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ROCK PHYSICS DIAGNOSTIC AND DENSITY VELOCITY ANALYSIS FOR HYDROCARBON EVIDENCE IN THE NAHR-UMR FORMATION, NASIRIYAH OIL FIELD, SOUTHERN IRAQ

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Abstract

Rock physics recently became widely utilized in classifying lithological units for various purposes in geophysics, depending on well-logging and seismic inversion datasets. Nahr Umr Formation is the targeted reflector, which was studied in well NS-1 as one of the most productive oil fields in Iraq, the Nasiriya field, to prove the performance and accuracy of Rock-physics productivities. Six cross plots were extracted and interpreted depending on the units of Density (RHOP) and Neutron (NHPI) logs, which were used for lithology-predicting of the Nahr Umr Formation, which consists mainly of porous sandstone, dolomite, clay, and shale. The challenge of locating the most profitable layer in hydrocarbon production was achieved using rock physics procedures to classify lithologic units of the Nahr Umr Formation. The matching between the results of well logging analysis and hydrocarbon probability for targeted units was extremely good due to the use of more reliable tools. The probability density function (PDF) technique was applied to visualize the space of rock physics in two dimensions, and the density distribution within rock units was prominently clear. Polynomial equation of Nasiriya oil field was extracted for Nahr Umr Formation, and it was equivalent to the standard equation of Nafe Drake according to density/ velocity curve readings.

Keywords: Rock-Petrophysics; Litho-Prediction; Density &Velocity analysis; Nahr Umr Formation.

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1. Introduction

Reservoir Characterization Modelling (RCM) is a critical integrative process that connects petrophysical parameters such as porosity, permeability, and shale volume with rock physics properties including compressional and shear wave velocities (Vp Vs), Poisson's ratio, and others. This integration allows for simultaneous interpretation of lithology and hydrocarbon saturation probability. In geophysical reservoir analysis, RCM often entails establishing empirical velocity-density relationships and benchmarking them against globally recognized models, such as the Nafe-Drake curve (Ludwig et al., 1970), or utilizing more advanced models like those proposed by Gardner et al. (1974) for distinguishing rock types and elastic attributes with higher resolution. Given the high costs associated with core acquisition and laboratory analysis, alternative methodologies rooted in rock physics are increasingly adopted. These include theoretical bounds (Avseth & Bachrach, 2005), empirical relations (Eberli et al., 2003), fluid substitution models like Gassmann's equation (Gassmann, 1951; Geertsma & Smit, 1961), as well as contact and inclusion models (Liu & Sun, 2015). However, conventional rock physics plots sometimes fail to yield reliable classifications, whereas seismic inversion provides more accurate probabilistic interpretations, especially when combined with well log data.

The use of well log data is indispensable in calibrating elastic logs for rock physics modelling. Typically, a consistent vertical coverage among density, compressional, and often shear sonic logs is required for accurate evaluation. Nonetheless, challenges in obtaining high-quality log data are common due to measurement variability, borehole environmental factors, and tool limitations. Consequently, preprocessing and correction of log data are essential to ensure robustness and reliability in reservoir characterization (Ali et al., 2020; Khudhair & Al-Zaidy, 2018). Rock physics serves as a fundamental bridge between qualitative geological observations and quantitative geophysical measurements (Jaheed & Karim, 2022). It facilitates the classification of reservoir rocks based on elastic and petrophysical properties such as compressibility, rigidity, and porosity, which in turn affect seismic wave propagation. The primary goal in reservoir geophysics is to relate the seismic response to subsurface rock properties to enhance interpretative accuracy. This linkage enables integration between seismic data, petrophysical information, geomechanics, and internal rock characteristics (Akhter et al., 2018). Acoustic Impedance (AI) is widely utilized to infer lithological and fluid characteristics. However, ambiguities still arise in distinguishing fluid effects from lithological variations. This limitation has been addressed by integrating shear impedance (SI) with AI to compute Lamé parameters, providing improved characterization (Hampson et al., 2005). Since variations in rock density cause observable changes in seismic impedance, seismic inversion—defined as the transformation of seismic reflectivity into impedance profiles—has become a standard approach (Geertsma & Smit, 1961; Yilmaz, 2001). The research aims to identify the most productive hydrocarbon-bearing layers within the Nahr Umr Formation by integrating rock physics approaches with well log analysis and employing probability density function (PDF) techniques to visualize rock units' distribution in two dimensions.

2. Location and Geological Settings

As noted by Jassim and Buday in Jassim & Goff (2006), the study area—illustrated in Figure 1 is situated within the unstable shelf zone of the Mesopotamian region. This area is characterized by a flat topographic surface predominantly covered by Holocene sediments, which mainly consist of floodplain deposits (Mohsen, 2019). The Nasiriya structural feature was formed during the Miocene epoch as a result of lateral tectonic displacement associated with the Alpine orogeny (Al-Khafaji, 2014). This tectonic activity contributed to the emergence and growth of the structure while maintaining its characteristic linear geometry. According to Buday (1980), the Nasiriya structure represents one of several tectonic elements in the region that originated due to the influence of basement uplifts. These uplifts had a significant impact on the deformation of both Paleozoic and Mesozoic stratigraphic units (Figure 2).

