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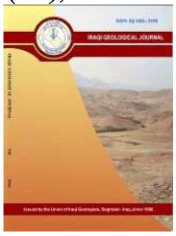

High-Resolution Sequence Stratigraphy of the Mauddud Formation Southern Iraq

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Abstract

Inner ramp carbonate and dolomitic limestone made up the late Albian Mauddud reservoir in Iraq. An age estimate for the Mauddud Formation is late Albian to early Cenomanian, with it overlying the Nahr-Umr Formation and underlying the Ahmadi Formation. The integration of microfacies with wireline logging data to predict the high resolution of the sequence stratigraphy framework. The microfacies description included more than 150 thin sections that covered the study area in southern Iraq. That results in five main microfacies. There are divided into eleven submicrofacies, as a result, for the microfacies, the depositional environment is gradual, from mid-ramp to shallow open marine, shoal-restricted lagoon. The study divided the formation into four orders of sequence stratigraphy: MSL1, MSL2, MSL3, and MSL4. The study includes identifying the maximum flooding surface (K110), which is identified as the original transgression in sea level that covered Arabian Plate. MSL1 represents the lower part of formation and evidence of environmental change to shall the marine environment with argillaceous limestone. The maximum flooding surface (K110) is signifying the deepest depositional environment (mid-ramp). Also, the study marked three marine flooding surfaces by changes as increased gamma ray and density logs values, whilst the highstand system reflects decreasing in logs values, This change was used in conjunction with microfacies data to construct the sedimentological environments that led to the documentation of the Mauddud high-resolution sequence stratigraphy framework.

Keywords: Mauddud formation; Microfacies analysis; Sequence stratigraphy; Third order

1. Introduction

The shallow-water carbonate Mauddud Formation (late Albian- early Cenomanian) is one of the imperative formations deposited during the lower Cretaceous. Hydrocarbon deposits in central and southern Iraq offered the formation new significance. The Mauddud Formation was initially described by Henson (1948) of the Qatar Petroleum Company's subsurface section (Sadooni and Alsharhan, 2003). This formation thickness between 110 and 148 m southern Iraq, while in northern Iraq, the thickness is more than 250 m (Jassim and Goff, 2006).

The Mauddud Formation was recognized in Iraq, Saudi Arabia, Kuwait, Oman, Bahrain, and United Arab Emirates in the southern Gulf. The limestonein in formation light gray and grainy. The upper part of formation is characterized by good porosity values, while the bottom has more clay content.

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Due to the fine calcareous debris, most of the type of this section in Qatar is called foraminiferal limestone. It goes from lime mudstone at the bottom to wackestone, pellet, skeleton packstone, and wackestone at the top. In these different sorts of horizons, *Orbitilina* and *trocholina* tests make up most of the formation (Al-Qaisi, 2021). Several authors, such as Sadooni and Alsharhan (2003), Al-Awadi et al (2017), and Manhi and Alsultani (2021) have written a lot about the petrophysical properties and lithology of the Mauddud Formation.

Time and stratigraphy are related in a framework known as sequence stratigraphy. Variations in sea level and tectonic settings have been taken into account (Catuneanu, 2006, 2017; Catuneanu et al., 2009). Understanding how stratigraphy and genetics are related is the key to predicting lithologic types and shapes and how basins form. The method of sequence stratigraphy is most relevant to identifying and correlating sedimentary surfaces, including sequence boundaries, marine, and flooding surfaces (Miall, 2016). Eustasy, relative sea level rise, sediment supply, tectonic activity, and basin reaction are all related, according to previous studies. To use the system tract method to predict the sequence stratigraphic framework, you need to know how the sediment budget works within the system tract approach. Several authors have found that using sequence stratigraphy to make basin-scale predictions of source rocks and reservoir units and to make regional connections between the identified units is useful. This work aims to learn more about how microfacies change by combining data from good data, core investigations, and thin-section studies. The goal is to predict the sequence and framework of stratigraphy and see how it fits with what is already there in the area.

X oilfield is located about 50 Km northwest west Basra city, 45 Km west of Y oilfield, and 50 Km of Z oilfield in southern Iraq on the northern section of the Arabian plate (Fig.1) (Ismail et al. 2021). This study aims to combine the geophysical well logs, core studies, and thin section studies to understand the changes in the microfacies, predict the sequence stratigraphic framework, and look at how it fits with the framework that has already been set up in the area.

