

Petrophysical Evaluation of the Early Cambrian Khewra Sandstone by Using Well Log Data, Potwar Plateau, Upper Indus Basin, Pakistan

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Abstract: This study presents a petrophysical analysis aimed at evaluating the reservoir characteristics of the Khewra Sandstone in the Saba-1 well, located in the Potwar Plateau, Upper Indus Basin, Pakistan. The study area lies in the southeastern part of the Potwar Plateau. The Early Cambrian Khewra Sandstone is extensively developed and widely distributed across the Upper Indus Basin of Pakistan. The thickness of the Khewra Sandstone in the Saba-1 well ranges from 2526 to 2654 m. Based on variations in petrophysical properties, the reservoir section of the Khewra Sandstone is subdivided into three distinct zones: Sb1, Sb2, and Sb3. Among these, Sb1 is primarily composed of sandstone and exhibits favorable reservoir potential for hydrocarbons, as indicated by relatively high effective porosity (13%) and hydrocarbon saturation (59.8%). Sb2 includes sandstone with minor shale and has moderate reservoir potential for hydrocarbons, as reflected by low effective porosity (10%) and hydrocarbon saturation (58%). Sb3 is composed of shale with minor sandstone and has poor reservoir potential due to its poor effective porosity (2.50%) and hydrocarbon saturation (40%), respectively. The prospective reservoir intervals are found in the upper and middle reservoir zones, and are recommended for future exploration and development. Overall, this study highlights the significance of integrating petrophysical analysis for reservoir characterization and provides valuable insight for future hydrocarbon exploration in the Potwar Plateau and adjoining areas of the Upper Indus Basin.

Keywords: Early Cambrian, Khewra Sandstone, Potwar Plateau, petrophysical analysis, hydrocarbon potential.

Introduction

The Potwar Basin, recognized as one of the oldest regions for petroleum exploration globally, is located at the northern edge of the Upper Indus Basin. (Shah et al., 2024; Ghazi et al., 2016; Siddiqui and Aamir, 2006). The first commercial oil discovery was made in the late 1800s when the first well was drilled, in 1915 at Khaur, located in the Attock district of Punjab, by the Attock Oil Company (Kadri, 1995). Since then, Potwar has been the primary source of hydrocarbons, and the Potwar Basin has seen the exploration of several wells for crude oil and condensate (Fig. 1). Geographically, Indus River borders it on the west, while the Jhelum River borders it on the east. In terms of structure, the Potwar Plateau may be separated into two deformed zones: the southern Potwar Zone and the north Potwar Zone, with the Soan syncline serving as the boundary (Lillie et al., 1987; Najman, 2006; Yeats Lawrence, 1984; Grelaud et al., 2002). The Main Boundary Thrust (MBT) borders the tectonically significant Potwar

Basin to the north, while the Salt Range Thrust (SRT) borders it to the south (Fig. 1).

The study area is situated in the eastern part of the Potwar Plateau, within District Chakwal, approximately 102 kilometers southeast of Islamabad (Fig. 1). The Saba-1 well is located in a structural trap consisting of a faulted anticline that extends from the northeast to the southwest. In the Saba-1 well, the Khewra Sandstone acts as a major reservoir rock, and is primarily composed of massive, fine-grained, purple to brown sandstone with medium to thick bedding, along with red, flaggy shale found in the bottom portion of the formation (Khan et al., 2024; Shah, 1977).

The information obtained from the well log is useful for assessing the reservoir and is appropriate for calculating the quantity of hydrocarbons in a reservoir rock (Sajid et al., 2021; Ali et al., 2023; Asquith and Krygowski, 2004). In addition to estimating the hydrocarbon reserves and reservoir bed thickness, the reservoir properties make it easier to differentiate between water-bearing and oil-and-

gas strata by looking at their relative permeability and electrical resistivity values (Omolaiye et al., 2013; Hill, 2017).

Extensive research has been carried out on the Khewra Sandstone however, most studies have remained limited to specific aspects rather than providing an integrated reservoir characterization. Baqri and Rajpar (1991) presented a detailed investigation of its clay mineralogy, whereas Khan et al. (2012) evaluated its reservoir potential by estimating porosity through a Helium Porosimeter and proposed it as a possible petroleum resource. Subsequent studies focused on its geomechanical attributes. Khan et al. (2013) assessed the durability of the Khewra Sandstone from the Salt Range, and Arslan et al. (2014) provided a quantitative evaluation of abrasion loss and strength properties of Cambrian sandstones. Provenance analysis was later conducted by Jehangiri et al. (2014), offering insights into the depositional history of the unit. Despite these significant contributions, the literature still lacks a comprehensive petrophysical characterization of the Khewra Sandstone. Such an integrated evaluation is critical for delineating its reservoir quality and assessing its implications within the framework of play fairway analysis, which remains an underexplored dimension of this stratigraphic unit. This study aims to apply well log data for an integrated petrophysical evaluation and detailed reservoir characterization of the Khewra Sandstone, with a primary emphasis on quantifying its hydrocarbon potential and delineating its reservoir quality attributes.