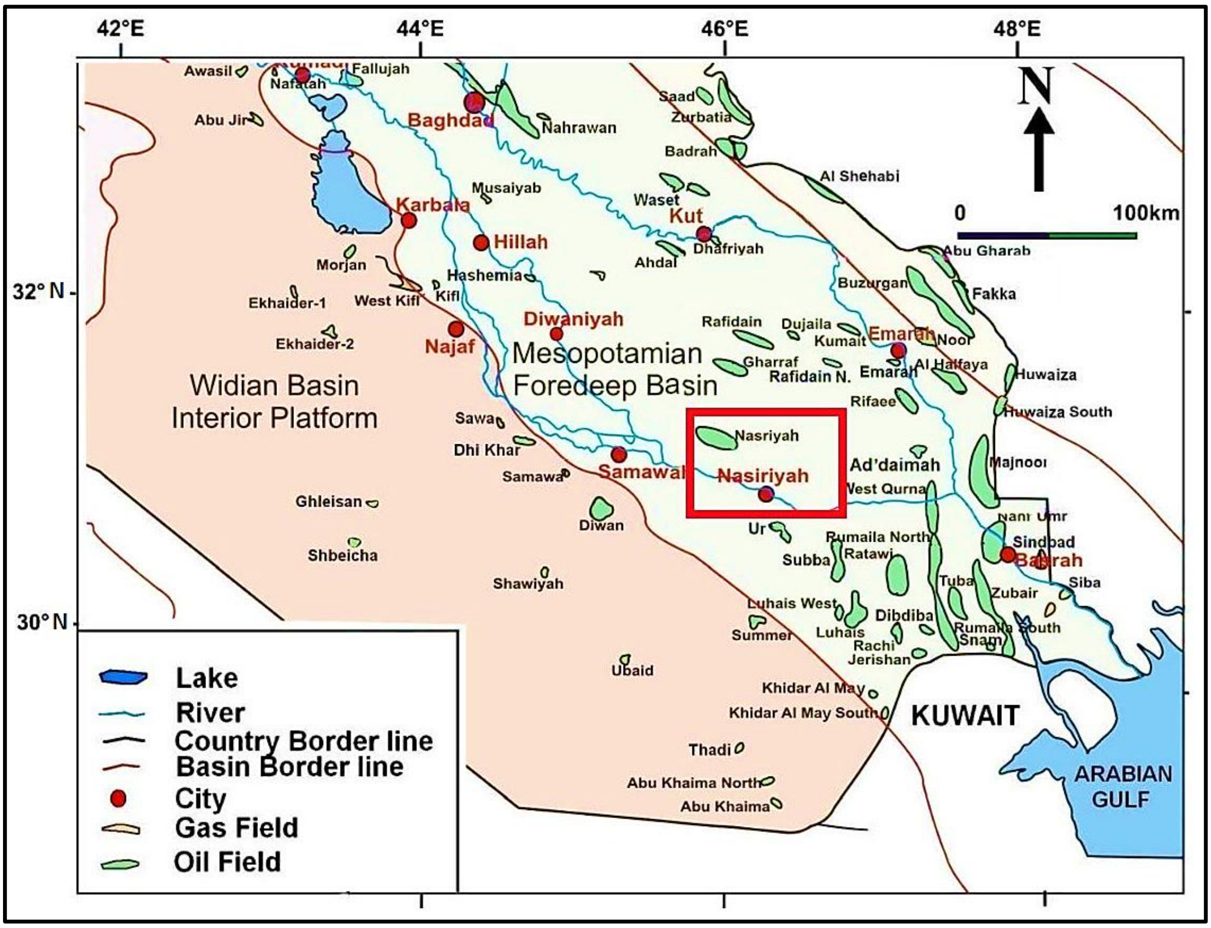

Figure1. Location map of Nasiriyah Oilfield, where the red rectangle represents the study area location.

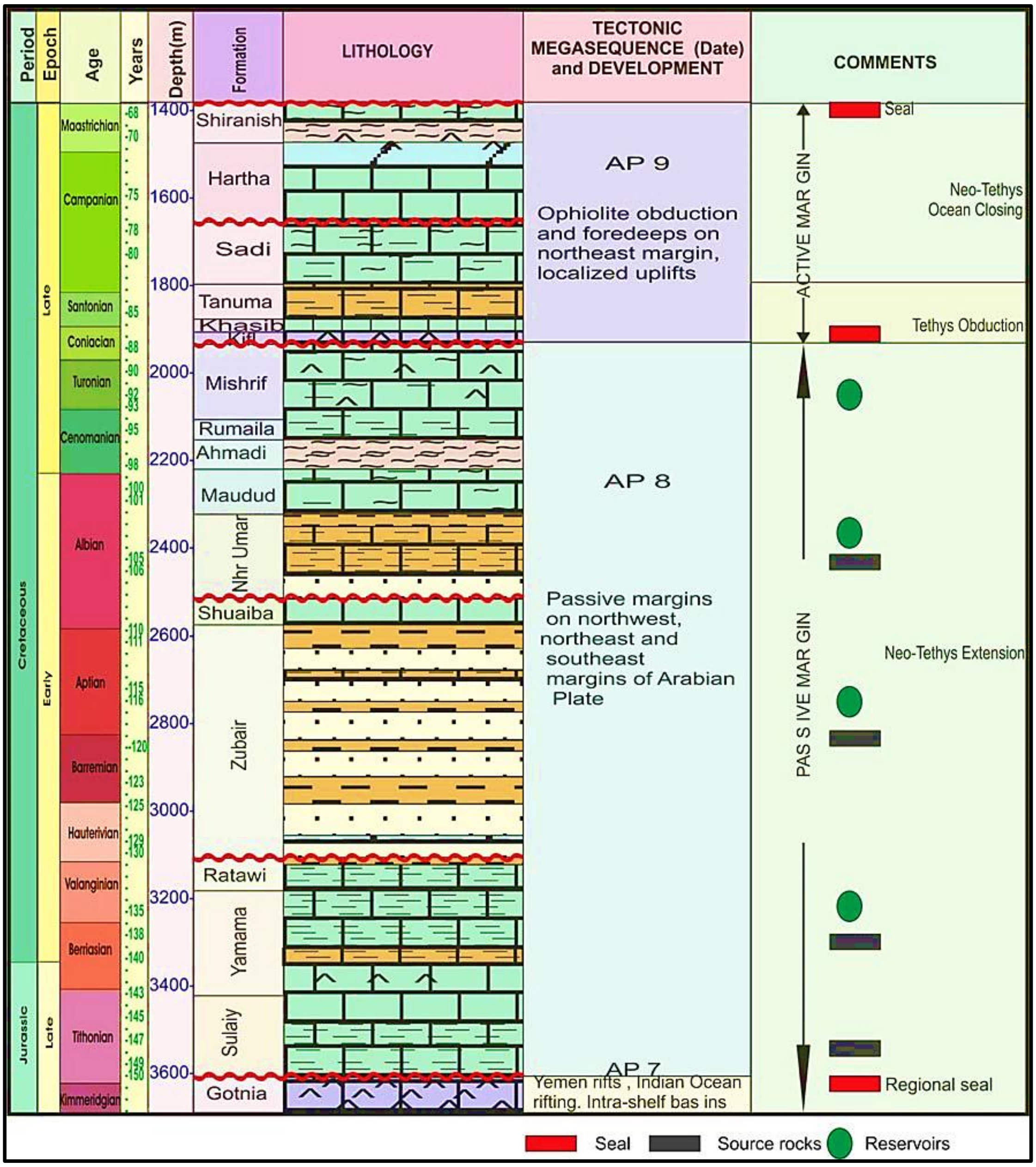

Figure 2. Nasiriya Feld stratigraphic column with regional seal, reservoirs, and source rocks elements (Al-Khafaji, 2014).

3. Materials and Methods

In well NS-1 of Nasiriyah Field, some types of wireline logs are available, such as neutron porosity (NPHI), sonic (DT, Δt interval transit time), and density (RHOB, ρb bulk density) logs. The data were imported to Petrel software to analyze and interpret well logs. Petrophysical analysis was used to identify rock characteristics utilizing well log data. The RHOB log provides information for reservoir characterization when studying mineralogical composition, porosity, hydrocarbon fluid type, and fluid saturation (Quijada & Stewart, 2007).

The values of density can be employed as a standard for evaluating the RHOB of the investigated rocks (Akhter et al., 2018). The gamma-ray (GR) log-log is an excellent indication of shale presence since it indicates the natural radiation emission in the rock. Whereas a high gamma value implies shale rock due to its high potassium, uranium, and thorium content, a low gamma result proves sandstone and limestone (Nwozor et al., 2017). The NPHI log is based on the quantification of hydrogen in the formation. It is employed to evaluate the porous structure of the formation and provides an essential index of fluid content and lithology when combined with other logs (Albakr et al., 2022).