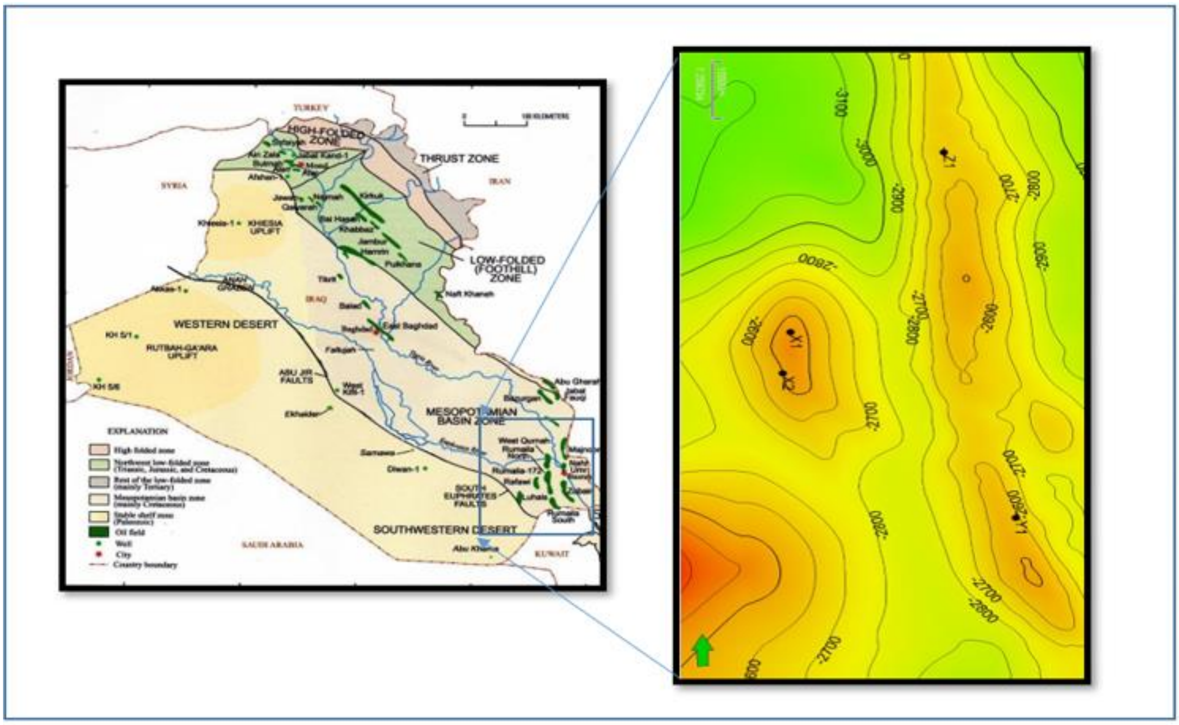

Fig.1. Location map of X, Y, and Z oilfields in southern Iraq.

2. Materials and Methods

Flügel (2010) defined the ramp-setting (RMF) as well as the depositional texture types suggested by Dunham (1962) for the microfacies study and the kinds of grains that are most common, such as skeletal (biograins) and non-skeletal grains. This describes the nature and varieties of the matrix. Then, compare the detected microfacies to the conventional microfacies types described by Flügel (2010) to determine the sedimentary environments of the Mauddud Formation. Microfacies discovered in the Mauddud Formation were compared with RMF model (Flügel, 2010). From core samples, 150 thin sections were made from the core sample to study. The thin sections were studied under a binocular microscope. Observation of thin sections was conducted to examine rock texture, identify grains, and examine microfacies., In contrast, wireline curves are used to associate the microfacies that have been seen with good answers for the temporal distribution of microfacies based on well-log data. All wireline data has been used and combined with sedimentological data. Stratigraphic sequence, key surface, and system tracts can be analyzed, found, and linked Based on the interpretation of microfacies and inter wall (basinal) correlation sequence and system tract were then created to estimate regional structures. The ideas of "system tract" and "key surface" are used throughout this analysis. (Catuneanu,2006. Catuneanu et al. 2009) when local remedies to this flooding are determining marine flooding surface used.

3. Results and Discussion

3.1. Microfacies of the Mauddud Formation

Limestone is the main component of Mauddud Formation based on wireline data. Most of the biograins that have been studied in microfacies consist of foraminiferal assemblages. These properties are affected by things in the environment like tectonic movement, changes in sea level, climate change, geological and biological processes, sediment movement and deposition, and other things. In sedimentary carbonate rocks, there is a connection between these two processes. Stratigraphic or sedimentary environments are spread across time to offer the geometric layout of the basin's stratigraphic architecture and to produce stratigraphic or sedimentary environments. Since then, Five lithofacies have been discovered in the Mauddud Formation.

3.1.1. Lime mudstone microfacies

These microfacies may be found at the base and the top of the Mauddud formation. They include a small number of bioclastic fragments in comparison to the other microfacies, they typically indicate the most shallowing facies that were deposited at the formation that was researched. Less than ten percent of it is made up of grains (Figs. 2A and B), and the fossils that make up these microfacies reflect several genera of planktonic foraminifera like Hedbergella and Globigerina. Moreover, it is comparable to the (RMF5) (Flugel, 2010)

3.1.2. Wackestone microfacies

The common microfacies in the Mauddud Formation These microfacies are characterized by micrite matrix skeletal and non-skeletal. Algal, rudist, benthic foraminifera, bivalves, and echinoderm fragments are bioclasts. The micrite results in the transformation of lime mud which has composed of calcite and or aragonite minerals (Al-Dabbas et al., 2013) There are four major submicrofacies within these microfacies.

