Iraqi National Journal of Earth Science
www.earth.mosuljournals.com

Paleoenvironment and Petrophysics Properties of Bajwan Formation at Kirkuk Oil Field, Northeastern Iraq

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Article information

Received: 17- Dec -2023

Revised: 25- Mar -2024

Accepted: 07- May -2024

Available online: 01- Apr – 2025

Keywords:
Microfacies
Petrophysics
Bajwan Formation
Kirkuk
Iraq

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ABSTRACT

The Bajwan Formation is one of the most significant formations of the Oligocene cycle and the oil resource in the Kirkuk region. The present study is based on samples taken from two wells; the first is (K-A), where the Bajwan Formation about (30 m thick), while the second is (K-B), about (26 m thick). The formation is composed of creamy-colored limestone and dolomitic limestone with a various hardness. Some sections are soft. The formation is made up of four microfacies; Non-Fossiliferous Lime Mudstone, Milioldal-bioclasts Lime Wacke-stone/Packstone, Rotalids Wackestone, and Miliolidal Lime Wacke-stone/Packstone. These microfacies show that the formation was formed at inner ramp carbonate tidal flat platform environment. The Gama Ray log is used to compute the volume of shale (V-Shale) of the Bajwan Formation after the shale influence is removed owing to porosity equation adjustment. Based on the results of the porosity values for both wells, the Bajwan Formation successions are categorized into two zones in the well K-B, good and very excellent porosity zones, and three zones in the well K-A, poor, good, and very good porosity zones.

DOI: 10.33899/earth.2024.145414.1198,

البيئة القديمة والخواص البتروفيزيائية لتكوين باجوان في حقل كركوك النفطي، شمال شرقي العراق.

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معلومات الارشفة

تاريخ الاستلام: 17– ديسمبر –2023

تاريخ المراجعة: 25– مارس –2024

تاريخ القبـول: 07– مايو –2024

تاريخ النشر الالكتروني: 01– ابريل –2025

الكلمات المفتاحية:

السحنات الدقيقة

البتروفيزيائية

تكوين باجوان

كركوك

العراق

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الملخص

يعد تكوين باجوان من أحد أهم تكاوين دورة الأوليكوسين ومورداً مهماً للنفط في منطقة كركوك. اعتمدت هذه الدراسة على اخذ عينات من بئرين، الأول هو(K-A)، اذ يبلغ سمك تكوين باجوان حوالي (30 متراً) والثاني هو(K-B)، اذ يبلغ سمك تكوين باجوان حوالي (26 متراً). يتكون التكوين بشكل عام من الحجر الجيري والحجر الجيري المتدلمت، كريمي اللون وذو صلابة متوسطة. وفقا للتقارير التي تم الاطلاع عليها في شركة نفط الشمال، فإن التكوين بشكل عام مسامي ويحتوي على العديد من المستحاثات. سحنياً، يتالف التكوين من أربع سحنات دقيقة هي الحجر الطيني الجيري غير المستحاثي، سحنة الحجر الجيري الواكي/المرصوص المليوليدي–الفتاتي العضوي وسحنة الحجر الجيري الواكي الروتاليدي وسحنة الحجر الجيري الواكي/المرصوص المليوليدي والتي تشير جميعها إلى أن التكوين قد ترسب في بيئة ممتدة من مسطحات المد والجزر إلى بيئة المنحدر الكاربوناتي الداخلي. تم توظيف سجل أشعة كاما لحساب حجم الطفَل (V-Shale) لتكوين باجوان بعد إزالة تأثير الطفَل لغرض تصحيح معادلة المسامية. اعتمادا على نتيجة قيم المسامية لكلا البئرين، فان تكوين باجوان ينقسم إلى نطاقين في البئر K-B ذات مسامية جيدة وجيدة جدا، وثلاث انطقة في البئر K-A ذات مسامية فقيرة وجيدة وجيدة جدا.

DOI: 10.33899/earth.2024.145414.1198, ©Authors, 2025, College of Science, University of Mosul.

Introduction

The Kirkuk oil field is made up of three domes, from northwest to southeast, they are Khurmala Dome, Avana Dome, and Baba Dome. The Baba dome is at around 16 kilometers from the Arafa neighborhood near the downtown of Kirkuk (Al-Hayali, 2019). The current research depends on the selection of two oil wells from the Kirkuk oil field restricted to the dome of Baba, in which the Bajwan Formation apears.

Due to the reasonable significance of the Bajwan Formation as an oil resource, Bellen et al. (1959) characterized it in the Kirkuk oil field (well-109) nicely. The Bajwan Formation generally made up of coralline algal reef limestone and miliolidal limestone that alternate with comparatively many coral pieces and thin argillaceous limestone layers that are roughly 40 meters thick.

This formation was divided into two parts based on the degree of porosity and the presence of fossils (Bellen et al., 1959), the dense unit at the top consists of dolomitized or chalky limestone with dense miliolid. Fatha Formation's basal conglomerate appears at the upper contact of the underlain Bajwan Formation, while the lower unit is composed of an alternation of dense slightly greater recrystallization, dolomitization, and porosity than the top unit with the porous and vuggy dolomitic limestone.

Although previous studies (Henson, 1950) found that the depositional environment of the Kirkuk Group was reefal, (Ghafur, 2012) argues that deposition happened on a carbonate ramp. According to the author's research on the Kirkuk group in southern Kurdistan, the depositional environment supports a ramp setting since the lateral facies vary with depth and there is no evidence of a rimmed shelf and steep slope. Based on the distribution of foraminiferal associations, nine depositional habitat zones were found, ranging from terrestrial to open marine habitats and spread across the inner, middle, and outer ramp. (Soltani *et al.* 2013) investigated the relationship between these stratigraphically and sedimentologically significant deposits and several case studies (in outcrops and sub surface) in south-west Iran and north-northeast Iraq. He concluded that, with the exception of a few minor changes, the deposits in southwest Iran and north, northeast Iraq are substantially comparable. (Al Qayim *et al.* 2016) investigated the microfacies and sequence stratigraphy of the Oligocene-Miocene rock units (Bajwan, Anah, Euphrates, and Jeribe formations) in the High Folded Zone's Gwlan mountain-Darbandikhan series. He discovered four third-order sequences that have a good association with regional and global eustatic sea-level trends. The Euphrates Formation (Aquitanian), Bajwan Formation (Late Rupelian), Anah Formation (Chatian), and Jeribe Formation (Burdigalian) are among these formations.

The petrographic and physical features of six chosen wells from Kirkuk oil field were studied by (Farhan *et al.* 2016). This study contributes in the evaluation of the microfacies and environment for the Bajwan and Baba Formations. The Baba Formation yielded two microfacies, but the Bajwan Formation yielded five carbonate microfacies. The depositional environment of the Bajwan Formation is characterized as a backreef/reef or a confined lagoon (inner ramp) by many types of microfacies, whereas the depositional environment of the Baba Formation is described as a shallow water forereef (middle ramp). The Oligocene succession's stratigraphy, lateral and vertical facies change, and depositional environment served as the foundation for the facies model's creation.

(Karim and Hama 2019) discovered the Oligocene succession (Kirkuk group) for the first time in the Dohuk area. They also discovered that the succession extended to about 20 kilometers inside the high folded zone and that the Oligocene's previous basin boundary shifted to the north for more than 50 kilometers. During the Oligocene, the platform transformed the Dohuk region's old high ground land into regular marine basins. Moreover, (Karim et al. 2014) indicated that just a few millimeters of Oligocene strata are extant, and that the rocks exposed in the Sinjar fold are largely from the Early Miocene Serikagni Formations.

(Ameen *et al.* 2020) studied the Upper Oligocene and Lower Miocene successions from Sulaimani City, Kurdistan region, northeastern Iraq, at the high/low folded thrust zone boundary, and concluded that the sedimentary environment was discovered to be an inner ramp setting that transitioned to a middle ramp setting during the Upper Oligocene (Bajwan Formation), and an inner ramp setting that transitioned to a semi-close.

(Ghafor, 2022) studied the paleoecology, biostratigraphy, and systematics of the Kirkuk Well 160s (Bajwan Formation) in northern Iraq. In his conclusion, the Bajwan Formation was formed in tropical to subtropical ecosystem at normal water salinity levels ranging from 34 to 50 ppm, in a confined shallower water depth, and under mesotrophic to oligotrophic circumstances.

The aim of this study is determining the sedimentary environment, drawing the sedimentary model, and recognize the nature of characteristics reservoir of Bajwan Formation within the examined wells.

Geological Setting and Location

The latest Eocene–Recent Megasequence (AP 11) is associated with the collision of Neo-Tethyan terrains along the northern and eastern sides of the Arabian plate, and the opening of the Aden Gulf at the southern side of the plate, and red sea at the western side of the plate. The north and northeast drift of the Arabian plate and the closure of the Neo-Tethys resulted in folding and thrusting of the Neo-Tethyan terranes along the NE margin of the Arabian plate. The latest Eocene-Resent Megasequence is more than 3 km thick in the foothill zone in southeastern Iraq. It is less than 0.5 km thick in an area extending from Mosul to the Tharthar valley towards the Euphrates River; this area detached between Sinjar basin in north-west, and the Kirkuk basin in the south-east of Iraq (Jassim and Goff, 2006) (Fig. 1).