Acoustic impedance (AI), shear impedance (SI), primary to secondary wave velocity) Ratio (V_p/V_s) and Young's Modulus are the most critical parameters of elasticity, which are calculated using Vp, Vs, and density (ρ) values. These moduli of elasticity were cross-plotted to conclude the lithologies. The Lambda-Mu-Rho (LMR) method has been developed by Goodway et al. (1997), which characterizes impedance and velocity in terms of the Lamé parameters of incompressibility (λ) and rigidity (μ). These parameters helped to extract (λρ) and (μρ), which are expressed by:

$$\lambda\rho = AI^2 - 2SI^2, \quad (1)$$

$$\mu\rho = SI^2, \quad (2)$$

Where SI represents shear impedance, while AI represents acoustic impedance.

λ is a function of a material's compressional and joint shear, whereas shear properties solely determine μ. Because μ is reliant upon shear properties, it is fluid independent (Avseth & Bachrach, 2005). This has upsides when plotting in LMR space, since one axis is fluid independent, as opposed to conventional domains such as AI vs Vp/Vs, in which both axes are influenced by porosity in wells. The use of rock physics templates (RPM) in cross plots provides a visualization of the effect of pore fluids, rock texture, and mineralization on elastic properties.

4. The Petrophysics and Rock Physics Prognosis

Porosity is one of the most important petrophysical properties that is affected by a number of geological and physical factors, most notably geological pressure and seepage, as previous studies (Schmidt et al., 1977) have shown that these factors have a clear effect on the primary and secondary porosity of rocks. In highly permeable formations, wireline logs can provide reliable estimates of porosity values. However, porosity does not remain constant along the geologic column, but rather changes as pressure values vary with depth. Telford et al. (1976) noted that the presence of overpressure can contribute to maintaining high levels of porosity even at great depths beyond the normal pressure range. Both confining pressure and the presence of hydrocarbons are critical factors in controlling porosity values, especially in anisotropic rock formations (Fuchtbauer, 1967).

In this context, rock physics is used as an effective tool to correlate the physical and elastic properties of formation rocks, to characterize reservoirs and analyze their rock structure accurately, as well as to infer porosity and fluid saturation through integration with quantitative seismic analysis. This match indicates the accuracy of the petrophysical interpretation used to characterize the rock units of the Nahr Umr formation within the Nasiriyah Oilfield. According to well log analysis, the Nahr Umr Formation starts with a thin layer of shale, topped by a very thin layer of porous sandstone. This lithological sequence reflects a mixed depositional environment and is indicative of successive periods of limited marine inundation and changes in depositional energy, which is consistent with the results of lithologic and porosity analysis from well logs and rock physics data.

The gamma-ray log is considered one of the most valuable petrophysical tools in sequence stratigraphy. It provides insights into the relative distribution of sand and mud within sedimentary successions. Typically, intervals dominated by sand reflect deposition in shallower marine settings, whereas muddier sections suggest deeper environments. A gradual upward decrease in gamma-ray values generally indicates increasing sand content, implying a shallowing-upward trend. Conversely, a sudden rise in gamma-ray readings is indicative of a higher mud content, which can signal a flooding surface or parasequence boundary. Variations in gamma-ray patterns across parasequence sets can reveal depositional trends such as progradation, retrogradation, or aggradation. Additionally, channel-fill deposits often exhibit a sharp basal shift to low gamma values (high sand content), followed by a progressive upward increase in gamma values as mud becomes more prevalent. Such patterns are useful in identifying fluvial or estuarine facies, which may serve as indicators of sequence boundaries (Nichols, 2009).

In the upper part of the Nahr Umr formation, high values were observed for both neutron porosity (NPHI) and gamma ray logging, indicating the predominance of shale and clay rocks, which often have limited reservoir properties. The Vp/Vs ratio cross-chart was prepared using Petrel software, and the results showed a clear identification of areas with low values that reflect the presence of sandstone, with some parts represent dolomite rocks, while areas with high values indicate the predominance of shale, as shown in Figure 3. This lithology that was predicted is then confirmed by GR / RHOB in Figure 4, using the color scale of NPHI.

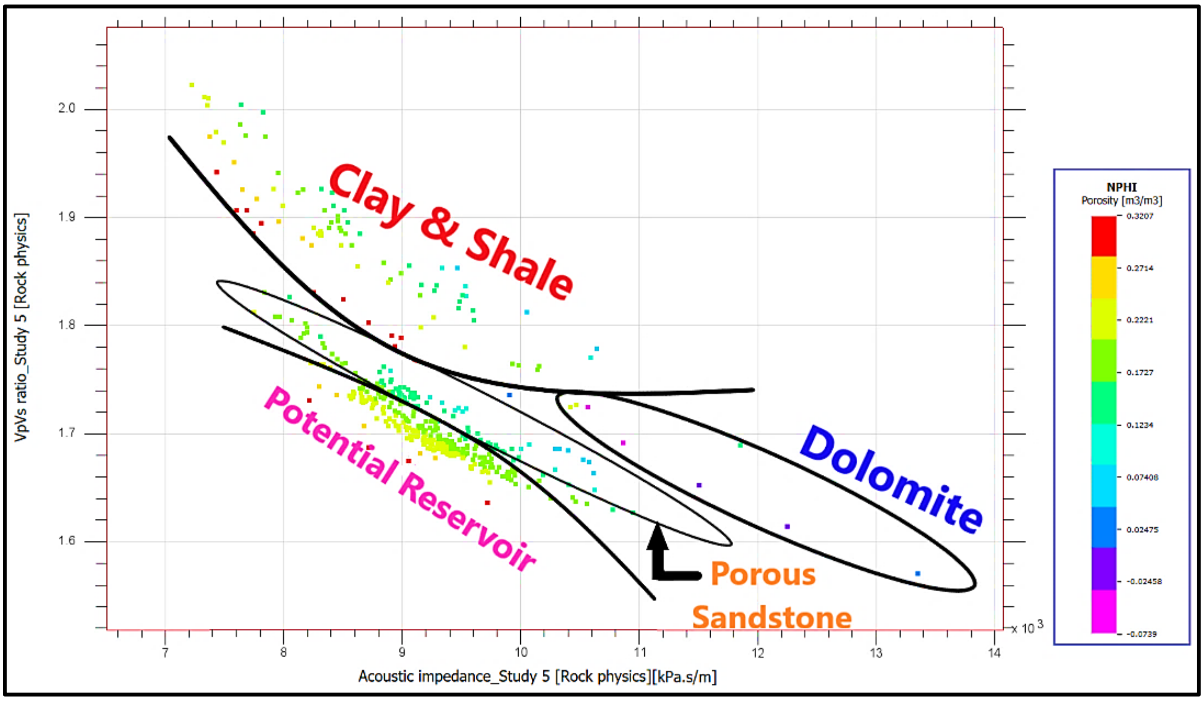

Figure 3. Vp/Vs versus (AI) plot of the Nahr Umr Formation in well NS-1. The data sets are colored based on their (NPHI) values, which are categorized into five lithological zones: clay, shale, porous sandstone, dolomite, and potential reservoir.