- Benthic foraminifera wackestone submicrofacies

Type A is characterized by the predominance of skeletal granules represented by benthic foraminifera submerged in a microscopic floor (Myzban et al., 2022). *Orbitilina* is one of the foraminifera genera identified for these facies, which represents index fossils for this formation. Pieces of echinoderms, miliolids, nazzazata, and other benthic organisms were also found *(*Fig.2C).

- Bioclastic wackestone submicrofacies

Type B is distinguished by the presence of 15 to 20 organic biological fragments of echinoids, mollusca, and pelecypod shells dispersed throughout a micrite groundmass. (Fig. 2F. It is the same as RMF17, which represents the lagoon and is restricted (Flügel, 2010).

- Algal wackestone submicrofacies

Green dasycladcean algae were an important part of the process of making rocks in the Mauddud formation. The Salpingoporella dinarica is the most frequent species, in Tethys Basin during Late Cretaceous (Elliot,1985). The debris from red algae makes up the second type of algae that was observed. The presence of algae on the limestone shows that Mauddud basin used to be a lagoon. These algae are often observed in association with pellets and miliolids. It is like RMF20 (Fig.2D)

- Peloidal wackestone submicrofacies

Peloids of various sizes are found submerged in a tiny floor, along with a few different types of biological detritus, such as bioclastic debris and the appearance of certain small and medium benthic foraminifera, in the fauna of this habitat. Type D correlated with RMF13, which represents the mid-ramp environments (Fig. 2E)

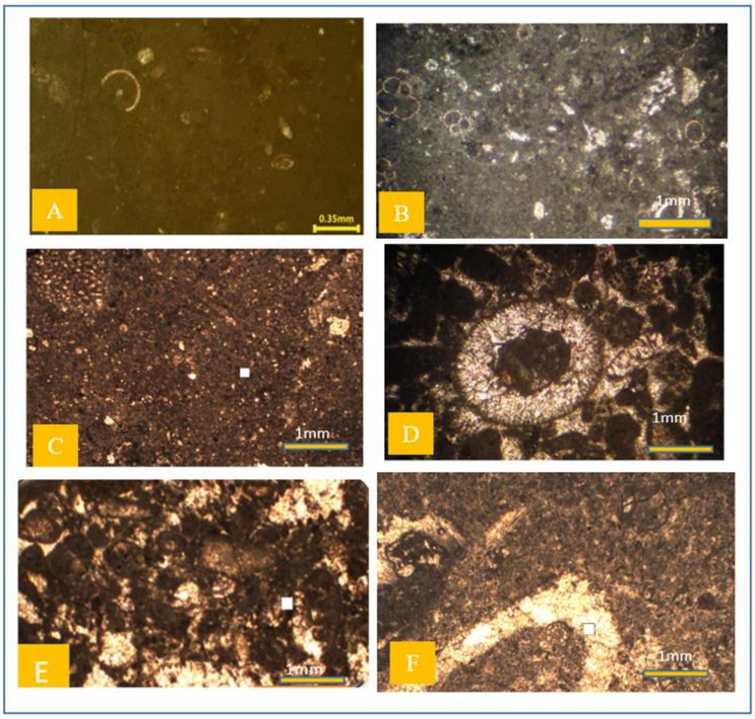

Fig. 2. Study area's primary and secondary Mauddud Formation microfacies: (Fig.3A) Bioclastic lime mudstone at depth 2539m.(Fig.3B) planktonic lime mudstone at a depth of 2749m.(Fig.3C) Benthic Wackestone depth 2561m.(Fig.3D) Algal wackestone at a depth of 2572.90m.(Fig.3E)) Peloidal wackestone at a depth of 2495m. (Fig.3F) Bioclastic wackestone at depth of 6360m.

3.1.3. Packstone microfacies

These microfacies are common in the study area, packstone seems to be common in the Mauddud Formation. These microfacies can be subdivided even further into the following submicrofacies:

- Bioclast packstone submicrofacies

Micrite and skeletal remnants, such as bivalves, can be found in the matrix. (Fig. 3B). Within these submicrofacies, there are a great number of burrows. Micrite is found in the chambers of several bioclasts. These submicrofacies are the same as the RMF3 mid-ramp (Flügel, 2010).

- Benthonic foraminifera Packstone submicrofacies

Packstone microfacies are characterized by an abundance of *orbitilina, miliolid*, and *alveolinids*, it also contains a percentage of the biological fragments represented by the pieces of the benthic foraminifera. Mollusks, echinoderms, algae, and a few foraminiferous organisms originally. It represents the shallow coastal lagoons with the open flow which, in every examined well, may be found near the top of the Mauddud Formation (Fig.3A).

3.1.4. Grainstone microfacies

Granular microfacies have more than 90% grains and less than 10% matrix. The matrix is composed of sparite. Bioclasts include (benthic foraminifera, bivalves' shells, rudist fragments, and algal). It was facies that reflected environments with high energy, representing reefs or shoals (Bathurst, 1993). It is representing the shoal environment and is located in the half-Mauddud Formation. Grainstone microfacies can be divided into sub-microfacies.