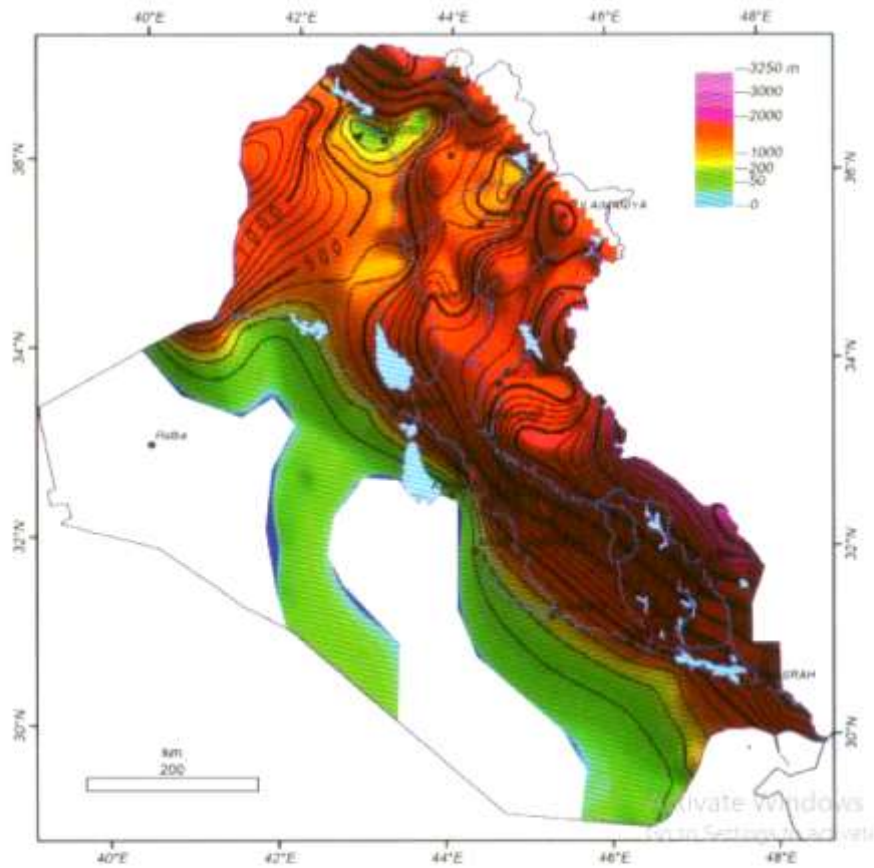

Fig. 1. Thickness of Megasequence AP 11 (Jassim and Buday, 2006).

The (AP 11) is divided into three sequences; Latest Eocene–Oligocene, E–M Miocene and L Miocene–Recent age (Bellen et al., 1959). At the end of Eocene, the intraplate basins became narrower, and the closed Neo-Tethys was a narrow seaway in which the clastic and carbonate were deposited. In Oligocene, the Oligocene basin was relatively narrow, and located in the Mesopotamian zone, foothill zone, Jazira subzone, Rutba subzone, while the Salman zone, Euphrate and Zubair subzones uplifted at the same time. Thick fringing reefs developed along the two sides of the basin, while the center of the basin was filled with the deep marine marls. The Eocene–Oligocene deposits are bordered from the lower and upper contacts by breaks of deposition (Jassim and Goff, 2006).

Iraq's Oligocene deposits are divided into three sequences: the early Oligocene (Palani, Sheikh Alas, Shurau Formations), the middle Oligocene (Tarjil, Baba, Bajwan, Ibrahim Formations), and the late Oligocene (Azkand and Anah Formations) (Bellen et al., 1959). These Formations were combined to form the Kirkuk group as it was discovered in the Iraqi province of Kirkuk. These sequences originated in a variety of settings including basins, reefs, and back reef facies. Ditmar et al. (1971) modified Bellen's three-cycle classification of the Oligocene sedimentary cycle into two subcycles. The Sheikh Alas, Shurau, Palani, and Tarjil formations make up the lower cycle, while the Anah, Azkand, Baba, Bajwan, and Ibrahim formations make up the upper cycle. Each sequence has back reef/reef, forereef, and basin facies.

The study area is located on an unstable shelf in Iraq's northeastern region. The selected boreholes are distributed across the foothill zone (low folded zone) of the Chemchemal-Erbil subzone. The wells to be studied are in Kirkuk Governorate, northeastern Iraq, near the Kirkuk oil field, which is roughly 147 kilometers southeast of Mosul.

According to North Oil Company authorization, the current research depends on the selection of two oil wells from the Kirkuk oil field restricted to the dome of Baba, which are well (K-A) and well (K-B). The well (K-A) is one of the most important oil wells in northeastern Iraq, Kirkuk Governorate, which is located at the intersection of longitude (E 44° 20’ 48”.39) and latitude (N 35° 31’ 2.81”), and the sequences of the Bajwan Formation in this well are limited to depths of (400-430) meters resulting in a thickness of (30) meters (Fig. 2). While the well (K-B) is located at the junction of longitude (E 44° 25’ 56.73”) and latitude (N 35° 26’ 54.91”), where the Bajwan Formation is restricted to this well at depths ranging from (642 to 668) meters and a thickness of (26) meters.

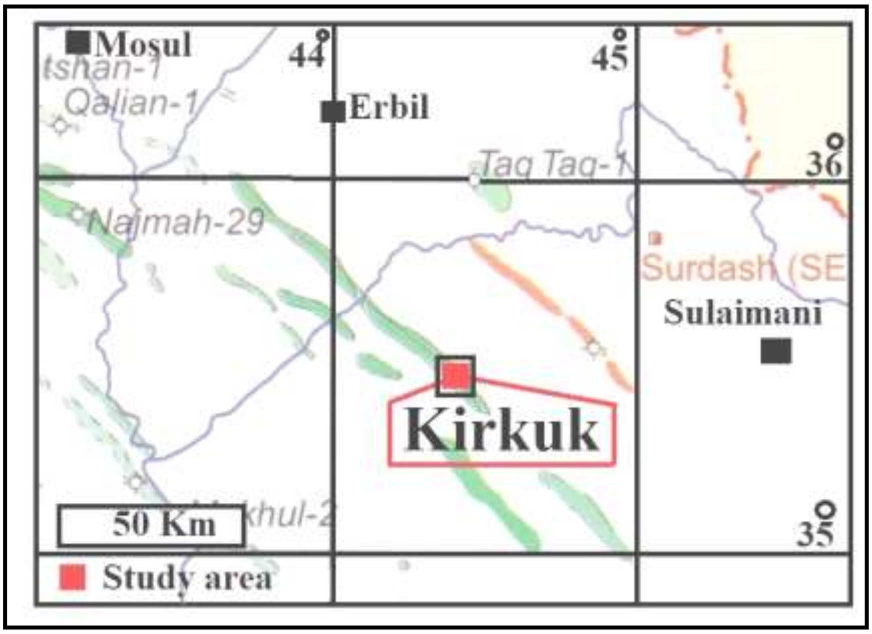

Fig. 2. Location map of the study area (After Aqrawi et al., 2010).

Methods and Materials

28 well cutting samples are collected and described to drawing columnar sections and doing thin sections. The carbonate microfacies and microfossils are identified and described from thin section using a polarizing microscope. Dunham's (1962) classification is used for the qualitative microfacies study. Dickson's (1965) approach for identifying calcite and dolomite is used to stain all thin sections with Alizarin Red Solution. According to Flügel (2010), sedimentological and biological evidences are employed to determine and locate the depositional environment.

On the other hand, the available logs are used to study the petrophysical properties such as the gamma ray log to calculate the size of the shale and neutron log, density and sound log to calculate the total effective porosity and secondary porosity, and the size of the shale. These logs are inserted into a scanner to convert their information from paper or image format to digital data within the Las file format, which facilitates dealing with them through the computer program (Neuralog V 2010.11). The porosity is then calculated using Interactive Petrophysics v3.6 by petrophysical analysis of logs data mainly from common mathematical equations and some standard schemes (Schlumberger, 1998) that were applied to probe studies (Schlumberger, 1997; Rider and Kennedy, 2011).

Results and Discussions

Lithological description of Bajwan Formation

The current study is based on two wells, the first (K-A) with a total thickness of the Bajwan Formation of roughly 30 meters, and the second (K-B), with a thickness of (26) meters. The formation is composed primarily of creamy-colored limestone and dolomitic limestone with a various hardness. According to North Oil Company studies, the deposit is usually permeable and includes fossils (Fig. 3).

