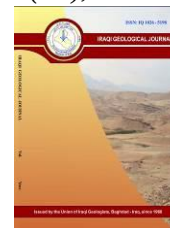




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Petrophysical Evaluation of the Zubair Formation in the Luhais Oil field, Southern Iraq

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Abstract

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This study analyses borehole log data from five producing wells to determine the petrophysical characteristics of the Zubair Formation in the Luhais Oil Field. This research aims to assess the mineralogical and lithological origin of the reservoir, calculate important petrophysical parameters, and evaluate reservoir units across various stratigraphic members. The NPHI-RHOB cross plot shown that sandstone is the primary lithological composition, while M-N plots which confirmed quartz dominance, revealing a sandy-clastic reservoir. Key parameters including shale volume, effective porosity, permeability, water saturation, and net pay thickness were all calculated using Computer Processed Interpretation (CPI). The Zubair Formation was divided into three members: the upper (Sandstone-Shale), which was further subdivided into six reservoir units (A-F), the Middle (Sandstone), and the lower (Shale-Sandstone). The evaluation results showed that unit C represents the production interval, with significant net pay thicknesses and attractive reservoir characteristics, whereas unit E has limited reservoir quality. Units A and B have weak properties, while units D and F are non-reservoir intervals. The findings also revealed that the middle and lower members' contributions to the study area are limited due to high water content and poor reservoir continuity, with penetration observed in only two of the wells investigated.

Keywords: Petrophysical properties; Porosity; Permeability; Water saturation; Zubair reservoir; Luhais Oilfield

1. Introduction

Petrophysical properties are essential in petroleum engineering because they indicate how well a reservoir can store and move fluids. These properties, such as porosity, permeability, and fluid saturation, are the most important factors that affect the volume and production of hydrocarbons (Asquith et al., 2004). In 1961, the Iraqi National Oil Company discovered the Luhais Oil Field and drilled well Lu-1, and drilling progressed to well Lu-58 by 2026. This field produces oil from the Nahr Umr and Zubair reservoirs. One of the most important Lower Cretaceous sequences in central and southern Iraq is the Zubair Formation (Al-Sayyab, 1989).

The Zubair Formation in Iraq is a major oil reservoir, particularly in the Rumaila, Zubair, and West Qurna fields, as well as in Kuwait. In Saudi Arabia is equivalent the Biyadh Formation, in the Ghawar Oilfield and the Gadvan Formation in Iran (Al-Husseini, 1997). The formation produces moderately sour crude oil with an API gravity of approximately 32° API (Alher et al., 2018; Al-Khafaji et al., 2019). The Wadi al-Batin Depression transported the sediments of this formation into the Basrah region. The

Zubair Formation occurs in the Luhais Oil Field at depths between 2777 and 3227 m, and in well Lu-3, its total thickness in the type section reaches about 450 m (Al-Yasi and Al-Baldawi, 2015).

This formation is described by Hasan (2011) as composed of interbedded sandstone, siltstone, and shale, with occasional thin carbonate beds present in the upper part. The composition consists predominantly of deltaic, fluvio-deltaic, and marine sandstones, covering a large region of southern and central Iraq and extending into northern Saudi Arabia and Kuwait (Powers et al., 1966). Harris et al. (2012) stated that the Zubair Formation was deposited mostly in deltaic, fluvial, and estuarine environments. These depositional environments produced an interbedded sequence of sandstone, shale, and siltstone. This facies variability forms a segmented reservoir architecture, resulting from vertically stacked, multi-storied sand bodies and lateral variations in deltaic channel facies (Al-Rubaye et al., 2019).

four distinct electrofacies were identified in the formation by Al-Samer and Al-Najm (2024): shale, sandy shale, shaly sand, and clean sand. This suggests a high degree of lithological heterogeneity. The clean sandstone zones have good to excellent petrophysical properties, which serve as strong indicators of reservoir quality (Aladwani and Alenezi, 2024). In contrast, a high percentage of the shale intervals are composed of clay minerals, mainly kaolinite and illite, that decrease reservoir quality in some areas (Abbas et al., 2018). In their explanation, Hasan and Shimary (2024) proposed that continuous changes in the physical and chemical conditions of the depositional environment resulted in diverse diagenetic processes that directly influenced the physical properties of the reservoir. Some processes, such as dissolution, caused an increase in porosity, and others processes, such as compaction and cementation, caused a decrease in porosity, which influenced permeability and of hydrocarbon movement. In southern Iraq, the Zubair Formation is divided into five members according to the sand/shale ratio, listed from bottom to top as follows: Lower Shale Member, Lower Sandstone Member, Middle Shale Member, Upper Sandstone Member, and Upper Shale Member (Al-Mudhafar et al., 2024). The absence of the Middle Shale Member in this field resulted in the combination of the Upper Sandstone Member, with the Lower Sandstone Member forming the Middle Sandstone Member. This study provides a quantitative evaluation of net pay thickness for each distinct unit together with an integrated five-well correlation (Lu-2, Lu-3, Lu-5, Lu-12, Lu-41).

The study aims to evaluate reservoir quality and hydrocarbon potential by calculating the volume of shale, effective porosity, permeability, and oil saturation; identifying to the lithological and mineralogical of the formation; and calculating net pay thickness by analyzing data from five selected wells using Interactive Petrophysics (IP) software, version 2018. It differs from previous studies in that it incorporates the most important reservoir properties.

2. Study Area

The Luhais oilfield is located in the Widyan–North Arabian Gulf Basin, approximately 105 km west of Basrah and 350 km southeast of Baghdad. The field measures about 20 km in length, and 10 km in width. Geographically, the field is located between 47°14'–47°19' longitude and 30°13'–30°24' latitude, as shown in Fig. 1.

3. Geologic Setting

The Luhais Oil Field is situated in the northern region of the Arabian Plate, southern Iraq, in the Zubair Subzone of the Mesopotamian Foreland Basin (Fouad, 2010). This is part of the Unstable Shelf (Jassim and Goff, 2006). The Luhais Oil Field can be described as a closed, asymmetrical anticline structure (Alher et al., 2018). The anticline trends northwest–southeast, as displayed in Fig. 1b, based

on the upper shale structural contour map. Glynn Jones identified the Zubair Formation in the Zubair Oil Field in 1948, and Nasr and Hudson modified it in 1953 (Van Bellen et al., 1959). The age of the formation was identified by Van Bellen et al. (1959) as Hauterivian to Aptian, or Barremian to earliest Aptian. In the central part of the basin, the formation's lower and upper contacts are generally gradational and conformable. However, in the Salman Zone to the west, the formation's lower boundary is unconformable, and its upper boundary with the overlying Albian sequences is also unconformable (Jassim and Goff, 2006).