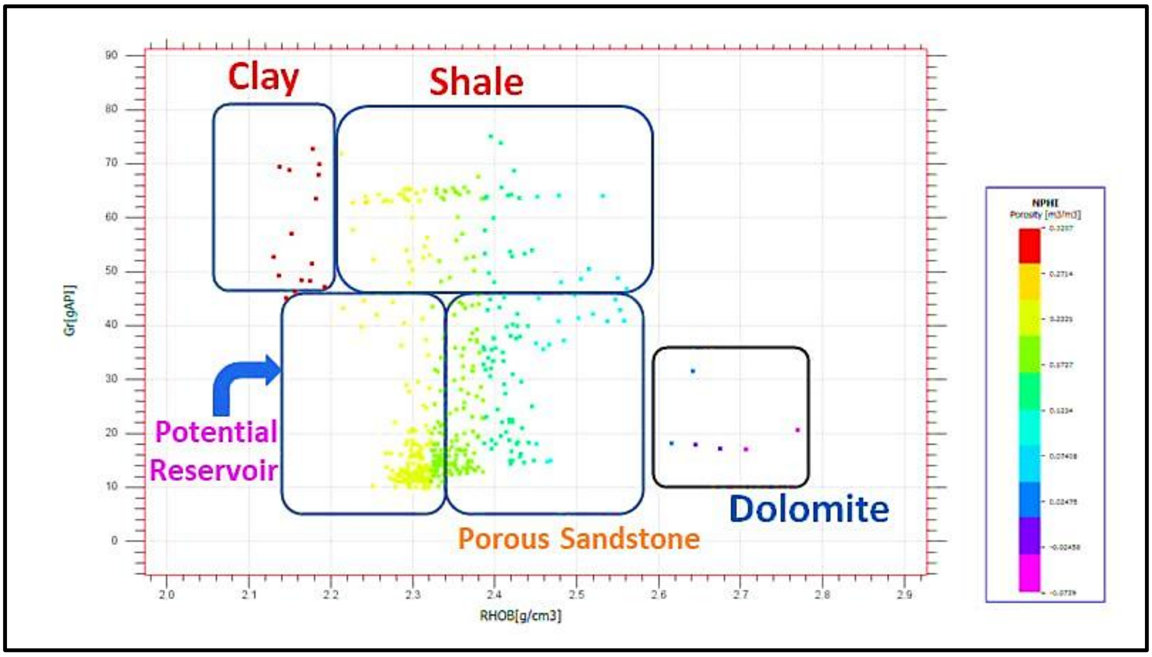

Figure 4. RHOB / GR cross-plot of the Nahr Umr Formation in well NS-1utilizing NPHI values to confirm the lithological units.

Bulk Modulus expresses the resistance of a rock to compression, while Compressibility is its reciprocal and reflects the rock's receptivity to compression. Poisson's Ratio measures the relationship between longitudinal and transverse strain and helps determine the type and elasticity of rocks. It is used interactively to characterize the geophysical and mechanical properties of rocks and contribute to improving the understanding of the behavior of hydrocarbon reservoirs under different stresses, as shown in Figures 5, 6, and 7.

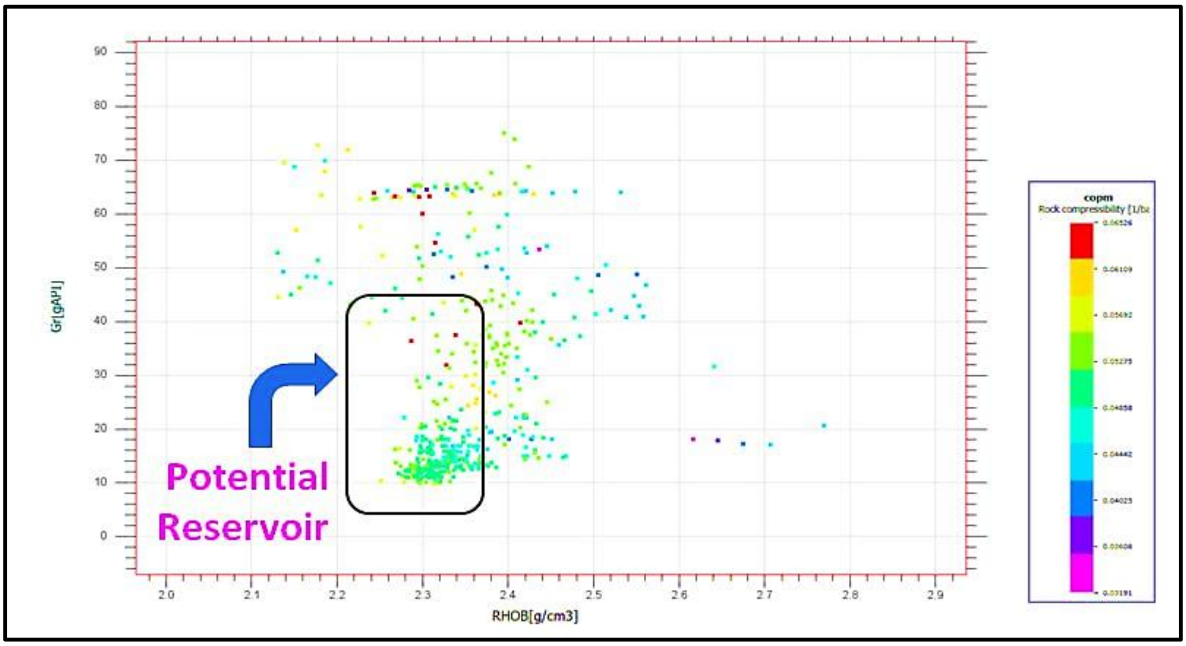

Figure 5. GR versus RHOB plot of well NS-1. The data sets are colored based on their Rock Compressibility values.