Microfacies Analysis of Bajwan Formation

The microfacies of Bajwan Formation successions are identified, and the nature of these microfacies and their accompanying fossils are critical in determining the ancient depositional environment. Dunham classification of carbonate rocks is used to characterize the microfacies precisely, which are compared to the RMF of Flügel (2010) and Buxton and Pedley (1989). Depending on the investigation and proper diagnosis of thin section components, the formation comprises four microfacies labeled as B1, B2, B3, and B4. The paleoecology and bathymetry of the formations are reflected in the microfacies study. These microfacies are explained in detail below:

1. Non-Fossiliferous Lime Mudstone Microfacies (B1)

This microfacies emerged in the upper part of the Bajwan Formation, which was around (8-14 m) thick. This microfacies is made up of lime mudstones. Some samples contain trace quantities of quartz grains and gypsum. There are no bioclasts or fossils, although the fenestrate structures are highly developed (Fig. 4. a).

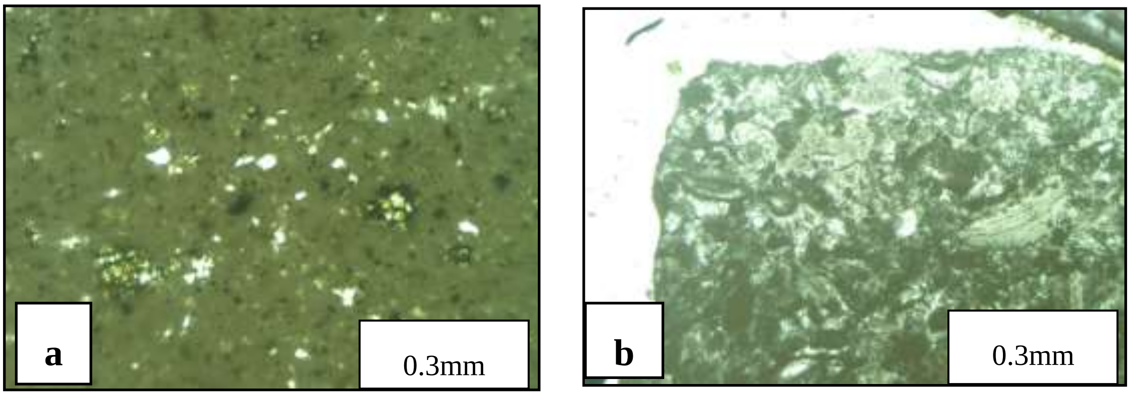

Fig. 4 . a. Non-fossiliferous lime mudstone microfacies; b. Miliold-bioclasts lime wackestone/packstone microfacies.

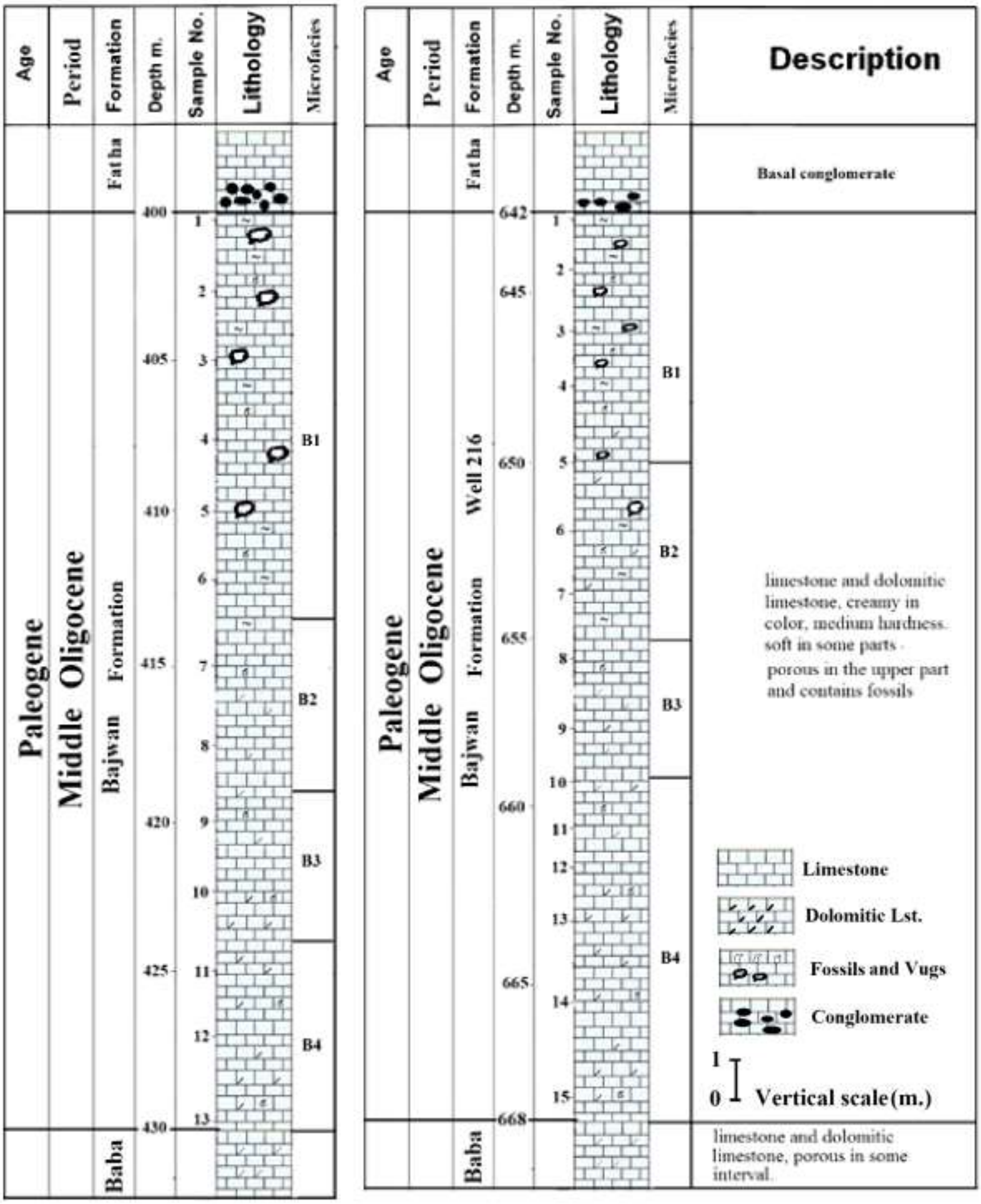

Fig. 3. Columnar section of Bajwan Formation for the two wells (K-A) to the left and (K-B) to the right.

Interpretation

The presence of lime mudstone, tiny quartz grains, and gypsum crystals suggests hypersaline conditions in a supratidal flat environment. Similar facies were regarded by Shinn (1983) to be characteristic of a tidal flat (supratidal) environment, where trapped air between deposits leading to the formation of irregularly shape fenestrate structures (Simo et al., 2023). The nearest facies of these properties are RMF 23 peritidal (Flügel, 2010).

2. Miliold-bioclasts Lime Wackestone/Packstone Microfacies (B2)

This microfacies is located in the center of the Bajwan Formation (5 m thick), above the Bajwan Formation's rotallids wackestone microfacies and below the non-fessiliferous lime mudstone microfacies. It is mostly composed of bioclasts (30%), as well as well-preserved skeletal grains from benthic foraminifera such as Miliolid, Rotalia, *Praehapydionina* sp., and *Archaias* sp. Furthermore, bioclasts include echinoids, pelecypods, ostracods, coral, and gastropods. A micritic matrix is used to integrate all of these components. Recrystallization has affected the groundmass as well as some of the skeletal grains (Fig. 4.b).

Interpretation

The presence of wackestone-Packstone facies and bioclasts (Rotalia, Miliolids, *Archaias* sp, *Praerhapyionina* sp, and Echinoids bioclasts) implies the platform's interior section (Corda and Brandano, 2003; Joudaki et al., 2020; Ameen et al., 2020). However, the presence of the species *Praerhapydionina* sp. (Fig. 5.a) in this microfacies is restricted to back reef settings with water depths of 8 to 10 meters and temperatures ranging from 11 to 33 degrees Celsius (Othman, 2007). According to the evidence of fossils, this microfacies is deposited along the inner ramp in shallow waters lagoon with open circulation. It resembles RMF 16 to may be RMF 18 that represents protected and low-energy inner ramp (Flügel, 2010, Al-Mawla and Al-Hamidi, 2024).

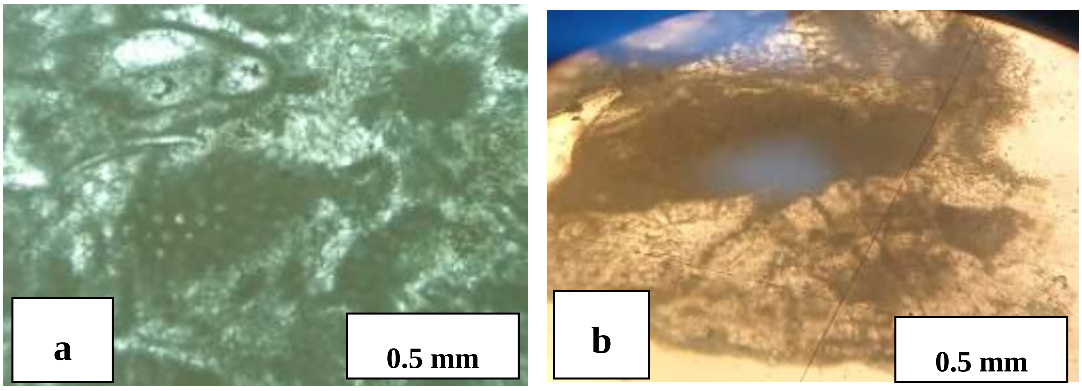

Fig. 5. a. *Praerhapydionina* sp. ; b. Rotalids wackestone microfacies.

