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BIOSTRATIGRAPHY AND MICROFACIES OF THE MAUDDUD FORMATION (LATE ALBIAN – EARLY CENOMANIAN) IN MUSAIYIB WELL NO.1, CENTRAL IRAQ

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Keywords: Biostratigraphy; Mauddud Formation; Late Albian- Early Cenomanian; Microfacies; Depositional environment; Central Iraq

ABSTRACT

Upper Albian and Lower Cenomanian biostratigraphy and microfacies types of the Mauddud Formation from Musaiyib well No.1, Central Iraq are described and examined, which consists of thick to medium bedded limestone, marly limestone rich in argillaceous material, green shale, and dolomitic limestone beds. Thirty-six species from twenty-two genera of benthic foraminifera in addition to calcareous algae, coral, bivalves, gastropods, rudist fragments, brachiopods, bryozoan, and echinoid fragments are recognized from the Mauddud Formation of the studied well. On the basis of the recognized benthic foraminifera three biozones were determined:

Mesorbitolina texana - *Orbitolina qatarica* Concurrent Range zone- *Orbitolina sefini*- Total R. Zone and *Orbtolina concava* Total R. Zone. Both suggest the Late Albian – Early Cenomanian age. The results of this study are compared with the work of others inside and outside Iraq. Based on the petrographical analyses, four major microfacies (Mudstone, wackestone, wackestone to packstone, and packstone), and nine sub-microfacies were identified. The Mauddud Formation was formed in a marine environment that was composed of the following three sub-environments: the inner ramp and the middle to the outer ramp.

الطباقية الحياتية والسحنات الدقيقة لتكوين مودود (ألبيان المتأخر – سينومانيان المبكر) في بئر مسيب رقم 1، وسط العراق

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الكلمات الدالة: الطباقية الحياتية؛ تكوين مودود؛ ألبيان المتأخر - سينومنيان المبكر؛ السحنات الدقيقة؛ بيئات ترسيبية؛ وسط العراق

المستخلص

تهدف هذه الدراسة الى تحديد العمر النسبي والسحنات الدقيقة لتكوين مودود في بيئر مسيب 1، وسط العراق. تم تشخيص ست وثلاثون نوعا من الفورامنيفيرا القاعية تعود الى اثنان وعشرون جنسا. وقد تم تسجيل ثلاث أنطقة حياتية المعتمدة على الفورامنيفيرا القاعية لعمر البيان المتأخر - سينومانين المبكر وهى من الأقدم الى الأحدث:

1-Mesorbitolina texana - *Orbitolina qatarica* Concurrent Range Zone
2- *Orbitolina sefini* Total Range Zone
3- *Orbtolina concava* Total R. Zone

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و من ثم تم مقارنة الأنطقة المشخصة في هذه الدرا سة مع الأنطقة الأخرى لدراسات سابقة داخل وخارج العراق. بناءً على التحليلات البتروغرافية، وعليه تم تحديد أربعة سحنات دقيقة أساسية مع تسع سحنات فرعية (Mudstone، wackestone، wackestone to packstone and packstone). ان تكوين مودود قد ترسب في بيئة بحرية تحتوي على البيئات الفرعية الثلاث التالية: المنحدر الداخلي والمنحدر الأوسط إلى الخارجي.

INTRODUCTION

The Mauddud Formation was first defined and described by Henson, from the subsurface section of Qatar Petroleum Company, well Dukhan No.1, where it takes its name from Ain Mauddud. (Mohammed, 1981). The Mauddud Formation was, in the beginning, introduced in Iraq by Owen and Nasr (1958), from Zubair Well No.3 in the Basra area. According to Shubber (1986), the Mauddud Formation is a subsurface, largely neomorphosed and dolomitized limestone. The lower contact of the Mauddud Formation is conformable and gradational with the Nahr Umr, Lower Balambo, or Sarmord Formations. The Cretaceous rocks in the Hijran area, in northeastern Iraq, have been studied by (Bakhal *et al*., 1993; and Ghafor, 2000). Ghafor, 1988, described the planktic foraminifera from Cretaceous rocks in well Tel-Hajar No. 1. Sinjar area, northwestern Iraq. Ghafor (1993) and Ghafor *et al.*, (2004), studied the planktonic foraminifera ranges from (Albian-Aptian-Turonian) in NE Iraq and gives Aptian-Turonian age to the formation. The upper contact is marked by a break and is either nonsequential or unconformable (Jassim and Goff, 2006). Sharbazheri *et al*., 2009; and 2011, studied the planktic foraminifera from Sirwan Valley, and the Dokan area, in northeastern Iraq. Al-Qayim and Ghafor (2022) separated the Cretaceous rocks in the Smaquli area, northeastern Iraq, based on the planktic foraminifera. Turonian to Early Late Campanian foraminifera have been studied by Al-Shaibani *et al*., 1993 and Ghafor and Al-Qayim, 2021 in northeastern Iraq. Microfossils of Cretaceous rocks in the Duhok area have been studied by Ghafor and Mohialdeen, 2016; and 2018. In the type locality, where the formation had been described for the first time, it is of 55 m thickness consisting of limestone rich in *Orbitolina* and *Trocholina* tests. In the northern Arabian Gulf, especially on the Saudi Arabia – Kuwait border, the Mauddud Formation was found to consist of limestone ranging in thickness from 30.5 to 97.6 m (Al-Dabbas *et al*., 2012). Sayyab and Mohammed (1985) studied Zubair well no.3, which was used as a supplementary type section for the Mauddud Formation in Iraq. Owen and Nasr (1958) described the formation as a detrital organic limestone, locally pseudo-oolitic creamy in color, containing blue to green shale in layers. The Mauddud Formation pinches out on the eastern flank of the HailRutbah Arch and also vanishes between Wara and Nahr Umr in western Kuwait (Ibrahim, 1981). The age of the Mauddud Formation is still in flux where the Albian age was cited by some, and the Cenomanian age by others. Abundant fossils cited by Bellen *et al.* (1959) support an Albian age. The formation was originally believed to extend into the Cenomanian because of the frequent occurrence of some species of the *Orbitolina concave* group (Bellen *et al*., 1959). The Mauddud Formation is the most widespread Lower Cretaceous Formation in Middle and southern Iraq (Figure 1; Jassim and Goff, 2006). The studied area (Musaiyib oilfield) is located in Babel province about 70 Km south of Baghdad (Figure 2).

The drilled structure is an anticline nose, 35 Km in length, trending NW – SE plunging, and closing to the southwest. Lithologically, it is composed mainly of thick to medium-bedded limestone, marly limestone rich in argillaceous material, green shale, and dolomitic limestone beds (Figure 3). The stratigraphic correlation chart and the position of the Mauddud Formation in southern, western, and northern Iraq in the geologic column of Iraq is shown in Figure (4) (Harland *et al*., 1990 and El Diasty *et al*., 2016). The formation conformably overlies by Ahmadi Formation and is underlain by the Nahr Omar Formation at the studied well. The main objectives of this research were focused on a description of the microfossils and their distribution on the Late Albian – Early Cenomanian carbonate platform, biostratigraphic and microfacies analysis, regional correlation of the recognized biozones with other studies of the shallow marine platform, and depositional environments of the Mauddud Formation.

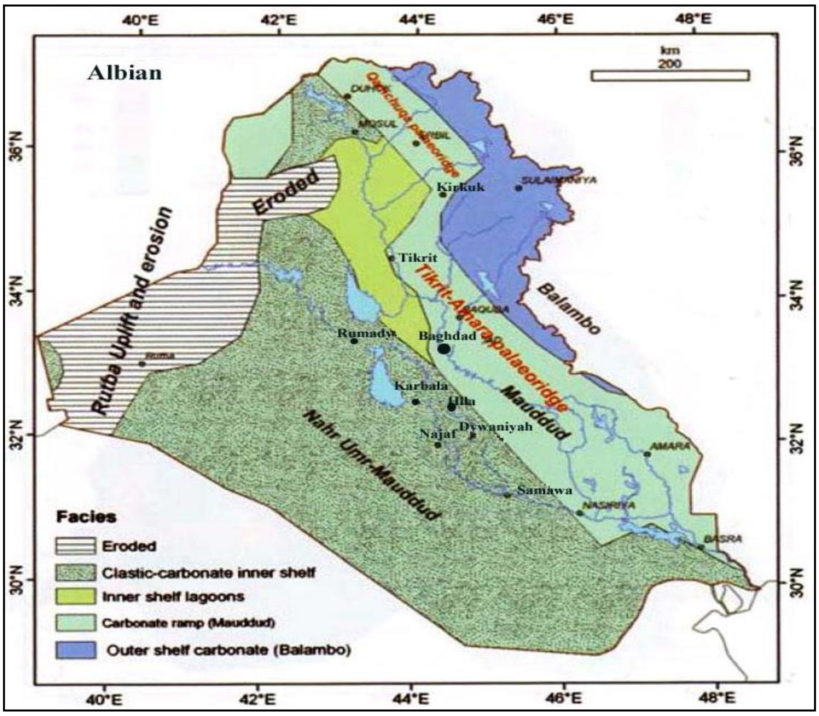

Figure 1: Albian paleogeography map shows the depositional basin of the Mauddud Formation (After Jassim and Goff, 2006).