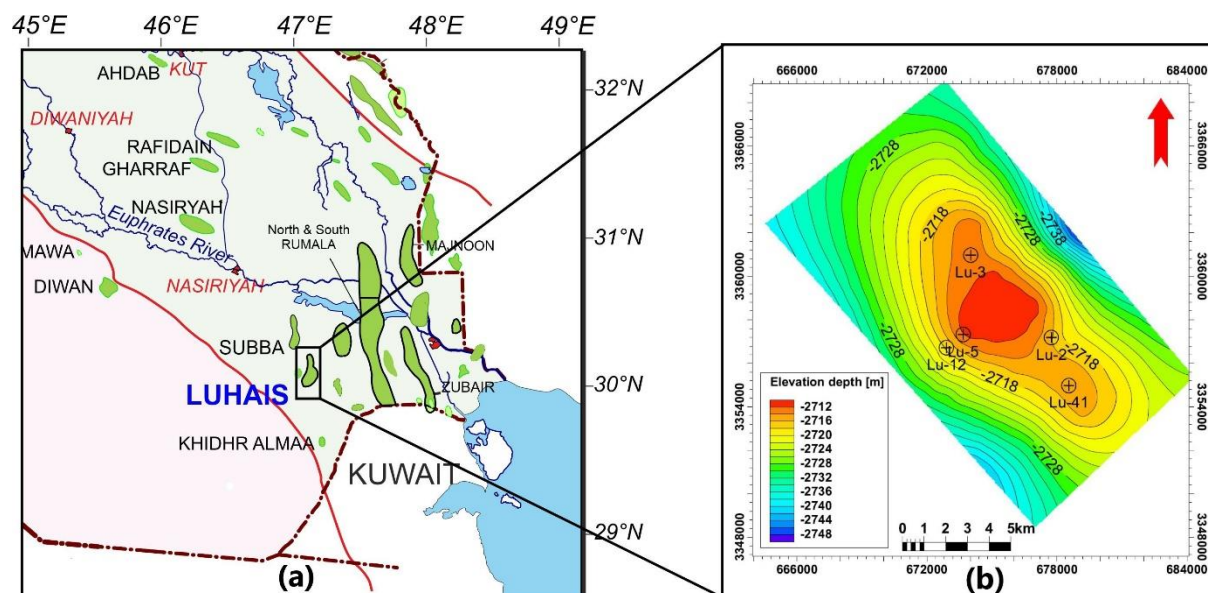


Fig.1. a) Location map of the study area, b) A structural contour map at the top of the Zubair Formation

4. Materials and Methods

The current study used open-hole well logs data from five selected wells, as shown in Fig. 1. The dataset included spontaneous potential, gamma ray, caliper, resistivity, neutron, density, and sonic logs, which are essential tools in petrophysical evaluation. The well data used to calculate the following parameters of reservoir by using Interactive Petrophysics (IP) software:

4.1. Lithological and Mineralogical of the Reservoirs

Accurate diagnosis of lithology and mineralogy of reservoir is an important component of petrophysical evaluation, because it allows for the distinction of constituent minerals and their effect on reservoir storage and flow behavior. This increases estimations of porosity, permeability and hydrocarbon saturation.

4.1.1. Lithology identification by Neutron-density cross plot

The integration of neutron and density logs represents one of the most effective methods for lithology identification, as the two tools respond to porosity while being affected by different physical properties of the rock. The neutron log can easily measure the hydrogen content, which is heavily impacted by fluid-filled porosity. Whereas the density log can measure electron density, which is closely related to rock matrix density. When plotted together in a cross-plot, these two variables form a powerful diagnostic tool for reservoir characterization (Asquith et al., 2004).

On a normal neutron-density cross plot (using limestone matrix as a reference), the clean sandstone always plots to the right of the limestone line, suggested greater density readings (matrix density ≈ 2.65

g/cm³) and slightly lower neutron porosity values. Limestone aligns with the reference line (matrix density = 2.71 g/cm³), but dolomite plots to the left due to its greater matrix density (≈ 2.87 g/cm³) and distinct neutron-density separation. These different placements enable reliable lithological identification of the Zubair Formation members (Schlumberger, 1989).

4.1.2. M-N cross plot mineralogy identification

The M–N plot requires acoustic, neutron, and density logs to calculate the lithology-dependent variables M and N. The M and N values are largely independent of porosity. A cross-plot of these two variables makes lithology more apparent. M and N values are calculated using the following equations (Schlumberger, 1972):

$$M = \frac{\Delta t_{fl} - \Delta t}{\rho_b - \rho_{fl}} * 0.01 \quad (1)$$

$$N = \frac{\phi N_{fl} - \phi N}{\rho_b - \rho_{fl}} \quad (2)$$

where: Δt = interval transit time in the formation (from the log); Δt_{fl} = interval transit time within the fluid in the formation; ρ_b = bulk density of formation (from the log); ρ_{fl} = fluid density; ϕN = neutron porosity; ϕN_{fl} = neutron porosity of the formation fluid (usually = 1.0)

4.2. Calculation of Shale Volume

Measuring shale volume is important for accurately assessing hydrocarbon units in any formation because it reduces pore space, decreases permeability, and lowers reservoir quality. The following formula is used to calculate shale volume in Jurassic and Cretaceous formations (Larionov, 1969):

$$V_{shale} = 0.33 * (2^{2*IGR} - 1) \quad (3)$$

$$IGR = \frac{GR_{log} - GR_{min}}{GR_{mix} - GR_{min}} \quad (\text{Krygowski, 2003}) \quad (4)$$

Where: IGR= gamma ray index; V-shale= shale volume; GR log: Gamma-ray log reading (API); GR max: Maximum gamma-ray log reading (shale) (API); GR min: Minimum gamma-ray log reading (clean sand) (API).

4.3. Porosity Determination

The volume of the internal pores in a specific amount of rock is known as total porosity (**PHIT**). Consequently, it is an indicator of the amount of fluid a rock **can** hold (Asquith et al., 2004). It is calculated by combining neutron and density logs and correcting the logs for the effect of shale. First, Tiab and Donaldson's equation is used to correct the porosity of the neutron log (Tiab and Donaldson, 2015):

$$\phi_{Nc} = \phi N - (V_{sh} * \phi_{Nsh}) \quad (5)$$

Where: ϕ_{Nc} = corrected Neutron porosity from affect shale, ϕN =Neutron log, ϕ_{Nsh} = Neutron porosity of shale.

Secondly, the porosity from the density log was computed for intervals with shale content less than 10% using the following equation (Wyllie et al., 1958):

$$\emptyset D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad (6)$$

$\emptyset D$ = Porosity from density log, ρ_{ma} = matrix density (2.644 for sandstone), ρ_b = formation bulk density, ρ_f = density of fluid (1.15) for saline water, measured in units (g/cm³) (Cannon, 2015).