3. Rotalids Wackestone Microfacies (B3)

This microfacies is around (4-5) meters thick and has been found in the center of the Bajwan Formation, above miliolid lime wackestone/packstone and below the Bajwan Formation's milioldal-bioclasts lime wackestone/packstone microfacies. Rotalids (10%) such as *Amphistegines* sp. and other benthonic foraminifera such as miliolid, *Austrotrillina* sp., *Archaias* sp., and *Sivasina* sp. dominate this microfacies, along with bryozoan and echinoid fragments. A micritic matrix includes these grains (Fig. 5.b).

Interpretation

The perforate foraminifera are frequently dominated at the lower section of the upper photic zone (Bassi et al., 2007). According to Brandano et al. (2009), the presence of hyaline perforate foraminifera, particularly when associated with Rotaliids, may be a sign of middle ramp habitats. While Buxton and Pedley (1989) indicated that Rotaliids can extend in existence from a shallow subtidal ramp to a deeper ramp. But the co-occurrence of typical marine biota such as Rotaliids and echinoids and associated with lagoonal biota such as miliolids showing that the sedimentation occurred in an open shelf lagoon environment (Vaziri-Moghaddam, 2010; Al-Taha and Al-Haj, 2024). The characteristics of this microfacies is close to the RMF 13 (Flügel, 2010). Therefore, this microfacies is deposited in open inner ramp environment (Flügel, 2010).

4. Miliolidal Lime Wackestone/Packstone Microfacies (B4)

It is located at the lowest part of the Bajwan Formation near the contact surface between the Bajwan and the underlain Baba Formation. This microfacies is roughly (6-9) meters thick. Miliolids (Fig. 6.a) (25%) *Austrotrillina* sp., *pyrgo* sp., others Soritoids, *Archaias* sp., Dendritina, echinoids) are the principal constituents. Oolite and lithoclasts (Fig. 6.b) are present in modest amounts. The matrix of micrite is altered by recrystallization.

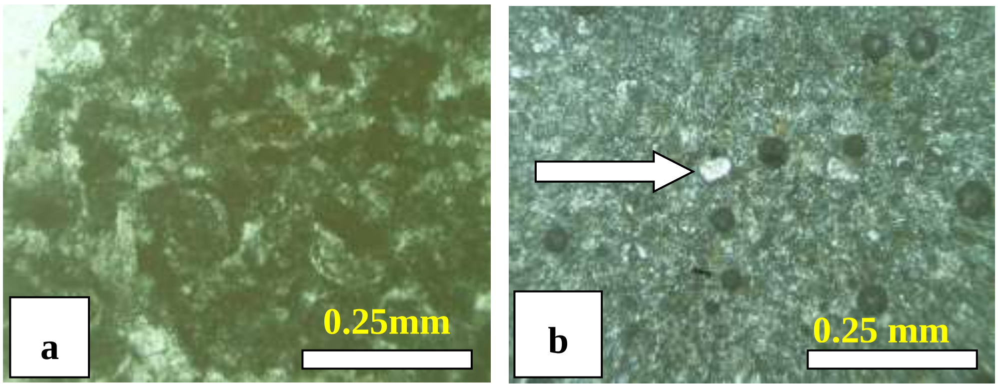

Fig. 6. a. Miliolidal lime wackestone/packstone microfacies; b. Lithoclasts (Qtz grains).

Interpretation

Milioids are typically found in limited maritime habitats and prefer to live in lagoons (Rafi et al., 2012; A l -Fandi et al., 2023) indicating eutrophic conditions with high nutrient content (Mehr and Adabi, 2014). The quantity and diversity of perforate benthic foraminifera (Miliolids, *Austrotrillina* sp., and Dendritina) are characteristic of a lagoon's shallow restricted environment (Hallook and Glenn, 1986). The predominant packstone texture together with an abundance of Miliolids (such as *Austrotrillina* sp.) indicate low-energy deposition (Vaziri-Moghaddam, 2010). According to Ameen et al. (2020) and Al-Shammary, et al., (2023), such microfacies was deposited in an inner ramp context because it is rich in benthic foraminifera (Miliolids, *Austrotrilina* sp., Soritoids, *Archaias* sp., and *Dedritina*) and bioclasts of echinoids, gastropods, and bryozoans. Buxton and Pedley (1989) described a comparable microfacies as ramp biofacies 4, which relates to a sheltered embayment in a shallow subtidal ramp (inner ramp). This microfacies is deposited in an inner ramp design, according to the previous information. It resembles RMF 16 protected and low-energy inner ramp (Flügel, 2010).

Depositional environment model

The suggested sedimentary model of Bajwan Formation in Kirkuk area is carbonate ramp. The facies in this research could be compared to various other analogous facies in this setting (Read, 1982; Tucker, 1985; Tucker and Wright, 2009). It has been utilized the notion of carbonate ramp developed by Burchett and Wright (1992) to present the entire view of the sedimentary model. According to Burchett and Wright (1992), there are three carbonate ramp subenvironments: inner ramp, middle ramp, and outer ramp. The sequence of facies and their inter relationships will be covered as the bulk of the fine facies identified in the current study lies within the range of the inner ramp (Fig. 7). The microfacies B1 is found in the upper zone of the inner ramp, which is near the land and is known as a tidal flat environment. Whereas the presence of lime mudstone, tiny quartz grains, and gypsum crystals with little indication of subaerial exposure suggests hypersaline conditions may be supratidal flat environment.

The microfacies (B2 and B3) are projected to be deposited in an open circulation lagoon in an inner ramp setting. The open lagoonal ecosystem is characterized by a mix of protected environment and open marine species, including echinoids and perforate foraminifera Rotaliids. The last microfacies (B4) was deposited in a constrained lagoon habitat (Inner ramp). There is a paucity of usual marine species here, with the exception of imperforate benthic foraminifera (miliolids, Dendritina), which implies quiet, sheltered circumstances. Because there are many porcelains imperforate foraminifera, the water is relatively hypersaline (Geel, 2000).

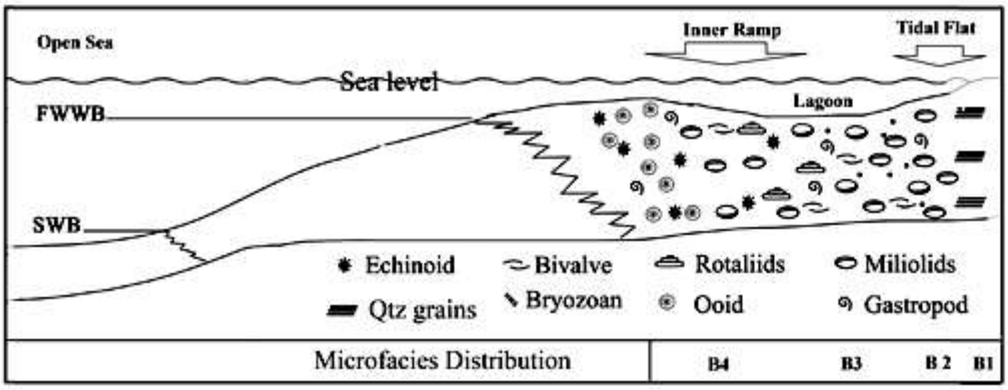

Fig.7. Bajwan Formation depositional model.

Reservoir Characterizations

Shale Volume Determination

The Gamma Ray log (GR) is used to calculate the size of the shale (V-Shale) for the Bajwan Formation, since it impacts porosity and water saturation levels and also regulates the number of hydrocarbons. The first step is to compute the Index of Gamma Ray (I_{GR}) function using the following equation:

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}} \quad \text{……….} \ (1)$$

Where: IGR ………Gamma ray

GR_{Log}……………. Gamma ray reading of formation.

GRmin…………… Maximum gamma ray.

GRmax…………. (Shale) Maximum gamma ray Shale.

The second step is to use the equation of Larionov (1969) for post-Cretaceous successions (young rock), which is described in detail below

$$\text{V-Shale} = 0.083 * (2^{(3.7 * I_{GR})} - 1) \ \text{……….} \ (2)$$

Were, V-Shale: .... shale volume

The calculations of the shale values in the succession of the selected wells have made it possible to portray them with depth, explaining their vertical distribution within the Bajwan Formation succession. Figures (8 and 9) depicts the emergence of the lowest value of gamma rays (GR) GR Clean 0.18 API and 4.67 API, respectively, and the maximum value of (GR) GR Clay 31.98 API and 23.64 API in wells K-B and K-A.

Figures (10, 11 and 12), on the other hand, illustrate the size of the shale in the Bajwan Formation within the two wells, with the greatest value of the shale size being 0.108. This modest size is attributable to the formation's overall composition of carbonate rocks.

