared at Sulaimani University/Department of Geology, and 286 previously prepared slices of thin sections by the North Oil Company for wells K-90 and K-306 have been studied and investigated under a binocular polarized microscope. Textural descriptions and microfacies interpretation follow (Dunham, 1962) and (Flügel, 2010).

## Results

### Stratigraphy of Avanah Formation

Geologically, north and northeastern Iraq represent a part of the extensive Alpine Mountain belt of the east, which developed through the collision of the Afro-Arabian and the Eurasian continents (Sharland *et al.*, 2004). Jassim and Goff (2006) divided the Middle Paleocene-Eocene Megasequence (AP10) into two sequences: The Paleocene-Early Eocene and the Middle-Late Eocene sequences. Dammam platform, Ratga fore slope, Jaddala deep basin, Avanah nummulitic shoal, Pila Spi lagoonal, and fluvial and fluviomarine (Gercus) formations along the final phase of the subduction and closing of the remnant part of the Neo-Tethys Ocean (Al-Hashimi and Amer, 1985; Jassim and Goff, 2006). The Avanah Formation, which belongs to the Middle-Late Eocene sequence, is laterally changing to the Gercus Formation in the north and northeast of Iraq (Al-Hashimi and Amer, 1985; Jassim and Goff, 2006; and Aqrawi *et al.*, 2010). Karim (1997) mentioned that the Pila-Spi and Avanah formations show homogeneous and continuous lateral extension. Ameen and Mardan (2019) reported that the Gercus Formation laterally changed to the Avanah and Sagrma formations in the south and southwest direction of the Darbandikhan area. This formation is occasionally inter-fingered with the lower part of the Pila Spi Formation in the Duhok area (Barzani, 2016). Due to the effects of depositional environments and diagenesis processes, the Avanah Formation in the studied sections is composed of different lithologies, such as limestone, dolomitic limestone, dolostone, and marly limestone.

The lower contact of the Avanah Formation, as observed across all studied sections, is marked by an unconformable surface overlying the Khurmala Formation. This boundary is characterized by abrupt changes from dark grey, highly porous, fossiliferous limestone of the Khurmala Formation, rich with organic matter, gastropod, and pelecypod shells (Fig. 2), to creamy-colored well-bedded, fine crystalline fossiliferous limestones of the Avanah Formation (Pirot, 2017) (Fig. 3). The upper part of the limestone bed of the Avanah Formation at the Sartak-Bamo section changed gradually from light gray, well-bedded fossiliferous limestone and dolomitic limestone to massive dolostone of the Pila Spi Formation (Figs. 3 and 5). In the Belula Gorge section, the contact between the Jaddala Formation and the Avanah Formation is clearly visible (Fig. 4). The upper part of the Avanah Formation changed gradually from creamy-colored, porous, fossiliferous limestone to the overlying dark grey marly limestone, rich with planktonic foraminifera of the Jaddala Formation (Figs. 4 and 6).

While at the subsurface sections (K90 and K306 Wells), according to the internal reports of the Kirkuk North Oil Company and within the current study, the upper contact of the Avanah Formation with the Lower Fars (Fatha) Formation is unconformable, surface, and marked by a conglomerate bed that is known as the basal Fars conglomerate (BFC).



**Fig. 2. (left) Dark grey, highly porous, fossiliferous limestone of Khurmala Formation, rich in organic matter, Gastropod and Pelecypod shells.**

**Fig. 3. (right) Field Photo showing underlying Khurmala and overlying Pila Spi formations of Avanah Formation at the Sartak-Bamo Section.**

Based on field observation and petrologic study, the Avanah Formation exhibits significant lithological variability across different sections. Three distinct lithological units (A, B, and E) are recognized in the Sartak-Bamo section (Fig. 5), whereas four lithological units in the Belula section (A, B, D, and E) (Fig. 6) are identified. At the (K-90 and K-306 Wells), four lithological units (A, B, C, and E) (Figs. 7 and 8) are identified. These sedimentary units are characterized by various fossil content (large and small benthic foraminifera and other fossils).

However, according to internal reports of Kirkuk North Company (KNOC), the Avanah Formation is divided into two units based on porosity properties (the lower and upper units).

Leached zone, heavily recrystallized, partially dolomitized, fractured beds, vuggy, porous, and fossiliferous limestone, occasionally saturated with oil, are the main characteristics of the whole lithology of the Avanah Formation (at these subsurface sections).

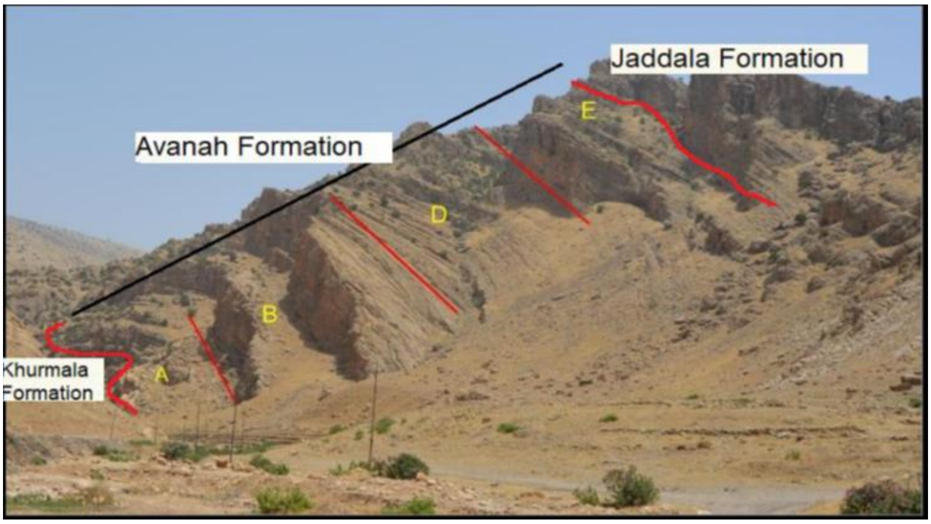
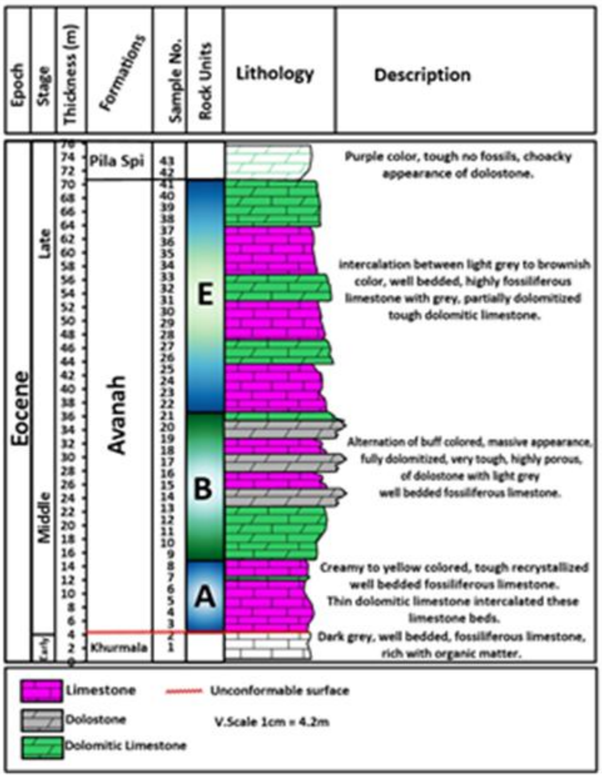



**Fig. 4. Field Photo for Avanah Formation from Belula section showing the underlying and overlying formations with the four identified lithostratigraphic units.**