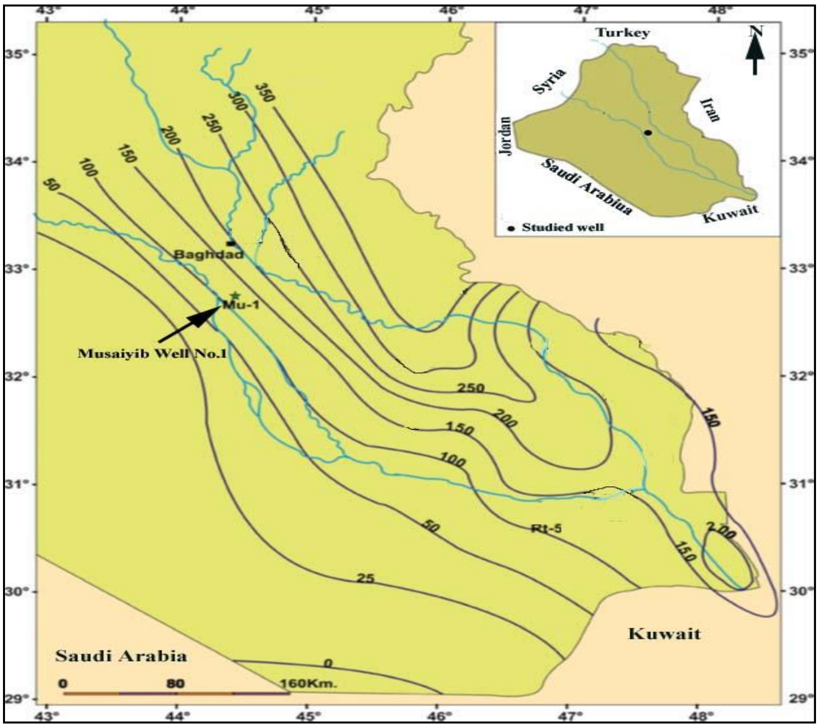

Figure 2: Location map for the studied well (Musaiyaib Well No.1), the Mauddud Formation (Modified after Shubber, 1986 and Ibrahim, 1981).

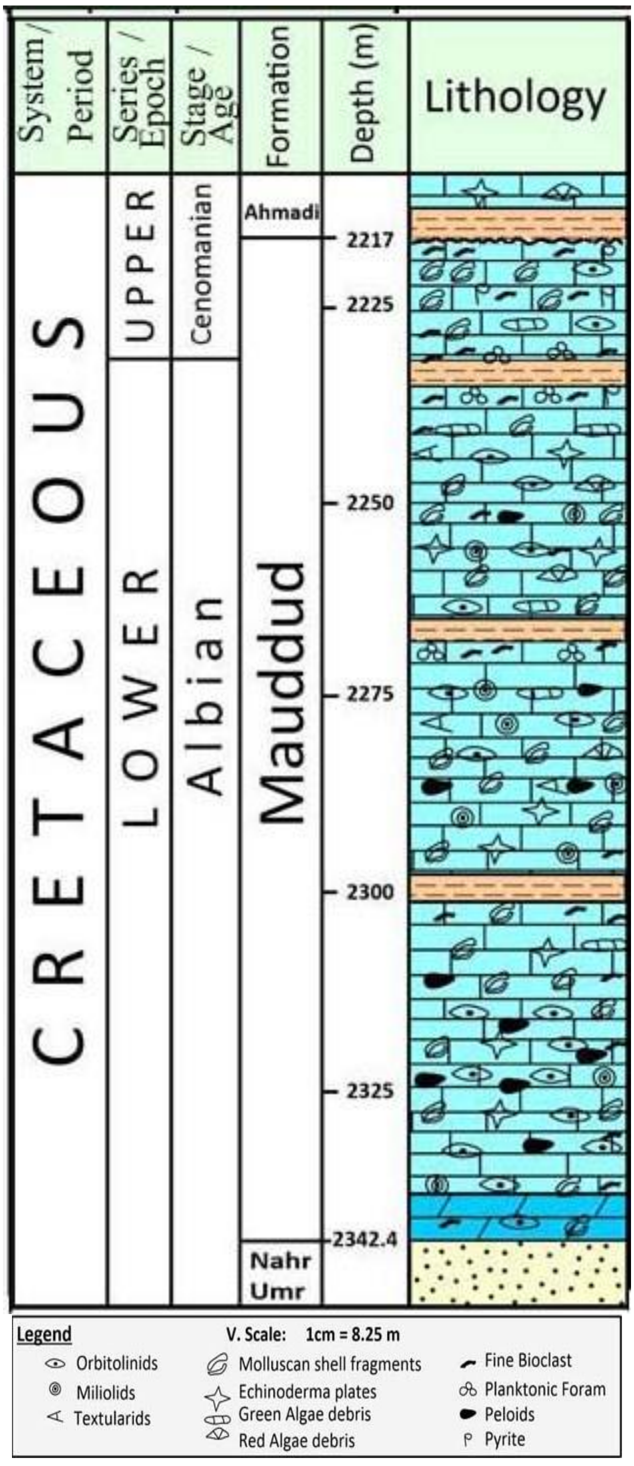

Figure 3: Lithostratigraphic column of the studied well.