- Bioclast grainstone submicrofacies

Type a is largely composed of bioclastic, represented by many fossilized pieces such as foraminifera, rudist, and others, (Fig. 3E). This type of facies is formed under a special environment represented by the depositional energy and the medium wave motion responsible for washing the clay materials. It is the upper part of the formation that was studied, and it is the same as the RMF27 in a typical shoal environment. (Flügel, 2010).

- Benthonic foraminifera grainstone submicrofacies

Type **b** is largely composed of bioclastic, represented by many fossilized pieces such as foraminifera, rudist, and others, (Fig. 3E). This type of secondary facies is formed under a special environment represented by the depositional energy and the medium wave motion responsible for washing the clay materials. It is the upper part of the formation that was studied, and it is the same as the RMF27 in a typical shoal environment. (Flügel, 2010).

- Peloidal grainstone submicrofacies

Type **c** is characterized by the predominance of non-skeletal granules represented by the peloidal resulting from the diageneses process to which skeletal granules, nuts of biocrumbs, echinoderms, and echinacea constitute a high percentage of the components of these facies, as well as a few benthic foraminiferas and some rare foraminifera floating. This facies has a fine, spherical surface, and the grains in it are large to medium-sized. (Fig.3D). Comparative studies were conducted using RMF16, a model of the shoal and shallow open marine environment.

3.1.5. Dolostone microfacies

The Mauddud Formation starts at the top with these layers. Micrite and subhedral dolomitic make up the studied facies (Fig. 3F). It is the stage in the basin with the least depth. Dolomite could be found in deep-sea deposits because of things like eustatic changes in sea level, flooding, and the emptying of shallow shelves (Lumsden, 1985).

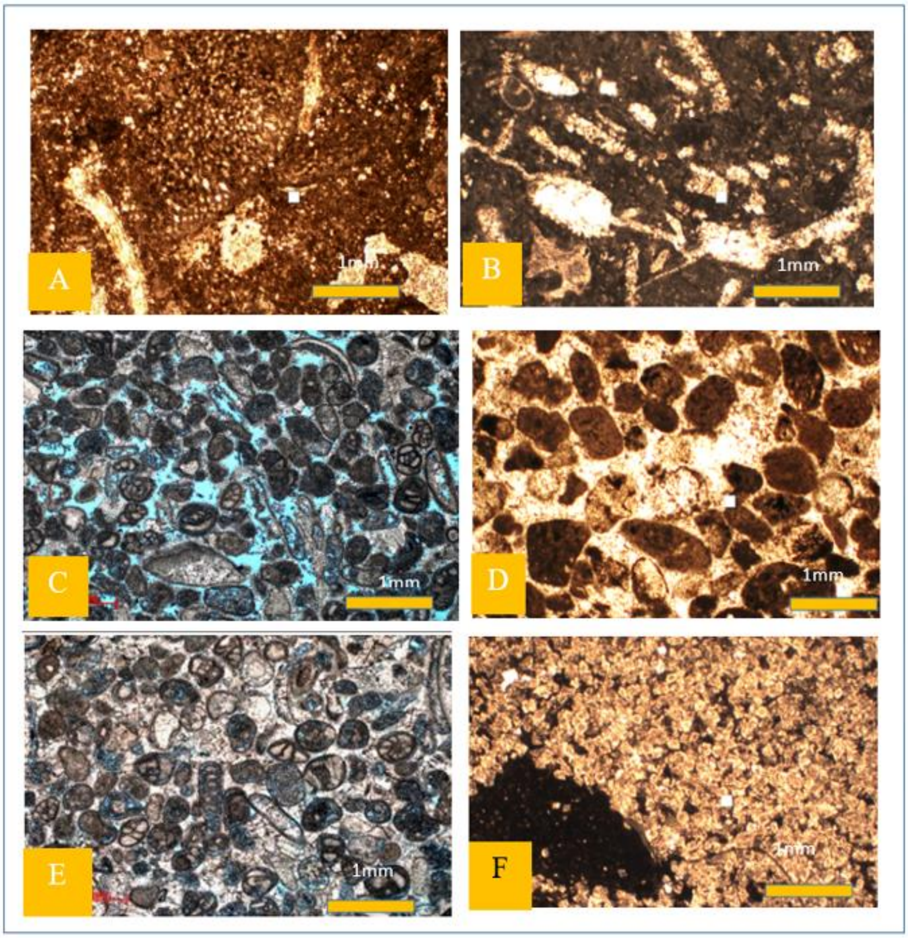

Fig.3. The various primary and secondary microfacies of the Mauddud Formation. :(A) Benthic packstone at depth 2535.98m. (B) Bioclastic packstone at depth 2697m. (C) Benthic grainstone at depth 2685m. (D) Peloidal grainstone at depth 2666.6m. (E) Bioclastic grainstone at depth 2640.50m. (F) Dolostone at depth 2543.50m.