Remove the shale influence from porosity calculations in intervals where the shale volume exceeds 10%, and use the following equation (Atlas, 1979):

$$\emptyset D_c = \emptyset D - (V_{sh} * \emptyset D_{sh}) \quad (7)$$

Where: $\emptyset D_c$ = Porosity derived from density log, corrected for shale effect; $\emptyset D_{sh}$ = density porosity of shale.

The following equation is used to compute total porosity ($\emptyset_t$) (Bowen, 2003):

$$\emptyset_t = \frac{\emptyset_{Nc} + \emptyset D_c}{2} \quad (8)$$

The effective porosity ($\emptyset_e$) is the volume of interconnected void space capable of fluid transfer. The following equation was used to calculate it (Darling, 2005):

$$\emptyset_e = \emptyset_t * (1 - V_{sh}) \quad (9)$$

4.4. Permeability Estimation

Permeability is a reservoir rock's ability to transport fluids through its interconnected pore space under a pressure gradient (Tiab and Donaldson, 2024). Permeability was calculated using the Timur equation due to the unavailability of core data. In these cases, empirical correlations derived from wireline logs are commonly used as reliable alternatives (Asquith et al., 2004). The Timur model combines permeability with porosity and irreducible water saturation, which are obtained from log interpretation, thereby making it suitable for log-based reservoir analysis (Timur, 1968). This method is particularly suitable for clastic reservoirs, such as the Zubair Formation, where reservoir properties match the empirical parameters of the formula.

$$K = 0.136 \frac{\emptyset^{4.4}}{S_{wi}^2} \quad (10)$$

Where: K = permeability in mD; S_{wi} = irreducible water saturation.

4.5. Determining Fluid Saturation

Water saturation (S_w) refers to the volume percentage of pore space occupied by water. Due to the high shale content in the reservoir under study, where shale volume exceeds 15% as indicated by gamma-ray log responses and neutron–density log separation, the Simandoux equation was used to estimate water saturation. Because Archie's Law depends on clean, clay-free formations, its application is limited under these conditions (Asquith et al., 2004; Simandoux, 1963):

$$S_w = \left(\frac{0.4 * R_w}{\emptyset_2} \right) * \left[\sqrt{\left(\frac{V_{shale}}{R_{sh}} \right)^2 + \frac{5 * \emptyset^2}{R_t * R_w}} - \frac{V_{shale}}{R_{sh}} \right] \quad (11)$$

Where: SW = water saturation; Rw = formation water resistivity (0.019 at 173° F, it was calculated by using a Pickett plot for a clean rock unit that fully water saturated, as illustrated in fig. 2); Rt = true resistivity recorded by log (Ωm); Rsh= true resistivity of nearby shale.

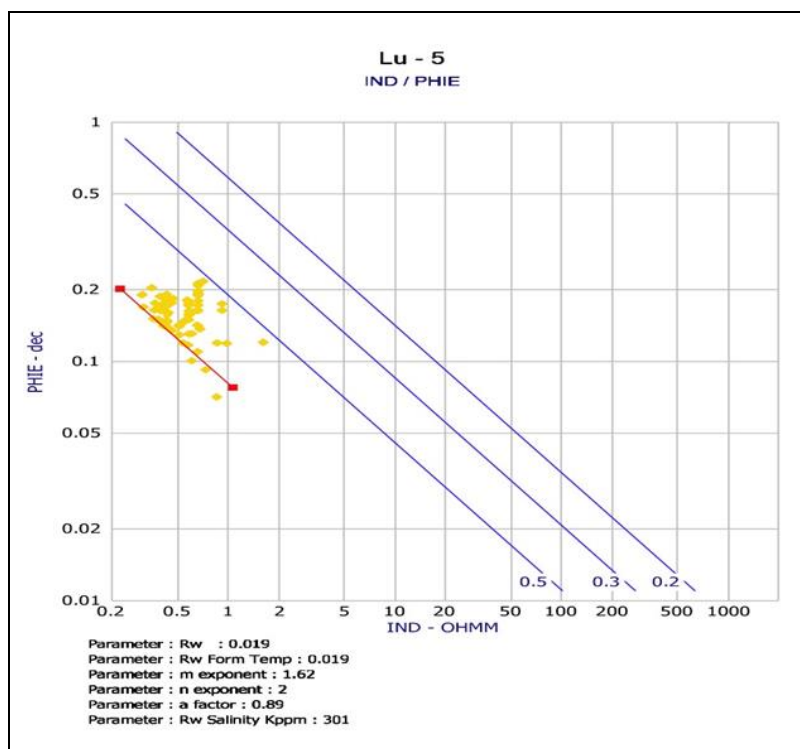


Fig. 2. Pickett plot to determined Rw,m,n and a parameter in the Zubair Formation

Hydrocarbon saturation (Sh) represents the volume of pore space that remains unfilled by water. It is determined using the following equation (Bateman, 2012): -

$$Sh = 1 - Sw \quad (12)$$

5. Results and Discussions

The main results of the study are shown below:

5.1. NPHI–RHOB Cross Plot

The NPHI–RHOB cross-plot results indicate that the majority of points are located on the sandstone line, suggesting that the dominant lithology in the Zubair reservoir within the study area is sandstone, with minimal clay and minor carbonate influence in select reservoir units. In most of the intervals under study, this clustering confirms the concept of lithological homogeneity and represents the clastic nature of the reservoir, as illustrated in Fig. 3.

5.2. M-N Cross Plot

The M–N cross-plot reveals that the majority of the data fall along the quartz line, displayed that quartz predominates in the reservoir rocks and confirming the reservoir's clastic origin. As shown in Fig. 4, the lithological analysis results obtained from the NPHI–RHOB plot are consistent with this mineralogical interpretation.