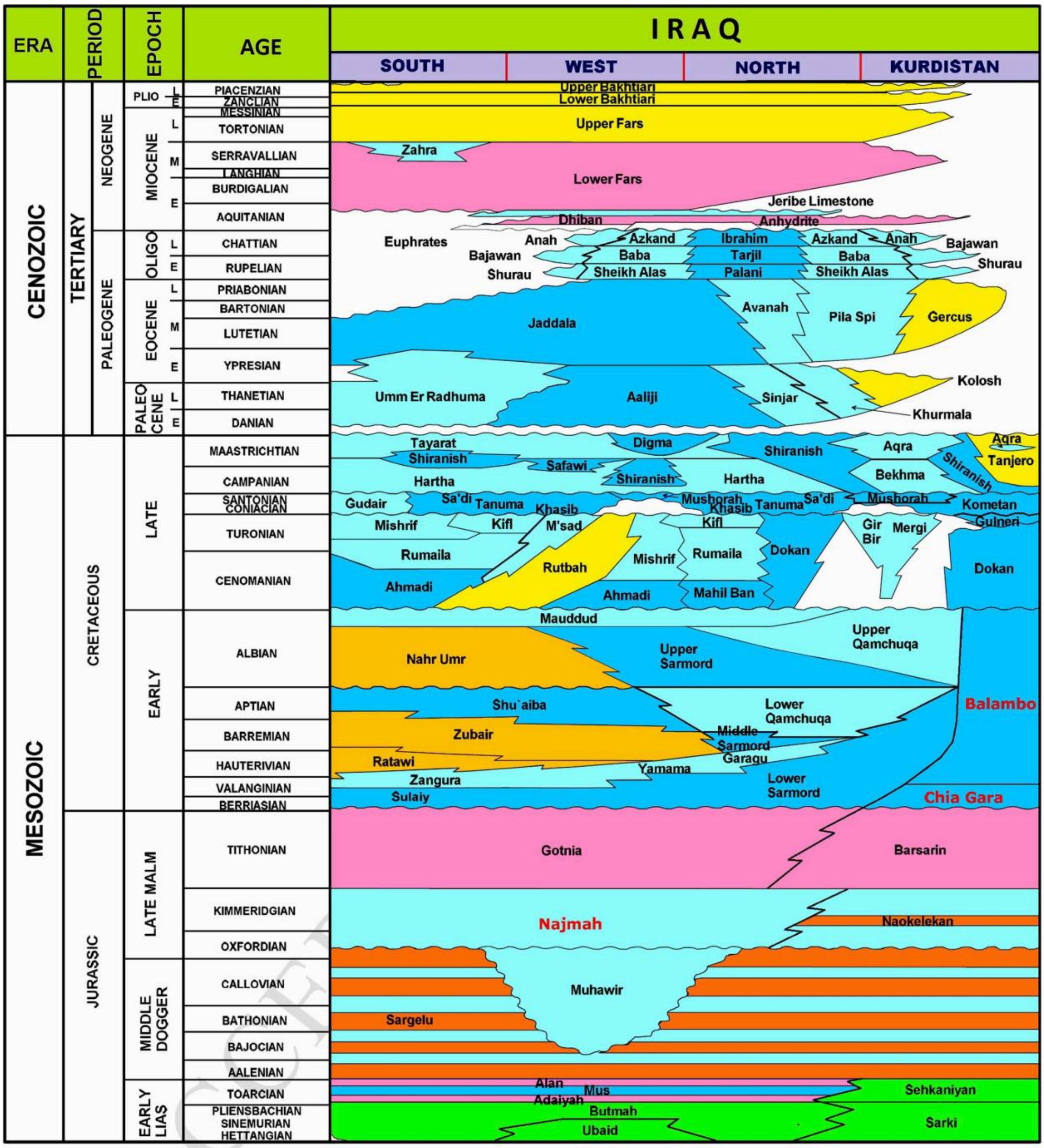

Figure 4: Stratigraphic correlation chart and the position of the Mauddud Formation in southern, western, and northern Iraq in the geologic column of Iraq (After Harland *et al*., 1990 and El Diasty *et al*., 2016). The area of Iraqi Kurdistan has been modified.

PREVIOUS STUDIES

During the late twentieth century (exactly 1948 – 1999), and from 2000 till now rich microfossil associations are collected and recorded from outcrops and subsurface of the Mauddud Formation by different authors. Owen and Naser (1958), defined two fossil zones that occur in the Mauddud Formation, at Zubair well No.3. Bellen *et al.* (1959) mentioned that Mauddud Formation does not outcrop in Iraq until it's pinching out the area near Mileh Al-Tharthar north of Awasil. Brun (1970), listed different microfossil species in the Mauddud Formation during his study of the Cretaceous rocks in different wells of oilfields in southern

Iraq. Al-Khersan (1973), studied and discussed the biostratigraphy and paleoecology of the Mauddud Formation in the Basra oilfields. Al-Shamlan (1975), studied microfacies analysis of the Mauddud Formation in Kuwait. Al-Siddiki (1978), studied the microfossils and depositional environments of the Mauddud Formation in the subsurface oilfields of southern Iraq. Buday (1980) mentioned that the Upper Qamchuqa, which crops out in northeastern Iraq may be equivalent to the Mauddud Formation. Mohammed (1981) put a long list of foraminifera and algal species from the Mauddud Formation in south and southeast Iraq. Ibrahim (1981) stated that the age of the Mauddud Formation is Albian. Sayyab and Mohammed (1984) mentioned that the Mauddud Formation represents one of the widely distributed oil-bearing formations in the Middle East, especially the Arabian Gulf area. Sayyab and Mohammed (1985) studied the biostratigraphy of the Mauddud Formation in the South of Iraq and mentioned that the identified fossils besides the lithological characters reflect basically four discriminated microfacies units. Shubber (1986) studied the sedimentology of the Mauddud Formation in middle and southern Iraq. He mentioned that the petrography of the Mauddud Formation is affected by digenesis processes like cementation, dolomitization, neomorphism, and compaction. Al-Nuaimy (1990), studied large foraminifera from the Mauddud Formation in Iraq. Mohammed (1996) studied Orbitolinds of the Lower Cretaceous of Iraq and discriminated three biozones in Mauddud Formation, they are *Orbitolina concava, Orbitolina sefeni,* and *Orbitolina qataricia*. Sadooni and Alsharhan (2003) studied the stratigraphy, microfacies, and petroleum potential of the Mauddud Formation. They mentioned that *Orbitolina* indicates tropical to subtropical water along shallow coastlines where the temperature would have been between 15 and 25 ºC. Strohmenger *et al.* (2006) studied sequence stratigraphy and reservoir architecture of the Burgan and Mauddud formations (Early Cretaceous), Kuwait. Al-Dabbas *et al.* (2012) studied the depositional environment of the Mauddud Formation. They said that the sedimentary microfacies of the Mauddud Formation include lime mudstone, wakestone, wakestone-packstone, packstone, packstone-grainstone, in addition to dolostone lithofacies, and green shale lithofacies. Al-Shakeri (2013) mentioned that the Mauddud Member is equivalent to Lower Sarvak Formation and designated to represent the *Orbitolina* bearing limestone of the southern Arabian Gulf. Biostratigraphy and microfacies analysis of the Mauddud Formation in the Badra oilfield, eastern Iraq was studied by Al-Yassery 2015; Al-Yassery *et al*. (2016) studied biostratigraphy of the Mauddud Formation in Badra well-1; eastern Iraq and gives Albian-Cenomanian in age. Khudhair and Al-Zaidy (2018) studied facies analysis and stratigraphic development of the Albian Succession in the Nasiriyah oilfield, southern Iraq. Faisal and Mahdi (2020) studied the diagenetic of the Mauddud Formation at the Badra oilfield, in central Iraq. Amer and Al-Zaidy (2021) studied facies analysis and depositional stages of the Albian-Aptian succession in the Balad oilfield, central Iraq, which includes the Shu'aiba, Nahr Umr, and Mauddud formations. Finally, Ezzulddin and Ibrahim (2022) divided the Mauddud Formation in Ratawi oilfield, south Iraq, into three zones (*Orbitolina qatarica* range zone; *Orbitolina sefini* range zone and *Orbitolina concava* range zone), and given the Late Albian – Early Cenomanian age for the Formation.

METHODOLOGY

The current study is based on the material from the Mauddud Formation. Twenty samples were collected from both carbonate and marly limestones of the studied well. More than 20 thin-sections are prepared in the laboratory. The thin sections are examined by using polarized and stereomicroscopes for foraminiferal identification. The taxonomic determination of the benthic foraminifers is based on the foraminiferal classifications by several famous classifications, such as (Velic, 1977 and 1988; Velic´ *et al*., 1995; Husinec *et al*., 2000).

RESULTS

- **Biostratigraphy**

The samples from the Mauddud Formation yielded rich and diverse benthic foraminiferal assemblages. About 100 m thick of the Albian-Cenomanian succession has been studied biostratigraphically with recognition of thirty-six species belonging to the twenty-two genera of benthic foraminifera, and echinoid fragments, bryozoan, red algae, green algae, bivalve fragments, coral, gastropods and pelecypods were recorded in the Mauddud Formation. (Figures 5 – 7). Three biozones have been recognized and arranged from the older to younger (Figure 8), and each biozone represents a specific rock unit and the biostratigraphic zones were correlated with the other biozones (Figure 8).

– ***Mesorbitolina texana-Orbitolina qatarica*** **Concurrent Range Zone** (Early Late Albian)**:** Biostratigraphic interval of this zone is characterized by the concurrent range of the nominate taxa (*Mesorbitolina texana* and *Orbitolina qatarica*), which starts by the First Appearance Datum (FAD) of *Mesorbitolina texana*, in the sample number 1, and ended by the Last Appearance Datum (LAD) of *Orbitolina qatarica*, in the sample number 5. This zone represents the lower part of the Mauddud Formation, from samples 1 – 7, (2342 – 2300 m depth) with a thickness of 42 m. The most recorded species in this zone include*:-* *Mesorbitolina aperta*, *Mesorbitilina oculata, Mesorbitolina* sp., *Mesorbitolina pervia, Mesorbitolina parva*, *Mesorbitolina texana, Mesorbitolina subconcava Orbitolina qatarica*, *Orbitolina conica*, *Conicorbitolina cuvillieri, Praeorbitolina cormy*, *Paleodictyoconus* sp., *Dictyoconus walutensis*, *Dictyoconus* sp., *Paracoskinolina sunnilandensis Paracoskinolina broenmanni, Marssonella* sp., *Cuneolina pavonia, Cuneolina* sp., *Neoiraqia convexa, Lenticulina* sp., and the non- foraminifera assemblages include calcareous algae (*Actnoporella iranica*), Sclerentina coral, echinoid fragments, gastropods, pelecypods, and bryozoa. This bio-zone is the time equivalent to the *Orbitolina qatarica* zone, which was recorded by Muhammed (1996) and Noori *et al.* (2016) as Late Albian, and it is correlated with the *Mesorbitolina texana* (part) biozone of Pegah *et al.* (2019) and equivalent to *Valdanchella dercourti* Partial Range Zone or *Valdanchella dercourti*, *Neoiraqia convexa* Interval zone of Velic´ (2007), also it is corresponding to the *Ammotium braunsteini – Verneuilinoides borealis assanoviensis* Zone of Podobina (2015), finally this zone is equivalent to the *Orbtolina qatarica* zone of Ezzuldin and Ibrahim (2022) (Figure 9).