Materials and Methods

Geological Setting

The Himalayan collisional orogen began to form during the Cretaceous period as a consequence of a collision between a continent and a volcanic arc (Kazmi and Jan, 1997). Major tectonic zones, including the Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), and Himalayan Frontal Thrust (HFT), comprise the complex NW Himalayan tectonic domain (Fig. 2, Tahirkheli et al., 1979; Ghazanfer, 1991). The Potwar sub-basin is a wide, approximately 130–150 km sheet of rocks with a Precambrian–Recent geological succession. The Salt Range Thrust (SRT) and the Main Boundary Thrust (MBT) bound the Potwar sub-basin to the south and north, respectively, and have been active for the past 15 million years. The east and west sides of the basin are delineated by the sinistral Jhelum and dextral Kalabagh strike-slip faults, respectively (Kadri, 1995; Jadoon et al., 2015).

The Potwar Plateau is separated by an uneven Soan syncline and is divided into two deformed zones: the southern Potwar Platform zone and the northern Potwar deformed zone (Jadoon et al., 2015; Jaswal et al., 1997). Compared to the isoclinal folds and thrusts seen to the south, the structures to the north a greater degree of complexity due to presence of tight folds and complicated faults. Pop-up structures in the eastern Potwar sub-basin have also been reported (Aamir and Siddiqui, 2006; Jadoon et al., 2015). The detachment plane is usually observed in the Salt Range Formation as a decollement. In addition to the presence of salt, these structural issues are attributed to the distinct mechanical behavior that occurs during the separation and extension of the Kalabagh and Jhelum strike-slip faults. While there are right-stepping structures in the east of the Kalabagh fault, the structures in the eastern Potwar sub-basin are left-stepping. The basin is generally migrating southward along the SRT, pushing across the Punjab, as a result of the joint action of these faults and related splays (Aamir and Siddiqui, 2006)

Subsurface geological record from the Saba-1 well indicates the presence of stratigraphic unconformities, representing significant gaps in depositional history of the basin. These interruptions occur at multiple geological boundaries, including Precambrian–Cambrian, Cambrian, Permian, Permian–Paleocene, and Miocene intervals. (Sajid et al., 2021). The underlying rocks of the Indian Shield, which are made up of metamorphic and volcanic rocks, are unconformably covered by Precambrian Salt Range Formation. Early Cambrian Khewra Sandstone is also unconformably covered (Yeast and Lawrence, 1982). The Jutana and Baghanwala formations were present, but the Kussak Formation was not found, based on data from the Saba-1 well. The Permian succession consists of Dandot Formation and Warchha Sandstone, which are mainly composed of sandstone with minute shale beds. The area includes formations that range from the Permian to the Lower Paleocene. In the Paleogene Tertiary Sequence, the Hangu Formation was laid down unconformably over Warchha Sandstone. In the central and northern Salt Range, a Permian, Triassic, Jurassic, and Cretaceous sequence may be found in wells such as Dakhni, Meyal, Dhurnal, and Karsal (Shah, 2009; Moghal et al., 2007). The Paleocene succession, which includes Hangu Formation, Patala Formation, and Lockhart Limestone, is well developed. Lower and middle Eocene Nammal, Sakesar, and Chorgali formations conformably cover the Paleocene layers. With a Himalayan origin, the Rawalpindi Group (Murree and Kamliyal formations) was unconformably deposited on top of the middle.