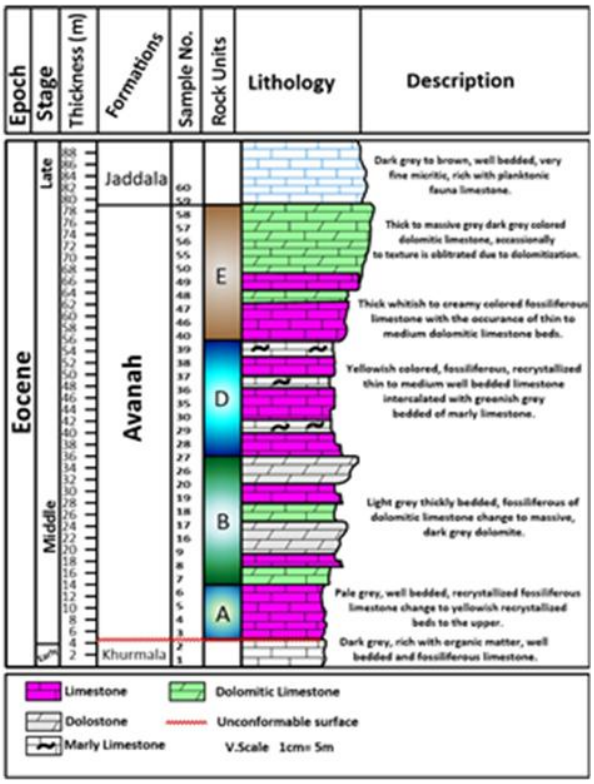




**Fig. 5. Stratigraphic column of Avanah Formation at the Sartak- Bamo section**

**Fig. 6. Stratigraphic column of Avanah Formation at the Belula section.**

## Lithological units of the studied sections

**Unit (A):** This unit unconformably overlays the dark grey limestone beds of the Khurmala Formation. It is composed of creamy to yellowish grey, fossiliferous, well-bedded limestone, dark grey, and highly porous dolomitic limestone beds (especially at the Sartak-Bamo section) intercalated with the limestone beds. Nummulite, Alveolina, and Orbitolites are the most identified larger benthic foraminifera (LBF) of unit A. Detecting the Orbitolites complanatus at the lower part of this unit can be suggested as a valuable indicator for identifying the presence of the Avanah Formation and determining its age. Dolomitization, recrystallization, and dissolution affected different parts of unit (A).

**Unit (B):** This unit is characterized by the alternation of light grey, highly porous, dolomitized fossiliferous limestone of (40-70 cm) thick, with buff-colored, massive dolostone of (1-3 m) thick. Some thin to thick yellowish-colored recrystallized fossiliferous limestone beds, especially from the subsurface sections (K-90 and K-306), are identified at the lower and middle parts. The fossil assemblages of this unit are the same as in unit (A), but the Orbitolite species no longer exist.

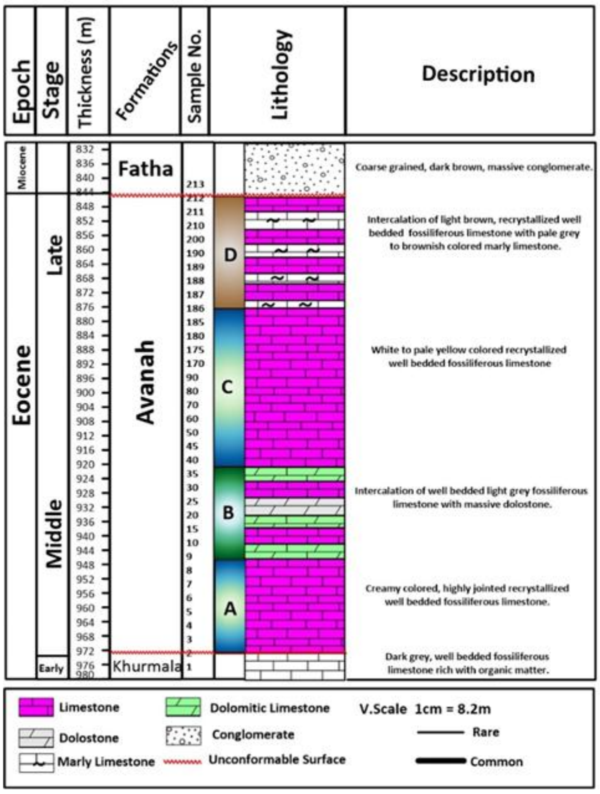



**Fig. 7. Stratigraphic column of Avanah Formation at Well (K 90).**

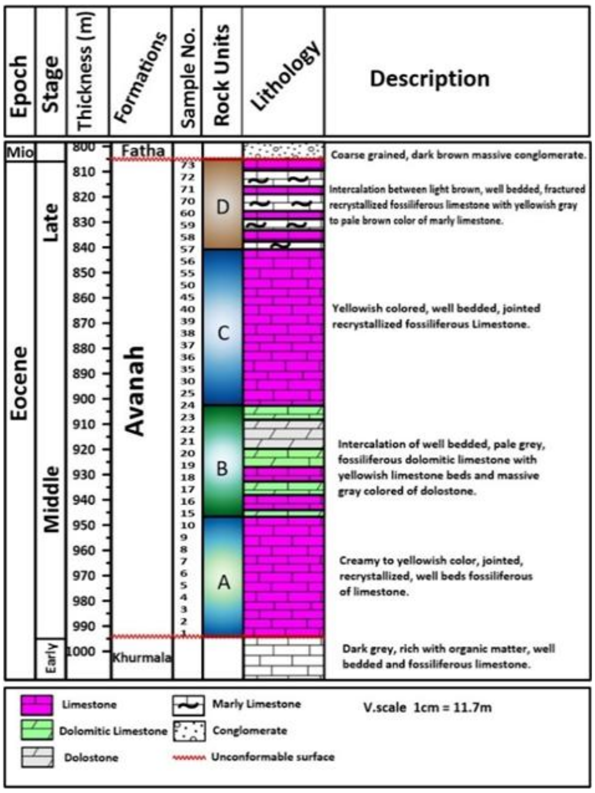



**Fig. 8. Stratigraphic column of Avanah Formation at Well (K 306).**

**Unit (C):** This unit is observed in (K-90 and K-306 Wells) with depths of (920- 876) m and (903- 842) m, respectively. It is characterized by yellow-to-brown colored well-bedded recrystallized fossiliferous limestone. Various types of porosities are detected in the lower part of this unit. Whereas the middle and the upper parts are affected by recrystallization and dissolution. Nummulites, Discocyclina, and Assilina species are the identified faunal assemblages of this unit.

**Unit (D):** This unit is observed at the middle part of the Belula Gorge and the upper parts of the K-90 and K-306 sections. It is characterized by yellowish to light brown, thin to medium well-bedded recrystallized fossiliferous limestone, alternated with greenish grey thin to thick marly limestone beds. Lenticular and flattened shapes, Discocyclina and Assilina species are the common recorded fossil assemblages, while Nummulite species and their bioclasts are less prevalent. The morphology test of these fossils strongly reflects the physical condition of a relatively shallow water and high-energy regime.

**Unit (E):** Alternation of light grey to creamy colored, medium to thick, well-bedded, fossiliferous limestone, with dark grey colored, thick to massive dolomitic limestone is the main characteristic of this unit. Nummulites, Assilina, and Discocyclina are the most identified fossil assemblages within this rock unit, in addition to small benthic foraminifera. While the Alveolina species are not observed in this unit. Recrystallization and dissolution had affected various parts of this unit.