– ***Orbitolina sefini Total*** **Range Zone** (Late Albian)**:** Biostratigraphic interval is characterized by the total range of the index species, which starts by the First Appearance Datum (FAD) of *Orbitolina sefini*. This zone represents the middle part of the section and 25 m thick of the Mauddud Formation from samples 7 – 17. (2300 – 2235 m depth) with 65 m thick. The most diagnostic species in this zone include: *Mesorbitilina oculata*, *Mesorbitolina* sp., *Mesorbitolina texana*, *Mesorbitolina subconcava*, *Iraqia simplex, Neoiraqia convexa, Lenticulina* sp., and the non-foraminifera assemblages include calcareous algae (*Actnoporella iranica*), *Sclerentina* coral, echinoid fragments, gastropods, pelecypods, and bryozoa. This biozone is the time equivalent to the biozone *Orbitolina sefini* zone, which was recorded by Muhammed (1996) and Noori *et al*. (2016) as Late Albian, and it is correlated with the *Ne. convexa (Nc.)* Taxon-Range Zone or *Neoiraqia convexa- Conicorbitolina conica* Interval zone of Velic´ (2007) and to *Mesorbitolina texana* (part) bio-Zone of Pegah *et al.* (2019), finally this zone is equivalent to the *Orbtolina sefini* zone of Ezzuldin and Ibrahim (2022) (Figure 9).

– ***Orbtolina concava*** **Total Range Zone** (Early Cenomanian)**:** Biostratigraphic interval is characterized by the total range of the index species, which starts by the First Appearance

Datum (FAD) of *Orbitolina concava* and by the Last Appearance Datum (FAD) of the same species *Orbitolina sefini*. This zone represents at the upper part of the section with 18 m thick of the Mauddud Formation from samples 17 – 20, (2235 – 2217 m depth), with 18m thick. This zone includes many species, such as *Mesorbitolina aperta*, *Mesorbitilina oculata*, *Mesorbitolina* sp., *Archaeoalveolata* sp., *Biconcava bentori*, *Naupleilla insolita*, *Lenticulina* sp., and the non-foraminifera assemblages include calcareous algae (*Actnoporella iranica*), Sclerentina coral, echinoid fragments, gastropods, pelecypods, and bryozoa. This bio-zone is the time equivalent to the biozone *Orbitolina concava* Zone of Muhammed (1996) and Noori *et al.* (2016), recorded as the Early Cenomanian, and to the biozones *Conicorbitolina conica/ Conicorbitolina cuvillieri* Range Zone of Velic´ (2007) and it is correlated with the *Conicorbitolina conica* biozone of Afghah *et al.* (2014) and equivalent to *Conicorbitolina* bio-zone of Pegah *et al.* (2019), finally, this zone is equivalent to the *Orbtolina concava* zone of Ezzuldin and Ibrahim (2022) (Figure 9).

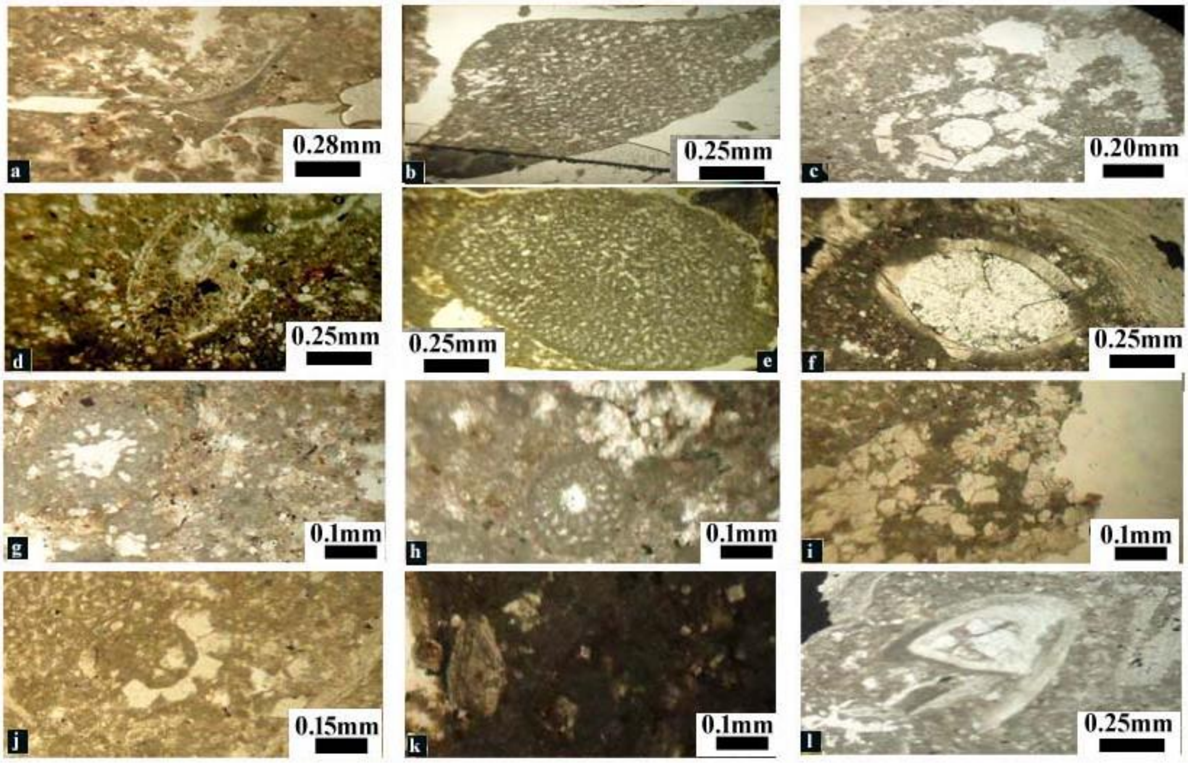

Figure 5: **a)** Rudist, sample no.1, **b)** *Mesorbitolina aperta*, sample no.1, **c)** *Pseudocyclamina hedbergi*, sample no.5, **d)** Bivalve shell, sample no.6, **e)** *Naupliella insolita*, sample no.2, **f)** *Lenticulina* sp., sample no.6, **g)** Dasycladacian algae. Sample no.1, **h)** *Arcaheoalveolata* sp., sample no.9, **i)** Alagae, Rudist, sample no.4, **J)** *Dasycladacian* algae, sample no.6, **k)** *Mesorbitolina aperta*, sample no.6, and **l)** *Lenticulina* sp., Rudist, sample no.5.