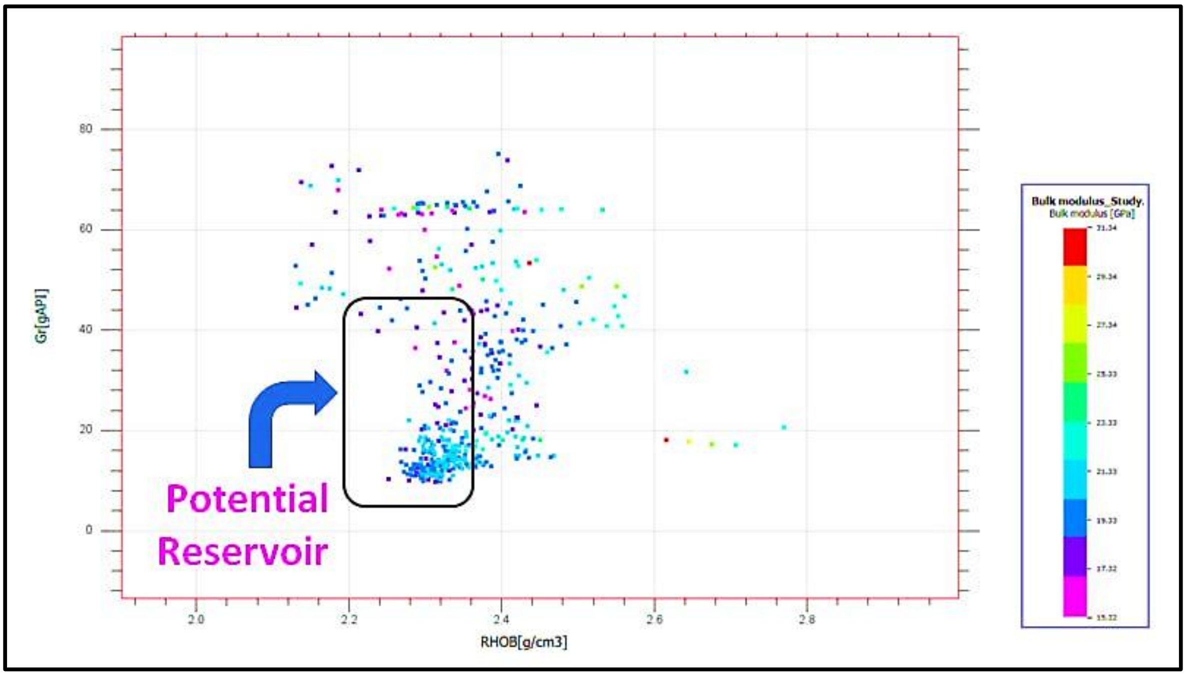

Figure 6. GR versus RHOB plot of well NS-1. The data sets are colored based on their (bulk modulus) values.

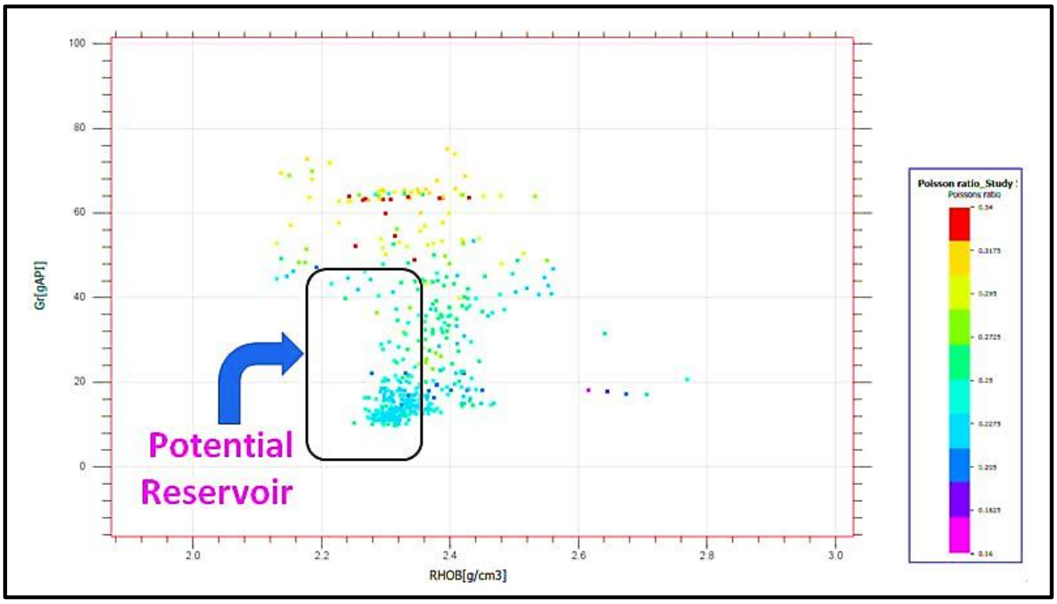

Figure 7. GR versus RHOB plot of well NS-1. The data sets are colored based on their (Poisson ratio) values.

The prediction of lithology that is achieved using the Vp/Vs ratio with Acoustic impedance, which reflects the actual change in physical properties within involved layers in the study area, these results are approved by Lamda-Rho in figure 8, in good conformity with lithology zones that were previously extracted. To identify the type of lithology found in the Nahr Umr Formation, Figure 8 employed cross plots. These charts employed a color scale based on NPHI values. To ensure precise prediction of the full results and to demonstrate the lithology of the specified formation using neutron values (Lamda-Rho and Mio-Rho), a $\lambda\rho - \mu\rho$ cross-plot type is also created.

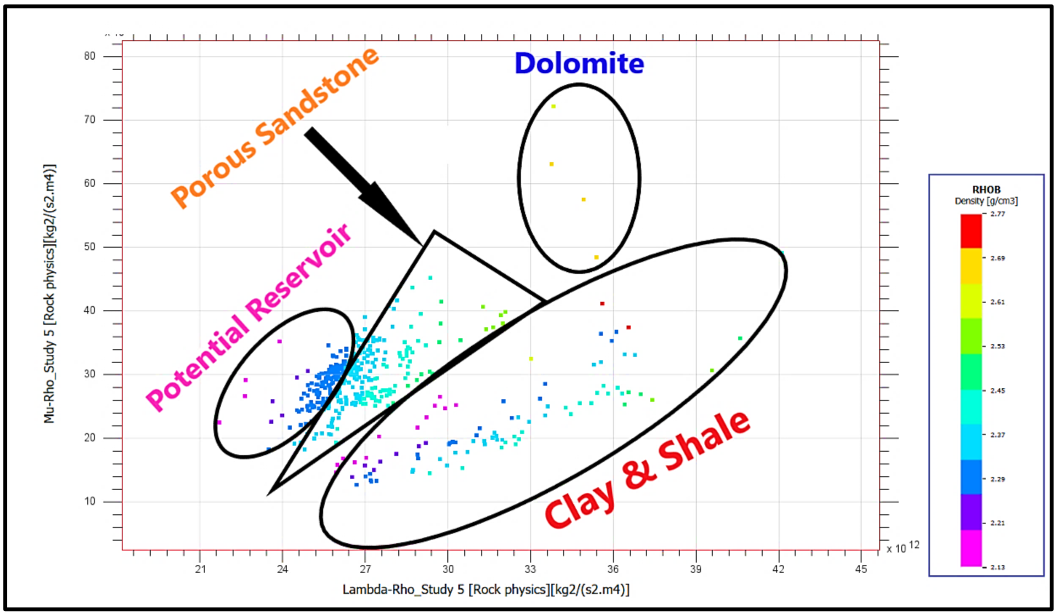

Figure 8. $\lambda\rho$ and $\mu\rho$ cross-plot of well NS-1, which is categorized into four zones: clay and shale, shale, porous sandstone, and reservoir.