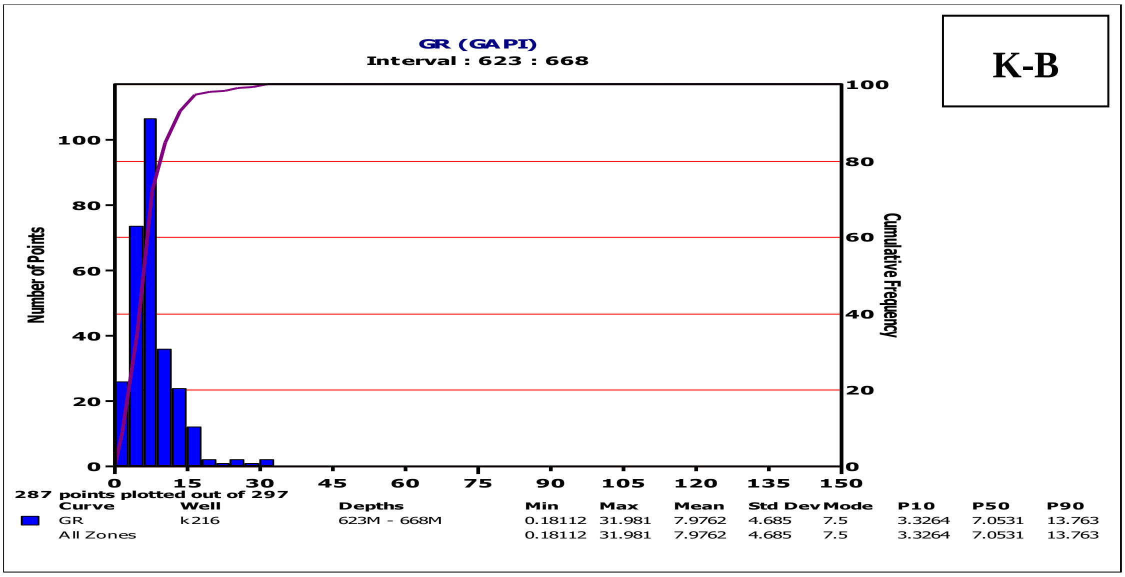

Fig.8. Histogram showing the highest and lowest GR values of the K-B well between 642-668 m depths of the Bajwan Formation.

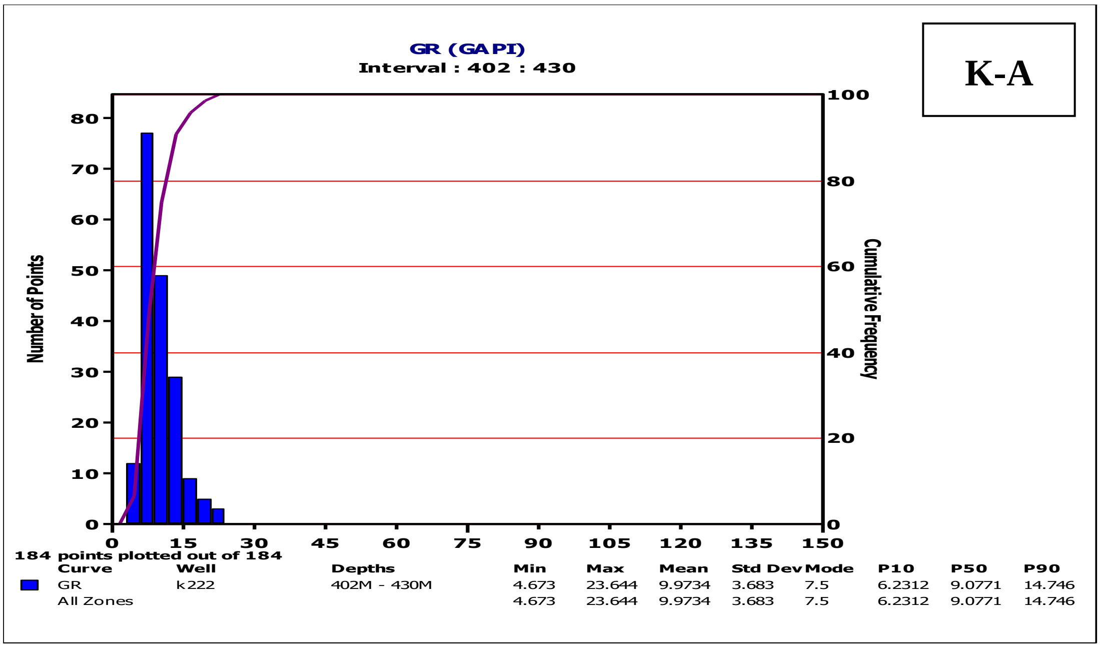

Fig.9. Histogram showing the highest and lowest GR values of the K-A well between 430-400 m depths of the Bajwan Formation.

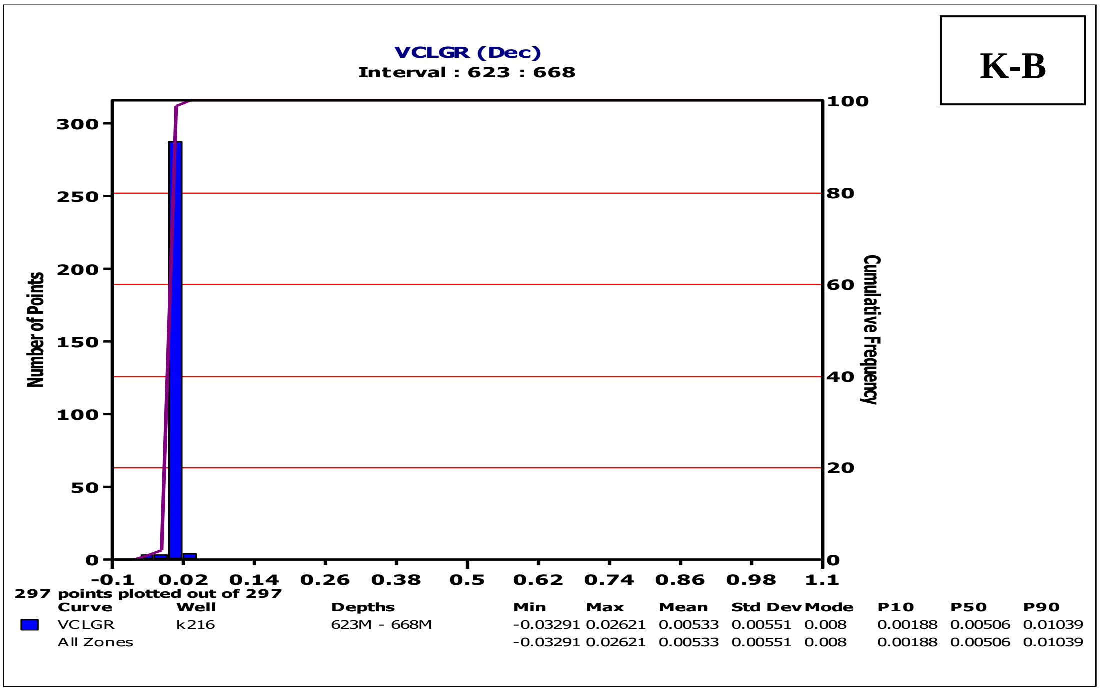

Fig.10. Histogram showing the highest and lowest values of the K-B well V. sh. between 642-668 m depths of the Bajwan Formation.

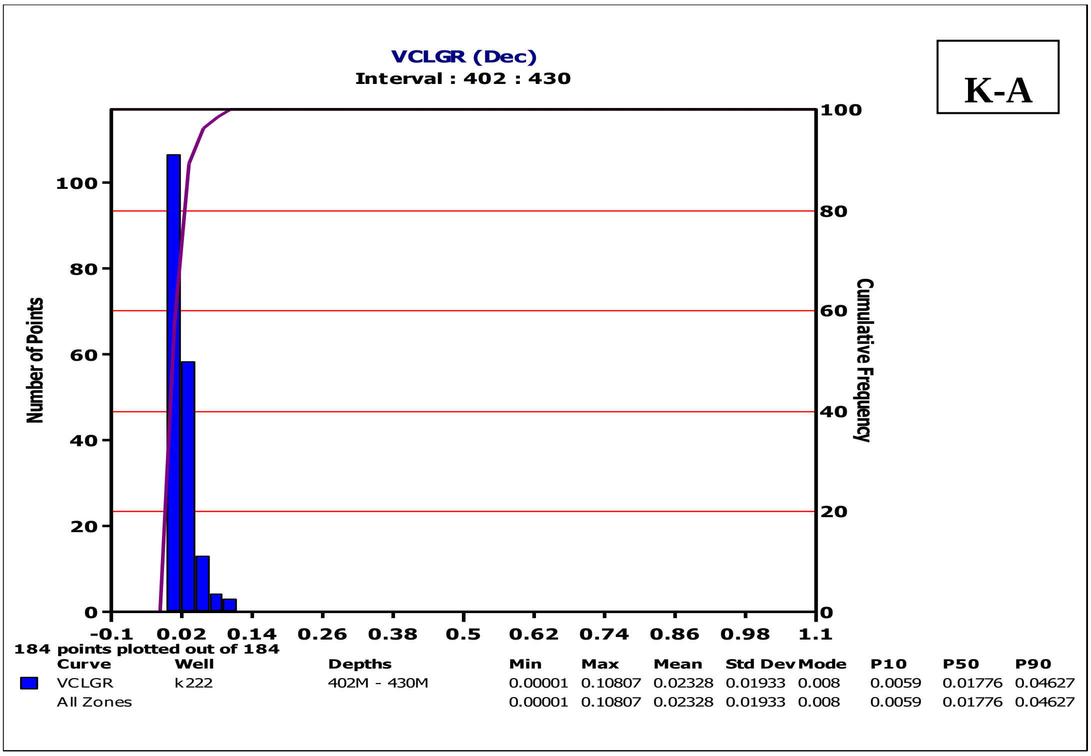

Fig.11. Histogram showing the highest and lowest value of the K-A well V. sh. between 430-400 m depth of the Bajwan Formation.