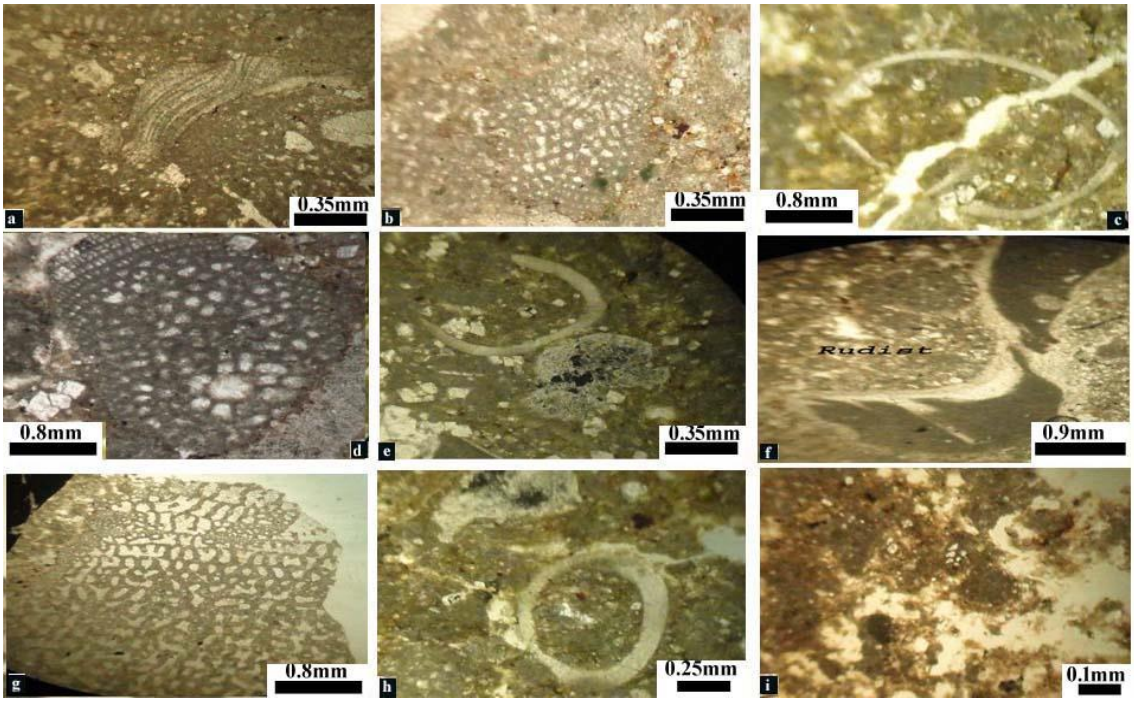

Figure 6: **a)** Rudist, sample no.1, **b)** *Iraqia simples*, sample no.7, **c)** Pelecypods, sample no.2, **d)** *Naupliella insolita* sample no.2, **e)** Mollusca, sample no.3, **f)** Rudist, sample no.3, **g)** *Orbitolina concave*, sample no.3, **h)** Calacarous algae, sample no.2, and **i)** *Cuneolina pavonia*, sample no.3.

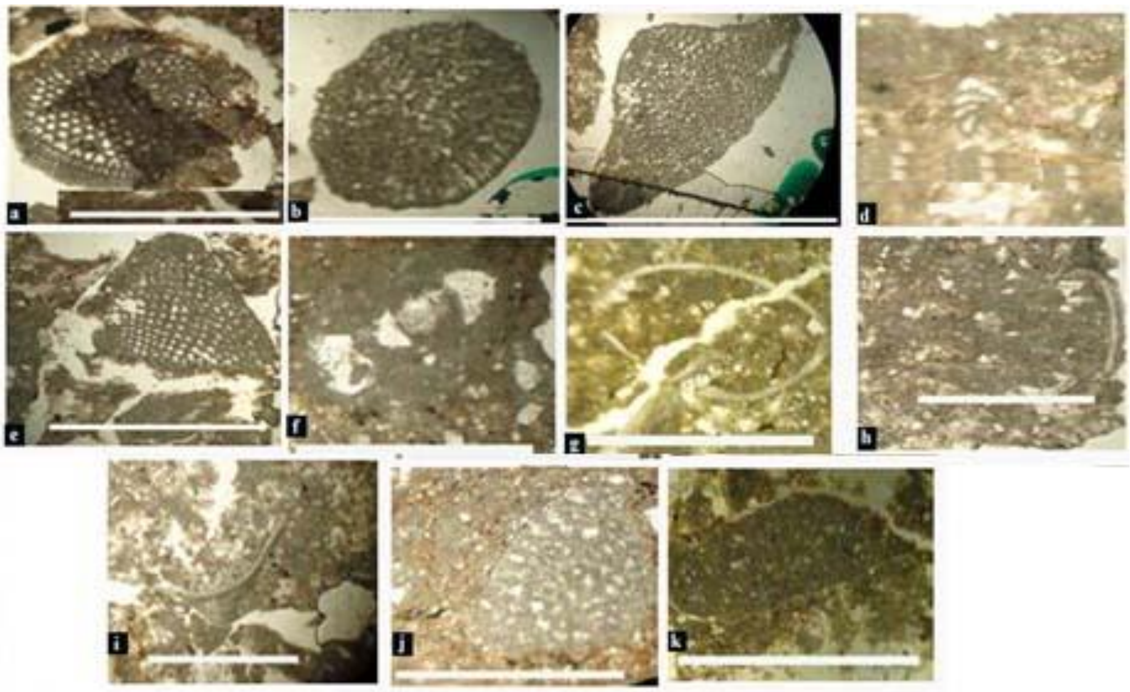

Figure 7: **a)** *Praeorbitolina cormy*, sample no.1, **b)** *Dictyoconus* sp., sample no.1, **c)** *Mesorbitoloina aperta* sample no.1, **d)** *Textularina* sp, sample no.1, **e)** *Dictyoconus walnutensis*, sample no.1, **f)** *Charnetia cuvelleri*, sample no.2, **g)** Pelecypods, sample no.2, **h)** Pelecypods, sample no.1, **i)** Pelecypods, sample no.4, **j)** *Mesorbitolina oculata*, sample no.3, and **k)** *Paleodictyoconus* sp. sample no.2.

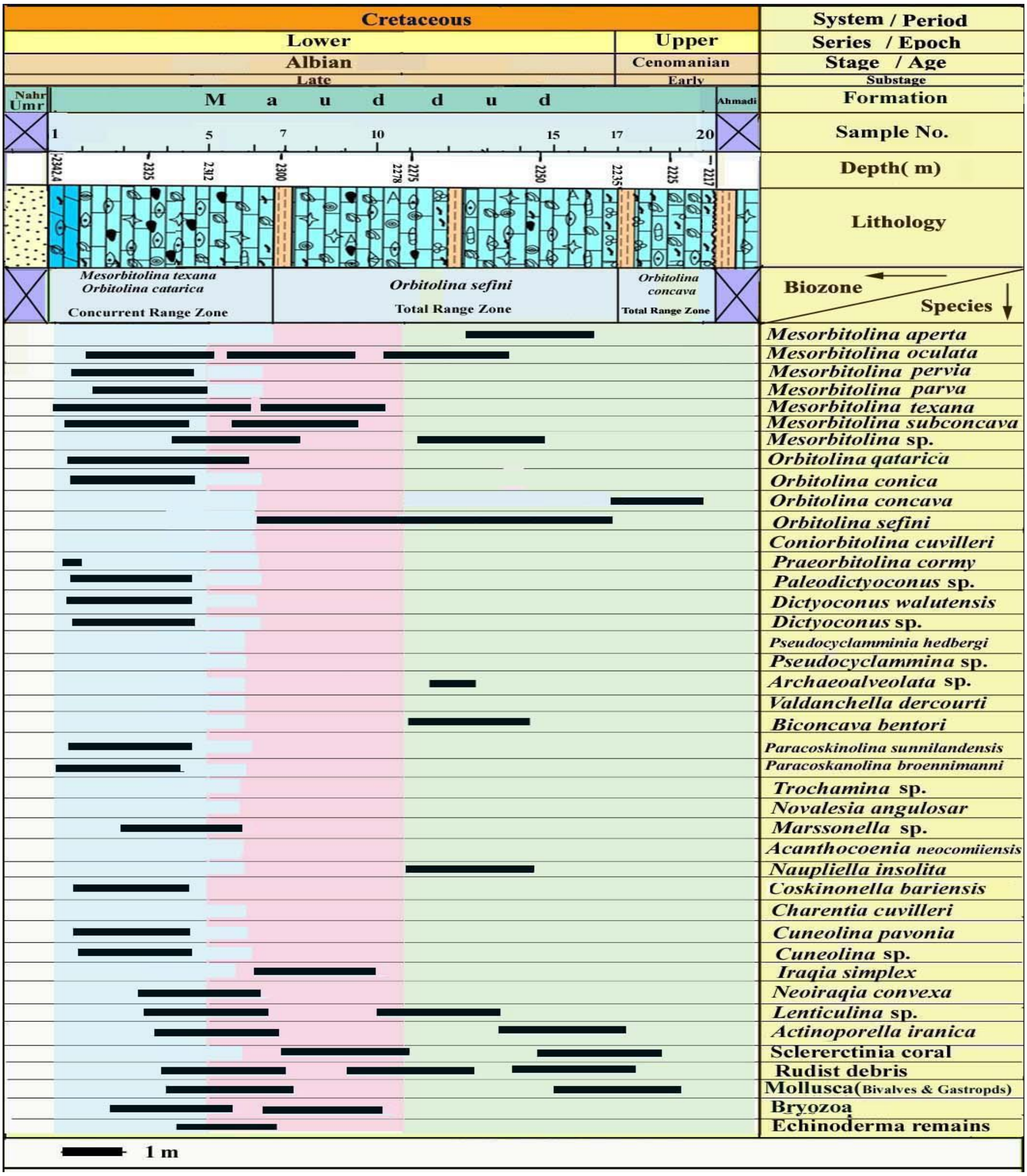

Figure 8: Biostratigraphic range chart of microfossils of the Mauddud Formation, Musaiyib Well No.1. Central Iraq.