3.2. Mauddud Formation Depositional Environment

3.2.1. Mid-ramp environment

Skeletal remains were discovered in deposits made at the mid-ramp, peloids, Skeletal remains were found in mid-ramp deposits, peloids, Wackestone, and wacke-packstone. The proximal half of the mid-ramp association has more skeleton than the distal half (Flugel, 2010).

There are fragments of green algae, rudists, echinoderms, and foraminifera in the proximal part of the mid-ramp, whereas planktonic foraminifera is more abundant in the distal part (Schlager, 2005). With argillaceous wackestone at the bottom and gradually more grain-rich Wackestone, and packstone at the top, there is a general cleansing trend up word. The best signs of cleared open marine conditions are a lack of diversity and richness in macrofauna, as well as uniform bedding and a high level of bioturbation.. Deepwater, mid-ramp conditions are reflected in the argillaceous and Wackestone

(Schlager, 2005). Micrite is more common in the mid-ramp zone in a low-energy environment. Storm activity is influenced by the migration of inner ramp material from the mid-ramp to the shoreline as well as the grainier lithology under fairweather wave bases. These microfacies are equivalent to RMF5 and RMF7 (Fig.4).

3.2.2. Shallow open marine environment

The shallow open marine environment with the open sea is characterized by abundance and funa diversity, including the following microfacies: foraminiferal Wackestone microfacies, and foraminiferal packstone microfacies. Orbitolina thrived in 15-25 C climates found in the tropics and subtropics along shallow coasts. (Douglass, 1960). *Orbitolinid* association with *miliolids* indicates shallow water, While its association with rudist fragments indicates deeper, more open water (Sadooni and Alsharhan, 2003)

3.2.3. Restricted environment

This group of organisms is represented by bioclastic Wackestone and bioclastic packstone, as well as miliolid fragments, rudist fragments, pelecypods, and gastropods. Lime mudstones and dolomitized mudstones, as well as foraminiferal bioclastic Wackestone-Packstone, miliolids, and gastropods can be found in this area (Al-Najim, 2006), this microfacies is like RMF-13(fig.4).

3.2.4. Shoal environment

The facies of the shoal environment was characterized by peloidal skeleton packstone to grainstone rudists bearings, floatstone, and rudstone. The grain is moderate to thoroughly sorted. Benthic foraminifera, bivalves, peloids, and Intraclasts. The intensity ranges from mild to high. When it comes to echinoderms, the shoal is clean, and organized, only slightly sloppier at longer time intervals.

As a result of a higher macropore component, shoal deposits are more porous than other types of deposits, with a lower density log value and a higher neutron porosity log value. Contrarily, the cementation diageneses process causes a high log value in the density (Fig.4).

3.2.5. Lagoon environment

This environment contains benthic foraminifera indicative of the environment for a lagoon such as mollusks, pieces of algae, echinoderms, and the shell of the bivalve. The main components of this environment are the facies of the benthic wackestone and the packstone that contains the large benthic foraminifera and the solid containing the bioclastic, as well as the facies of the peloidal packstone. The energy is low to moderate level (Schlager, 2005).

Wireline log responses from lagoon facies show increased gamma radiation due to the preservation of organic matter. Gamma-ray log responses are low for grainier deposits that have peaked but high for argillaceous and Wackestone-fabric deposits.. Early cement has fewer open pores because of the tight weave, increasing density, and decreasing neutron porosity associated with lagoon facies (Fig. 4).

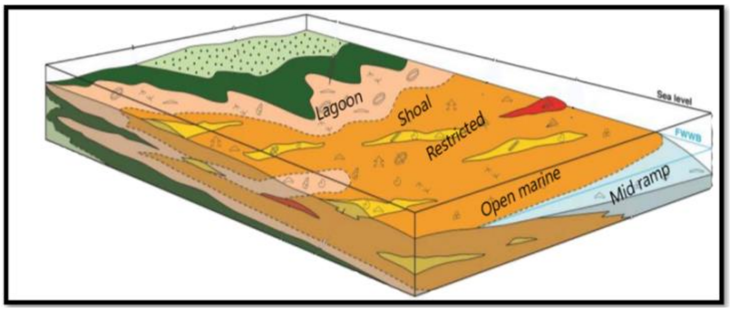

Fig.4. Depositional model of the Mauddud Formation Modified from Al-Awadi. et al. (2017)

3.3. Sequence Stratigraphy

The Mauddud Formation is the same as the early face of the highstand that is part of the Wasia Group from the Albian to early Cenomanian time period(Sharland et al., 2001). The results of this investigation led to the discovery of the following sequences and important surfaces: (Figs. 5, 6, 7and 8).

3.3.1. Mauddud sequence (MSL1)

SB1(sequence boundary 1): This surface is located at the top of the Nahr-Umr Formation and corresponds to the characteristic top of a gamma-ray peak. The indication of this surface is the increased gamma-ray log, increase density log, and decrease acoustic log.