## Description and interpretation of major microfacies types (MFTs)

The facies component percentages in the studied thin sections are identified. Various large and small benthic foraminifera, such as Alveolina spp. (Fig. 9-a), Nummulites spp. (Fig. 9-b, c, and d), Discocyclina spp. (Fig. 9-e), *Orbitolites complanatus* (Lamarck) (Fig. 9-f), Assilina spp. (Fig. 10-k), Miliolids spp., Rotalids spp., calcareous algae, skeletal fragments of echinoderms, pelecypods, and others are identified. These fossil assemblages are good indicators for detecting the sedimentary environment and age of the formation.

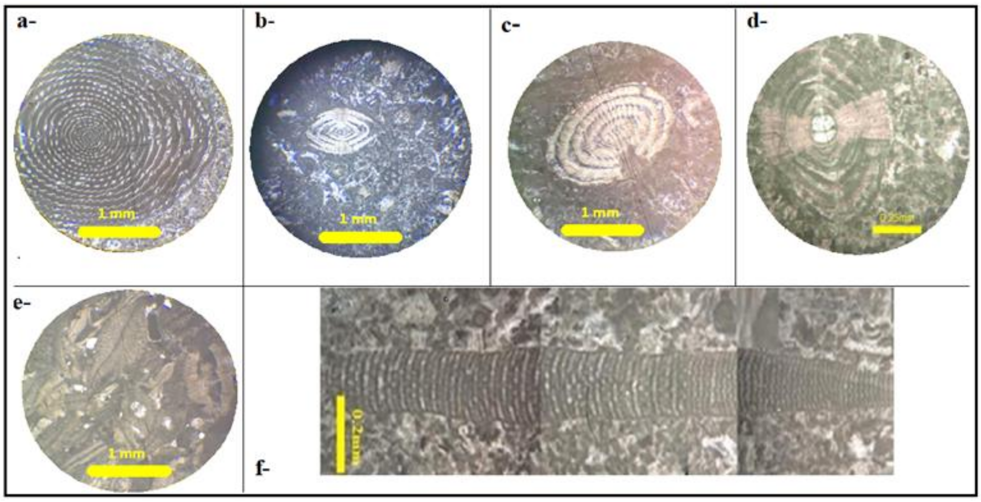


**Fig. 9. Photomicrographs showing the foraminiferal taxa identified in the Avanah Formation. (a) Alveolina spp., Sartak-Bamo section, S.No.13; (b) *Nummulites* spp., Sartak-Bamo section, S.No.14; (c) *Nummulites* spp., Sartak-Bamo section, S.No.12; (d) *Nummulites* spp., Sartak-Bamo section, S. No. 21; (e) *Discocyclina* spp., Belula section; (f) *Orbitolites complanatus* (Lamarck) Sartak-Bamo section, S. No. 3.**

Studying the skeletal and non-skeletal components, textural and lithological characteristics of the carbonate rocks, reveals the presence of four major carbonate microfacies that are subdivided into 11 submicrofacies types (Table 2).

**Table 2: Main microfacies and submicrofacies types of the Avanah Formation.**

| Mudstone | Wackestone | Packstone | Packstone-Grainstone |
|---|---|---|---|
| ● Micritic mudstone Submicrofacies<br>●Bioclastic mudstone Submicrofacies | ●Miliolidal wackestone Submicrofacies<br>●Bioclastic wackestone Submicrofacies<br>●Discocyclina, Nummulite Wackestone Submicrofacies | ●Alveolinal packstone Submicrofacies<br>●Bioclastic packstone Submicrofacies.<br>●Miliolidal packstone Submicrofacies<br>● Assilina, Discocyclina-Nummulitic packstone Submicrofacies. | ● Nummulitic packstone-Grainstone submicrofacies<br>●Bioclastic Peloidal packstone-grainstone Submicrofacies. |

## 1- Micritic mudstone submicrofacies (Mf 1)

***Description:***

Dark brown micritic groundmass and lack of fossils except some scattered fine bioclasts with a high amount of argillaceous material and organic matter are the main characteristics of this submicrofacies (Fig. 10a). This microfacies type is very common in all studied sections, especially in the two subsurface wells and Belula sections. It is observed only in the middle part of the Sartak-Bamo section. The effects of dolomitization processes are obvious in different parts of the studied sections, which occasionally cause to change in the micritic mudstone submicrofacies to dolomitic mudstone submicrofacies (Fig. 10-b).

***Interpretation:***

The dominance of the micritic matrix within this submicrofacies indicates that it had deposited in a low-energy and low-oxygenized setting of calm conditions with no water circulation. The fine-grained micritic groundmass is common in a deeper outer ramp and inner ramp; therefore, this submicrofacies corresponds to lagoonal environments of the inner ramp setting, and it is correlated with (RMF 19) according to a homoclinal carbonate ramp of Flügel (2010). This submicrofacies falls within the range of (FZ8) of Wilson (1975) and may have an appropriate situation with the (SMF23) of rimmed carbonate platform.

## 2- Bioclastic Mudstone submicrofacies (Mf 2)

***Description:***

This submicrofacies is recognized at the upper part of all the studied sections, and it is mostly composed of highly recrystallized bioclasts of fine to medium-sized fragments. Bioclasts of calcareous green algae and Mollusks with low diversity of some skeletal grains (such as small miliolids and rotalids) and their bioclasts are embedded in a micritic matrix (Fig. 10c). Many diagenetic processes affected this microfacies, especially dolomitization, which is the most obvious diagenetic process that obliterates some of the constituents.

***Interpretation:***

The prevailing bioclasts of algae and mollusks, with some skeletal grains of miliolids and rotalids, can reveal insights into the water depth, salinity, biological diversity, and environmental stability of the lagoon over time. The predominance of bioclastic shell fragments within a mud-supported microfacies indicates shallow water with limited circulation, of lagoon depositional environments (Flügel, 2010). This submicrofacies corresponds to (RMF17) of the inner ramp setting and is appropriate with the (SMF12) of rimmed platform within the range (FZ8) of Wilson (1975).

### 3- Miliolidal wackestone submicrofacies (Mf 3)

***Description:***

This microfacies is observed at different levels throughout the studied sections. Small miliolids foraminifera, with few Peneroplis and Rotalids, are embedded in the micritic groundmass of this submicrofacies (Fig. 10-d). While some skeletal debris of different fossils and algae are the subordinate components. Micritization is the abundant diagenetic process that affects the allochems and causes them to form a micritic envelope surrounding these grains.

***Interpretation:***

The sedimentation of this submicrofacies occurred under relatively low-energy conditions, typically found in calm, shallow water environments of the inner ramp. According to Flügel (2010), such sediments accumulate in these quiet settings, where energy levels are insufficient to transport larger particles, leading to the deposition of finer sediments. According to Hallock and Glenn (1986)Shallow-water lagoon environments are often characterized by imperforate foraminifera (e.g., miliolids, soritiidae, alveolinidae, and small rotalids). The presence of miliolids within the mud matrix confirms that these submicrofacies types were deposited in low-energy, shallow marine (lagoon) settings (Flügel, 2010). The miliolids inhabit quiet and shallow-water conditions (Khatibi Mehr and Adabi, 2014). Depending on the dominant matrix-supported rock fabric and the moderate to low diversity of the above-mentioned foraminifera, this submicrofacies correlates with the (RMF16), and it was deposited in protected and low-energy inner ramp settings. It corresponds to (FZ 7) of Wilson (1975).