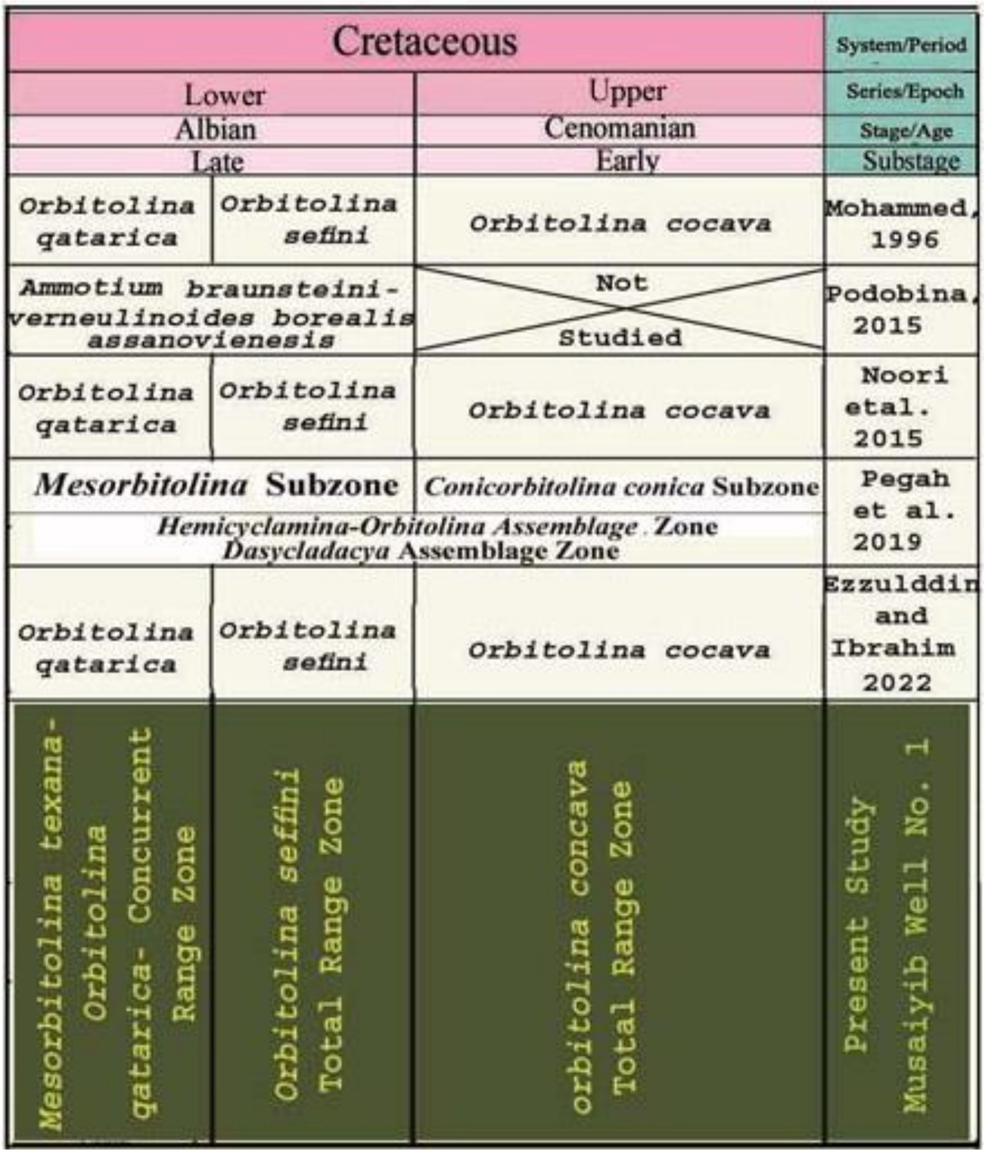

Figure 9: Correlation chart showing the biostratigraphic zones of this study with the other studies.

- **Microfacies Analysis**

Petrographic components of carbonate rocks are valuable for identifying the microfacies then gathering information to enhance the facies association and finally reconstructing the depositional environments. The major facies types that were distinguished within the current study were based on the main characteristics of the sedimentary textures and the relative abundance of the biotic components. Therefore, four major microfacies types (Mudstone, wackestone, wackestone to packstone, and packstone) and nine submicrofacies were identified based on Dunham's (1962), classification and taking the Wilson (1975) and Flugel's (2010) standard microfacies and facies belts in consideration. The main submicrofacies, which are recognized within this study represent:

– **MF-1 Bioclastic Lime-Mudstone submicrofacies:** This submicrofacies is characterized by consisting only of fine bioclasts (without whole fossils) distributed in a dark grey-colored mud-supported groundmass with some argillaceous material, (Figure 10C). Some disseminated subhedral to euhedral rhombs of dolomite were observed. These submicrofacies represent a clam environment and correspond to RMF 19 (Flugel, 2010), which is deposited in a low-energy lagoonal environment of the Inner Ramp setting.

– **MF-2 Bioclastic Wackestone submicrofacies:** Bivalve shell fragments, echinodermal plates, and algal debris of different sizes are the prevalent components of these submicrofacies. Some benthic foraminifera such as Miliolids, *Textularia* sp., *Nezzazata* sp., and some *Orbitolina* sp., are also distinguished. Some argillaceous materials with detrital-fine sand grains were observed. The presence of some foraminifera such as Miliolids and *Textularia* species and other allochemes within a micrite mud-supported texture is evidence of deposition in a relatively low-energy environment of the inner ramp of lagoon facies and corresponds to RMF 20 of Flugel (2010).

– **MF-3 Microbioclastic Wackestone submicrofacies:** Microbioclasts are the main constituents of this submicrofacies with few planktonic foraminiferas, such as *Heterohelix* sp., and *Hedbergella.* These allochemes were distributed in a brown to dark-brownish micritic groundmass rich with organic matter and pyrite grains. Some chambers of the planktonic foraminifera were filled with dark pyrite minerals, (Figure 10A). The high amounts of lime mud, lack of mechanical sedimentary structures, and bearing of planktonic foraminifera recommend that these facies were deposited in low-energy conditions with normal salinity (Wilson, 1975) and corresponding to RMF 2 of mid to outer ramp setting, Flugel (2010).

– **MF-4 Foraminiferal Wackestone submicrofacies:** These submicrofacies were characterized by consisting of several benthonic foraminiferas such as Miliolids; Textularids; Orbitolinids; Nezzazata sp., and others, which are embedded in grey to dark-grey micritic groundmass. Some medium to coarse bioclasts of Mollusca and green algal debris are also observed. Diagenetic processes such as cementation, recrystallization, micritization, and dolomitization affected the components and the groundmass of these submicrofacies. The association of the above-mentioned benthonic foraminifera is a good indicator for the shallow open marine environment and corresponds to RMF 13 of the inner ramp setting, Flugel (2010).

– **MF-5 Bioclastic Wackestone – Packstone submicrofacies:** Diverse size bioclasts of bivalves; echinoids and calcareous green algae with some skeletal grains of benthic foraminifera, which are represented by Orbitolinids, Miliolids, and Textularids, were identified in this submicrofacies. Some peloids were also observed embedded in the micritic groundmass (Figure 10B). Different diagenetic processes (dolomitization, dissolution, and stylolitization) affected the groundmass and some of the allochemes. It is interpreted to indicate a shallow water environment with a relatively moderate-energy, and it corresponds to RMF 17 of the inner ramp setting (lagoon environment) (Flugel, 2010).

– **MF-6 Orbitolinal Wackestone – Packstone submicrofacies:** Well-preserved Orbitolinids (large benthic Foraminifera) are the main skeletal components of this submicrofacies, which is embedded in dark partially argillaceous groundmass (Figure 10D). Also, limited numbers of some other benthic foraminifera such as *Valvulammina* sp., *Pseudocyclammina* sp., some pelecypod shell fragments, echinodermal plates algal debris, and few non-skeletal peloids grains were identified. Diagenesis processes such as compaction, neomorphism, cementation, and dolomitization affected various grain components and the groundmass. These facies are interpreted to indicate a warm- shallow -open marine environment corresponding to RMF 13 of the inner ramp setting.

– **MF-7 Peloidal Bioclastic Packstone submicrofacies:** Bioclastic fragments of echinoids; Mollusca and other skeletal debris are the main components of this submicrofacies, with less-occurrence of sub-rounded peloids (non-skeletal grains) embedded in the dark -grey to the brownish -colored micritic matrix (Figure 10E). A few fine detrital sand grains were also recorded. In addition to this few benthic foraminiferas, such as Orbitolinids and Textularids were also observed with very few proportions of planktonic foraminifera. These submicrofacies were deposited in open marine environments of inner to mid-ramp settings and corresponding to RMF 7 (Flugel, 2010).