MF1(marine flooding 1): The behavior of this surface peak of gamma-ray, decrease of gamma-ray and density log whereas the increase of sonic log.

The MSL1 is the bottom part of the lower Mauddud Formation, which is on top of the Nahr-Umr Formation. The transgressive system tract (TST) corresponds to the peak of gamma-ray, characteries by an increase of gamma-ray and density logs while the acoustic log is decreased. The trend is dirtying upward and the decrease of porosity reached the marine flooding surface. Gamma-ray and density logs of the highstand system tract (HST) are low, while acoustic logs are high. The trend of the highstand system tract is cleaning upward. The core description for the Parasequence is limestone, light grey-grey, compaction limestone, argillaceous bond, bioclastic, and contain shell fragment. In this part of the Mauddud Formation, mudstone and wackestone dominate the microfacies associations, which reflect a moderate to low-energy intertidal or lagoon environment. Rare bivalves, algal fragments, and benthic fragments have been observed in lithofacies

3.3.2. Mauddud Sequence 2 (MSL2)

SB2: pointed on the peak of gamma-ray having greater gamma-ray and density logs and a decreased acoustic log.

MF2: The corresponds of this surface peak of gamma-ray, a decrease of gamma-ray and density log whereas an increase of acoustic log.

This sequence corresponds to the top portion of the lower Mauddud Formation in terms of its stratigraphic position. In response to the high level of gamma rays, the transgressive system tract, or TST. characterized by a rise in gamma-ray and density logs, while the acoustic log is decreased. The trend is dirtying upward with a decrease in porosity reaching the MF2. The highstand system tract (HST) is characterized by low of both gamma-ray and density logs and high acoustic logs. The trend of the highstand system tract is cleaning upward. The core description was limestone, brown-dark brown, compact, vuggy porous, fossiliferous, fracture, pyrite, rudist, bioturbation, and oil show. The common microfacies association, the Wackestone, and packstone are dominant in this part, which reflects the open marine, restricted, and early-mid ramp, which are moderate to low energy. This sequence is marked by a diversity of fossils: echinoderm, Gastropoda, Bivalve, Rudist fragment, Benthic foraminifera.

3.3.3. Mauddud Sequence 3(MSL3)

SB3: Pointed on the peak of gamma-ray, accompanied by a rise in gamma-ray and density values and a fall in the sonic log.

K110(maximum flooding surface): This MFS, which corresponds to the peak of the gamma-ray spectrum, is regarded as another simple "3rd order" TST driven by eustacy and subsidence, with a diminishing contribution from sediment supply and plate-wide spread. The gamma-ray log and the density log increased, and the acoustic log fell.

MSL3 represents the lower part of the upper Mauddud Formation, and the transgressive system (TST) corresponds to the gamma-ray peak, characterized by an increase in the gamma-ray log and density log and a decrease in the acoustic log. The trend dirtying upward and low porosity until reached maximum flooding surface. The highstand system tract (HST) has low gamma-ray and density logs as well as high acoustic logs. The trend of the highstand system tract is recorded coursing and cleaning upward and increase in porosity with varying amounts of sorting. The primary geological constituent is a dark brown limestone that is variously described as compact, vuggy, porous, fracture, peloidal, oil show, and cement rich. The most prominent microfacies associations in this section are grainstone-mud lean packstone and biostorms Wackestone. which transformed the high-energy shoal environment from open subtidal conditions. Fossils observed were rudist, echinoderms, algal, mollusks, and bioclastic fragment

This MFS is composed of a planktonic foraminifera mudstone microfacies-dominated surface of regional maximum flooding. This regional MFS K-110 is a regional key surface. according to a lot of research (Sharland et al., 2001).

3.3.4. Mauddud Sequence 4(MSL4)

SB4: This surface is distinguished by a gamma-ray peak, a reduction in density and gamma-ray log, and an increase in sonic log.

MF4: The match of this surface peak of gamma-ray, the decrease of gamma-ray and density log, and the increase of acoustic log.

The MSL4 represents the upper part of the upper Mauddud Formation that is located at the base of the Ahmadi Formation. The transgressive system tract (TST) coincides with the peak of the gamma-ray log, demonstrating characteristics of decreased both gamma-ray and density logs while increasing the acoustic log. The trend is cleaning up above the sequence boundary and the increase in porosity reached MF4, the highstand system tract (HST) characterized by high density and gamma-ray log and low acoustic log. The high-stand system tract is becoming increasingly dirty. The core description for the Parasequence is limestone, dark brown, compact, vuggy, porous, patchy oil show, fracture, benthic foraminifera, and poloidal with buff limestone. The main microfacies associations are mixed lithology; Wackestone to packstone with a few mudstones are dominant in this part, which reflects the intertidal to the restricted environment, which is moderate to low energy. Certhid Gastropoda and benthic fragments were observed in this part.