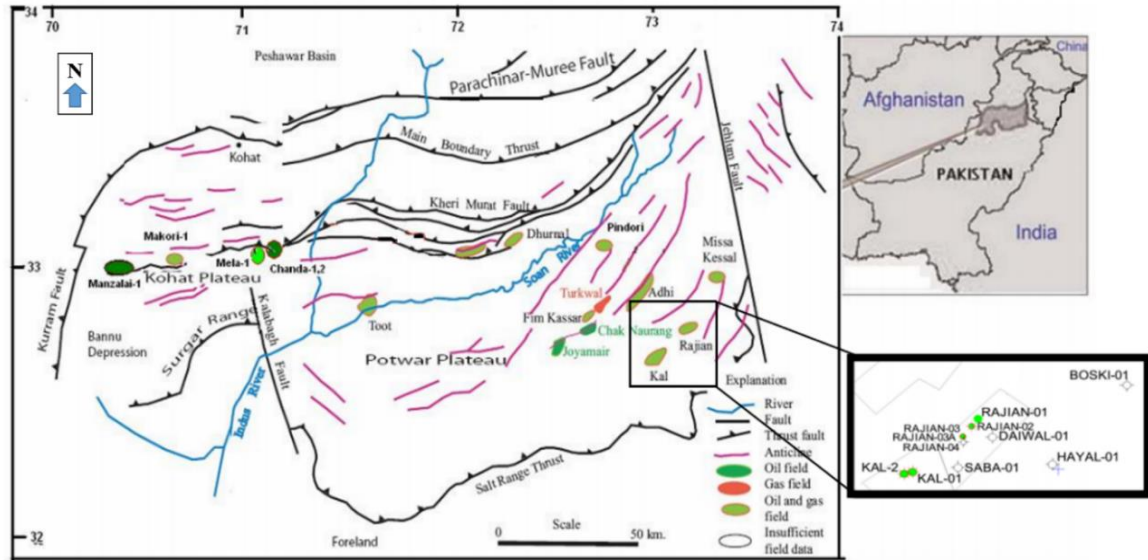


Fig. 1 Generalized oil and gas map of Kohat–Potwar area (modified after Kazmi & Rana, 1982; Khan et al., 1986).

Eocene Chorgali Formation (Salim et al., 2022; Ghazi et al., 2012). In the study area, top of Miocene molasses series contains the Chinji and Nagri formations. (Fig. 2).

Petrophysical Characteristics

The data used in this study were obtained from the DGPC using LMKR. The Saba-1 well from the Potwar Plateau was chosen based on its sonic, neutron, density, and spontaneous potential, resistivity, and gamma-ray logs. The petrophysical characteristics of a rock, such as permeability, porosity, hydrocarbon content, water content, rock lithology, and mobility of hydrocarbons, are supportive in reservoir and formation potential evaluation (Khan et al., 2024). Two software's, Microsoft Excel and GeoGraphix Discovery, were utilized for data processing and analysis (Sajid et al., 2021). The Khewra Sandstone hydrocarbon potential and reservoir characterization were deduced from a variety of log responses. Reservoir parameters in a well were assessed, and the variance in the response curve of various logs was examined due to changes in lithology and reservoir potential (Fig. 3).

Gamma ray (GR) logs were utilized to calculate the amount of shale interval. The log response varies depending on the shale interval hence, every shale bed has a unique log response (Hu et al., 2018). The resistivity logs were used to identify the hydrocarbon (Shahat et al., 2021; Sajid et al., 2023). The sonic log provides the mean time for the formation interval. It gauges how well a structure can transmit sound waves. Geologically, this capacity changes with rock textures, particularly

porosity, liquid-filled holes, and lithology (Joshi et al., 2021; Iqbal et al., 2022). The bulk density of a formation is continuously recorded by the density log. This is the total density of a rock, which includes the fluid inside the pores as well as the solid matrix. Indirectly, hydrocarbon density and porosity are computed using the density log (Ghosh, 2022). The neutron log serves to assess porosity and offers continuous documentation of a formation segment as a result of swift neutron bombardment. It is represented in neutron porosity units, which correlates with a formation's hydrogen index, acting as a measure of its hydrogen content (Senosy et al., 2020).

Log analysis: The kind of rock lithology and the location of the oil and gas zone are ascertained using log analysis. Following values were computed in this analysis: porosity, water saturation (S_w), water resistance value (R_w), and V_{sh} value. These data points were utilized to determine the reservoir's oil and gas concentration. Additionally, the examination of logs is utilized to pinpoint the area of interest, defined by pristine sand that contains hydrocarbons. The GR log, which measures the natural radioactivity within the rocks, was utilized to determine the sand/shale lithology in the research area (Track 1). The differentiation between hydrocarbon and non-hydrocarbon zones was established by utilizing the resistivity log (LLD) alongside the GR log (Track 2). Consequently, clean zones characterized by hydrocarbon saturation (indicated by low gamma ray and high resistivity values) were identified as the area of focus for petrophysical analysis. By employing neutron and density logs, various fluid types were differentiated. The intersection of the density log and neutron log,