### 4- Bioclastic wackestone submicrofacies (Mf 4)

***Description:***

This submicrofacies is characterized by fine to medium grain size of bioclasts with few worn skeletal grains (Fig. 10-e). This microfacies is common in the two subsurface sections (Well K90 and Well K306) and the Belula section, but is partially present in the Sartak-Bamo section. The identification of the bioclasts is difficult due to wave currents that have caused significant fragmentation.

***Interpretation:***

Most of the particles, which represent fine to medium shell fragments, are typically transported from high-energy to low-energy environments (such as from shallow water to nearby deeper water). This type of sediment transport and deposition is characteristic of lagoonal environments within an inner ramp setting, and corresponds to (RMF17) (Flügel, 2010); or it corresponds to (SMF10) of Wilson (1975) and facies zone (FZ7).

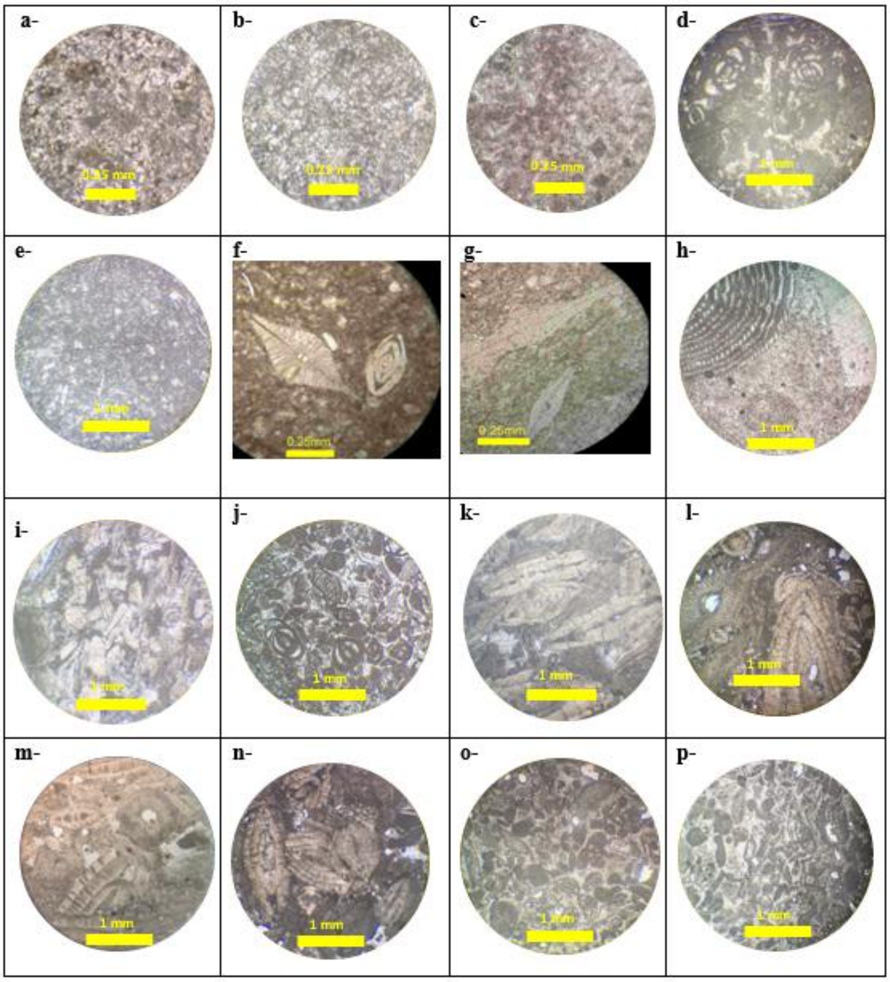



**Fig.10. Photomicrographs revealing the identified submicrofacies types (MFTs) of the Avanah Formation. a- Micritic mudstone submicrofacies (Mf 1). b- Dolomitization causes to change in the micritic mudstone submicrofacies to dolomitic mudstone submicrofacies. c- Bioclastic Mudstone submicrofacies (Mf 2). d- Miliolidal wackestone submicrofacies (Mf 3). e-Bioclastic wackestone submicrofacies (Mf 4). f- Discocyclina-Nummulite wackestone submicrofacies (Mf 5). g- Actinocyclina spp. within the (Mf 5), Belula section. h- Alveolinal packstone submicrofacies (Mf 6). i- Bioclastic packstone submicrofacies (Mf 7). j- Miliolidal packstone submicrofacies (Mf 8). k and l- Assilina, Discocyclina- Nummulitic packstone submicrofacies (Mf 9). m and n- Nummulitic packstone-grainstone submicrofacies (Mf 10). o-Bioclastic Peloidal packstone-grainstone submicrofacies (Mf 11). p-Thin micritic enveloped process around some grains within (Mf 11).**

**5- Discocyclina-Nummulite wackestone submicrofacies (Mf 5)**

***Description:***

This microfacies is observed in the middle part of the Belula section and the two subsurface wells (K 90 and K306) sections. The diagnostic feature of this submicrofacies is the appearance of some well-preserved and easily recognizable large lenticular benthonic foraminifera such as Discocyclina and Nummulites (Fig. 10f). These foraminifera constitute up to 25% of the components of this submicrofacies. Some other skeletal benthic forams, such as *Actinocyclina* spp. (Fig. 10-g) and *Operculina* spp., in addition to some bioclasts, are also observed, which are embedded in a micritic groundmass.

***Interpretation:***

The abundance of the above-mentioned biotic assemblage that disseminated in a micritic matrix and the fine-grained texture indicate a low-energy environment. Beavington-Penney and Racey (2004) and Payros *et al.* (2010) have pointed out that the Nummulites thrived in an open marine environment with a depth of (40–80 m). This submicrofacies represents a shallow open marine of the inner ramp and corresponds to (RMF 13) of Flügel (2010), and according to Wilson (1975), it corresponds to the facies zone (FZ7) and correlates with the standard microfacies type (SMF8).

**6- Alveolinal packstone submicrofacies (Mf 6)**

***Description:***

This submicrofacies is observed at the lower to middle part of the Avanah Formation, especially at the Sartak-Bamo section, and it is characterized by a grain-supported texture in which most of the grains are packed together (Fig. 10-h). Alveolina is a diagnostic large benthic foraminifer of this submicrofacies, which is associated with orbitolite, miliolids, rotalids, echinoid plates, with some bioclasts. The allochems and the groundmass of this submicrofacies, affected by recrystallization, suffered from compaction processes, which caused the packing of the grains, and deformed some of them.

***Interpretation:***

Alveolinids are known to tolerate a wide range of environmental conditions, particularly temperature and salinity variations. This adaptability allows them to thrive in diverse habitats within shallow-marine carbonate platforms (Hadi *et al.*, 2019).

Scheibner *et al.* (2007) regarded that microfacies dominated by alveolinids are characteristic of an inner platform. Orbitolitids, along with a high abundance of alveolinids and a micritic groundmass, often point to conditions typically found in a calm, shallow marine setting (Hottinger, 1983) and (Rasser *et al.*, 2005). The occurrence of Alveolina assemblages confirms an inner ramp depositional setting (Adabi *et al.*, 2008). This submicrofacies of the current study represents shallow open marine sedimentary environments and corresponds with (RMF 13) of the inner ramp setting, and it corresponds to the facies zone (FZ7) of Wilson (1975) and with the standard microfacies type (SMF8).

**7- Bioclastic packstone submicrofacies (Mf 7)**

***Description:***

This submicrofacies is identified within the wells K90 and K306 and Belula sections, but is less common in the Sartak-Bamo section. Several worn-out and micritized skeletal debris are distributed within a grain supporting texture of this facies (Fig. 10i). Some of these bioclasts are smashing and disturbing, and mostly they represent the bioclasts of benthonic foraminifera such as Rotalids and Nummulites with echinoid fragments. Recrystallization, micritization, leaching, and dissolution are the most common diagenetic processes that affected the allochems and the groundmass.