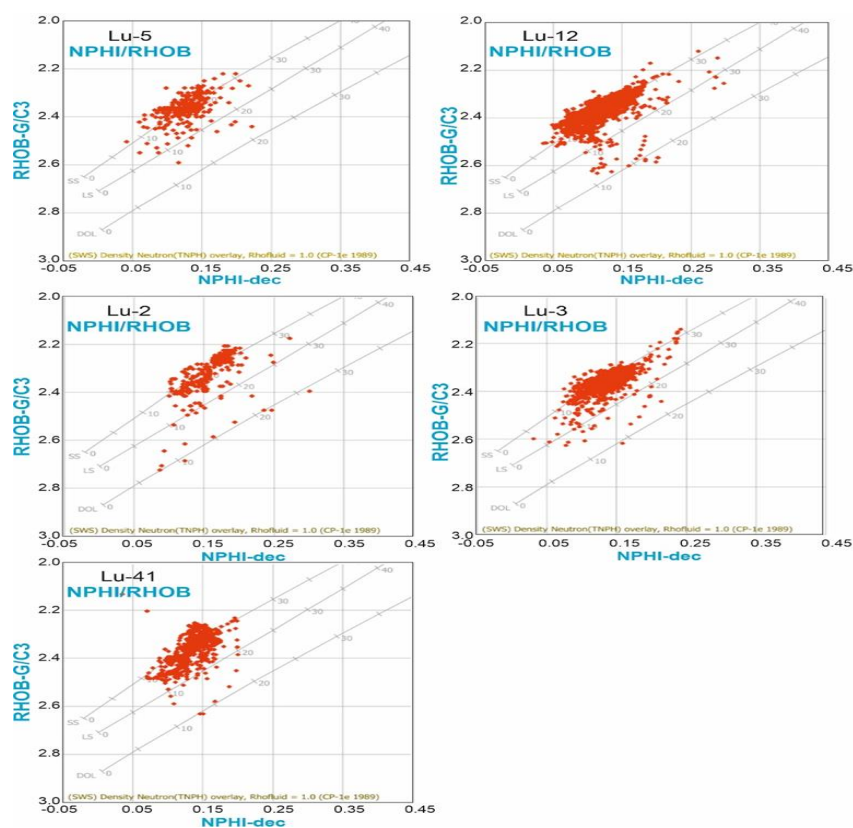


Fig. 3. Cross-plot of neutron and density logs for the studied wells

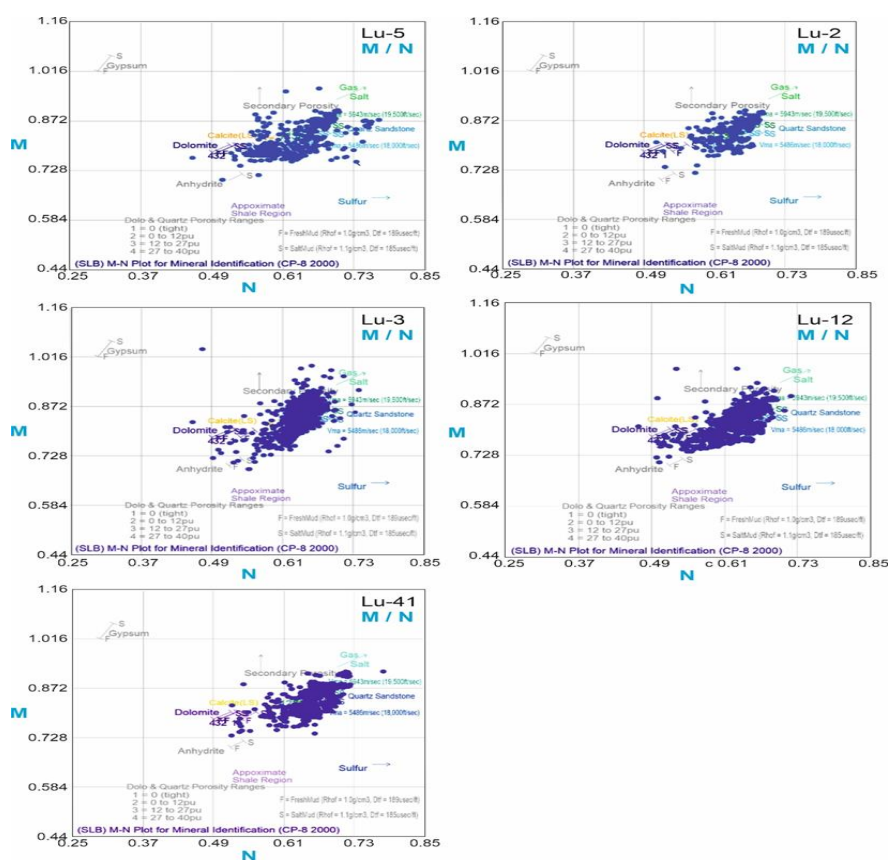


Fig. 4. M-N Cross plot for the studied wells

5.3. Computer Processed Interpretation (CPI)

The CPI of wells delineates the vertical distribution of borehole logs and petrophysical parameters, including clay content, effective porosity, and water saturation, while also assessing the net yield. The caliper log was used to identify intervals of cavities (shale). These logs helped in distinguishing productive from non-productive intervals and correlating them with the lithological and mineralogical properties of the reservoir, as illustrated in Fig. 5. The Zubair reservoir can be categorized into three major members based on the results of the computer process interpretation, as shown in Figs. 6–9.