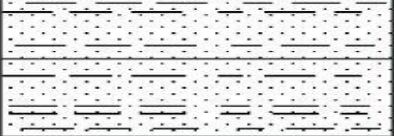
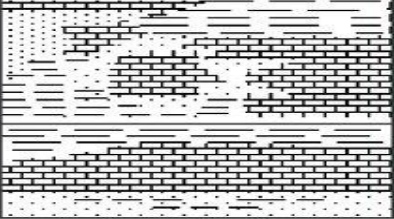
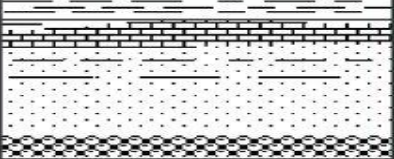
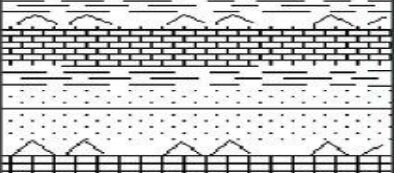
AGE / EPOCH		LITHOLOGY	FORMATION
NEOGENE	Pliocene		Nagri Chinji
	Miocene Oligocene		Kamlial Murree Kohat
Oligocene		Unconformity	
PALEOGENE	Eocene		Mamikhel Chorgali # Sakesar # Nammal #
	Paleocene		Patala * # Lockhart * # Hangu * #
Mesozoic & Late Permian		Unconformity	
JURASSIC			Datta
PERMIAN	Early Permian		Chhidru Wargal Amb Sardhai Warcha Dandot Tobra #
Carboniferous to Ordovician		Unconformity	
CAMBRIAN TO PRE- CAMBRIAN	Cambrian		Baghanwala Jutana Kussak # Khewra * #
	Infra Cambrian		Salt Range *

Fig. 2 Generalized stratigraphic column of Potwar Basin showing source and reservoir rocks (after Wandrey et al., 2004).

or porosity logs, serves to elucidate the gas zones. In contrast, water zones are recognized by their association with extremely low resistivity, whereas oil zones are analyzed based on elevated resistivity log values.

Volume of Shale: The shale content within the formation was assessed utilizing gamma ray (GR) log data. The volume of shale (V_{sh}) is calculated using the formula provided below (Serra, 1985).

$$V_{sh} = \frac{GR \log (\text{value}) - GR (\min)}{GR (\max) - GR (\min)} \quad (1)$$

Where;

V_{sh} = Shale volume

$GR \log (\text{value})$ = GR log response at given point

$GR (\min)$ = Minimum value of GR log (clean beds e.g clean sand or carbonate).

$GR (\max)$ = Maximum value of GR log (shale beds).

Porosity: Porosity has been determined through well logs utilizing density log (ϕD), Neutron log (ϕN), total porosity (ϕT), and effective porosity (ϕE) with the assistance of the subsequent formulas. The bulk density measurements derived from the formation density log for each reservoir were

utilized in the subsequent equation to calculate density porosity (ϕD) (Dresser Atlas, 1979).

• Density Porosity (ϕD)

Density porosity is determined by the following formula

$$\phi D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad (2)$$

Where;

ρ_{ma} = Rock matrix density

ρ_f = Fluid density

ρ_b = The bulk rock density measured through log response within the area of interest.

• Neutron Porosity (ϕN)

$$\phi N = (1.02 \times \phi_{Nlog}) + 0.0425 \quad (2a)$$

Where;

ϕ_{Nlog} = Log response (NPHI)