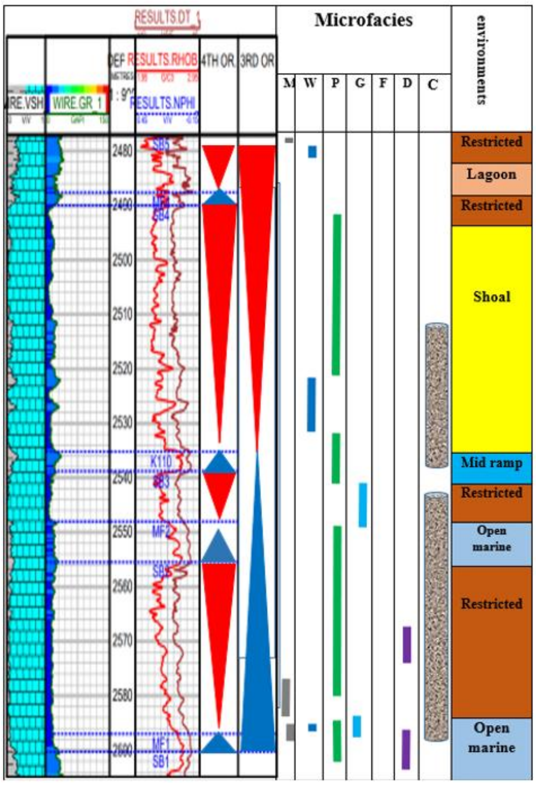

Fig.5. The stratigraphy of the Mauddud Formation in well X-1 and its sequence Sequence boundary (SB), maximum flooding surface (MFS) calculated using thin section and wireline data.

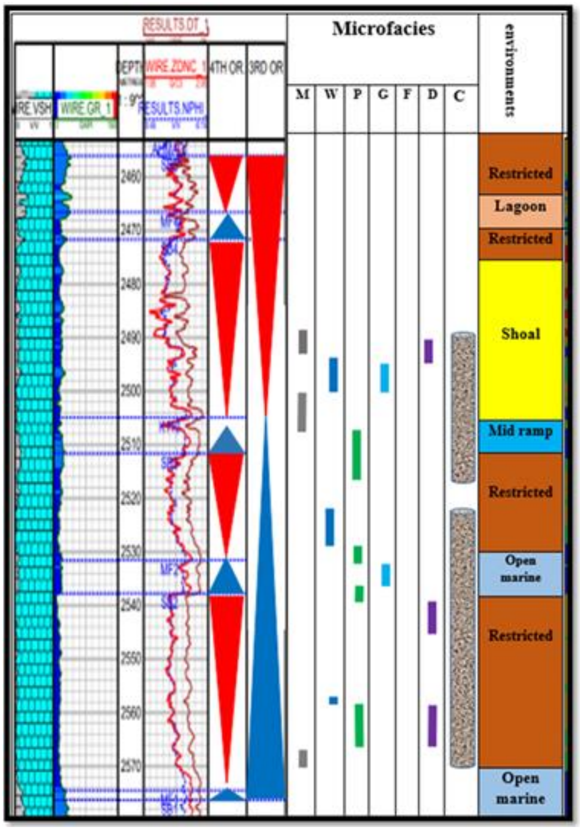

Fig.6. Well X-2 Mauddud Formation sequence stratigraphy, Sequence boundary (SB), and maximum flooding surface (MFS) derived from thin section and wireline data.

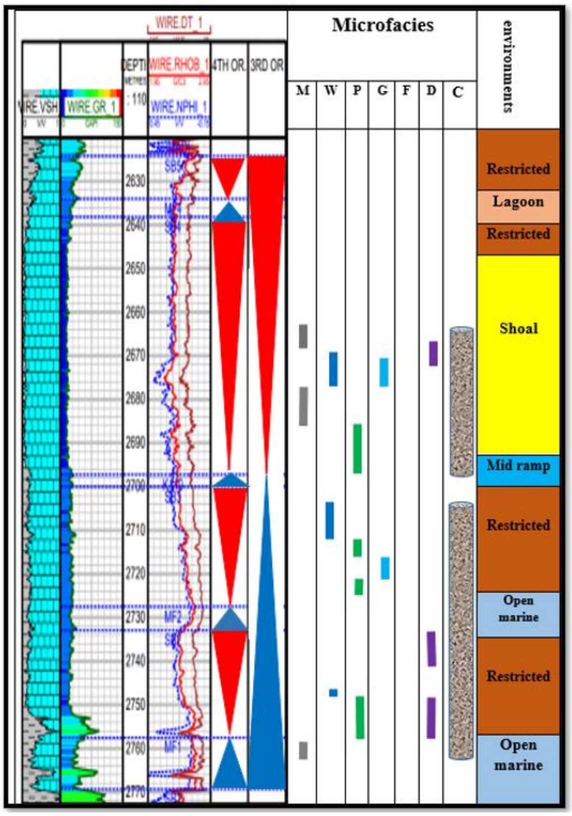

Fig.7. The maximum flooding surface (MFS) and the sequence boundary (SB) were estimated using thin section and wireline data to identify the stratigraphy of the Mauddud Formation in well Z.