***Interpretation:***

Most of the particles are worn out and micritized, indicating that these bioclasts were transported before deposition, from high-energy settings to low-energy environments. The presence of worn medium to large-sized fragments of nummulites with other bioclasts in the studied samples indicates an open, shallow marine environment with medium salinity, (Milliman *et al.*, 1974).

This submicrofacies represents the mid-ramp setting and corresponds to the (RMF7), and according to Flügel (2010); it is equivalent to (SMF 10).

**8- Miliolidal packstone submicrofacies (Mf 8)**

***Description:***

Grain-supported texture with a few amounts of micrite between or around the allochems is the main characteristic of this facies. Miliolids are the predominant skeletal grains with some peloids and green algae bioclasts (Fig. 10-j). Micritization and recrystallization processes are the main diagenetic processes that affect the components. This submicrofacies is well developed only at the lower part of the Sartak-Bamo section, and is not recognized at Belula and the two subsurface wells sections.

***Interpretation:***

Miliolids are observable in shallow and restricted lagoon environments (Wilson, 1975). Diversity and abundance in a large number of miliolids are good indicators of low-energy, shallow marine, clean tropical, saline waters of the restricted inner platforms (shelf-lagoon) and inner ramp setting (Flügel, 2010).

The miliolids inhabit calm and quite shallow water conditions, and their great dominance suggests nutrient-rich and lagoonal marine conditions of the inner ramp (Racey and Simmons, 1994; Beavington-Penney *et al.*, 2006; Adabi *et al.*, 2008; Khatibi Mehr and Adabi, 2014). Miliolid foraminifera are prevalent in lagoonal environments, particularly those with elevated salinity, during the Mesozoic and Cenozoic eras, and are well-adapted to the specific conditions found in restricted inner platforms and inner ramps (Abd El-Moghny and Afifi, 2022).

Accordingly, this submicrofacies is compatible with shelf lagoons with open circulation (FZ 7) and may correlate with the standard microfacies type (SMF18-For) and (RMF 16) of the inner ramp setting.

**9- Assilina, Discocyclina- Nummulitic packstone submicrofacies (Mf 9)**

***Description:***

This submicrofacies is well identified at the lower and middle parts of the Avanah Formation at the Belula section, in addition to the lower parts of the two subsurface Wells (K90 and K306). Large benthonic forams such as *Nummulite* spp., *Discocyclina* spp., and *Assilina* spp. are the most abundant components of this submicrofacies, with their large bioclasts.

These allochems are well preserved, highly packed, and form a grain-supported texture (Fig. 10-k and l). Granular sparry calcite cement partially fills the intergranular spaces between skeletal grains.

***Interpretation:***

Large benthic foraminifera, prevalent throughout a grain-supported texture, indicate deposition in the mid-part of the ramp setting, below the fair-weather wave base (Mateu-Vicens *et al.*, 2012; Moallemi *et al.*, 2014).

The association of flat and discoidal shapes of large benthonic foraminifera, such as discocyclina and nummulites, generally suggests that these organisms lived in relatively deep, low-energy environments with low light conditions. (Sarkar, 2017). Flourishing of flat Nummulitic foraminifera in deeper mesophotic, clay-dominated settings reflects their adaptation to low-light, low-energy environments with fine sediments (Mateu-Vicens *et al.*, 2012). Hottinger (1997) suggested that the large benthonic foraminifera, like Assilina, with thinner tests, are typically found in environments with low water transparency or in deeper waters due to their adaptability to low-light conditions (Banerjee *et al.*, 2018).

So, the occurrence of large disc-shaped nummulites that are associated with large discocyclina and assilina within this submicrofacies of the current study was deposited below the fair-water wave base (FWWB). According to Rasser *et al.* (2005); Flügel (2010) and Hadi *et al.* (2019), this facies in the current study is suggested to correspond to (RMF 8) as assigned by Flügel (2010) and it is typically deposited in a middle ramp environment open marine setting.

**10- Nummulitic packstone-grainstone submicrofacies (Mf 10)**

***Description:***

This submicrofacies is common in the middle and upper parts of the studied subsurface wells and the Belula section, but it does not appear in the Sartak-Bamo section. It is characterized by a high abundance of large, robust to flat forms of Nummulites, with a compact texture (Fig. 10-m and n). Fragments of Assilina, Discocyclina, Nummulite, algae, and echinoderms are also identified. The recrystallization process affected the micrite ground-mass, forming microsparite or pseudosparite cement between the skeletal grains.

***Interpretation:***

In the current study, this submicrofacies is indicative of a shallow water environment, where high-energy processes played a dominant role in sediment deposition. Racey (2001) observed that smaller and lenticular forms of Nummulites tests are more commonly found in shallower, inner platform, shelf, or ramp settings, and conversely, they are generally absent from more restricted water environments. The nummulites accumulation forms in a broad range of water depths in the inner and mid-ramp within the photic zone. According to Martín-Martín *et al.* (2021), during the middle Lutetian to Bartonian period, hyaline LBF (larger benthic foraminifera)-rich facies were prevalent, leading to the creation of extensive, thick nummulitic banks. These banks were primarily composed of large, robust to flat forms of Nummulites tests. Within these bank (shoal) environments, the shapes of Nummulites tests range from spherical and robust to more flattened forms (Fig. 11). The morphology of larger foraminifera is influenced by various environmental factors, including water depth gradients, light intensity, and hydrodynamic forces (Hottinger, 1983).

Hadi *et al.* (2016) proposed that the distinctive morphology of A-form Nummulites is characterized by their robust and ovoid tests, and they can serve as a useful indicator for identifying palaeohighs in shallow inner-ramp environments. Moreover, Attila *et al.* (2016) mentioned that the predominance of the abraded Nummulites assemblages indicates that the deposits were deposited in a shallow water environment with high hydrodynamic activity in a wave-dominant setting. Accordingly, the robust to flat nummulites of this submicrofacies in the current study can be developed in a shoal setting corresponding to (RMF 26) of a shallow inner ramp environment.

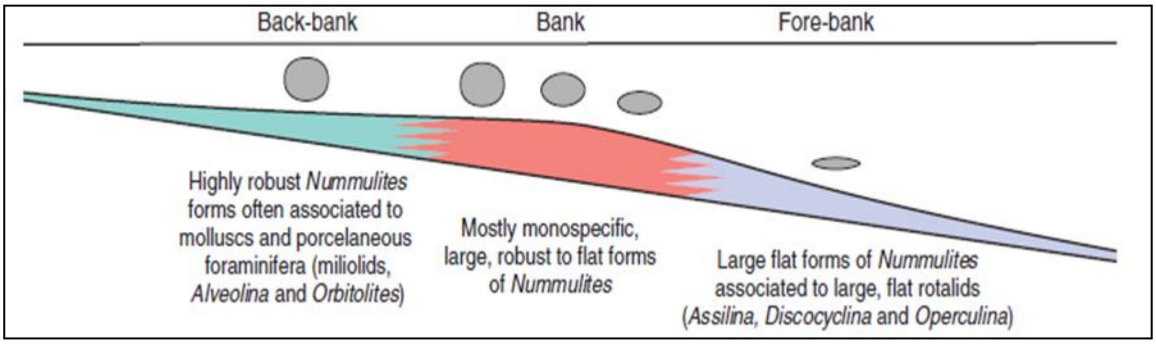



**Fig. 11. General scheme of a nummulitic bank, after Mateu-Vicens *et al.* (2012).**

**11- Bioclastic Peloidal packstone -grainstone submicrofacies (Mf 11)**

***Description:***

This type of submicrofacies is only observed in the Sartak-Bamo section. Sub-rounded to rounded, medium-sized allochems embedded in sparry and micritic matrix. The allochems are represented by bioclasts, peloids, intraclasts, and some small-coated foraminifera skeletal grains (miliolids) with amounts of calcareous algae (Fig. 10-o). Due to the effects of thin micritic enveloped process around some grains, the identification of them became very difficult (Fig. 10-p). In addition to this, dissolution, recrystallization, and compaction diagenetic processes affected some allochems and parts of the groundmass. Different types of porosity (molds; intra and inter particles) are observed.