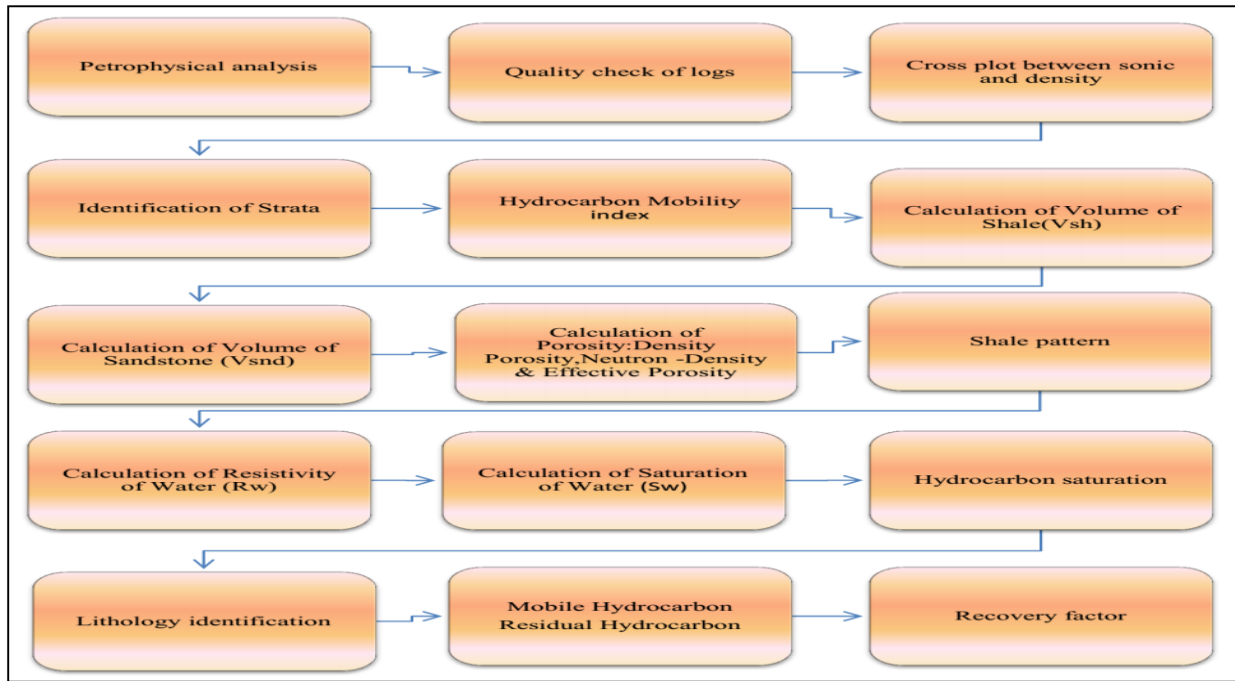


Fig. 3 Flowchart depicting the methodological framework adopted in this study.

• Total Porosity (ϕ_T)

Total porosity is represented by ϕ_T the following formula

$$\phi_T = (\phi_D) + (\phi_N) / 2 \quad (3a)$$

Where: ϕ_D = density porosity and (ϕ_N) = Neutron porosity

• Effective Porosity (ϕ_E)

Effective porosity is calculated by formula

$$\phi_E = \phi_T \times (1 - V_{sh}) \quad (4a)$$

ϕ_T = total porosity
 V_{sh} = shale volume.

Water saturation: The quantity of water found within the pore spaces of rocks is referred to as water saturation. Various formulas exist for determining water saturation, such as the Archie Model, Indonesian Model, Fert-Hammack Model, Fertl Model, and Laminated Shale Model. Nevertheless, the Archie equation is deemed most suitable for calculating water saturation. Initial step in calculating the water saturation (S_w) involves determining the water's resistivity (R_w), which is subsequently calculated using the Archie equation. The SSP chart can be utilized to ascertain the water's resistivity (R_w) (Bateman and Konen, 1978).

Archie's Equation is used to determine the water saturation (S_w).

$$S_w = [(a / \phi^m) \times (R_w / R_t)]^{1/n} \quad (5)$$

Where;

S_w = saturation of water

R_w = water resistivity

ϕ = porosity

m = cementation factor

a = constant factor

R_t = response of log (LLD)

Hydrocarbon Saturation: Hydrocarbon saturation (S_{hc}) quantifies the pore volume, indicating amount of gas and oil present within the formation. Following formulas, derived from well logs, have been employed to calculate hydrocarbon saturation:

$$S_{hc} = 1 - S_w$$

OR

$$S_{hc} \% = 100 - S_w \% \quad (6)$$

Where;

$S_{hc} = S_o + S_g$

If $S_g = 0$, then $S_h = S_o$

S_w = Saturation of water

Permeability: The permeability (K) for each recognized reservoir is determined using the equation provided below:

$$K = \frac{\sqrt{250 \times \phi^2}}{S_{wir}} \quad (7)$$

Table 1. Showing the reservoir characterization of the Khewra Sandstone.

Well	Formation	Zone	Thickness (m)	Volume of Shale (%)	Effective Porosity (%)	Rw	Water Saturation (%)	Hydrocarbon Saturation (%)
Saba-01	Khewra Sandstone	Sb 1	2526-2551	28	13	0.38	40.2	59.8
		Sb 2	2553-2560	35	10	0.38	42	58
		Sb 3	2561-2654	60	2.5	0.39	60	40

Where S_{wir} represents the irreducible saturation of water (Tixier, 1949). By analyzing the results of their computed petrophysical parameters using equations 1 to 7, the productivity of each identified reservoir rock in the area of interest is determined.