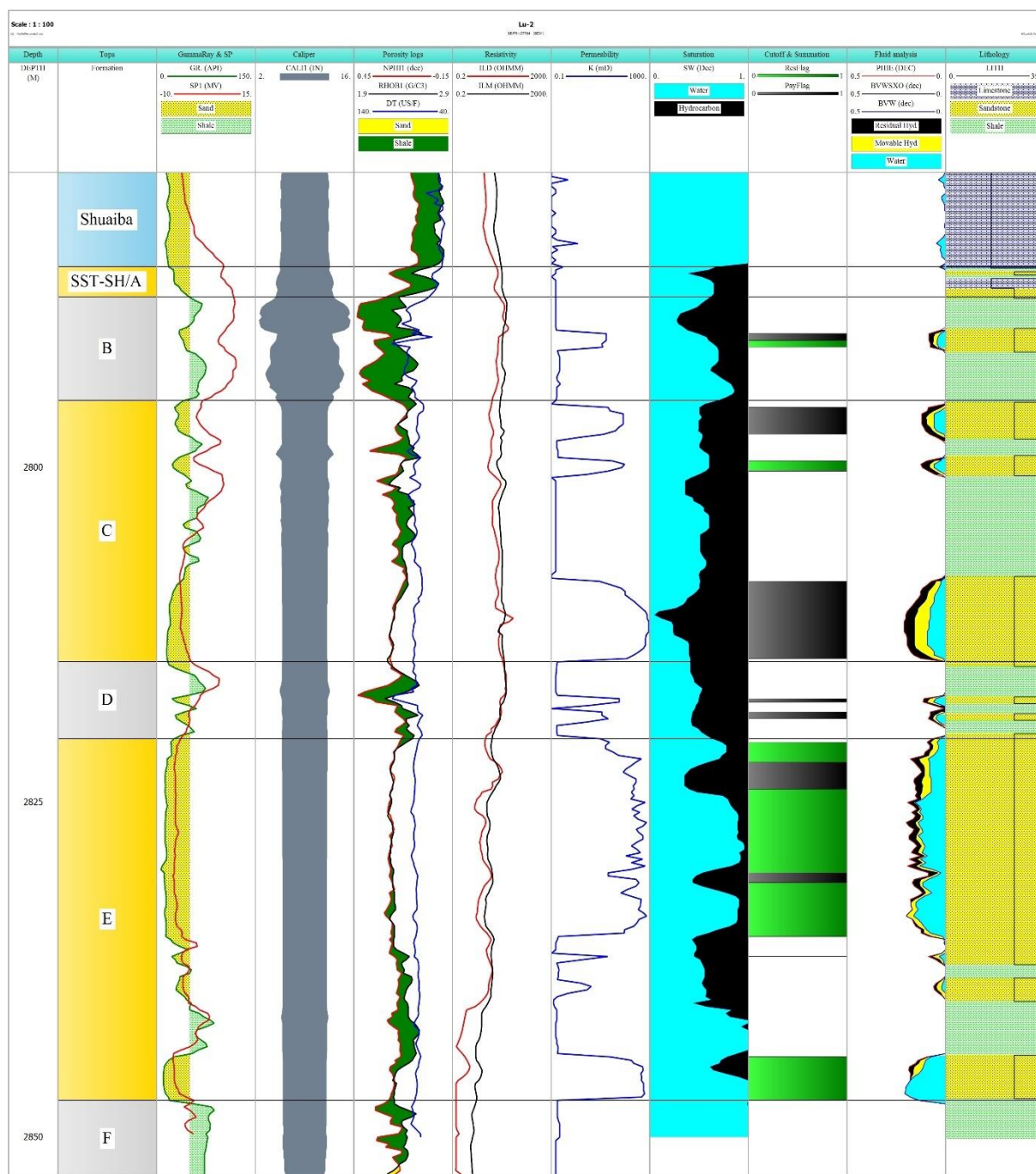


Fig. 5. CPI of the upper member of the Zubair Formation in Lu-2

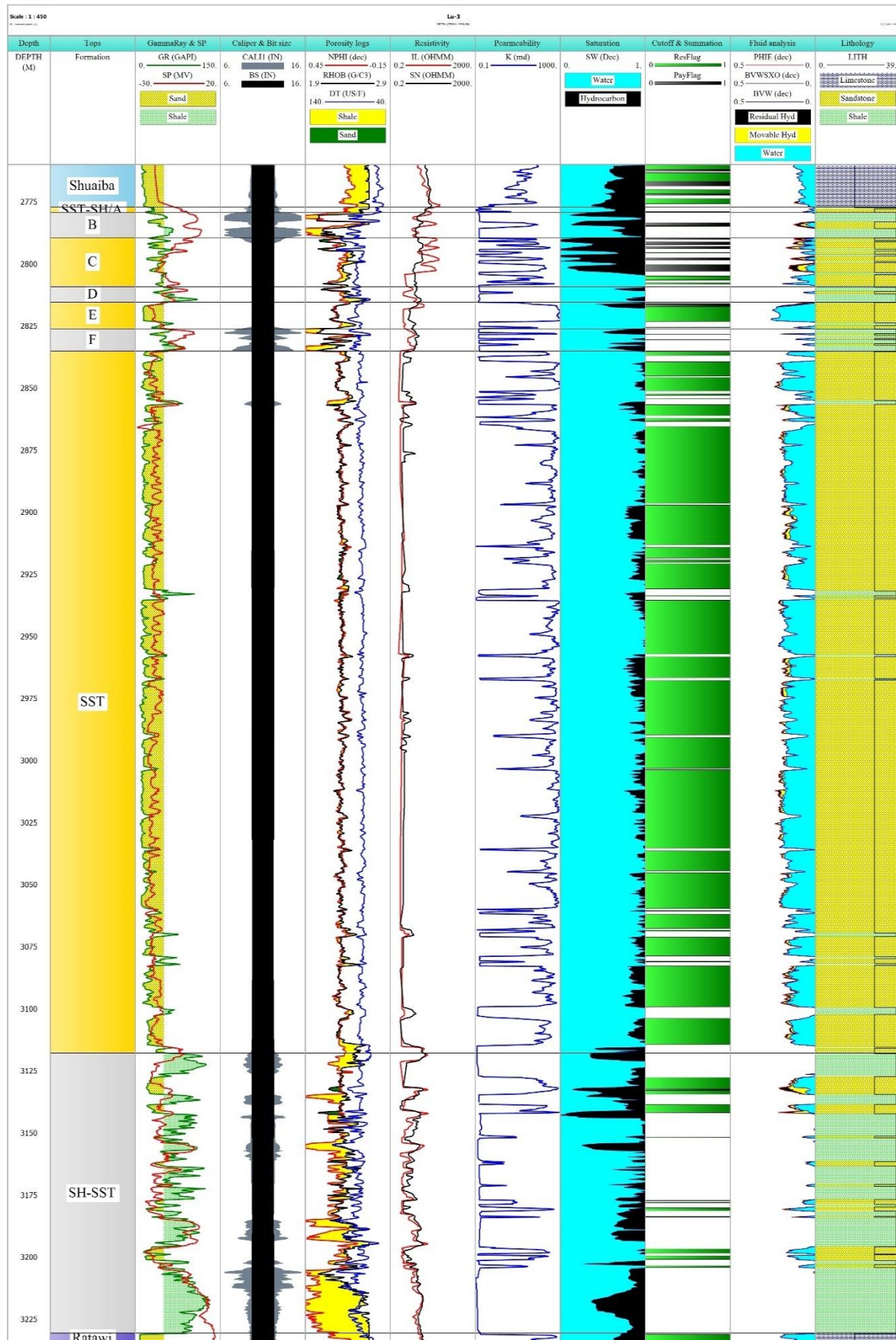


Fig. 6. CPI of the Zubair Formation in Lu-3

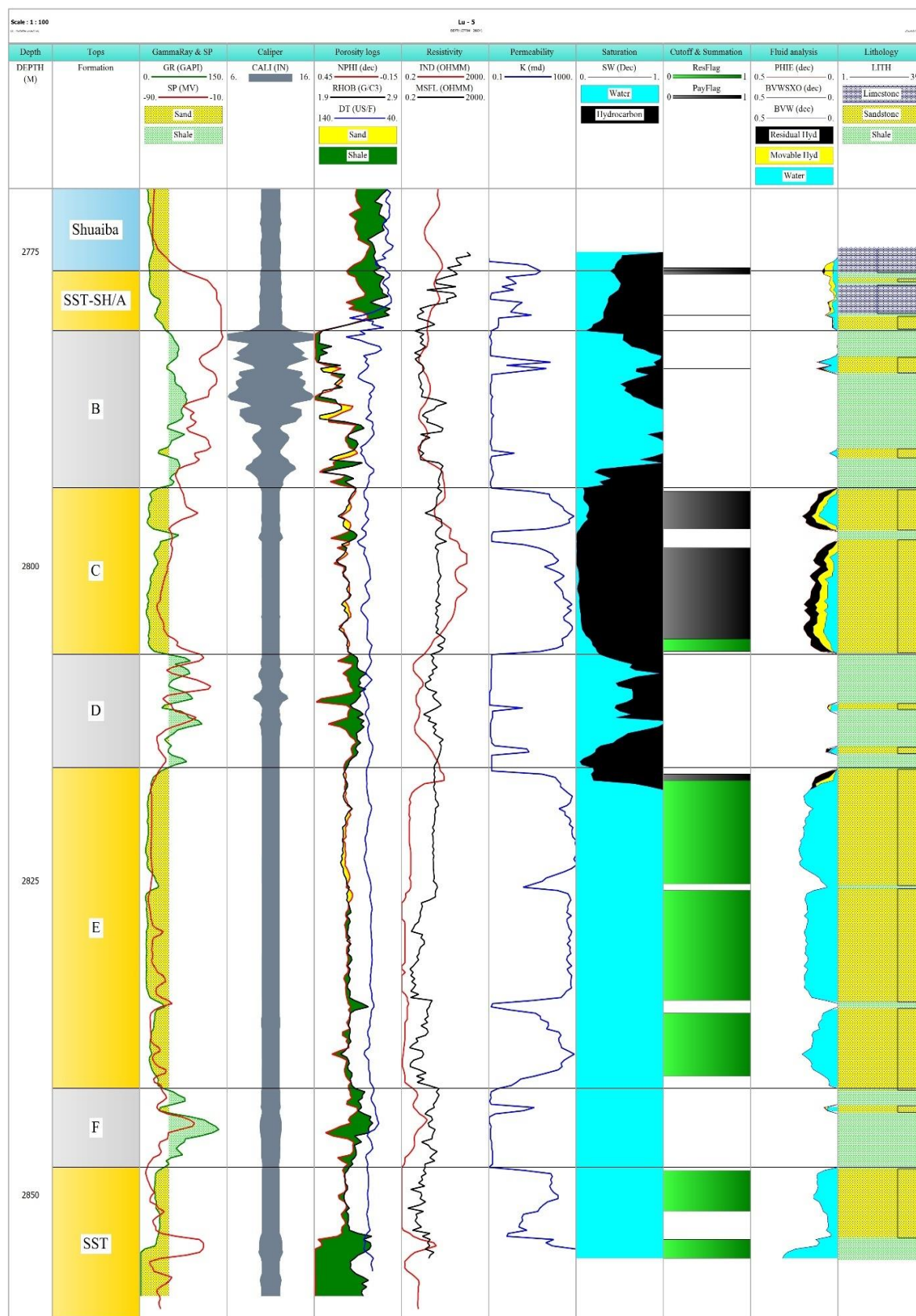


Fig. 7. CPI of the upper member of the Zubair Formation in Lu-5

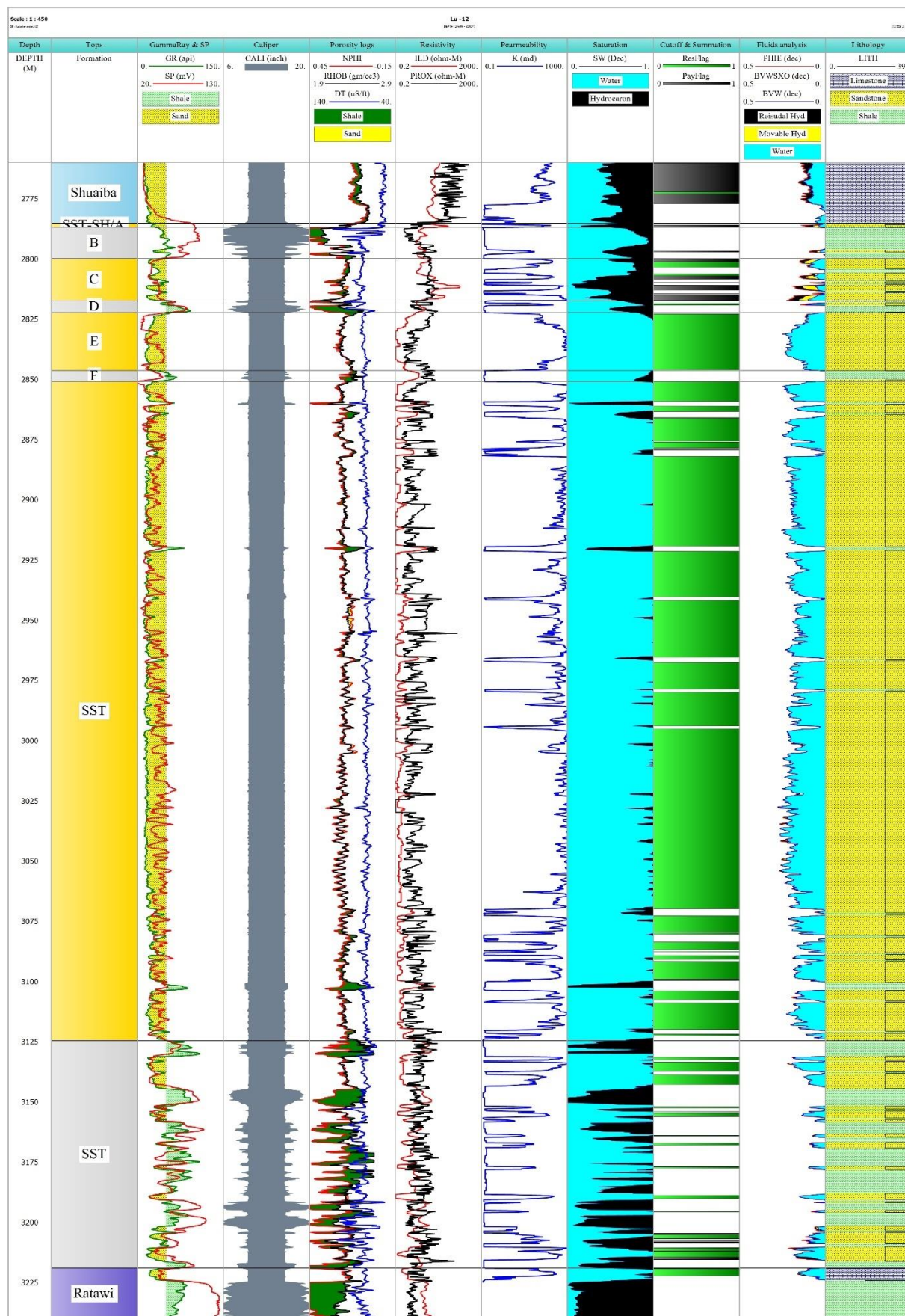


Fig. 8. CPI of the Zubair Formation in Lu-12

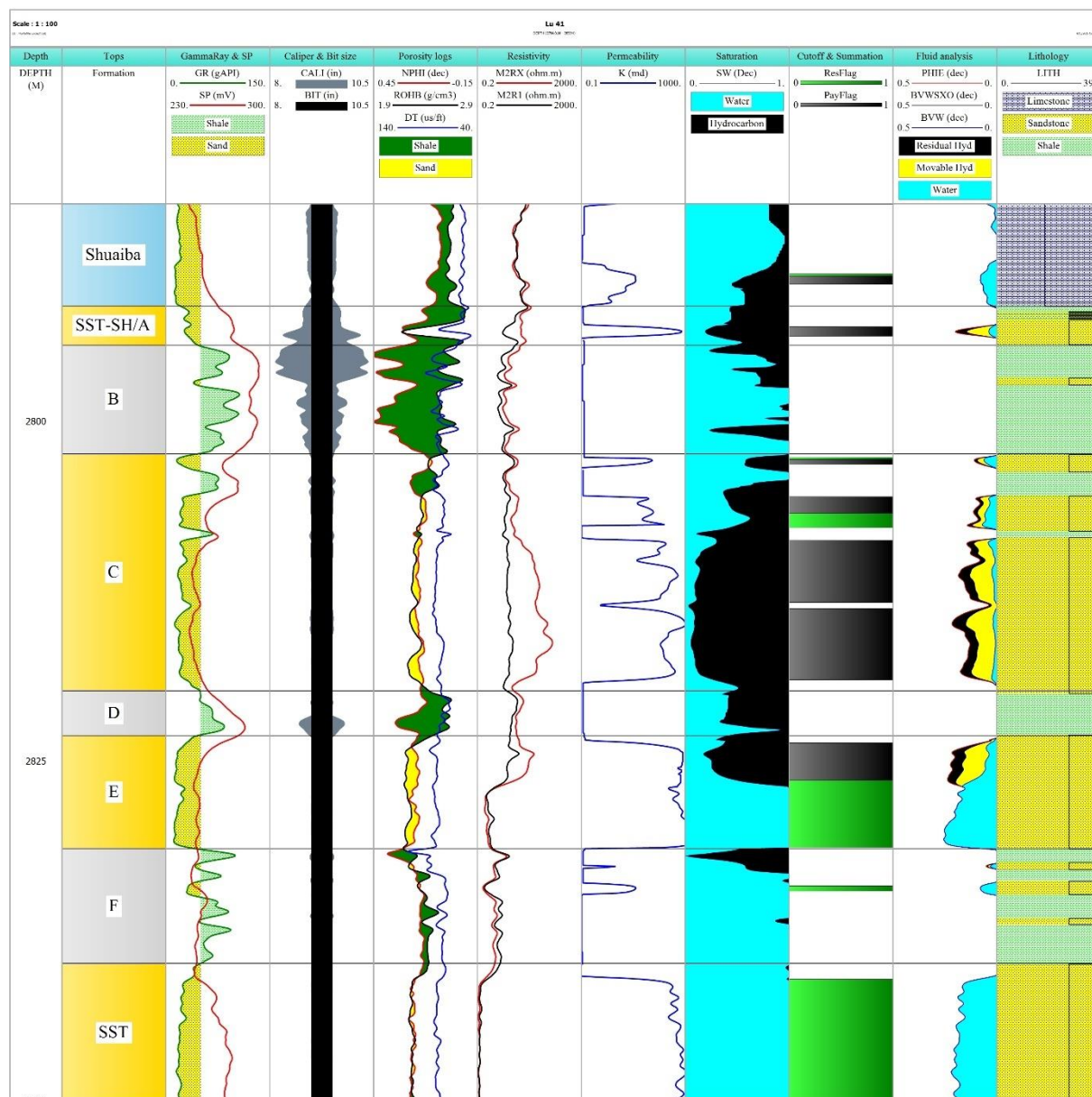


Fig. 9. CPI of the upper member of the Zubair Formation in Lu-41

5.4. Well Correlation

The petrophysical evaluation reveals a clear variation in net yield and reservoir quality among the five wells studied. Stratigraphic correlations confirm good lateral continuity of the main reservoir units, particularly Unit C, with thickness ranging from 13.5 m in Lu-5 to 20.0 m in Lu-2, reflecting acceptable horizontal continuity for this unit across the field. In contrast, Unit E exhibits the highest lateral variation in gross thickness, ranging from 8.31 m in Lu-41 to 27.0 m in Lu-2. These stratigraphic correlations and petrophysical characteristics explain the differences in productivity between the wells. The variations are primarily attributed to the different structural positions of the wells on the Luhais anticline and to the contrasting depositional environments, as illustrated in Fig. 10.