– **MF-8 Miliolidal Packstone submicrofacies:** These microfacies were characterized by various types of miliolids (*Quinqueloculina* and *Pyrgo*) (Figure 10F), with different assemblages of benthic foraminifera such as *Textularia* sp., *Nezzazata* sp., *Cuneolina* sp., and *Ovalveolina* sp. Also, a few pelecypods shell fragments algal debris, and detrital sand grains were reported and distributed in a dark -argillaceous groundmass. These fauna assemblages are characteristics of shallow-warm water, of open to restricted circulation, and corresponding to RMF 16 of low-energy inner ramp environments.

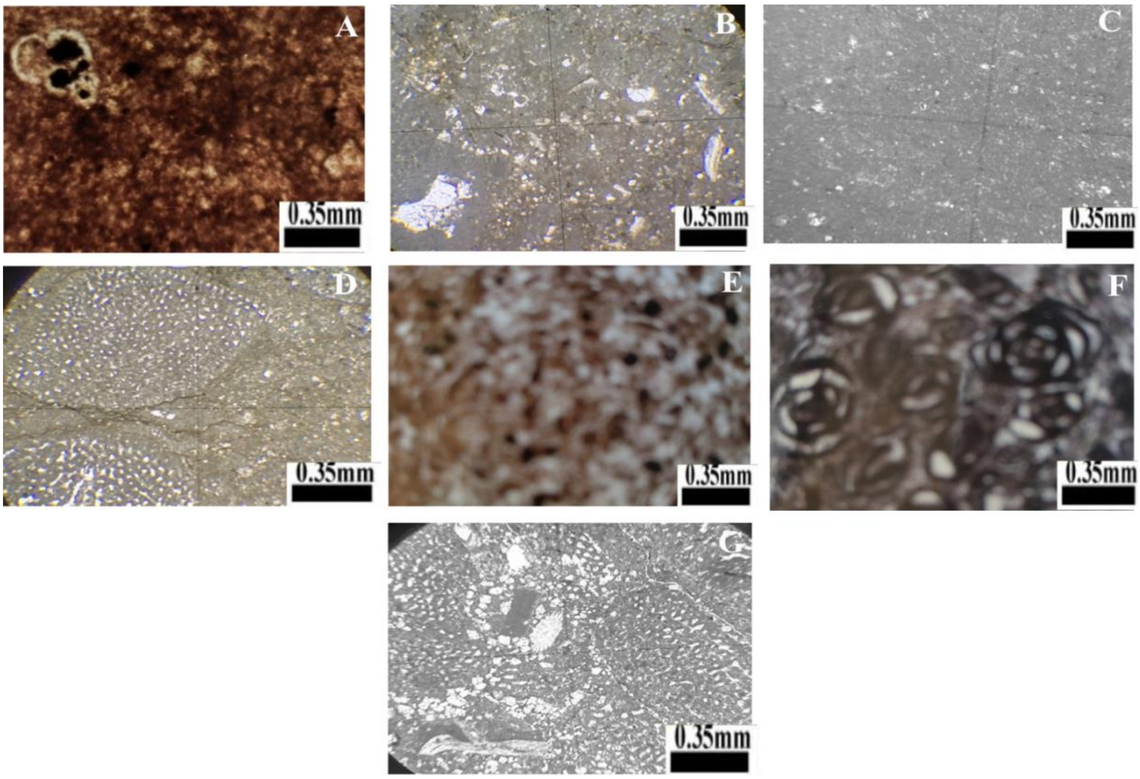

Figure 10: Submicrofacies types of Mauddud Formation at Musaiyib Well No.1,
A) Microbioclastic wackestone, **B)** Bioclastic wackestone-packstone,
C) Bioclastic lime mudstone; **D)** Orbitolinal wackestone-packstone;
E) Peloidal bioclastic packstone, **F)** Miliolidal packstone,
and **G)** Orbitolinal rich packstone submicrofacies.

– **MF-9 Orbitolina rich Packstone submicrofacies:** The main characteristic of these submicrofacies is the high percentage of different species of the Orbitolinidae family that are dispersed in dark argillaceous, highly stylolitic micrite, (Figure 10G). Also, some peloids, mollusca shell fragments, echinoderm plates, and some large benthic foraminifera were identified. Most of the observed fauna were worn and coated due to the effectiveness of moderate to extensive wave agitation. Compaction, cementation, and dolomitization are the observable diagenetic processes. These submicrofacies are interpreted to indicate a warm-shallow open-marine environment and correspond to RMF 13 of the inner ramp setting.

- **Depositional Environments**

One of the most important factors for interpreting the sedimentary paleoenvironmental condition is to describe and identify types of sedimentary facies (Walker, 2006). Detailed environmental reconstruction of the Mauddud Formation at Musaiyib well-1 is based on descriptive and interpretative microfacies analysis. According to this study, three depositional environments were identified, which are represented by Inner ramp, mid ramp, and mid ramp to outer ramp settings, Figure (11).

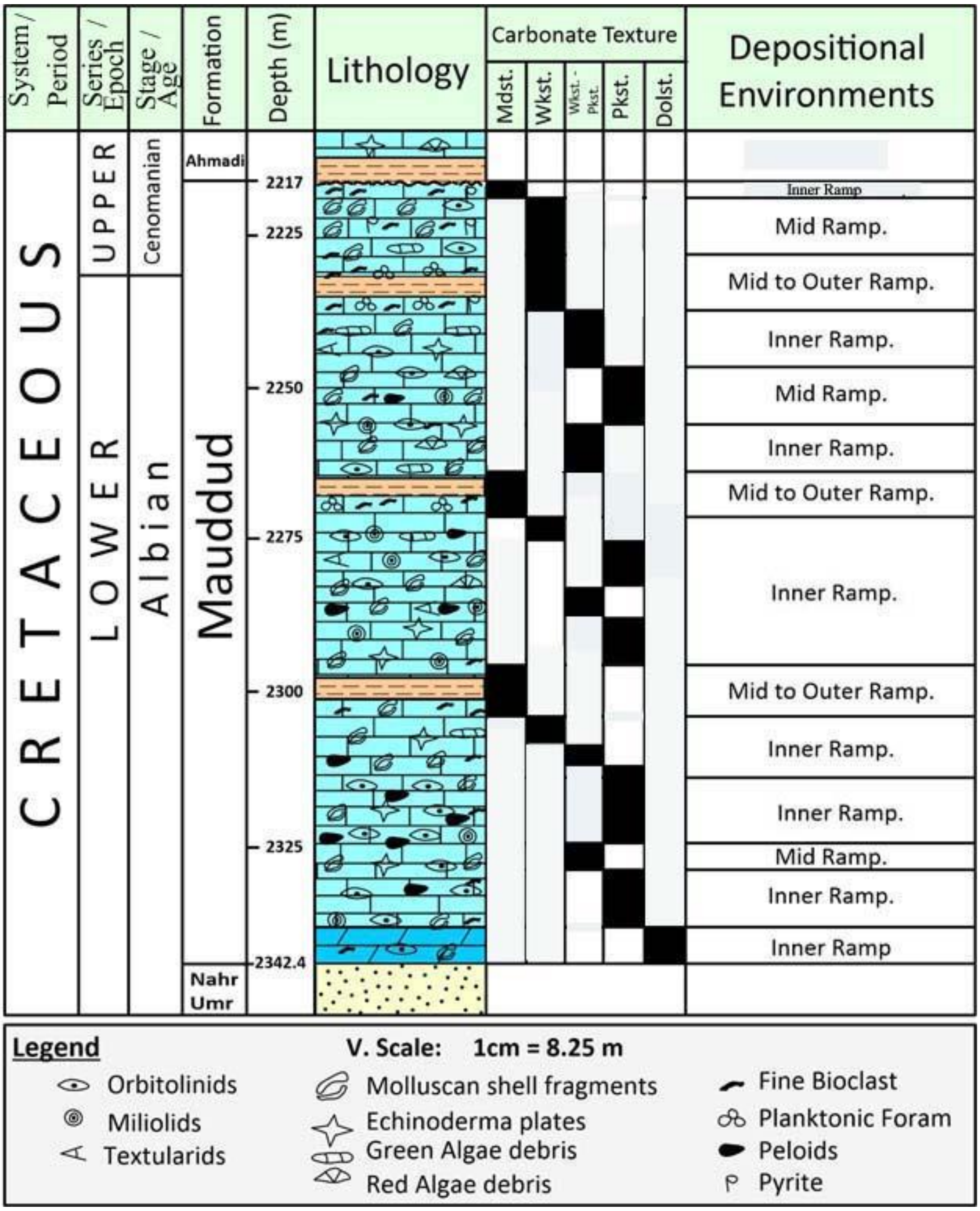

Figure 11: General stratigraphy, microfacies distribution, and depositional environments of the Mauddud Formation in Mu-1.