Results and Discussion

The Khewra Sandstone interval is used to analyze all of the Saba-1 well accessible logs for petrophysical study. The upper sections of the Khewra Sandstone are composed of sandstone that shows a comparatively low gamma ray response along with fluctuations in the SP response. Conversely, the lower section of the formation is made up of shale and claystone, which demonstrate a high gamma ray response.

Petrophysical Analysis

A variety of log methods, including GR, LLD, LLS, NPHI, RHOB, and Spontaneous Potential (SP) logs, have been used to identify several reservoir zones (Moore et al., 2011; Mavko et al., 2011; Alexeyev et al., 2017; Aguilera and Aguilera, 2003). All recognized areas of interest are designated and examined via curve response interpretation, utilizing several acronyms; for example, RHOB signifies the density of the borehole and the rocks that the drill bit has traversed. The PHIN, ϕ_N , NPHI and logs are employed to evaluate the hydrogen content present in a geological formation. In formations devoid of clean shale, where the porosity is filled with either oil or water, the NPHI, PHIN, and ϕ_N logs reflect liquid-filled porosity. The photoelectric effect (PEF) measures the emission of electrons resulting from the interaction of electromagnetic radiation, including light with a material. Density porosity, represented in decimal form (v/v), reflects the water saturation in the formation encountered during drilling (S_w). Higher v/v values denote increased porosity, while lower v/v values suggest reduced porosity. The resistivity of water at the temperature of the formation (R_w) is assessed, while ResD or laterolog deep (LLD) functions as a resistivity instrument for comprehensive analysis in undisturbed areas. In contrast, the ResS laterolog shallow (LLS) is utilized for resistivity measurements in shallow studies within transition zones. Furthermore, Micro Spherically Focused Log

(ResM or MSFL) serves as a resistivity instrument intended to evaluate flush zone resistivity, while G/C3 represents a density unit (g/cm^3).

If a zone has high LLD values, low GR log values, low SP log values, and raised NPHI values, it may be classified as a reservoir. According to cut-off factors, the following cut-off parameters are used to identify reservoir zones: $V_{sh} < 30\%$, $S_w < 60\%$, and effective porosity $\phi_E > 7\%$ (for primary porosity rock), or $V_{sh} < 30\%$, $S_w < 60\%$, and $\phi_E = 1\%$ (for secondary porosity or carbonate rock) (Table 1).

In Saba-1, the total thickness of Khewra Sandstone is 128 m, ranging from 2526 to 2654 m. On the basis of well log interpretation, the formation is divided into three zones, namely Sb1, Sb2, and Sb3. Zone Sb1 ranges from 2526 to 2551 m, while the Sb2 zone ranges from 2553 to 2560 m, and Sb3 ranges from 2561 to 2654 m. The volume of shale in zone Sb1 is 0.28 (28%). Water resistivity, as determined by the Schlumberger chart, is $0.38 \Omega \cdot m$. Effective porosity is 13% on average. Water is 40.2% saturated, whereas hydrocarbons are 59.8% saturated. The average shale volume in zone Sb2 is 0.35 (35%). The effective porosity of the formation is 10%, with a formation water resistivity (R_w) of $0.38 \Omega \cdot m$. The calculated water saturation is 42%, while hydrocarbon saturation accounts for 58%. High gamma-ray readings in the Sb3 zone indicate that shale is the dominant lithology. However, intervals with low gamma-ray values suggest the presence of thin sandstone layers. The volumetric analysis reveals that shale constitutes approximately 60% of the Sb3 zone. Formation water resistivity, determined using the Schlumberger chart, was $0.39 \Omega \cdot m$. The average effective porosity is estimated at 2.5%, with fluid saturation values showing 60% water and 40% hydrocarbons (Table 1, Fig. 4).

Cross Plots Analysis

The characteristics of reservoir rock, including porosity, permeability, pore-size geometry, and net-to-gross ratio, can be significantly influenced by the improper delineation of sand intervals. Consequently, it is essential to employ well log cross-plots to precisely delineate the sand body and accurately assess the petrophysical properties of the identified sandstone intervals.