The results of the comparison between the cross-sections derived from the rock physics analysis and the lithologic column of well NS-1 showed a good match, as shown in Figure 9. The results of the stratigraphic analysis showed a thin porous sandstone layer interbedded with shale and clay layers at a depth of approximately 2394 – 2430 meters. The central part of the formation is considered a potential reservoir, extending from 2430 to 2496 meters, interbedded with porous sandstone layers, and is characterized by a significant decrease in gamma ray readings, indicating low shale content and favorable depositional environments for hydrocarbon accumulation. The section from 2496 to 2512 meters showed a lithological intrusion with thin layers of porous Sandstone and shale, reflecting a clear change in lithology and rock formation characteristics. The lithological units encountered at depths of 2433 – 2445 m, 2455 – 2465 m, and 2485 – 2497 m are considered potential hydrocarbon-bearing reservoirs; therefore, they represent zones of significant geophysical interest.

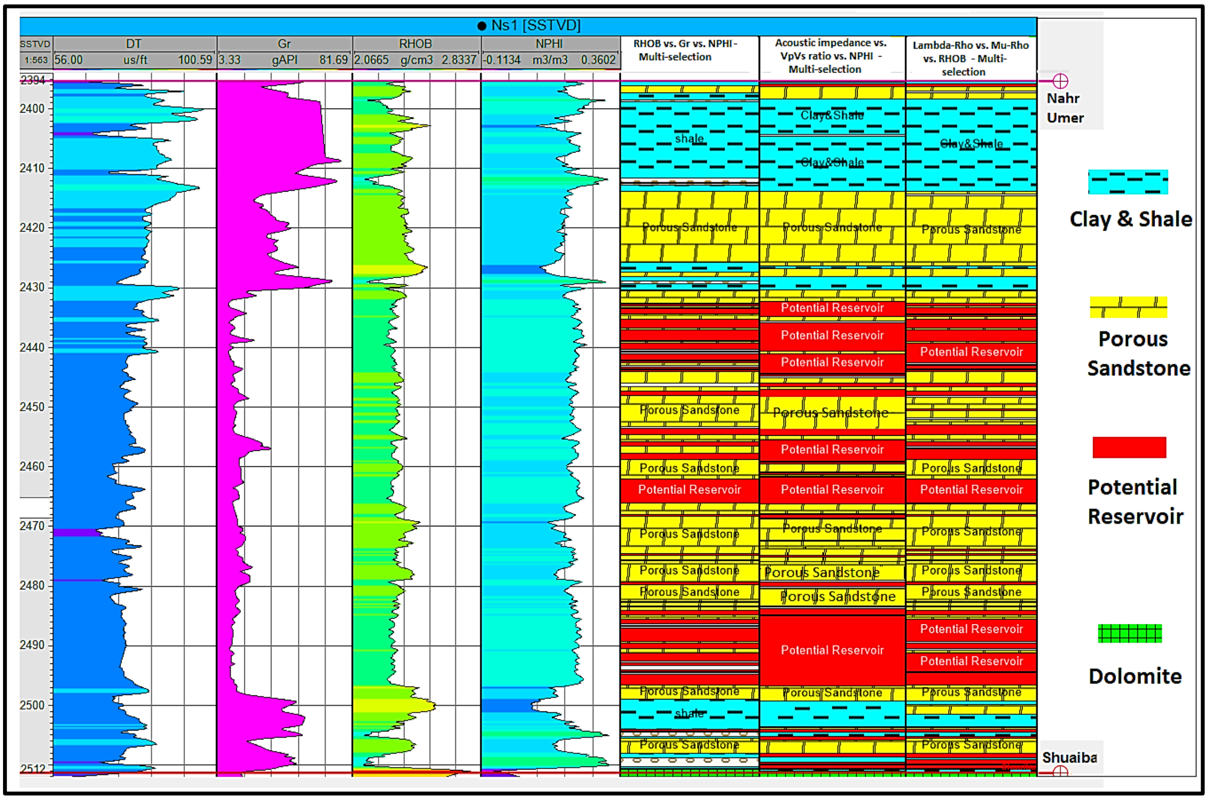

Figure 9. The lithological units of well NS-1represent rock-physics and petrophysics analysis column using AI, Vp/Vs versus, λρ, and $\mu\rho$ cross-plot, where the results are very closely related.

In reservoir geophysics, the probabilistic approach plays an extraordinary role in assessing different characteristics. Bayesian classification possesses a strong optimality flavor when considering error probability, that is, the probability of wrong class/decision predictions that a classifier commits. The Bayesian classification rule gives a set of M classes, i = 1, 2, 3,... M, and the respective posterior probabilities classify an unknown feature vector, x, and can be expressed in terms of probability density functions (PDFs; Theodoridis, 2020):

$$\text{Assign } \chi \text{ to } \omega i \ = \ \arg.\max \omega j \ p\ (x|\omega j) p\ (\omega j) \tag{3}$$

Where, j = 1, 2, 3 ……, M

The Bayesian classification reduces misclassification error, and the probability of error can be expressed by:

$$P_e = P(\omega_2)\int_{\{R_1\}} p(x|\omega_2)\,dx + P(\omega_1)\int_{\{R_2\}} p(x|\omega_1)\,dx \tag{4}$$

To enhance the reliability of the petrophysical interpretation, a two-dimensional visualization of the rock physics space was used to accurately represent the probability of each rock unit via the Probability Density Function (PDF), which is used to describe the probability distribution of continuous random variables (Figure 10). In other word, a probability density function (PDF) can be explained as a shape which describes the probability of an event (density) occurring within a portion of a continuous space, and Tables 1 & 2 represent PDF confusion matrix statistics that are used in software to compare Facies with prediction parameters to be more confirmed with density distribution places in different petrophysical units. The first case in the table (Prediction / true) defines the probability of classification given true class, whereas the second case (true / prediction) defines the probability of a sample belonging to some class, given the predicted class. To be noted, the Dolomite unit is not present in this classification because its data is not enough for estimation, especially within formations like these clastic formations.