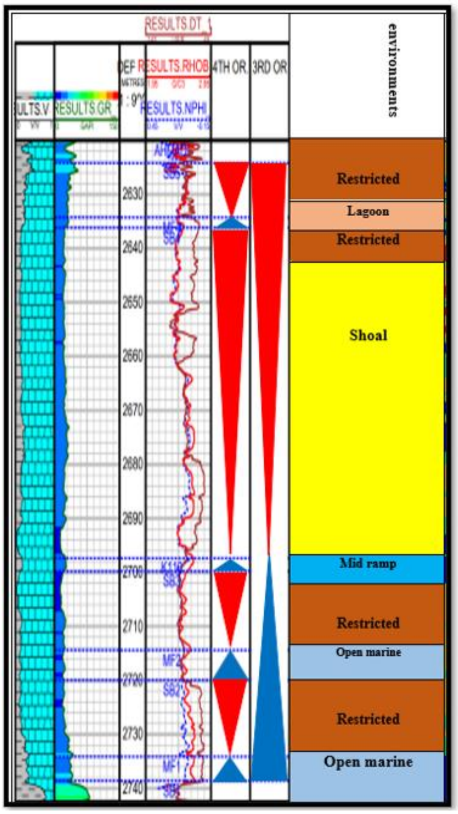

Fig.8. Based on thin-section and wireline data, well Y Mauddud Formation sequence stratigraphy is (SB) sequence boundary and (MFS) maximum flooding surface.

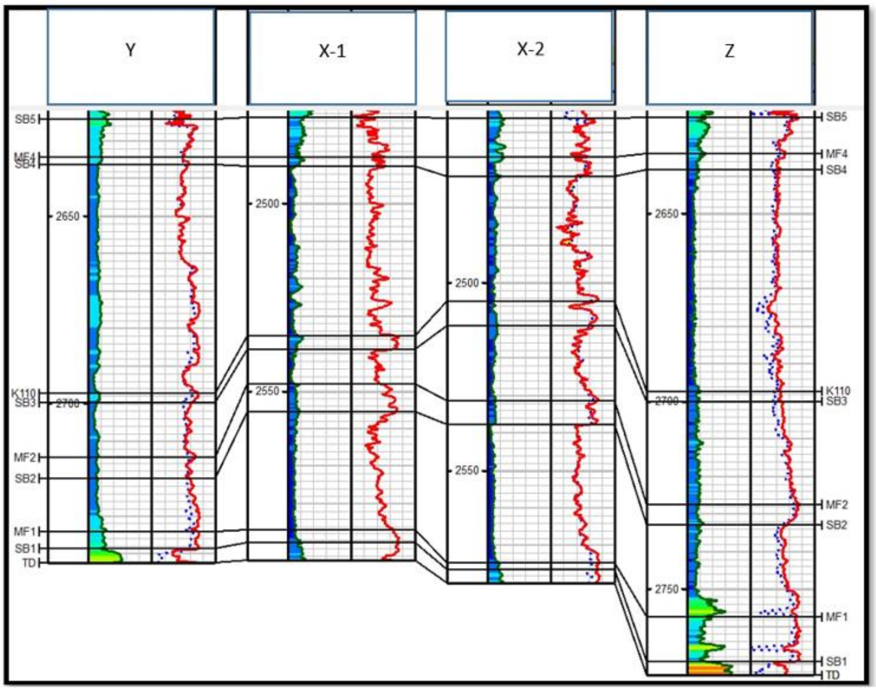

Fig.9. Stratigraphic succession of the Mauddud Formation in three oilfields, illustrating four marine flooding surfaces.

4. Conclusions

- The Mauddud Formation is made up of limestone with no lithological variation. The most often observed microfacies are Wackestone with packstone, that underscored by index fossils. Mauddud Formation carbonate sediments represent an inner ramp environment dominated by *miliolids*, *prealveolinids*, *orbitolinids*, *trocholinids*, and green algae. The recognized depositional environments start with the mid-ramp and end in the lagoon environment.
- Mauddud Formation secessions are 3rd-order sequences, characterized by transgressive and highstand system tracts. As the transition between the Mauddud and Ahmadi formations is marked by an erosive surface.
- Based on the results of this study, the MFS (K-110) has a lot of planktonic foraminifera like *Hedbergella*, in contrast to the other maritime incursions that have been observed for this investigation, (FS1, FS2, and FS4) evidence a wide variety of benthonic foraminifera (*nezzazata* simplex, *orbitilina*, *miliolid*) and planktonic foraminifera with an increased proportion of planktonic foraminifera.
- The thickness of the Mauddud Formation is increased toward the north direction in the Z oilfield, reaching 147 m, whereas the formation in the west has a thickness of 110 meters (Fig. 9).
- The Mauddud Formation (Cenomanian) is considered as one of the most important oil reservoirs in the southern fields of Iraq, due to its good petrophysical properties and geographical extensions. It represents the second reservoir economically after the Yamama Formation in some oilfields south of Iraq.

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