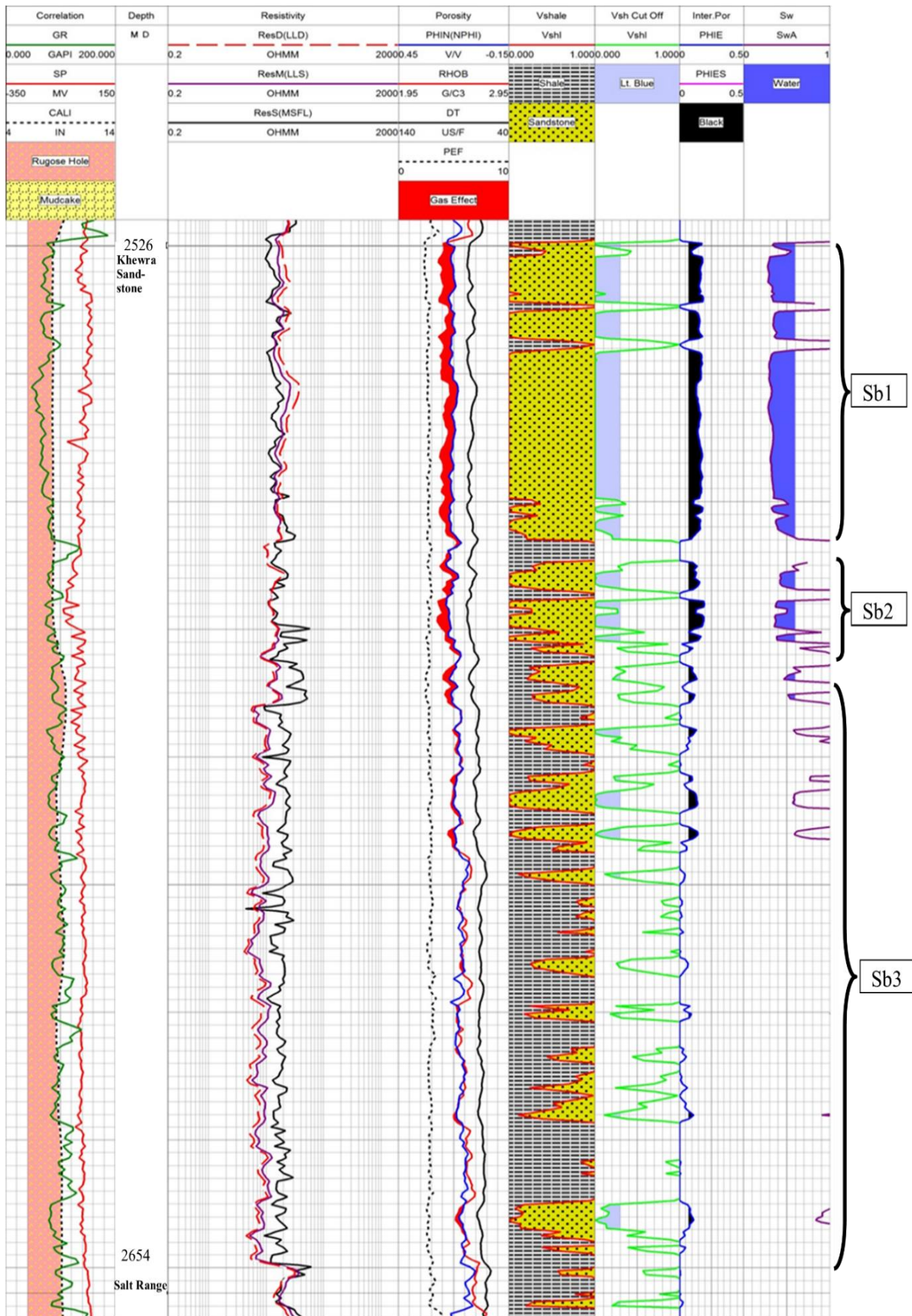


Fig. 4 Petrophysical analysis of Khewra Sandstone in the Saba-1 well.