- **Inner Ramp**

Within the current study, the inner ramp setting is represented by:

– **Lagoon and open marine environment:** This environment consists of some submicrofacies such as (Lime-Mudstone; Bioclastic Wackestone; Bioclastic Wackestone – Packstone and Miliolidal packstone submicrofacies). These sediments are characterized by dark-grey to dark-brownish-colored sediment rich with argillaceous materials and occasionally some fine detrital sand grains. This environment was characterized by shallow-warm and claim water of low energy, which consisted of some well-preserved skeletal grains of benthic foraminifera, represented by (Orbitolinids, Miliolids, and Textularids), with shell fragments of bivalves; echinodermal plates, and calcareous green algae of different size in addition to some peloids grain. The occurrence of orbitolinids provides valuable chronostratigraphic information (Simmons and Williams, 1992) and the *Orbitolina* flourished in tropical to subtropical shallow-water with a temperatures range between 15 – 25 ºC, (Sadooni and Alsharhan, 2003).

The predominant miliolids indicate limited circulation and probably euryhaline conditions in a lagoon setting (Sadeghi *et al*., 2011).

- **Mid-Ramp**

The Mid-ramp consists of variable carbonate sediments and it is characterized by a shallow to moderately deep marine depositional environment. The main submicrofacies that belong to this environment are represented by (Foraminiferal wackestone; Orbitolinal wackestone-packstone; Peloidal bioclastic packstone; Miliolidal packstone and Orbitolinal rich packstone submicrofacies). Various well-preserved skeletal grains of some benthonic foraminifera such as Orbitolinids; Miliolids; Textularids; *Nezzazata*; *Cuneolina; Ovalveolina* and *Pseudocyclammina*, are embedded in the dark-grey micritic groundmass, occasionally rich with argillaceous material. Medium to coarse grain size shell fragments of bivalves; calcareous green algae and peloids are also observed. The orbitolina-bearing limestone was deposited in an intermediate water depth above the storm wave base (SWB). Whereas the occurrences of Orbitolinids with Miliolids were suggested to be present in shallow-water environments, (Douglass, 1960 in Al-Dabbas *et al*., 2012).

- **Mid-Ramp to Outer Ramp**

According to carbonate sedimentary texture and petrographic components, this environment within the current study represents the deepest settings. The main submicrofacies related to this sub-environment involved the (Microbioclastic lime-mudstone and Microbioclastic wackestone submicrofacies). Various fine bioclasts, which are distributed and embedded in the dark mud-supported groundmass, rich with organic matter and few amounts of argillaceous materials, are the main characteristics of the sediments of this sub-environment. Within these facies, some planktonic foraminifera Heterohelix sp., Hedbergella sp., Pithonella sp., and Calcispheres in addition to their debris also were identified. Rich organic matters with dispersed grains of pyrite, filling some porosity, indicated the deposition in a euxinic condition. Accordingly, the occurrence of distinct fine bioclasts and planktonic foraminifera assemblages within dark- dark-argillaceous sediments, which accumulated in euxinic conditions, are good indicators for a low-energy and more claim deposition setting.

DISCUSSION

The Mauddud Formation is characterized by the appearance of different types of benthic foraminifera, especially the large ones, which are important tools for age determination and facies analysis, and paleoenvironmental interpretations. Orbitolinidae together with other larger benthic foraminifera are particularly important in the Lower Cretaceous shallow-water limestones, (Schlagintweit, 2010b). So the large benthic foraminifera in the studied section implies the shallowing of the depositional environment. According to previous studies, the Late Albian – Early Cenomanian age was determined for the Mauddud Formation. Sadooni and Alsharhan, 2003, recorded the Albian – Cenomanian age for the Mauddud Formation, by direct dependence on the assemblages of foraminifera. The late Albian – Early Cenomanian age was recorded for the Mauddud Formation by Al-Yassery, 2015 and Al-Yassery *et al.* 2016. however, the interpretation of the present work at the Musaiyib well No.1, which was studied for the first time in detail with the viewpoint of microfossils and biostratigraphy is interpreted that the studied area is rich in large benthic foraminifera with few planktonic foraminiferas in addition to microfossils of non-foraminifera and the age of Mauddud Formation shows the close result from Late Albia – Early Cenomanian age, as the following:

- *Mesorbitolina texana-Orbitolina qatarica* Concurrent Range Zone. Early Late Albian age: Yavari *et al.* (2017) recognized *Mesorbitolina texana* at the Aptian-Albian age. According to (Schroeder, 1975; and Mohammed, 1996; Ezzuldin and Ibrahim, 2022), *Orbitolina qatarica* was started in the Late Albian age.
- *Orbitolina seferi* Total Range Zone. Late Albian age; This zone is limited to the Late Albian – Early Cenomanian boundary (Schroeder, 1975), *Orbitolina sefini* was also found in Late Albian (Berthou and Schroeder, 1978; Mohammed, 1996). According to {Homberg and Bachmann, 2010, Safari *et al*., 2009, Ezzuldin and Ibrahim (2022)}, it is found in Late Albian – Early Cenomanian.
- *Orbitolina concave* Total Range Zone, Early Cenomanian age; *Orbitolina concave* was determined in Early Cenomanian age (Schroeder, 1975, Mohammed, 1996, Douglass, 1960, Satorio and Venturini, 1988, Zhang, 2000, Ezzuldin and Ibrahim, 2022).

Hydrodynamic conditions affect and control the texture of the carbonate rock, and it is responsible for the distribution of different microfacies within the studied borehole. Accordingly, the inner ramp, middle ramp, and mid to outer ramp were determined. These depositional environmental settings can be observed, relatively due to the effects of sea level fluctuation, so various microfacies developed vertically at the Mu-1, borehole. Different depositional cycles were observed within the Mauddud sedimentary basin, which started with a transgressive phase developed over a continental shelf and gradually fluctuated to a moderately deeper basin then terminated by shallow open platform and lagoonal environments and finally falling the sea level and ended the regression phase with the top of the Mauddud Formation, which represented by erosional surface and separated this Formation from the overlying Ahmadi Formation. The occurrence of thin green shale beds in the studied borehole may refer to rapid and local subsidence in the Mauddud depositional basin, (Al-Dabbas *et al*., 2012). The occurrence of fine bioclasts (microbioclasts) and some planktonic foraminifers, with the absence of benthonic foraminifera, suggest that the (MF3) was deposited at the Mid-Ramp to Outer Ramp below the (FWWB and may be reached below SWB), which is beneath the photic zone (Geel, 2000). The shoal environment cannot be developed within the inner ramp setting of this study, because the conditions were not favorable for the development of typical barrier bars.

CONCLUSION

From the above results and discussions, it can be concluded that the:

- Albian – Early Cenomanian Cretaceous rock units in the Musaiyeib Well No.1, were studied in detail and based on the 35 species from 22 genera of identified benthic foraminiferal assemblages.

- Distribution of benthic foraminiferal assemblages helps to recognize three benthic foraminiferal assemblages: (*Mesorbitolina texana-Orbitolina qatarica* Concurrent Range Zone; *Orbitolina seferi* Range Zone and *Orbitolina concave* Range Zone).
- In addition to benthonic foraminifera assemblages, other fossils of non-foraminifera are identified such as coral, algae, pelecypods, gastropods, bryozoa, and fragment and spine of echinoids.
- The Mauddud Formation is of Late Albian – Early Cenomanian age.
- Four major microfacies and nine sub-microfacies were distinguished for the Mauddud Formation.
- These microfacies types were deposited in carbonate ramp environments, and represented by the inner ramp (Lagoon, shallow open marine); mid ramp, and mid to outer ramp setting.

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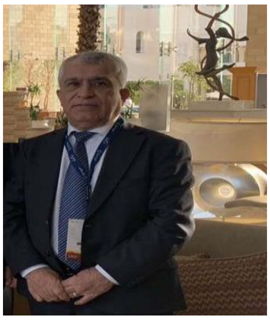

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