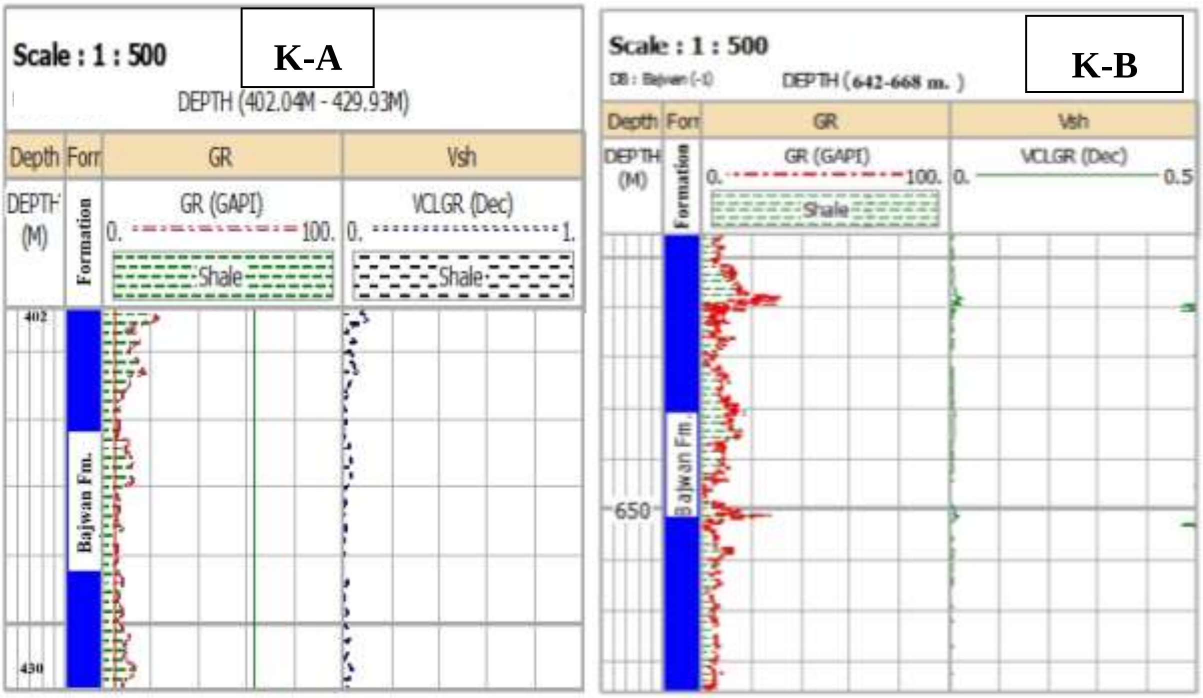

Fig.12. Relationship between GR and V. Sh. of Bajwan Formation.

Porosity Estimation

Porosity is represented as a proportion of the total volume to the size of the rock pores:

$$\textit{porosity}\ \emptyset\,(\%) = \frac{Vb - Vgr}{Vb} \times 100 = \frac{Vp}{Vb} \times 100 \quad ....(3)$$

Were, *Vb*: bulk volume; *Vgr*: grains volume; *Vp*: pore volume.

Porosity is typically assessed indirectly using well logs such as neutron logs and density logs using the following equation:

$$\emptyset\, t = \frac{\emptyset D + \emptyset N}{2} \quad ....(4)$$

Were, *Øt*: total porosity; *ØD*: porosity from Density Log; *ØN*: porosity from Neutron Log.

This approach is used to indirectly assess the rocks porosity by measuring their density and using it to calculate the porosity using the equation below:

$$\phi_\rho = \frac{(\rho_{ma} - \rho_b)}{(\rho_{ma} - \rho_f)} \quad .... (5)$$

Where, *Øρ*: Porosity by density log; ρ_b: Bulk density from log; ρ_{ma}: Matrix density, which is a constant value for each type of rock; ρ_f: Fluid density

According to Schlumberger (1972), the calculated visceral density values (Matrix density), the visceral density of the sequences is as follows:

The visceral density of the Bajwan sequences (limestone) is (2.71 gm/cm^3), while the fluid (f) is employed in drilling operations for selected wells (salt clay) is (1.1 gm/cm^3).

The neutron log is derived directly from the probe and entered into the calculation.

Effective porosity (Øe) is the ratio of the size of continuous voids to the volume of total voids (Bulk Volume) or the total volume of the rock occupied by the clay or shell, and it may be computed using the equation:

$$Øe = Øt \times (1 - V_{sh})............(6)$$

Were, Øt: total porosity

Secondary porosity is the porosity generated inside the reservoir after deposition, such as voids in carbonate rocks caused by chemical processes of dissolution or breaking pores in reservoirs, and it may be estimated using the equation:
Secondary Porosity index SPI

$$SPI = Ø_t - Ø_S..........(7)$$

Were, $Ø_t$: Total Porosity; $Ø_S$: Porosity from Sonic Log

Through the calculation of porosity and based on the sonic log, it is discovered that the composition of Bajwan Formation changes its lithology, and in order to compensate this in equation (7), the sound porosity is calculated using the following equation and the rock changes of the succession studied in the wells (K-B and K-A):

$$Ø_s = \Delta tlog - \Delta tma / \Delta tfl - \Delta tma.......(8)$$

Where: Δtlog : Sonic log travel time, Δtma :Matrix travel time

Δtfl : Fluid travel time (Wyllie Typical values (μsec/ft)

Matrix Δt: 51-55 SS; 47.5 LS; 43.5 DOL

Fluid Δt: 189 - salt water

Bajwan Formation is mostly made of limestone (tma = 47.5 sec/ft) and the fluid used in drilling operations for selected wells (salt clay) (189 sec/ft) Figures (13 and 14) illustrate the relationship between GR - density – neutron and sonic porosity in the two wells.

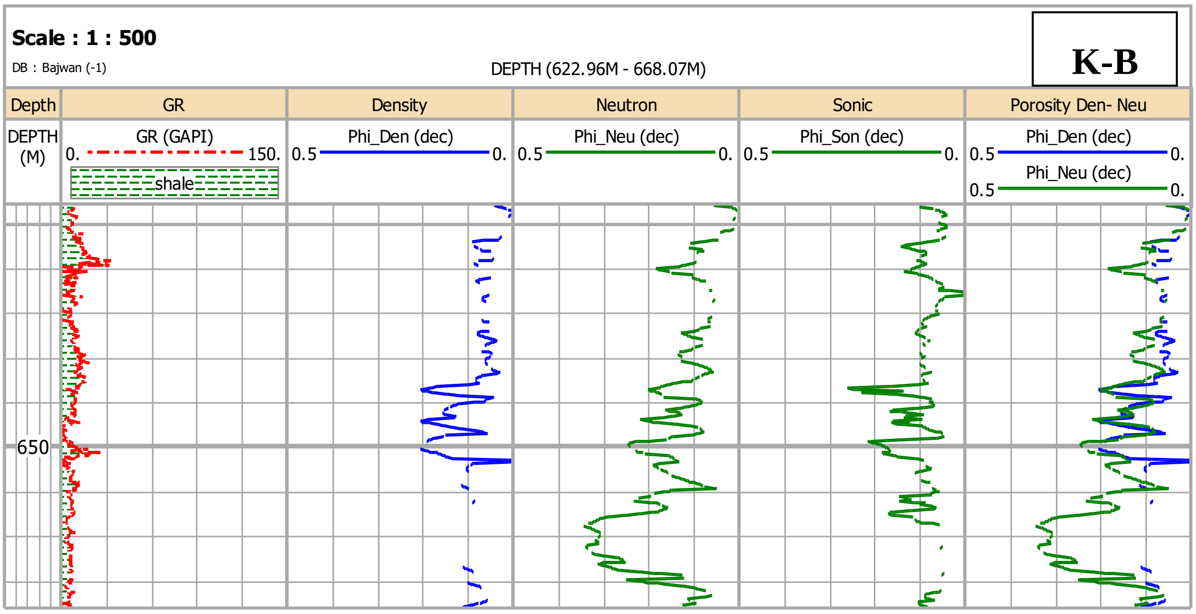

Fig.13. Relationship between GR - density – neutron and sonic porosity in the well K-B