***Interpretation:***

The variance morphology of the allochems suggests that the deposition took place under moderate to high-energy conditions in a shallow condition of subtidal setting, which caused reworking and deposition of the sub-rounded to rounded grains within the basin. The relatively identified textures (sub-rounded to rounded, micritic outlines, grains, moderately sorted allochems, and grain-supported texture) are a good indication that these sediments of this submicrofacies could be deposited in shallow marine environments (Hashmie *et al.*, 2016) with active and winnowed hydrodynamic conditions. This submicrofacies corresponds with the (RMF 27) shoal and bank of the inner ramp setting.

## Depositional environments

Integrating all collected data (depositional texture, grain types, their abundances, and their ratio to groundmass according to Dunham (1962), can be used to infer depositional environments both horizontally and vertically. Determining the microfacies is the main indicator of the carbonate platforms (Flügel, 2010; Zhang *et al.*, 2020). Different investigations were carried out, which proposed determining and interpreting the depositional environment of the Avanah Formation. Therefore, all the identified data of the current study, such as microfacies, faunal assemblages, lithological association, and the field observations, can be employed to identify and distinguish the three main facies associations that are related to energy conditions. Consequently, it can be suggested that the Avanah Formation was deposited in a carbonate ramp environment.

### Detailed explanation of the depositional environments

### I-Inner ramp

In the current study, three sub-environments were distinguished in the inner ramp setting.

### I-A Semi-restricted lagoon facies associations

This setting comprises five microfacies as follows: 1) Micritic mudstone submicrofacies (Mf1), 2) Bioclastic Mudstone submicrofacies (Mf2), 3) Miliolidal wackestone submicrofacies (Mf3), 4) Bioclastic wackestone submicrofacies (Mf4), and 5) Miliolidal packstone submicrofacies (Mf8). At several intervals of the Avanah Formation in the studied sections, the high proportion of micrite matrix, occasionally represented by miliolids wackestone and packstone microfacies types are good indication of a low-energy environment that was deposited in a quiet environment, such as a restricted lagoon or semi-barred basin environments (Adachi *et al.*, 2004). The coexistence of Alveolina with miliolids and orbitolitids with their micritized skeletal fragments in the micritic texture has a significant role in a shallow water inner ramp- semi-restricted lagoonal setting and a back shoal setting (Boudaugher-Fadel, 2018). This situation conforms to the lower part of the Avanah Formation at the Sartak-Bamo section.

It is revealed that the above-mentioned submicrofacies were deposited within the (FZ 7 and 8) of Wilson (1975) and Flügel (2010), which represent semi-restricted platforms in inner ramp settings. Abd El-Moghny and Afifi (2022) concluded that shallow nearshore and lagoonal environments, down to about 50 m, are characterized by porcelaneous miliolid foraminifera.

### I-B Shoal facies associations

The main microfacies represented in the shoal association of the current study comprise three submicrofacies: Nummulitic packstone-grainstone submicrofacies (Mf 10) and Bioclastic Peloidal packstone-grainstone submicrofacies (Mf 11).

These submicrofacies associations are characteristics of shallow water, under the influence of a moderate-to-high energy current-swept condition. They are typically suggested by the presence of coated bioclasts, nummulites assemblages, and micritized grains, which are set in a packstone-grainstone texture with low portions of mud content. This idea is consistent with Al-Hashimi and Amer (1985), that the Avanah Formation was deposited in a shoal bank.

Nummulites inhabited a wide range of open marine environments, including both ramps and shelves (Mateu-Vicens *et al.*, 2012) (Fig. 9). Racey (2001) stated that “Nummulitic banks are common in Early and Middle Eocene Tethyan shallow-marine carbonates, especially in oligotrophic settings”.

While Jorry *et al.* (2006) suggested that the autochthonous Nummulites deposits can be found as in situ winnowed bioaccumulations or be accumulated offshore, onshore or alongshore, away from the original biotope according to various geological and oceanic processes.

Coated bioclastic packed-grainstone, within grain-supported textures, moderately sorted grains, and cemented material indicates a relatively high-energy setting under shoal environment agitated water (winnowed platform area) with content wave action at or situated above the fair water wave base (Flügel, 2010).

**I-C Shallow open marine facies associations**

This setting comprises 2 to 3 submicrofacies, such as Alveolinal packstone submicrofacies *(*Mf 6) and Discocyclina-Nummulite wackestone submicrofacies *(*Mf 5*)* types. The abrupt change from restricted to shallow open marine microfacies and again to restricted platform environments indicates the oscillation in sea-level during the deposition of the Avanah Formation.

Moderately sorted large porcelaneous foraminifera, mainly comprising sub-globular to ovoid tests of Alveolina, characterize Alveolinal packstone submicrofacies. Sub-globular to ovoidal alveolinids suggest a shallow-marine depositional setting corresponding to euphotic and oligotrophic conditions (Sarkar, 2019). Sediment rich in alveolinids/rotalids assemblages is typically habitat in inner ramp environments in non-vegetated substrates (Španiček *et al.*, 2017).

Hallock and Glenn (1986) pointed out that the larger foraminifera (such as Discocyclina and Nummulites) appear in shallow, well-lit sea bottom, and if they are not transported to the deeper basins, their appearance is indicative of depth less than 30m. Porcelaneous larger benthic foraminifera assemblages are commonly indicative of oligotrophic environments, which are the characteristics of the inner ramp setting. These foraminifera thrive in conditions of sufficient light with low nutrient levels (Martín-Martín *et al.*, 2023). So, the above-mentioned submicrofacies in the current study can be associated with and correspond to the shallow open marine environments of the inner ramp setting.

**II- Middle ramp facies associations**

The association of middle ramp facies consists of Bioclastic packstone submicrofacies (Mf 7) and Assilina, Discocyclina- Nummulitic packstone submicrofacies (Mf 9) types.

In the current study, the occurrence of worn-out and micritized medium to large-sized echinoid fragments with bioclasts of some benthonic foraminifera indicates that these bioclasts were transported before deposition from high-energy settings to low-energy environments.

On the other hand, the coexistence of large flat to discoidal benthic foraminifera like Assilina sp. and Discocyclina sp. with large flat Nummulites sp. suggests a range of depositional environments within the middle ramp setting. These environments are described as spanning from the distal parts of the inner ramp to the proximal open-marine middle ramp environments.

Nummulite-rich facies with a paucity of alveolinids and orbitolitids indicate deposition below the fair-weather wave base (FWWB) and in the middle platform environment (Rasser *et al.,* 2005; Hadi *et al.,* 2019).

## Discussion

Detecting microfacies types is crucial for inferring paleoenvironmental conditions and understanding sedimentological processes of the Avanah Formation. Accordingly, all the detected microfacies types of the current study are compared with the standard microfacies types in the Facies Zones (FZ) of the rimmed carbonate platform model and microfacies types in different parts of a homoclinal carbonate ramp of (Wilson, 1975; Flügel, 2010).