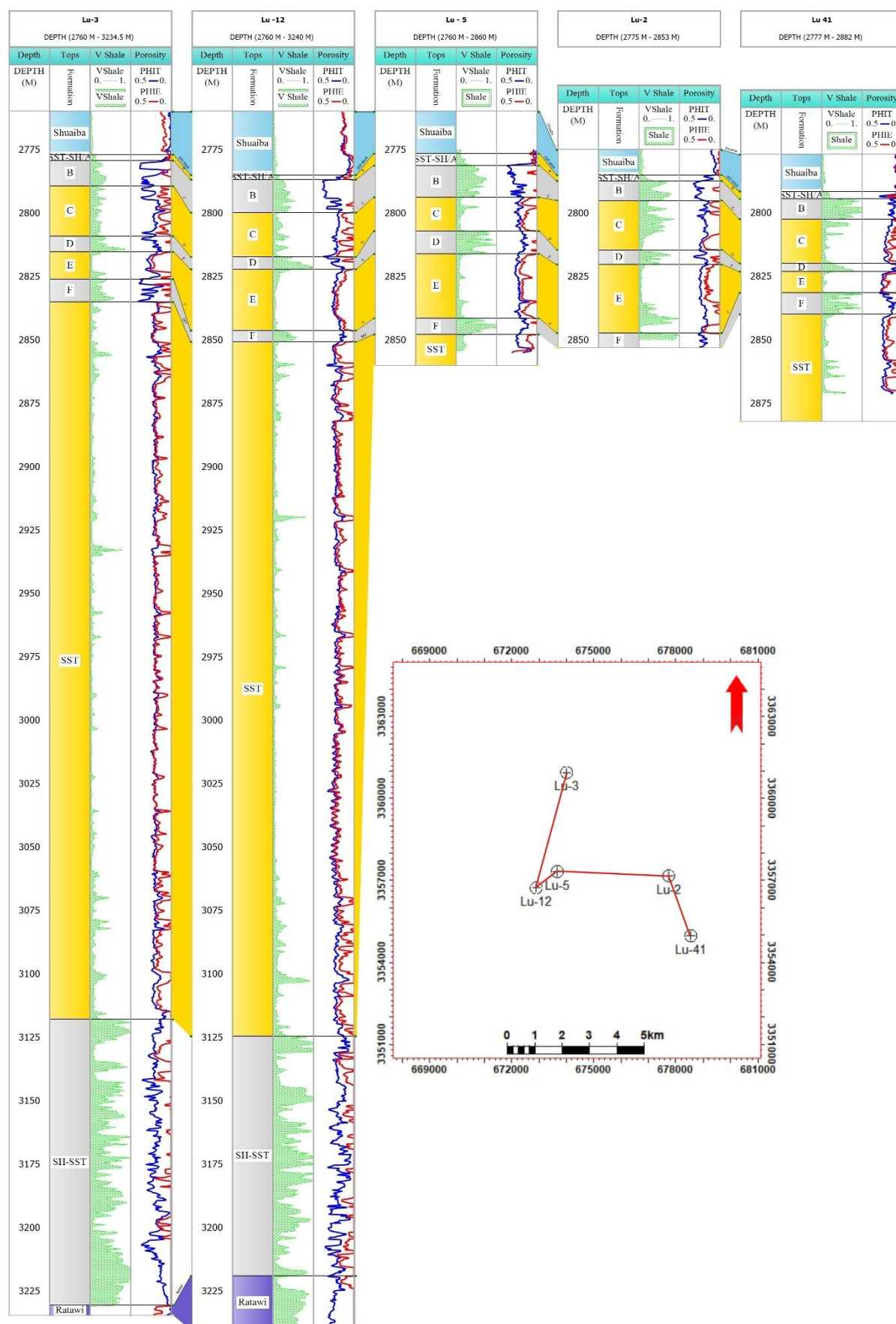


Fig. 10. Correlation Profile of the Zubair reservoir members and units in Lu-2, Lu-3, Lu-5, Lu-12, and Lu-41

Table 1 provide calculated averages of petrophysical parameters only within the net pay thickness, which represents the true reservoir properties of the productive unit. Petrophysical averages (Φ_e , K , S_w , and V_{sh}) were not computed for Units D and F within the upper member and middle member (SST) due to the absence of net pay intervals in any of the wells studied.

Table.1 average reservoir properties and net pay thickness of the Zubair reservoir in the Luhais oil field

Well	Units	Thick (m)	Net pay (m)	PHIE %	K (md)	Vsh %	Sw %	Sh %
Lu-2	upper member (SST-SH) unit (A)	2.25	0	-	-	-	-	-
Lu-3		2.25	0.25	7	11	31	55	45
Lu-5		5	0.38	8	18	28	42	58
Lu-12		1.75	0.88	11	80	25	20	80
Lu-41		2.9	0.76	15	328	27	21	79
Lu-2	upper member (SST-SH) unit (B)	7.7	0.25	8	18	32	59	41
Lu-3		10	1.5	11	48	29	21	79
Lu-5		12.25	0	-	-	-	-	-
Lu-12		13	0.63	9	79	28	41	59
Lu-41		8	0	-	-	-	-	-
Lu-2	upper member (SST-SH) unit (C)	19.5	5.6	21	268	11	30	60
Lu-3		19.75	7.25	17	116	13	19	81
Lu-5		13.5	11	19	273	18	6	94
Lu-12		17.5	7.88	21	318	17	34	66
Lu-41		17.45	11.73	20	222	21	15	85
Lu-2	upper member (SST-SH) unit (E)	27	4.5	20	324	19	42	58
Lu-3		10.75	1.25	17	400	11	52	48
Lu-5		25.7	0.75	18	387	17	18	82
Lu-12		24.25	0	-	-	-	-	-
Lu-41		8.31	2.8	20	620	16	28	72
Lu-3	lower member	112.7	1.5	19	574	12	15	85
Lu-12	(SH-SST)	94.5	2.13	16	198	14	38	62

5.5. Reservoir Unit Evaluation

5.5.1. Upper member (SST-SH): Units A-F

Unit A reservoir characteristics of Unit A are weak due to limited net pay thickness and notable well-to-well variation in petrophysical parameters. High water saturation and clay content in most wells reduce production potential. As a result, this unit contributes very little to the productivity of the study area.

Unit B has significant reservoir weaknesses, with almost all of the wells having little to no net pay thickness. The relatively high shale content and water saturation have negatively influenced both porosity and permeability. This unit is regarded as poor and unsuitable for productive development.

Unit C provides the most optimal reservoir unit in the Zubair reservoir within the research area. It is distinguished by substantial net pay thickness and evident lateral continuity within wells. This unit shows favorable effective porosity and enhanced permeability values, along with relatively low water saturation, identifying it as the primary production unit. These properties confirmed remarkable

lithological quality and a sandstone-dominated lithology, show its higher efficiency compared with other units. This confirms that environmental factors played a role in this improvement, and it may have been deposited in a delta-front to distributary-channel environment.

Unit D seem to be an absolute absence of net pay in all studied wells, indicating that it is a cap rock or a non-reservoir unit. This is generally because its result of high shale content, which acts as a barrier within the stratigraphic sequence.

Unit E exhibits good reservoir properties, containing clean, porous, and highly permeable sandstone with low shale content. However, most of its thickness is water-saturated, with hydrocarbons present only at specific net pay thicknesses, and an oil-water contact is show within the unit. Therefore, its productivity is limited because of high water saturation.

Unit F is unproductive because little to no net pay thickness was determined in any of the wells. These results show that the rock quality is low, and it is unable to hold hydrocarbons, making this unit undevelopable.

5.5.2. Middle member (SST)

The middle part primarily consists clean sandstone with high water saturation, which limits oil production. This member has only been penetrated in wells Lu-3 and Lu-12 among all wells drilled to date, restricting its ability to be studied across the field.

5.5.3. Lower member (SH-SST)

The lower part predominantly consists of shale, showing only minor net pay thickness. Having been reached by only two wells (Lu-3 and Lu-12), these poor properties indicate that this member has limited production capacity across the current study field.

6. Conclusions

The Zubair Formation is divided into three main members (upper, middle, and lower) based on the petrophysical interpretation of well log data from five wells (Lu-2, Lu-3, Lu-5, Lu-12, and Lu-41) in the Luhais Oil Field, with the Upper Member comprising six units (A-F). This study demonstrates that the Zubair Formation consists of sandy clastic rocks, as validated by the NPHI–RHOB cross-plot, and that the majority of the mineral composition is quartz, as indicated by the M–N cross-plot analysis. Unit C in the Upper Member (SST-SH) represents the main production interval; it accounts for approximately 70-85% of the total net pay in the study area, with an average PHIE of 20% and an average permeability (K) of 239 mD. In contrast, Unit E has good porosity and permeability, but its high water saturation restricts its local reservoir quality. Units A and B exhibit weak properties, while Units D and F are non-reservoir intervals. Due to high water saturation and inadequate well management, the Middle and Lower Members contribute minimally to production in the study area.

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