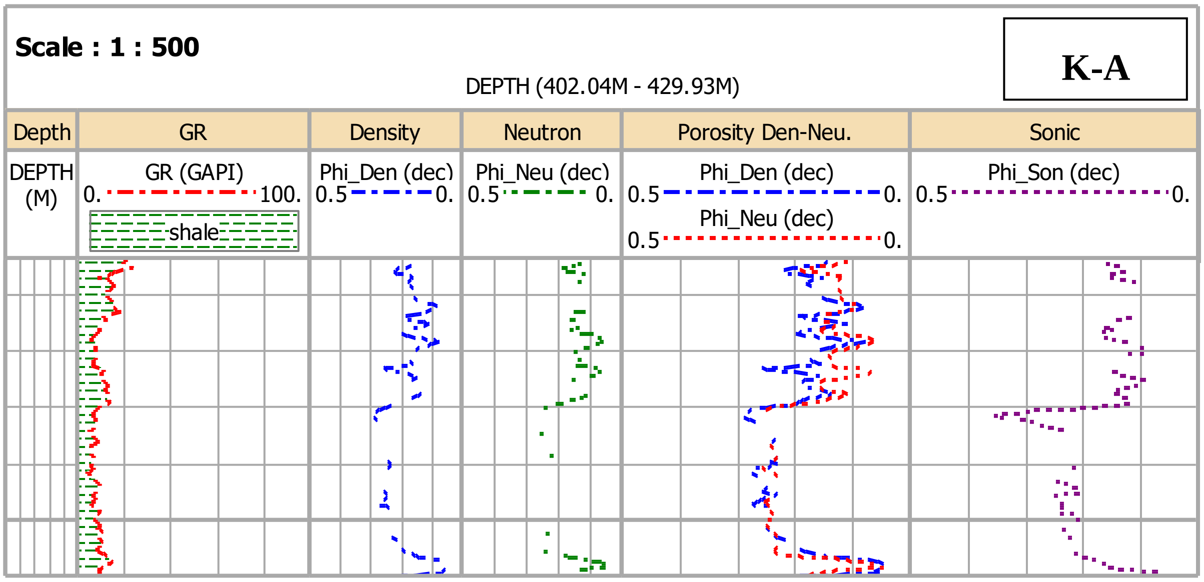

Fig.14. Relationship between GR - density – neutron and sonic porosity in the well K-A.

Reservoir division:

The sequences of the Bajwan Formation were divided into different zones based on the predicted porosity values of the sequences of the sections selected indirectly (logs) and depending on the effective porosity:

Zones of Bajwan Formation

This area is represented by the successions of the formation of Bajwan composed of limestone in general, as a thickness of about (26) meters between the depths (642-668) meters in well (K-B) and about (30) meters between the depths of (400-430) meters in well (K-A), the units of this range are divided into the area's preparation, which are as follows:

Zone A

This zone is represented by the limestone rocks of the Bajwan Formation, which has a thickness of roughly (9.2) meters between the depths (409.2-400) meters in well (K-A). The porosity of the rocks in this zone is classified as low (5-10%). As a result, they are characterized as low-productivity reservoir rocks (poor reservoir rocks) in classic exploration literature.

Zone B

This zone has a thickness of approximately (9.6) meters between the depths (651.6-642) meters in well (K-B) and a thickness of about (6.3) meters between the depths (415.5-409.2) meters in well (K-A), and the porosity of the rocks in this zone is classified as good (15-20%). As a result, they are recognized as well-productive reservoir rocks (Good reservoir rocks) in classic exploratory literature.

Zone C

The range is about (16.4) meters thick with a depth interval (651.6-668) meters in well (K-B) and approximately (14.5) meters thick with a depth interval (430-415.5) meters in well (K-A), and the porosity of the rocks in this range is regarded as very excellent (25-27%). As a result, it is referred to be extremely good reservoir rocks.

We see that the overall value of porosity is the largest, and there is no significant difference between total porosity and effective porosity in some areas of the tiny shale (shale volume).

The Bajwan C zone depicted in Figures (15-16) as the most porous section in the reservoir, has the greatest value of the highest index of effective and secondary porosity SPI. As a result, this unit may be dependent as a significant influence area in the transmissibility and storage capacity of the Tertiary reservoir.

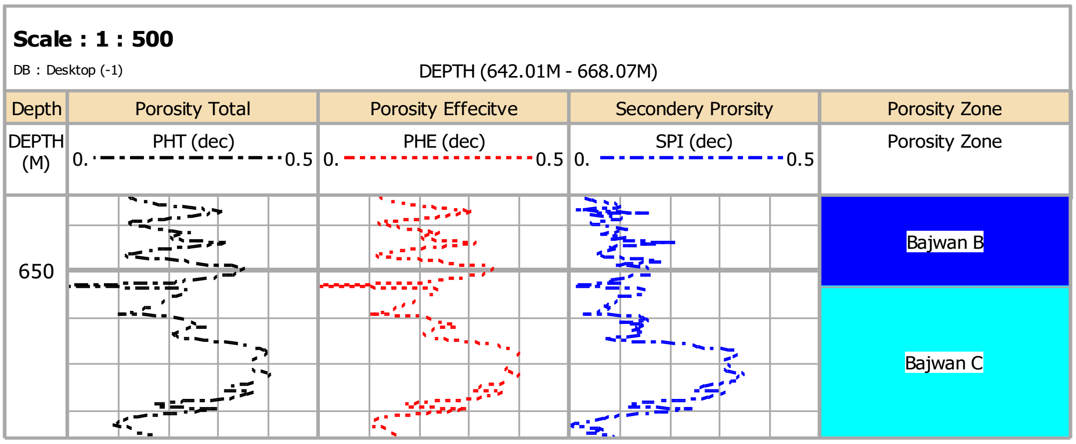

Fig.15. Reservoir division of total and effective porosity of Bajwan Formation with secondary porosity in K-B well.

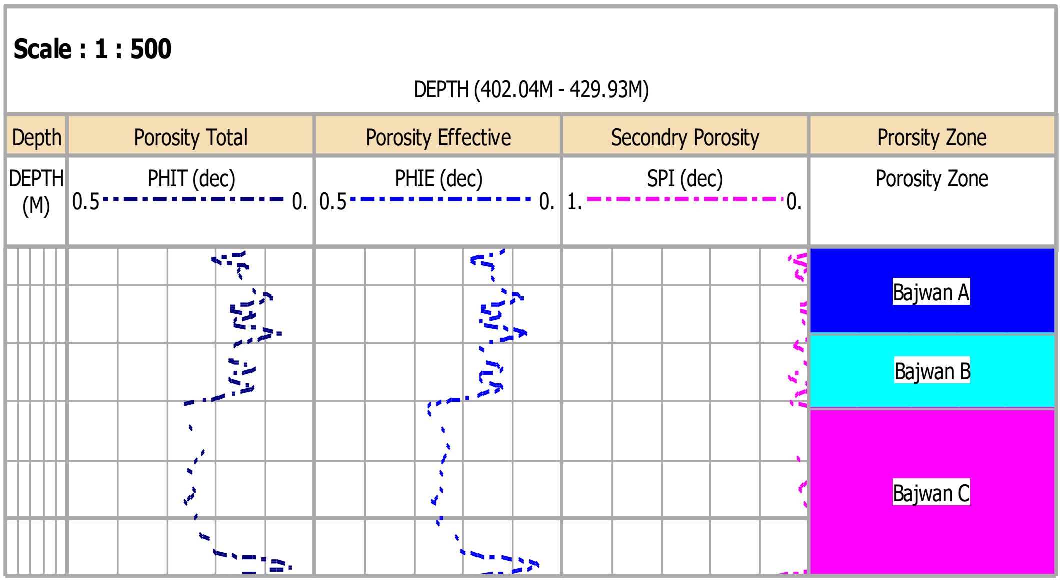

Fig.16. Reservoir division of total and effective porosity of Bajwan Formation with secondary porosity in K-A well.

Identification of lithology and Mineralogy

The physical and chemical qualities of the hydrocarbon-bearing and water-bearing rocks impact the assessment of the composition's properties, hence determining the lithology of the formation is vital for its reservoir properties.