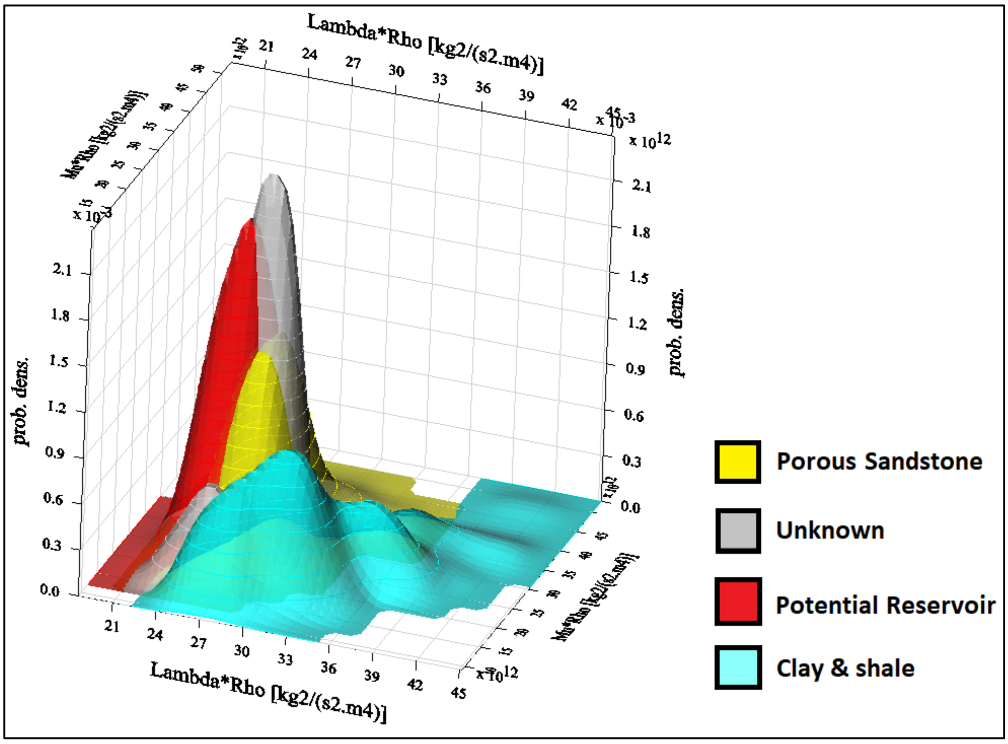

Figure 10. (PDF) Probability density function of the Nahr Umr Formation at wel

Table 1: PDF confusion matrix statistics (Facies vs prediction), case1: P (Prediction | True)

Facies name	Unknown	Potential Reservoir	Clay&Shale	Porous Sandstone
Unknown	59.33%	32.76%	3.57%	28.71%
Potential Reservoir	19.62%	54.02%	0.72%	14.81%
Clay&Shale	4.50%	0.64%	93.20%	2.46%
Porous Sandstone	16.55%	12.58%	2.52%	54.02%

Table 2: PDF confusion matrix statistics (Facies vs prediction), case2: P (True | Prediction)

Facies name	Unknown	Potential Reservoir	Clay&Shale	Porous Sandstone
Unknown	47.71%	22.00%	4.46%	19.32
Potential Reservoir	26.35%	60.58%	0.6319	14.68%
Clay&Shale	2.87%	0.81%	92 46%	21.94%
Porous Sandstone	23.08%	16.61%	2.44%	63.06%

5. Density Velocity Analysis

Geological contexts, stratigraphic history, and the physical characteristics of the rock itself are the primary determinants of the variation in the relationship between seismic velocity and rock density (Ojha & Sain, 2014). These elements are in charge of the connection between lithology and the density/velocity relation (Faisal & Ali, 2021). The density (ρ)/velocity (Vp) ratio has been the subject of numerous scientific publications, all of which have concluded that it is mostly helpful for determining the characteristics of subsurface lithology. Nafe-Dark performs one of the well-known applicable equations (Brocher, 2005; Ludwig et al., 1970).

The type of rock has a considerable impact on the petrophysical parameters, such as density (ρ), tensional wave velocity (%), and heat flow. The empirical relationship between density and velocity can be used to estimate RHOB from (Vp), and density can be used to determine velocity. In addition to lithology, local conditions in each location also have an impact on many interactions (Telford et al., 1976).

Conversion between the various relations discussed here is ultimately made easier by the traditional use of density-velocity as a function of Vp. In this portion, numerous global equations have been reported, such as the Nafe–Drake curve (Ludwig et al., 1970).

Nafe-Dark equation:

$$\rho(\mathrm{g/cm3}) = 1.6612\mathrm{Vp(km/s)} - 0.4721\mathrm{Vp2} + 0.0671\mathrm{Vp3} - 0.0043\mathrm{Vp4} + 0.000106\mathrm{Vp5} \quad (5)$$

Gardner et al., 1974:

$$\rho(\mathrm{g/cm3}) = 1.74\mathrm{Vp0.25} \quad (6)$$

Christensen & Mooney, 1995:

$$\rho(g/cm3) = 0.541 + 0.360\,Vp \quad (7)$$

Godfrey et al., 1997:

$$\rho(g/cm3) = 2.4372 + 0.0761\,Vp \quad (8)$$

The 2nd polynomial (Figure 11) relation of density - velocity for well NS-1gives an equation:

$$RHOB = 0.0640637 + 0.94083\,Vp - 0.088246\,V^2p \quad (9)$$

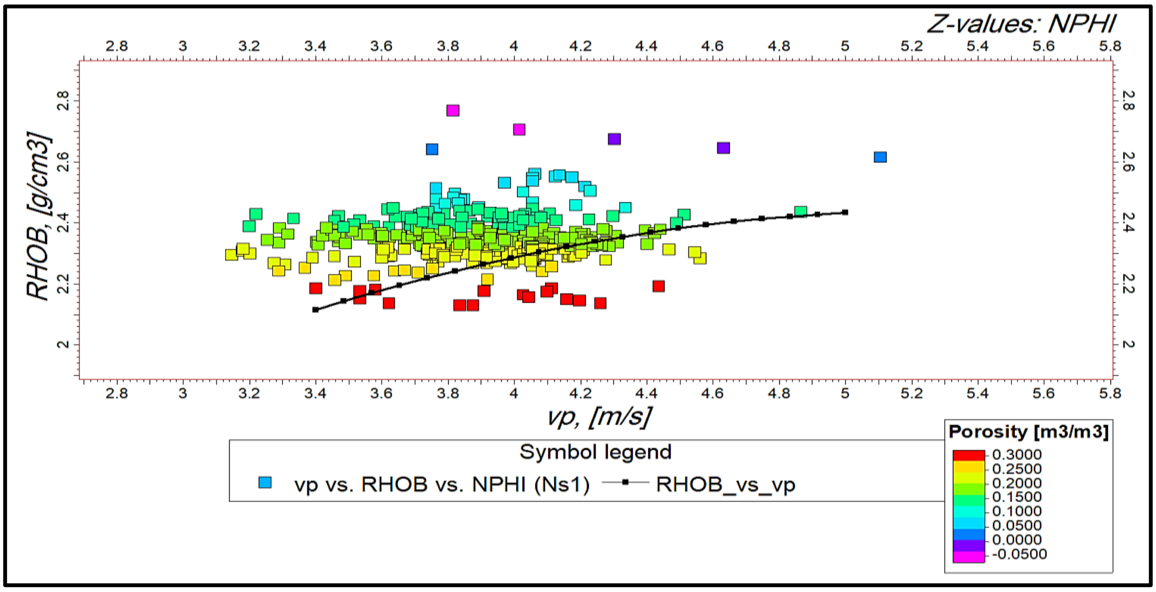

Figure 11. velocity (Vp)/density (ρ) relationship based on well NS-1 data.