In general, the mudstones and wackestones microfacies are often formed and indicative of low-energy environments and revealing that the energy levels are not high enough to rework sediments, allowing for fine particles and carbonate materials to settle and accumulate. These microfacies types have a wide distribution in the semi-restricted lagoon environments of the inner ramp setting in the studied sections, and are represented by the submicrofacies (Mf 1, Mf 2, Mf 3, and Mf 4).

Whereas, the rich-miliolid packstone submicrofacies (Mf 8) that is characterized by a low-diversity of foraminiferal association, could reflect an environment protected from strong wave action, and it can be deposited in a shallow semi-restricted lagoonal environment of an inner ramp environment with low energy. This situation conforms to the lower part of the Sartak-Bamo section.

The Alveolinids tend to thrive in relatively calm, clear, and warm marine environments, and are represented by the submicrofacies (Mf 6) in the current study. It indicates shallow water, vegetation-covered substrates behind the nummulitic bank based on the abundance of Orbitolites and Alveolina species (Jorry *et al.,* 2006). This submicrofacies (Mf 6) is associated with the Discocyclina-Nummulite wackestone submicrofacies (Mf 5), which can infer the depositional environments of the Avanah Formation in the studied sections.

The combination of these submicrofacies suggests a shallow, open marine environment typical of the inner ramp setting, which is characteristic of relatively shallow depth, resulting in varied energy conditions. The packstones indicate areas of higher energy or more active sediment transport, while the wackestones point to slightly quieter conditions. These variations in sediment types and associated fauna help to paint a picture of a dynamic shallow open marine environment with both high-energy and more sheltered zones of the inner ramp setting.

The Avanah Formation shows a clear gradient from open shallow water of low-energy conditions to the more energetic conditions shoal setting with better-sorted coarser sediments.

The shoal facies association of the Avanah Formation consists of Nummulitic packstone-grainstone submicrofacies (Mf 10) and Bioclastic Peloidal packstone-grainstone submicrofacies (Mf 11).

At Sartak-Bamo, the moderate to well-sorted, sub-rounded to rounded, coated bioclastic packstone-grainstone indicates episodic events, which exhibit micritization, grain-supported texture, and cemented rims that highlight their deposition in a high-energy condition, situated above the (FWWB) in a shoal environment (Flügel, 2010). While the middle and upper parts of the Belula section and both subsurface sections (wells K90 and K306) contain large and robust to flat forms of Nummulites assemblages, indicating that these parts were deposited within shoal environments of an inner ramp setting. The Nummulites formed significant accumulations in various marine environments. Nummulites inhabited a wide range of open marine environments, including both ramps and shelves (Mateu-Vicens *et al.,* 2012). Whereas

Racey (2001) mentioned that their deposits are often found in inner and mid-ramp settings within the photic zone.

In the current study, the middle ramp facies association consists of Assilina, Discocyclina- Nummulitic packstone submicrofacies (Mf 9) and bioclastic packstone submicrofacies (Mf 7). Assilina, Discocyclina, and Nummulites forms are generally well-adapted to environments with low to moderate energy conditions. The presence of large benthic disc-shaped foraminifera such as Nummulites, Assilina, and Discocyclina in the Avanah Formation at the Belula section and both studied subsurface wells (K306 and K90) indicates that these organisms typically inhabited shallow open marine environments, particularly ranging from the inner to middle ramp settings.

Based on the evidence provided and the accumulation of the mentioned foraminiferal fossils (and other petrographic components), it suggests that the Sartak-Bamo section is characterized by environments ranging from a semi-restricted lagoon to a shoal environment at the inner ramp setting (Fig. 12). The Avanah Formation at the Belula section exhibits a progression from a low-energy, back shoal environment through a more energetic shoal setting to a shallow open marine environment within an inner to middle ramp setting (Fig. 13).

At the wells (K90 and K306), the depositional environments of the Avanah Formation show a consistent pattern of transition from shoal to shallow open marine environment, and extending from the inner to middle ramp settings (Figs. 14 and 15).

This suggests that overall, the depositional environments of the Avanah Formation at the studied areas began as semi-restricted lagoonal settings to high-energy environments (shoals), to a shallow open marine condition of the inner ramp, then extending to a middle ramp setting (Fig. 16).

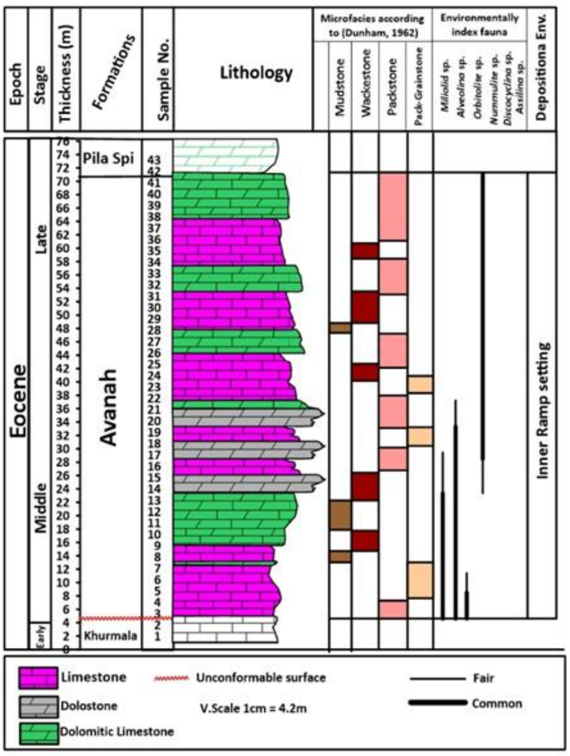



Fig.12. Sartak-Bamo Section.

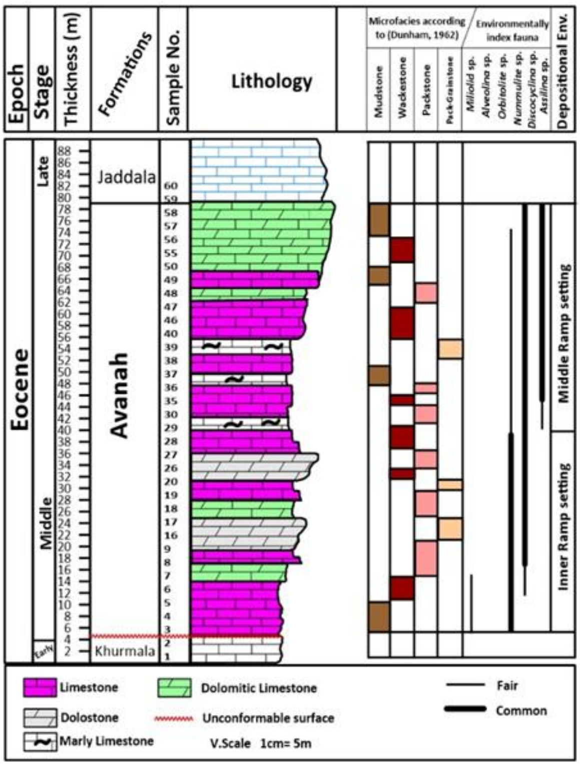



Fig. 13. Belula Section.