Neutron –Density Cross Plot for Lithology Identification

In order to determine the porosity values resulting from their combination, this approach depends on the intersection of the porosity plotter and the density of the composition (Schlumberger, 1979). The plotters reveal a scattered pattern of values indicating diversity in rock formation. Figures (17 and 18) show that the sequences of the Bajwan Formation are primarily distributed between the limestone via the sites shown on the plotter below:

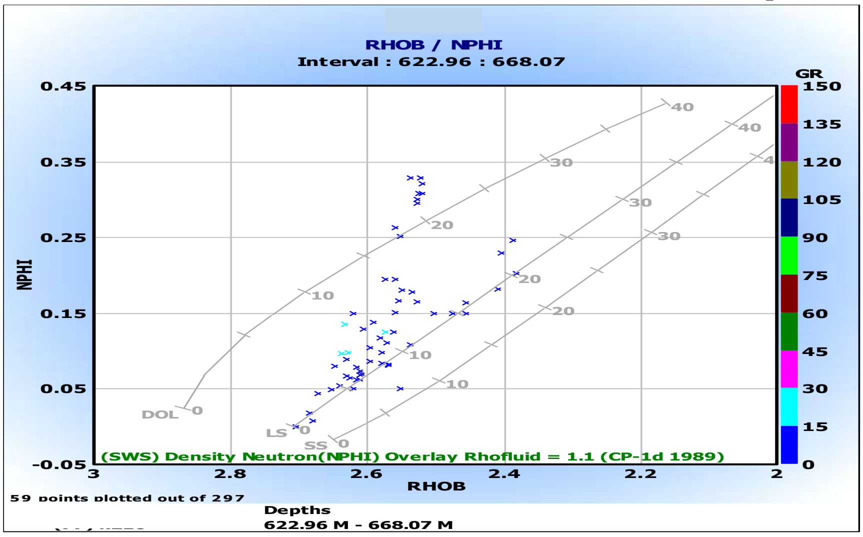

Fig.17. ρb vs Neutron plot of a dispersed distribution of values reflecting variation in a rock stack of the Bajwan Formation in the K-B well.

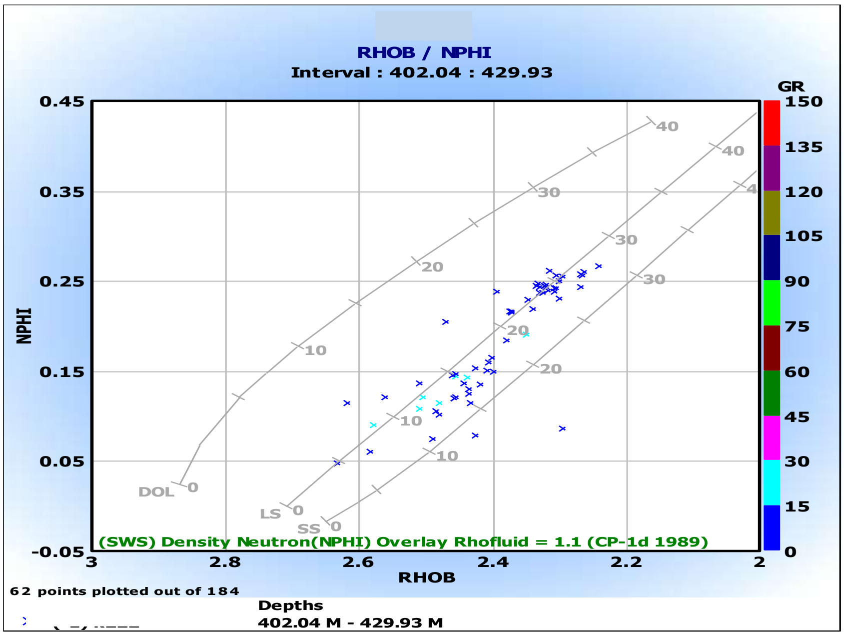

Fig.18. ρb vs Neutron plot of a dispersed distribution of values reflecting variation in a rock stack of the Bajwan Formation in the K-A well.

M-N Cross Plot for Mineral Identification

The M-N Cross Plot diagram, which is used to identify the complicated mineral structure of the rocks of the Bajwan Formation, reveals that these rocks are a mixture of limestone rocks and secondary porosity as shown in Figures (19-20).

$$M = \frac{\Delta tf - \Delta tlog}{\Delta tlog - \Delta tlog} \quad \text{......... (9)}$$

Where, Δtlog: transit travel time from sonic log µsec/ft; Δtf: transit travel time of the formation fluid equals 189 µsec/ft. ρb: bulk density from density log g/cc; ρf: bulk density of the formation fluid equal to 1.1 g/cc; ØNlog: porosity from neutron log; ØNf: porosity for the formation fluid equal 1.1.

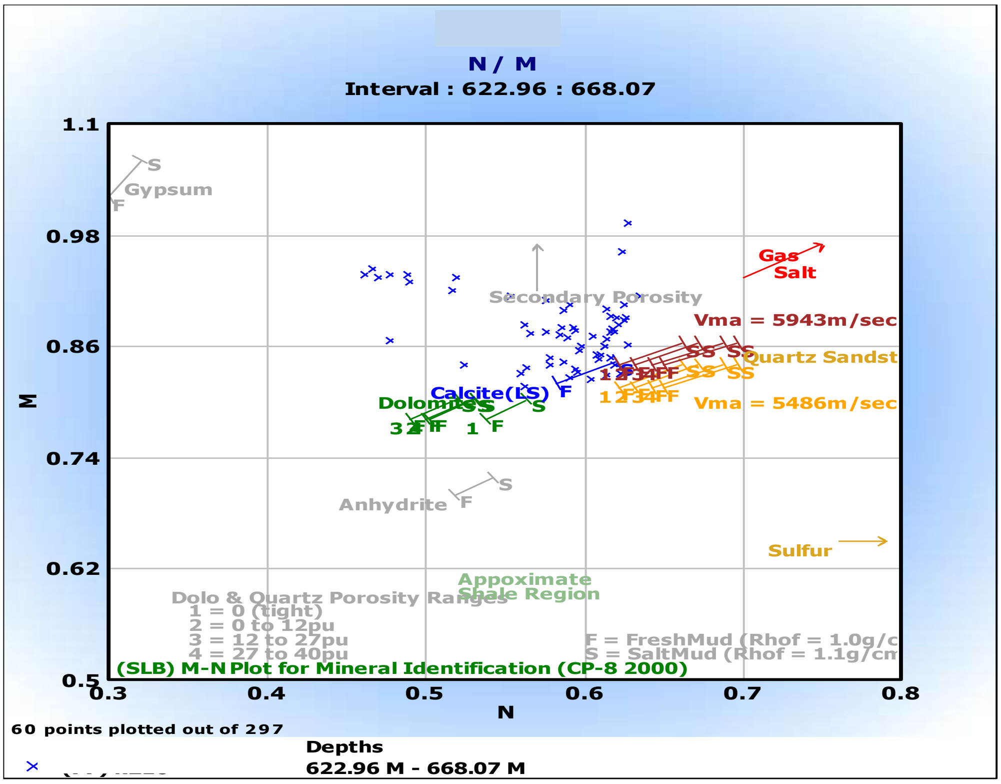

Fig.19. Determination of the mineral composition of the Bajwan in the K-B well.

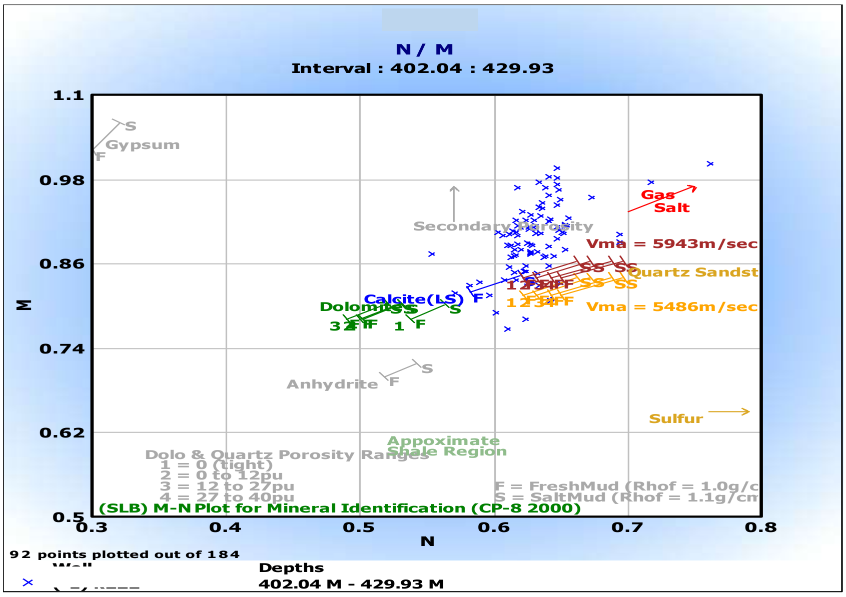

Fig.20. Determination of the mineral composition of the Bajwan in the K-A well.

Conclusions

• The Bajwan Formation is approximately 30 m thick in the well (K-A) and approximately 26 m thick in the well (K-B). The formation is composed of creamy-colored limestone and dolomitic limestone with a medium hardness. The formation is usually porous and retains fossils, while being soft in some places.

• According to Dunham's classifications, the formation comprises mostly four microfacies labeled as B1, B2, B3, and B4.

• The microfacies are classified according to their environmental context, with vertical variations indicating that the formation is deposited in an inner ramp carbonate platform environment.

• Based on the results of the porosity values for both wells, the Bajwan Formation successions are categorized into two zones in the well K-B, good and very excellent porosity zone, and three zones in the well K-A, poor, good, and very good porosity zone.

Acknowledgements

The authors are very grateful to the College of Science, University of Mosul for their provided facilities, which helped to improve the quality of this work. The authors are very grateful to the Editor in Chief Prof. Dr. Rayan Ghazi, the editorial board members and the technical editors for their great efforts and valuable comments.

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