In the Nasiriyah Oilfield, the density-velocity relation for well NS-1 was carried out based on the readings from various logs, as illustrated in Figure 12. The horizontal axis (X) represents the seismic velocity, while the vertical axis (Y) represents the density, and the Best-Fit Line is drawn in red to represent the statistical correlation between the two variables. The relationship is found to be very close to a linear one, and if a linear regression is performed, the p-value is obtained as very small (0.0001), which is indicated as a very high significance in the density-velocity relationship. The statistical analysis showed that the correlation coefficient (R) was 0. 766, indicating a strong correlation between velocity and density in this formation. The variance value was about 0.00542329, while the standard deviation of velocity and density was recorded at (3.532 – 4.864) m/s and (2.137 – 2.436) g/cm³, respectively, reflecting the limited variability in the measurement data.

When the results were compared with the classical Nafe-Drake curve (Figure 12), the Nahr Umr Formation data were found to be in good agreement with this reference model, enhancing the reliability of the derived relationship. The main rock units in the formation showed the following velocity ranges:

Shale/clay trend: 1.92 to 2.27 km/s

Porous Sandstone: 2.04 to 2.55 km/s

Dolomite: 2.51 to 2.6 km/s

Potential reservoir: 2.15-2.4 km/s

A new polynomial equation describing the density–velocity relationship was derived based on the Nafe–Drake curve. This equation was calibrated using the NS-1 well data, allowing more accurate estimation of reservoir unit velocities within the Nahr Umr Formation. Such refinement enhances the reliability of petrophysical evaluations and the geological characterization of the reservoirs.

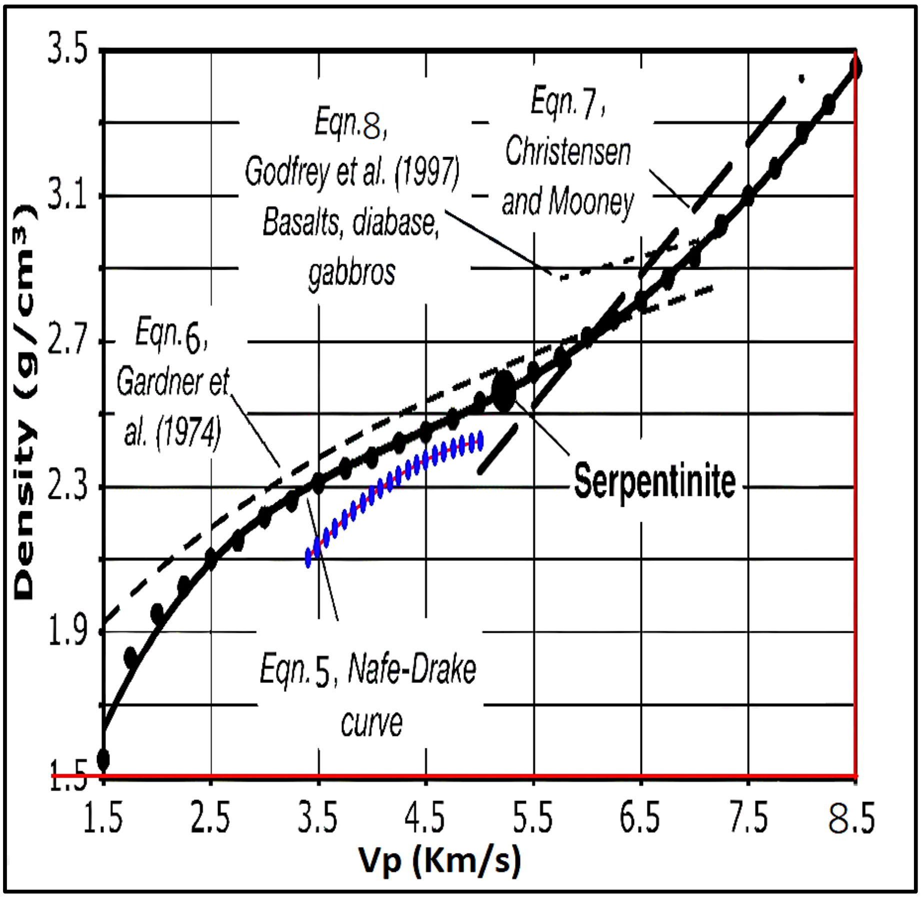

Figure 12. Density–velocity analysis where the Nahr Umr Formation in the Nasiriyah Oilfield is labeled by a red trend line.

The red trendline, representing the Nasiriyah Oil Field's density-velocity relationship, lies below the Nafe-Drake due to many reasons: a high Porosity and/or Fluid Saturation. Low density at relatively high velocities suggests significant pore space, possibly filled with fluids (oil, gas, or water). b. Both oil and gas reduce density and velocity relative to water saturation. The effect is strongest with gas, which lowers both values much more than oil does. A common observation is that the presence of hydrocarbon gas in a rock formation results in a lowering of the seismic velocity (Alsadi, 2017). This may indicate hydrocarbon-bearing zones in the reservoir. c. Unusual Lithology or Alteration: Rocks may be unconsolidated, fractured, or chemically altered (e.g., carbonate dissolution, clay content), which could reflect shales, carbonates, or mixed lithologies common in reservoirs. d. Overpressure Zones: If the formation is overpressured, it may retain fluids that reduce compaction and hence, bulk density. Nahr Umr Formation in the Nasiriyah Oilfield appears to consist of low-density rocks with relatively moderate to high velocities, a signature consistent with productive hydrocarbon reservoirs. Falling below the Nafe-Drake curve suggests a potential for oil and gas presence and points to reservoir rocks with high porosity and/or light hydrocarbons. Nahr Umr Formation's velocity-density trend falling below the Nafe-Drake curve indicates geologically significant anomalies most likely due to fluid-filled, porous reservoir rocks, possibly indicating hydrocarbon saturation and good reservoir quality.

6. Conclusions

The seismic density-velocity correlation technique proved to be effective in characterizing the units of the Nahr Umr Formation, as it contributed to estimating the seismic wave velocities within the formation with good accuracy.

The inferred relationship between density (ρ) and longitudinal velocity (Vp) in well NS-1showed a remarkable agreement with the classical Nafe-Drake curve, enhancing the credibility (very small p-value 0.0001) of this model in characterizing the clastic rocks in the studied area.

The physical and petrophysical characterization based on the available well logs yielded positive results in terms of Lithology Interpretation of the Nahr Umr Formation, with strong indications of the potential for productive carbonate reservoirs (porous and saturated with hydrocarbon fluids). Three promising units have been identified as potential reservoirs within the formation, located at the following depths: (unit I: 2433 – 2445 meters), (unit II: 2455 – 2465 meters), and (unit III: 2485 – 2497 meters).

These units exhibit elastic and petrophysical properties indicating favorable conditions for hydrocarbon accumulation and storage, especially in porous sandstone, making these depths a priority for future reservoir evaluations.

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