**Microfacies types, faunal assemblages, and depositional environments of the Avanah Formation at Sartak-Bamo section (left) and Belula section (right).**

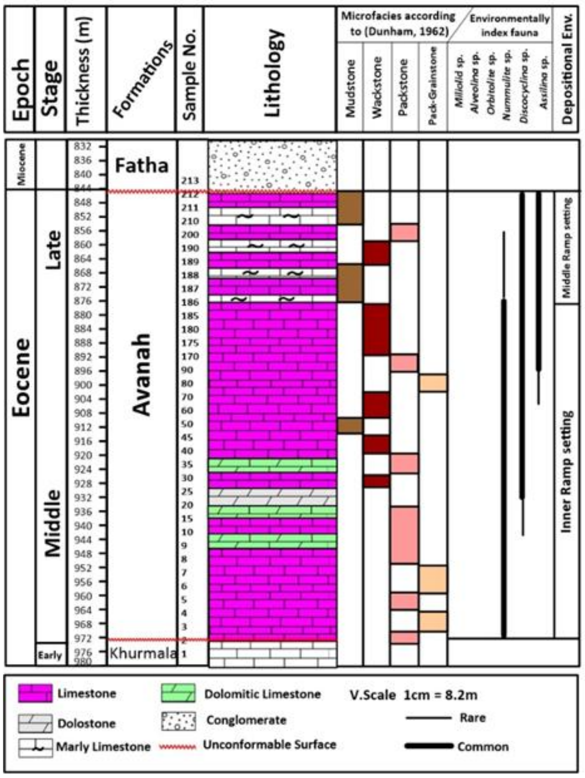



**Fig. 14. Well K-90**

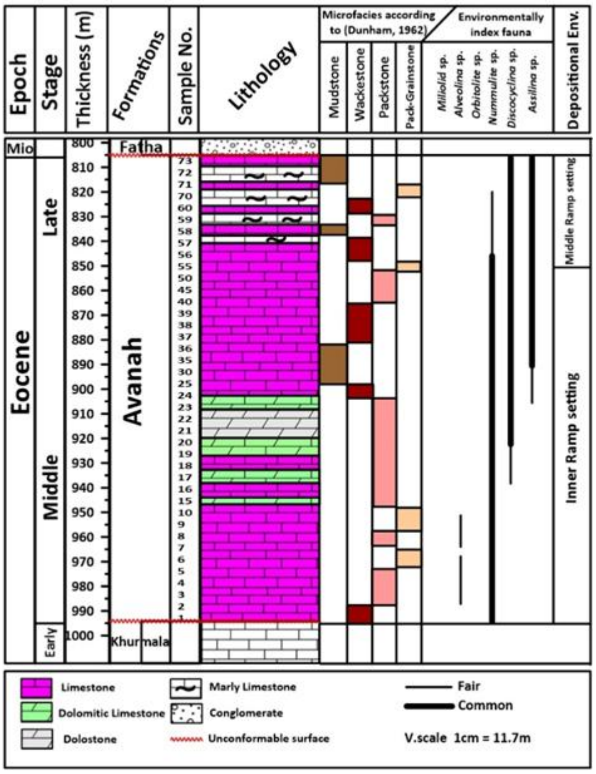



**Fig. 15. Well K-306**

**Microfacies types, faunal assemblages, and depositional environments of the Avanah Formation at Well K90 (left) and Well K306 (right).**

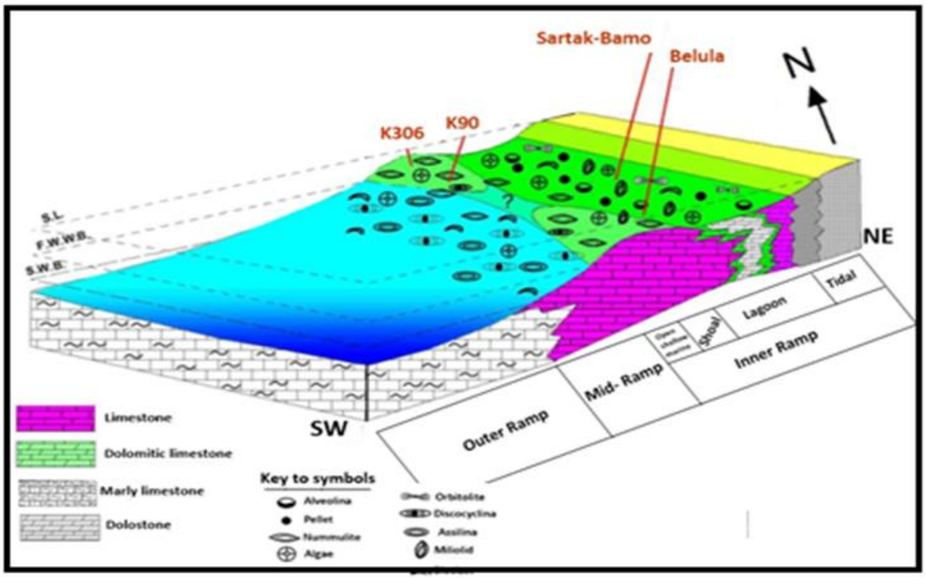



**Fig. 16. Depositional and facies model of the Avanah Formation in the studied area.**

## Conclusion

1-The Avanah Formation shows a significant spatial variation in thickness across the studied sections. In the subsurface wells (K90 and K306), which are located in the ZLFZ, the Avanah Formation is thicker, with measurements of 127 meters and 186 meters, respectively. In contrast, the thickness of the Avanah Formation decreases towards the ZHFZ direction at surface sections, with measurements of (64 m at Sartak-Bamo and 75 m at Belula section. This pattern indicates a spatial variation in the thickness of the Avanah Formation due to various geological factors such as sedimentation, tectonic activity, or erosional processes that might be influencing the distribution and development of this formation.

2- The Avanah Formation unconformably underlain by the Khurmala Formation at all studied sections. At Wells K90 and K306, the Avanah Formation is unconformably overlain by the Fatha Formation, whereas at the Sartak-Bamo and Belula sections, the Avanah Formation has a conformable upper contact and is overlain by the Pila Spi and Jaddala formations, respectively.

3- Petrographically, the Avanah Formation is composed of micrite, cement, skeletal grains (Nummulite, Alveolina, Miliolid, Discocyclina, Assilina, Orbitolite, Alga, Bioclasts… etc.) and non-skeletal grains (Peloids, Extra clasts and Intra clasts).

4- In the studied sections, several distinct lithofacies have been identified (limestone, dolomitic limestone, dolostone, and marly limestone). Notably, the Sartak-Bamo section stands out as having thicker dolomitic limestone and dolostone lithofacies compared to the other three sections.

5- The Marly limestone lithofacies present in the middle to upper parts of the formation at the Belula section and wells (K90 and K306) reflect a deeper water environment compared to the Sartak-Bamo section, which lacks this lithofacies and may represent a shallower, more carbonate-dominated setting. This stratigraphic evidence helps in reconstructing the paleoenvironments and understanding the changes in depositional conditions over time and space within the Avanah Formation.

6- Different diagenetic processes have affected the carbonate rocks of the Avanah Formation, such as recrystallization, cementation, neomorphism, dolomitization, micritization, dissolution, and compaction.

7- Four main microfacies (Mudstone, Wackestone, Packstone, and Packstone-Grainstone) are identified, which they typically categorized into eleven submicrofacies based on their composition, texture, and fossil content.

8- The depositional environments of the Avanah Formation range from more restricted lagoonal settings to open marine conditions. Environments ranging from a semi-restricted lagoon to a shoal (bank) setting characterize the Sartak-Bamo section. The depositional environment of the Belula section, K90, and K306 Wells, starts with shoal (bank) conditions, then transitions to a shallow open marine environment extending from inner to middle ramp settings.

The depositional environment of the Avanah Formation encompassed a variety of settings ranging from the semi-restricted shallow lagoons, shoals (banks), to shallow open marine environments (of the inner ramp) and extending from the inner to the middle ramp setting.

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