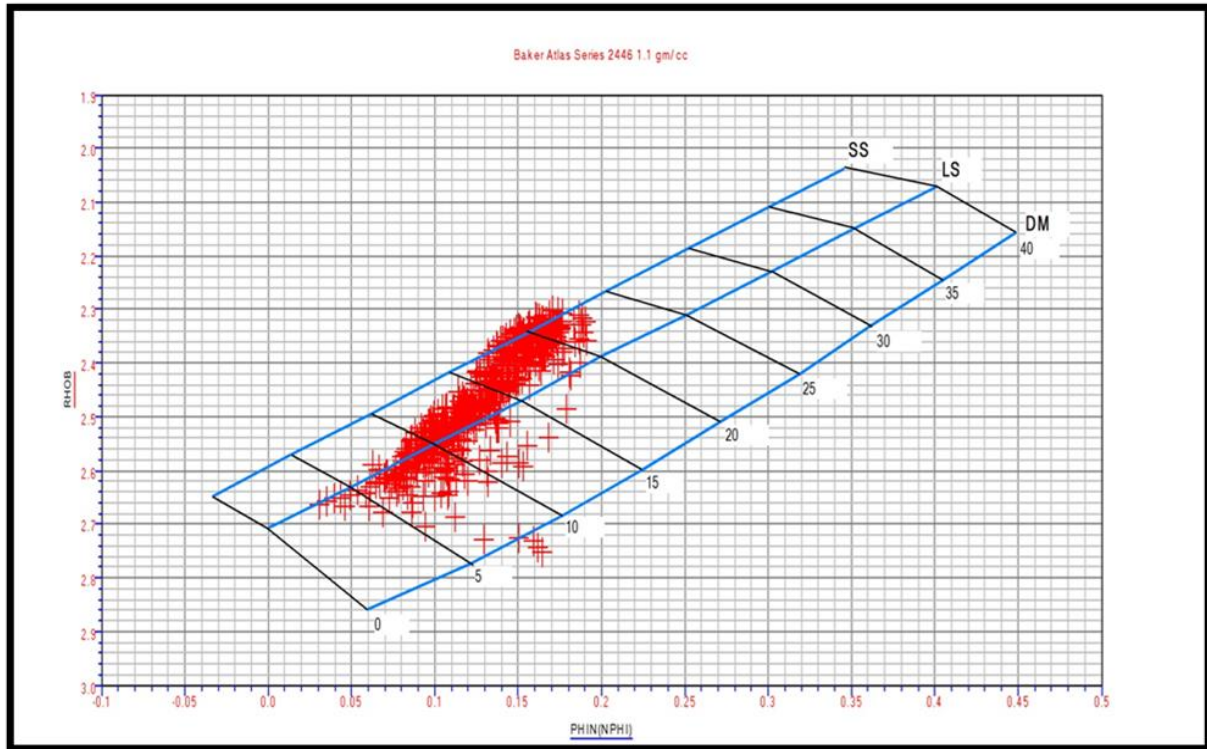


Fig. 5. Cross-plot illustrating lithological variations within Khewra Sandstone in the Saba-1 well.

Lithology can be recognized through cross plots. Density-Neutron cross plots were created utilizing the well log data; Density (RHOB) is represented on the vertical axis, whereas Neutron (NPHI) is depicted on the horizontal axis. The lithological lines depicted on cross plots are composed of dolomite, limestone, sandstone and (DM, LS, SS). Points that align with one of these lines signify a pure formation. Conversely, when points are situated between the lines, it suggests the existence toward the limestone border in cases where the cement is calcareous (Moore et al., 2011). The rock lithology was determined by analyzing the cross plot models. Together with the knowledge gained from the cross plot, shown in Figure 5 is intended to aid in the comprehension and identification of lithology.

Conclusion

The petrophysical assessment of the Early Cambrian Khewra Sandstone, utilizing well log data from the Potwar Plateau in the Upper Indus Basin, has yielded essential insights regarding the reservoir quality and hydrocarbon potential of this geological formation. In the study area, the examination of essential petrophysical parameters such as porosity, shale volume, water saturation and hydrocarbon saturation demonstrates moderate to favorable reservoir properties. The formation primarily consists of clean to moderately shaley sandstone, highlighting

advantageous porosity and saturation profiles, especially in the upper zone (Sb1) and middle zone (Sb2). The bottommost zone (Sb3) of the Khewra Formation includes shale with minor traces of sandstone.

The combination of gamma ray, resistivity, density, and neutron logs has facilitated the precise identification of hydrocarbon-bearing intervals and has enhanced the comprehension of both lateral and vertical variability in reservoir quality. These findings underscore the potential of the Khewra Sandstone as a promising exploration target for hydrocarbons in the Potwar Plateau.

In conclusion, this study highlights the significance of utilizing well log-based petrophysical assessments to define reservoir characteristics and improve the success rate of hydrocarbon exploration in intricate geological environments like the Upper Indus Basin. It is advisable to conduct additional studies that integrate core data and seismic analysis to enhance and clarify the results discussed in this research.

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